IRRIGATION AND DRAINAGE
Irrig. and Drain. **65**: 57–65 (2016)
Published online 5 April 2016 in Wiley Online Library (wileyonlinelibrary.com) **DOI**: 10.1002/ird.1992

IRRIGATION CANAL NETWORK FLOW ANALYSIS BY A HYDRAULIC MODEL†

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ABSTRACT

For agricultural water management to be successfully achieved, flow analysis of irrigation canal network flows is essential to determine the proper distribution of crop water requirements and to contribute to an optimized irrigation operation and water allocation. This study developed a hydraulic analysis model for irrigation canal flow by using the Storm Water Management Model (SWMM) module by adding the network modelling and paddy water balance model. This model was applied to a rice paddy field rehabilitation project area in the Daesan District located in the western part of South Korea. Results obtained from the calibrated simulation model were compared with the actual measurement data from water-level gauges at the irrigation canals. The irrigation hydraulic analysis model for canal network flow indicates the significance of using irrigation management tools in improving the analysis for accurate irrigation scheduling based on its simulation results, such as flow travel time, water level and flow amount. Copyright © 2016 John Wiley & Sons, Ltd.

KEY WORDS: agricultural water management; hydraulic model; irrigation canal; network modelling; SWMM

Received 27 October 2015; Revised 23 November 2015; Accepted 23 November 2015

ABSTRACT

Pour la réalisation réussie de la gestion de l'eau agricole, il est essentiel d'analyser les écoulements dans les canaux d'irrigation, afin d'optimiser le fonctionnement du système d'irrigation et d'améliorer l'allocation de l'eau en fonction de la répartition des cultures. Cette étude a élaboré un modèle d'analyse hydraulique de l'écoulement des canaux d'irrigation en ajoutant la modélisation en réseau et un modèle de bilan hydrique du riz à un module du modèle de gestion des eaux pluviales (SWMM). Ce modèle a été appliqué à une rizière en réhabilitation dans le district de Daesan (ouest de la Corée du Sud). Les résultats obtenus après calibrage du modèle ont été comparés pour validation avec les données de jaugeage dans les canaux d'irrigation. Le modèle d'analyse hydraulique des flux de réseau de canaux d'irrigation montre l'importance d'utiliser des outils de gestion de l'irrigation pour améliorer la planification de l'irrigation en se basant sur des résultats de simulation, tels que le temps de transit, le niveau de l'eau et le flux.

MOTS CLÉS: gestion de l'eau agricole; modèle hydraulique; canal d'irrigation; modélisation du réseau; SWMM (modèle de gestion des eaux pluviales)

INTRODUCTION

Agricultural water operation and management can be defined as a combination of agricultural infrastructure maintenance and decisions about the quantity of the water supply at the appropriate time for higher productivity of crops and draining off excess water in times of flooding (Hsu and Cheng, 2002; Chen and Goldscheider, 2014). Irrigation systems in South Korea have been built and maintained based on the design frequency to withstand a 10-year drought (Nam *et al*., 2015). In the case of agricultural infrastructure, approximately 56% of agricultural facilities (39 000 out of 69 000 locations) are over 30 years old and have deteriorated considerably. Moreover, the percentage of areas that can withstand drought for the designed criteria is 52.9%

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†Analyse des écoulements dans un réseau de canaux d'irrigation par un modèle hydraulique.

(Ministry of Agriculture Food and Rural Affairs (MAFRA), Korea Rural Community Corporation (KRC) (2011)). There has been a management problem caused by infrequent maintenance of the designed canal capacity and operation of irrigation systems relying on traditional experience. For successful agricultural water management, irrigation canal network flow analysis is essential to determine the proper distribution of crop water requirements, and to contribute to an optimized irrigation system operation and water allocation. Therefore, a decision-making support system based on a simulation model is needed to improve agricultural water management and to allow decision makers and stakeholders to implement appropriate operational strategies.

