Agricultural Water Management 143 (2014) 131–141

Contents lists available at ScienceDirect

Agricultural Water Management

journal homepage: www.elsevier.com/locate/agwat

Modeling water flows in a serial irrigation reservoir system considering irrigation return flows and reservoir operations

Mingoo Kang[a,*], Seungwoo Park[b]

[a] Future Resources Institute, Woolim Lions Valley C-405, 371-28 Gasan-dong, Keumcheon-gu, Seoul, 153-786 South Korea
[b] Department of Rural Systems Engineering, Research Institute for Agriculture and Life Sciences, Seoul National University, Seoul, South Korea

ARTICLE INFO

Article history:
Received 1 February 2014
Accepted 3 July 2014
Available online 3 August 2014

Keywords:
Serial irrigation reservoir system
Irrigation return flow
Joint operation
Irrigation water management
Water supply capacity
Operation rule

ABSTRACT

A water flows network modeling system was constructed to quantify water flows in the Balan Watershed, South Korea, which has two serial irrigation reservoirs. A modified version of the Synthetic Streamflow and Reservoir Regulation (SSARR) model was used to simulate the water flows, taking into account irrigation return flows and reservoir operations. The model parameters were calibrated using a heuristic search method, Shuffled Complex Evolution method developed at the University of Arizona (SCE-UA). The simulated streamflows and reservoir water levels were in good agreement with the observed. The irrigation return flows from paddy fields considerably affected the flow regimes of the streams. Specifically, the return flow rates of the irrigation water ranged from 28.0% to 35.0%. In addition, the water supply capacities of the irrigation reservoirs were evaluated using the modeling system, and joint operation rules were assessed. The results showed that these could have negative influences on the water supply of existing irrigation districts, and the potential effects of these rules on water management should be investigated. The modeling system is useful for identifying the states of water flows in multiple irrigation reservoir systems and for providing information about reservoir operations to water managers and stakeholders.

1. Introduction

The purpose of irrigation reservoirs is to supply specific irrigation districts with required amounts of irrigation water in a timely and efficient manner. However, changes in socio-economic systems, ecosystems, climate, and water demands have altered water usage and water supply priorities (Cai and Wang, 2006; Rani and Moreira, 2010; Yoo et al., 2013). The initial physical characteristics of irrigation reservoirs and their operation rules can be modified to adapt to these changing circumstances. For example, sustainability has been incorporated into irrigation water management, which can be defined as managing irrigation water in an economically efficient and socially equitable manner, considering the conservation of the environment and ecosystems (Pereira et al., 2012). The amount of irrigation water usage has increased globally and accounts for about 70% of the amount of total water withdrawals (Rani and Moreira, 2010). Effective water management policies, such as water-saving practices, water reallocation, joint operations of multiple reservoir systems, and hedging rules, have been developed and implemented to meet the changing goals and objectives of water management (Labadie, 2004; Raje and Mujumdar, 2010; Pereira et al., 2012; Guo et al., 2013; You, 2013).

To ensure a stable supply of irrigation water and to operate irrigation reservoirs efficiently, variations of inflows and demands of irrigation districts for irrigation water need to be accurately predicted. Particularly, in cases of multiple irrigation reservoir systems that consist of several components, such as sub-watersheds, irrigation reservoirs, irrigation districts, and channel reaches, water flows between the components must be analyzed (Hwang et al., 2009; Lee et al., 2012b). The runoff characteristics of watersheds that include the systems differ from the natural states, in which runoff is determined by the simple relationship between rainfall and runoff, due to irrigation return flows and reservoir operations (Lee et al., 2012a). Irrigation return flows can influence the flow regimes of rivers. The operation of irrigation reservoirs and water intake downstream can have a considerable impact on water quantity and water quality (Dewandel et al., 2008; Kim et al., 2009; Lin and Garcia, 2012; Yakirevich et al., 2013). Therefore, simulation models and empirical equations of river flows are needed to estimate runoff from the watersheds, considering the effects of the irrigation return flows and reservoir operations.

Simulation models of reservoir operations, such as the Hydrologic Engineering Center-5 (HEC-5), MODified SIMyld (MODSIM), and Multireservoir Simulation and Optimization Model (SIM-V), generally use historical streamflow data (Martin, 1982; Jain et al.,

* Tel.: +82 1034299199; fax: +82 232810427.
E-mail addresses: kmg1218@gmail.com, kmg901@hanmail.net (M. Kang).

http://dx.doi.org/10.1016/j.agwat.2014.07.003
0378-3774/

1998; Dai and Labadie, 2001). When the quality of the data pertaining to the observed inflows is not assured, inflow data are generated using hydrologic models. River basin network models, such as the SSARR [US Army Corps of Engineers (USACE), 1991], National Weather Service River Forecast System (NWSRFS) (Panagoulia, 1992), Precipitation Runoff Modeling System (PRMS) (Evers et al., 1998), Soil and Water Assessment Tool (SWAT) (Wu and Liu, 2012), and Hydrologic Simulation Program-FORTRAN (HSPF) (Göncü and Albek, 2010), have been used to simulate water resource system operations in river basins. Among these, the SSARR model has been employed to simulate runoff in large river basins, such as the Columbia River (Rockwood, 1961), the Mekong River (Rockwood, 1968), and the South Saskatchewan River (Axelson et al., 2009), as well as in several watersheds (Cundy and Brooks, 1981; Brendecke et al., 1985). With regard to simulations of water flows in river basins that have multiple reservoir systems and irrigation districts, the model has been utilized to simulate the runoff in the Han River basin and to establish a joint operation plan for its multiple reservoir system (Lee et al., 2012b). The accuracy of the model was improved by incorporating irrigation water use of small-scale water resource facilities and their return flows into a hydrologic modeling system of the Geum River basin (Lee et al., 2012a).