Traditionally, hydraulic simulation models of an irrigation area are used for water resources planning and management (Al-amin and Abdul-aziz, 2013; Shrestha *et al.*, 2013) and for determining proper irrigation and drainage strategies by calculating water requirements (Bayat *et al.*, 2011; Karamouz *et al.*, 2011). In South Korea, HOMWRS (Hydrological Operation Model for Water Resources System), a reservoir operation model, has been frequently used for managing irrigation systems. However, a canal flow simulation model has not often been applied to achieve higher distribution efficiency and proper irrigation water allocation.

In this study, the network modelling function and paddy water balance simulation function were combined to develop a hydraulic analysis model for irrigation canal flow by using the Storm Water Management Model (SWMM) module, which provides a hydraulic analysis for rainfall and water flow in canals of city areas. A set of nodes and links was used to form the irrigation network for the network modelling process, and the irrigation block data, including the area, soil and crop characteristics, were prepared for the model input. The developed model was applied to Daesan Irrigation District, located in the western part of South Korea, where there was a rice paddy field rehabilitation project area.

BASIC THEORY

Theory of hydraulic analysis in a canal section

The fundamental equation of flow is the continuity equation and one-dimension equation for gradually varied unsteady flow in open canals, where the following Saint-Venant equation is used. In the case of hydraulic analysis at a confluence, the calculation of surcharge, the counter-current, drainage and loop shape flow are available (Bae and Jang, 2009). Additionally, the water level and flow at nodes and links composing the canal network were calculated depending on each interval of operation time (Lee *et al.*, 2010).

$$\frac{\partial Q}{\partial t} + \frac{\partial A}{\partial t} = 0 \tag{1}$$

$$\frac{\partial Q}{\partial t} + \frac{\partial\left(\frac{Q^2}{A}\right)}{\partial t} + \mathrm{g}A\frac{\delta H}{\delta x} + \mathrm{g}AS_\mathrm{f} = 0 \tag{2}$$

where S_f is the friction slope of the canal (dimensionless), x the canal length (m), t the time (s), A the cross-sectional area of flow (m^2), Q the canal flow (m^3 s^{-1}), and n the canal's coefficient of roughness (dimensionless).

Parameters such as the coefficient of roughness, the cross-sectional area, the hydraulic radius and the canal length are associated with the link. For numerical stability of the numerical analysis, the length of the canal is converted to the equivalent length. The friction slope in the SWMM-Extran block was calculated by an equation converted from the Manning formula, as follows:

$$S_\mathrm{f} = \frac{K}{\mathrm{g}AR^{4/3}}Q\left|V\right| \tag{3}$$

where R is the hydraulic radius (m), K is gn^2 and A the cross-sectional area of flow (m^2).

Equation 3 is substituted into the Saint-Venant equation and the following momentum equation, Equation 4, is derived (Islam *et al.*, 2008). The momentum equation is used as a fundamental hydraulic equation for the link. Flow is the important independent variable in the link for each interval of the operational section. The equation is written as follows:

$$Q_{t+\Delta t} = \frac{1}{1+\frac{K\Delta t}{R^{4/3}}\left|V\right|}\left[Q_t + 2\overline{V}\left[\frac{\Delta A}{\Delta t}\right]_t\Delta t + \overline{V^2}\frac{A_2-A_1}{L}\Delta t - \mathrm{g}\overline{A}\frac{H_2-H_1}{L}\Delta t\right. \tag{4}$$

where the flow velocity $\left|V\right|$ (m s^{-1}) is the weighted average values at both ends of the link when the time is t.

Nodes indicate the presence of structures or junctions in the canal system. Based on the flow at the link, the water level in the nodes can be calculated by the following continuity equations:

$$\frac{\partial H}{\partial t} = \frac{\sum Q_t \Delta t}{A_\mathrm{s}} \tag{5}$$

$$H_t + \Delta t = H_t + \frac{\sum Q_t \Delta t}{A_\mathrm{s}} \tag{6}$$

where H is the depth of water (m) and A_s is the water-surface area of the mode (m^2).

Using the continuity and momentum equations, both the water depth of the node at each operation time section (Δt) and the flow at the link can be calculated numerically using the explicit finite difference method. The important independent variable of the node is the water level.

Hydraulic analysis theory of sluice gates

In the case of water outflow from a sluice gate (diversion gate and regulating gate) in irrigation canals, the flow coefficients may change depending on the type of gate. According to the flow condition at the sluice gate, there could be a submerged outflow. The flow out from the bottom of the sluice gate in the outflow case is supercritical, causing a hydraulic jump when it meets the slow-flowing water downstream. In the submerged outflow case, the flow out from the bottom of the sluice gate goes under the water surface. The different flow equations for water outflow at sluice gates have been introduced. This study adds the function of flow analysis at the sluice gate by using Equation 7:

$$Q = C_a{*}b{*}d\sqrt{2gh_1} \tag{7}$$

where Q is the quantity of water (m^3s^1), C_a the flow coefficient, b the width (m), d the height (m) of the gate, and h_1 the upstream water level of the gate (m).

Water balance theory in a paddy field

The water consumed in fields comes from evapotranspiration, infiltration and rainfall. The field is treated as a tank that has a water surface causing evapotranspiration and an infiltration ditch on the bottom. This study is developed to conduct a water balance study in paddy fields by adding a node element of the canal network to the SWMM hydraulic simulation module using Equation 8:

$$\begin{aligned} D(t) = {} & D(t-1) + R_a(t) + R_{eq}(t) \\ & - U(t) - SD(t) \end{aligned} \tag{8}$$

where $D(t)$ is the water depth of day t (mm), $D(t-1)$ the water depth of the day before t (mm), $R_a(t)$ the rainfall (mm), $R_{eq}(t)$ the irrigation quantity, $U(t)$ the consumptive use (ET + I), SD (t) the inlet overflow quantity, ET the quantity of evapotranspiration (mm) and I the quantity of infiltration (mm).

The simulation of the hydraulic calculation of inner irrigation canals by using SWMM is possible as well as the ability to set the irrigation time randomly for single or continuous irrigation. The estimation data of evaporation were calculated as a loss before water outflow and infiltration. In this study, , the simulation time interval in Equation 8 was changed to hours or days to solve the simulation interval problem between the SWMM hydraulic calculation and the water balance analysis days. In addition, consumptive use should be deducted as a loss after evaporation and infiltration are divided by the hour.

MATERIALS AND METHOD

Current status of the study area

For the hydraulic analysis of the irrigation canal network, Daesan District was selected as a study area. In Daesan District, a paddy field consoliation project was begun in 1998, and an irrigation system established. However, it was difficult to supply and maintain a sufficient water level during the cultivation season because there was no main water supply facility, and most irrigation canals were earthworks. In 2010 an agricultural irrigation development project in Daesan District started. In addition, 257 ha of field area (served area 231 ha) were extensively consolidated through a project and the main work of the project was canal construction and land readjustment to use the land efficiently and to make agricultural systems mechanized.

Current status of irrigation facilities

According to design specifications, the project area is allocated for the canals: 2.95 km of 8 tertiary canals, 3.57 km of 6 secondary drains and 14.53 km of 43 tertiary drains. There are plans for 12.44 km of 32 tertiary canals, water supply facilities and pumping stations. Current irrigation facilities at Daesan District have one reservoir (Yangoh) and one pumping station (Dangsan). The current status of the Yangoh Reservoir is shown in Table . From an on-field survey and drawings, the existing and recently maintained irrigation canals are estimated to be: 8984 m of 3 main canals (Yangoh 1st, Yangoh 2nd and Dangsan), 3301 m of 4 branch canals (Dangsan 1st, Dangsan 2nd, Dangsan 3rd and Sungrae) and 15 326 m of 41 tertiary canals. In the case of the drains, there are 3568 m of 6 secondary drains (Naegok stream is included in the secondary drains) and 14 969 m of 44 tertiary drains. The Dasong River has its start and end point within the district, and its extension is 3640 m long. In the main stream of the Dasong there are three sluice gates, including the gates at the start and end points. The main water supply in the Daesan District is Yangoh Reservoir, but it covers only 161 ha (approximately 70%), which means it is difficult to secure sufficient water from the reservoir. To secure water, the water stored in drains and streams is pumped to the Yangoh Reservoir through the Yangoh pumping station located in the Dangsong Stream in the rainy season.