In this study, a modeling system was constructed to quantify water flows in multiple irrigation reservoir systems and to simulate their operations. The system integrates the SSARR model with an irrigation water demand estimation submodel. It incorporates a global parameter optimization method, SCE-UA which automatically calibrates the parameters of the SSARR model. The modeling system was used to simulate the runoff from a watershed containing two serial irrigation reservoirs, and its prediction capability was validated. The water supply capacities of the reservoirs were then analyzed using the modeling system, and the simulation results were employed to assess joint operation rules.

2. Methods

2.1. Process of runoff

In the SSARR model, cascades of conceptual reservoirs are employed to route flows from watersheds and rivers, assuming that flows propagate to the outlets through a series of n conceptual reservoirs (USACE, 1991). The model synthesizes four components of runoff: surface flow, subsurface flow, base flow, and lower zone flow, with which to estimate the runoff at the outlet of a watershed. Specifically, base flow and lower zone flow are viewed as shorter-term and longer-term parts of the base flow component, respectively. Several methods are used to separate each component from precipitation and snowmelt. First, the sum of precipitation and snowmelt is categorized into soil water and runoff using the relationship between the soil moisture index and the runoff percent (SMI-ROP). Second, the runoff is classified into upper and lower level runoff using the relationship between the base flow infiltration index and the percent of runoff to base flow (BII-BFP). Third, the upper level runoff is divided into surface flow and subsurface flow using the surface-subsurface separation function (S-SS). Finally, the lower level runoff is split into base flow and lower zone flow using the rate of lower zone flow to total base flow. The runoff of each component can be estimated by independent routing. The four components are then synthesized into the amount of runoff at the outlet of a watershed during each period.

2.2. Simulation of irrigation return flows

Hydrologic processes in irrigation districts are complex, as they are affected by irrigation water management customs, which are related to several factors, such as weather conditions and the available labor force. Particularly, irrigation, drainage, evapotranspiration, infiltration, and rainfall influence the water budget in a paddy field (Fig. 1(a)). In watersheds that include irrigation districts, considerable amounts of seepage and operational losses of irrigation water return to drainage canals, streams, and rivers. The water then flows downstream where it can be reused for irrigation (Fig. 1(b)). There are two types of irrigation return flow, specifically: quick return flow and delayed return flow. Quick return flow is the sum of conveyance losses from canal systems, spilled irrigation water from paddy fields, and seepage of irrigation water through bunds. Delayed return flow is the discharge of groundwater recharged by the percolation of irrigation water (Kim et al., 2009) (Fig. 1(b)). When simulating irrigation return flows using the SSARR model, quick return flow was simulated with a specific ratio of irrigation water running directly into a river; in the case of delayed return flow, it was assumed that the estimated amount travels through a pseudo-drainage channel for a long time. Related parameters were calibrated by comparing the observed streamflow data and the simulation results.

2.3. Estimation of irrigation water demands

The SSARR model simulates reservoir water levels and storage amounts of irrigation reservoirs during a specified period. The outflow is computed by summing up the amounts of diverted irrigation water and overflow through a spillway (USACE, 1991). The SSARR model was modified by incorporating an irrigation water demand estimation submodel into the modeling system to fix the amount of diverted irrigation water. The irrigation water demand estimation submodel predicts the demands of irrigation districts for irrigation water during the growing season as follows:

$$\mathrm{EDIW}_t = (\mathrm{EWR}_t + \mathrm{MWR}_t + \mathrm{WRPT}_t) \Big/ \left(1 - \frac{\mathrm{DL}}{100}\right) \times \frac{\mathrm{AID}}{1000} \quad (1)$$

where EDIW is the estimated demand for irrigation water from an irrigation district (m^3), t is the computation day, EWR is the estimated water requirement for growing paddy rice in a paddy field (mm), MWR is the minimum water requirement for maintaining canal flow (mm), WRPT is the water requirement for puddling and transplanting paddy rice in a paddy field from nursery beds (mm), DL is the delivery loss (%), and AID is the area of the irrigation district (m^2). The daily EWR value is estimated by computing the gap between the recommended and actual ponding water depths in the paddy field, which are the optimal condition for the growth of paddy rice during each cropping period in South Korea (Kim and Park, 1994) and the real condition maintained by a farmer (Fig. 2), as follows:

$$\mathrm{EWR}_t = \mathrm{RPWD}_t - \mathrm{APWD}_t \quad (2)$$

where RPWD is the recommended ponding water depth (mm), t is the computation day, and APWD is the actual ponding water depth (mm). When the actual ponding water depth draws down below the recommended ponding water depth, a farmer needs to supply water, EWR, to a paddy field and to maintain the actual ponding water depth at the recommended ponding water depth. The actual ponding water depth was computed using a water balance equation for a paddy field (Fig. 1(a)) as follows:

$$\mathrm{APWD}_t = \mathrm{APWD}_{t-1} + \frac{\mathrm{IN}_t + \mathrm{IN}_{t-1}}{2} - \frac{\mathrm{OUT}_t + \mathrm{OUT}_{t-1}}{2};$$

$$\mathrm{IN} = \mathrm{IRRI} + \mathrm{RAIN};$$

and

$$\mathrm{OUT} = \mathrm{EVAP} + \mathrm{SURDR} + \mathrm{INF} \quad (3)$$