The current configuration of the measuring facilities

Regarding the development project of agricultural irrigation, Daesan District had already installed an observation and management system for agricultural water. There are water-level recorders installed at 15 points in 8 places, such as reservoirs, pumping stations, streams and irrigation

Table I. Current status of Yangoh Reservoir in Daesan District

Year of construction	Water storage (1000 t)	Unit storage (mm)	Flood discharge ($m^3 s^{-1}$)	Area served (ha)	Levee (length, height) (m)	Full-water area (ha)
2013	1551	488	35.0	290	201, 18	24.0

canals. Figure 1 shows the location of the devices. The main water supply area, Yangoh Reservoir, was fitted with a water-level recorder and rainfall observation device. There are water-level measuring devices at the start points of Yangoh main canal and Dangsan Main Canal to measure and manage the irrigation amount from the reservoir. In addition, a water-level measuring device is installed in the Dasong Stream, and the Daesan pump station has a measuring device at its entrance. In the case of the Sungrae branch canal, its auxiliary pump station has a measuring device at its oultet. There are eight measuring devices in the canals: one where the Yangoh 1st main canal diverges to the Yangoh 2nd main canal, two where the Yangoh 2nd main canal diverges after passing Dasong Stream, and some where the Dangsan 1st branch canal diverges and where the Dangsan 3rd branch canal diverges.

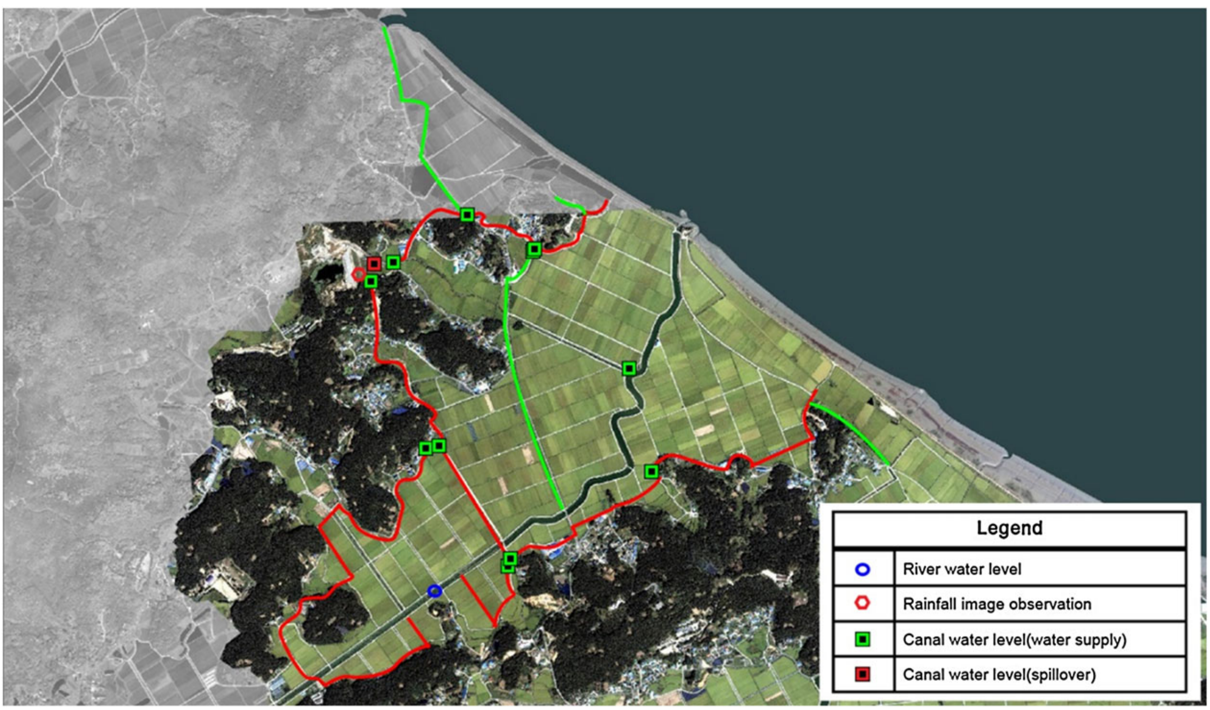

Figure 1. Configuration of the measuring facilities

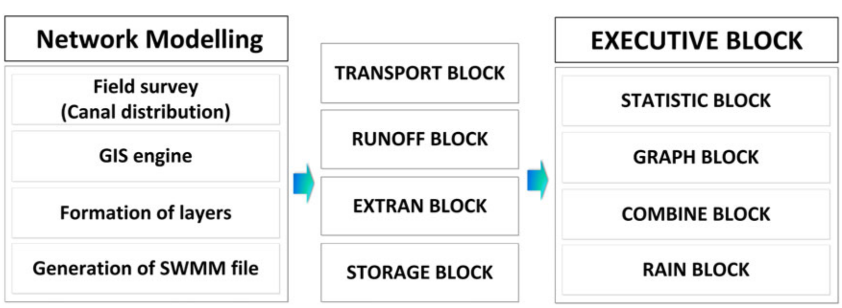

Figure 2. Modelling process

Table II. Network modelling for agricultural facilities

Field	Topographic features	Model features	Remarks
1	Water resource (reservoir)	Node	Storage
2	Water resource (pump station)	Node	Pump
3	Irrigation canal start	Node	Apply to inflow
4	Main canal	Link	Connection of node and node
5	Junction	Node + gate	Control of flow by gate
6	Branch canal	Link	Connection of node and node
7	Tributary junction	Node + gate	Control of flow by gate
8	Sluice gate of a paddy	Link	–
9	Paddy	Node	Storage
10	Unused water	Node	–

Composition of the canal network

Irrigation water is supplied from the agricultural reservoir into the paddies through the branch and tertiary canals, and water on the field flows into the stream through the tertiary, branch and drains.

This study developed a network model using dynamic programming for effective water distribution for optimal irrigation capacity distribution. The network model displays a complicated river valley and water supply system in a network form using nodes and links. The network model optimizes all elements with a network algorithm. The network model simply describes the complicated lines on the field with nodes and links. One of the physical elements of the system, the node, starts from the water supply source, such as a reservoir or a pump station. The node is classified as reservoir node or non-reservoir node. Reservoir nodes are applied at a confluence point where lines are divided or they are located in the irrigation areas of the paddy. On the other hand, non-reservoir nodes are drainage points (or discharge points) and mid-hydrophore points.

Links are used to describe the main canals, branch canals and pipes and connect nodes. Links connect nodes by acting as a flow-transporting canal. The main hydraulic elements are the value of the coefficient of roughness, the length, the cross-section area, the hydraulic radius and the river width. The values, such as the cross-section area, hydraulic radius and river width, are determined as a function of the water depth (Kim and Kim, 2002). The crucial independent variable

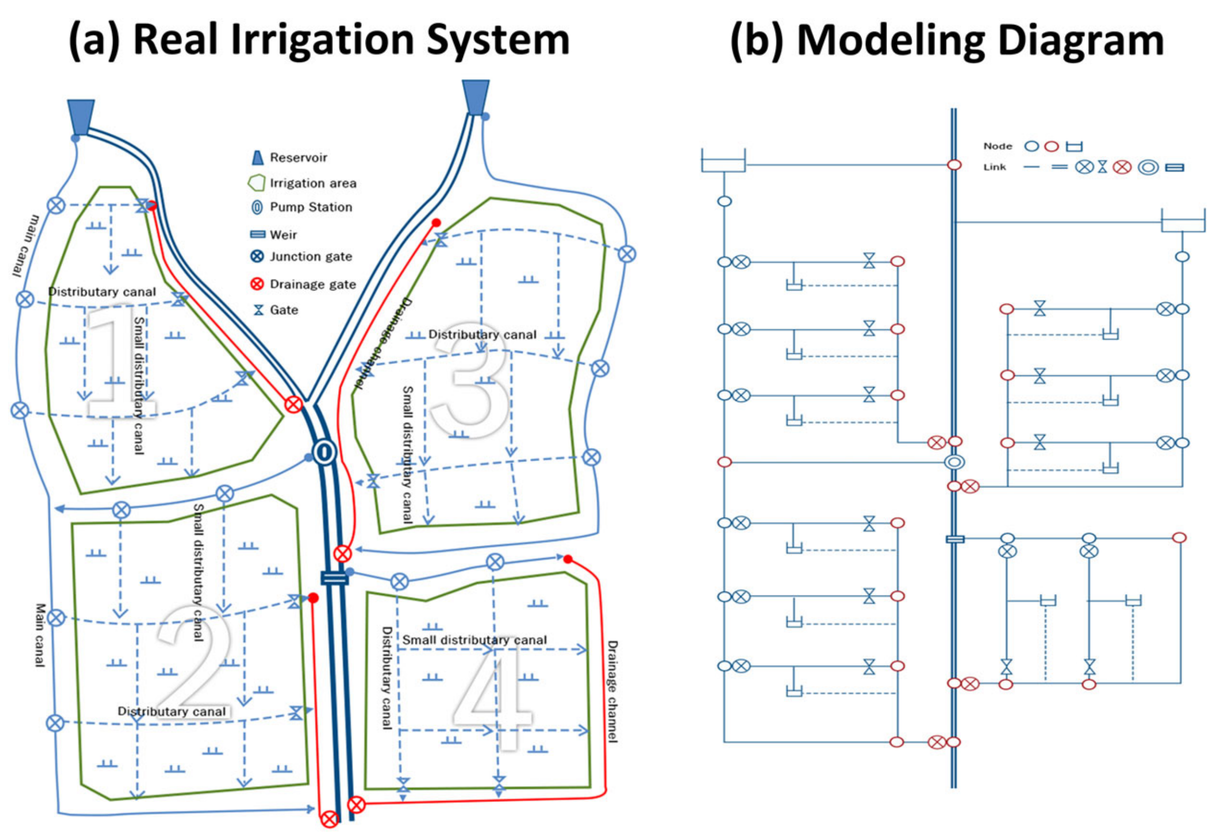

Figure 3. Composition of irrigation canal network modelling

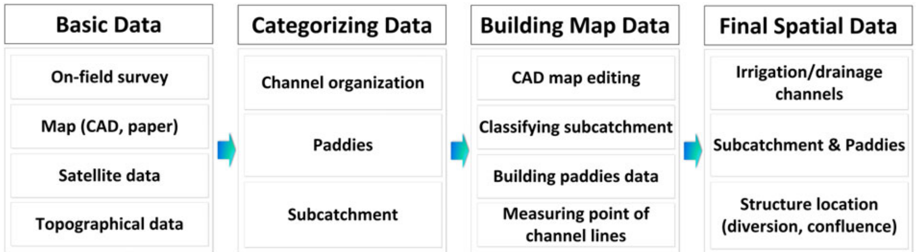

Figure 4. Basic data construction process

in a link is water flow. Numerical integration of the value gives the average flow in the link. The node is the element of junction and reservoir, such as a junction point or a confluence point in the system. The variables related to a node are flow, water depth and water-surface area. The crucial dependent variable is water level.

Development of the canal network model

The basic structure of the model is composed of network modelling and SWMM (Figure 2). Additionally, the analysis model of the water supply in the field and the analysis model of the hydraulic phenomenon at the gate (diversion and regulating gates) are designed to be connected. The network modelling generates input data for the model for gate and hydraulic analysis. Each geomorphic element should have coordinates indicating a real location. Examples of information are canal organization, division from the main canal to branch canals, change of canal size or material, and location of the sluice gate.

Irrigation canal network modelling

The water supply facilities can be classified as open canals and pipe canals. For hydraulic analysis of these irrigation systems, canals and facilities were described by nodes, links and their network (Table 2). The main variables for measurement are the flow or water depth. The main numerical measurements

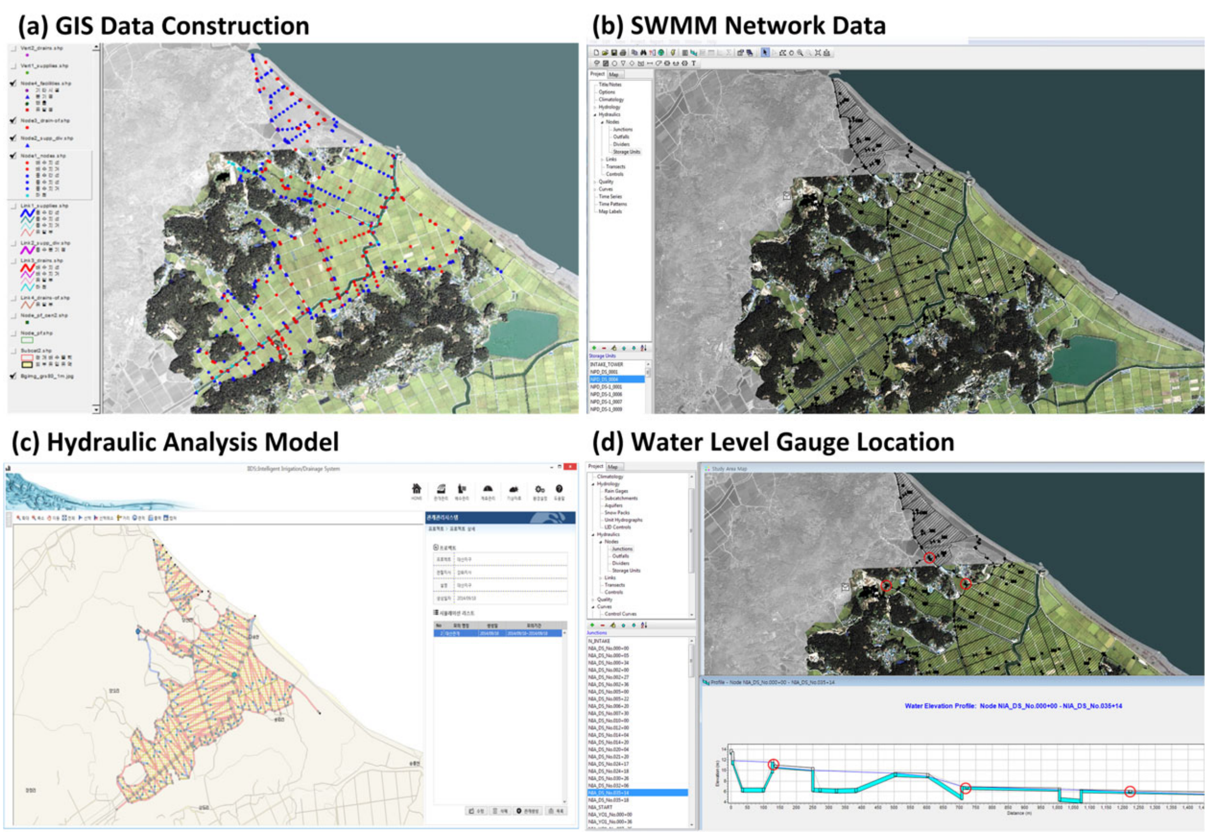

Figure 5. Construction results of hydraulic analysis model

are the coefficients of roughness, length, cross-section area, hydraulic radius and river width, and the important independent variable is the flow.

As shown in Figure 3, the nodes indicate water storage facilities, such as reservoirs and dammed pools, and the links indicate water pump facilities, such as pumping stations. The links describe the water intake facilities, such as the intake tower and the circular orifice that has specific diameter intake holes. The water supply and drains are recognized by the links, whereas the junction points of the water supply and drainage are recognized by the nodes. The paddy field is regarded as a tank with runoff sinks on the upper side of the sidewall and infiltration sinks on the lower side of the sidewall. In the tank, the runoff holes on the upper side of the sidewall show an overflow water quantity of the paddies, whereas the infiltration holes on the lower side of the sidewall show an infiltration quantity.

RESULTS AND DISCUSSION

Network modelling construction

The fundamental elements and networks required in the SWMM model were constructed. The network files are generated based on drawings and field surveys, and the file types are the shape files using GIS and SWMM input files. The canal network modelling process for agricultural water analysis consists of four major steps: data acquisition, mapping process, modelling process, and drawing up of input data. The main spatial data were composed of canals, junction/confluence, land area, sub-basin and facilities. First, these spatial data were built in CAD form, and then the properties were added to the data to build the GIS data, which was converted into the model input files. In the case of the target area, the CAD and paper maps were combined to construct basic spatial data, and the data construction followed the process of Figure 4. Each element composing the spatial data was described by separate layers. The GIS data were converted from the CAD data, and we constructed basic attribution data related to the water supply areas, reservoirs and inflow areas.

Canal network construction

The irrigation network data of SWMM were generated by using the network data of the junction, outfall, the floor elevation in the nodes, and the conduits and gates in the links. The diversion gate was defined as a point where the branch canals are divided into the tertiary canals and where the canal water is divided into paddies. The paddy fields

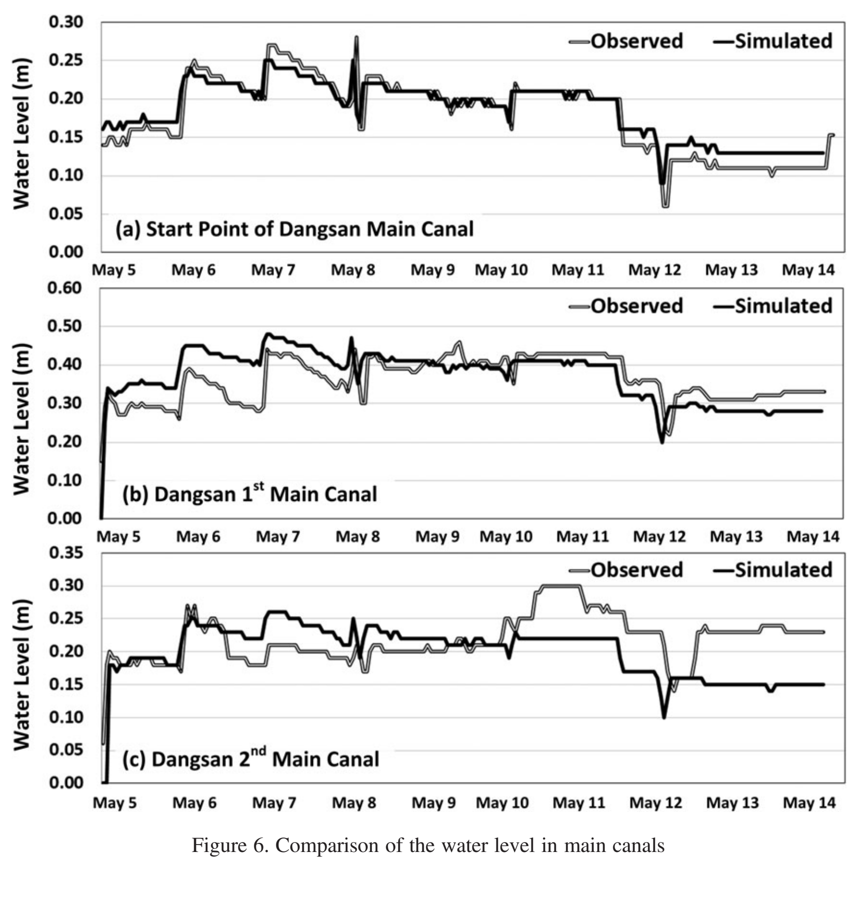

Figure 6. Comparison of the water level in main canals

were marked as tanks, and we used in the method where the floor surface area was the same according to the depth of the water. All input files can be converted to the input file form of the SWMM model. The SWMM input files are entered automatically by the input file process function of the hydraulic analysis model, as illustrated in Figure 5.

Simulation result of the test area

Using the hydraulic analysis model of the irrigation canal network, network modelling was conducted on the irrigation system of Daesan District. The water level and change of flow according to time was simulated. The canal irrigation system started at 7 a.m., 5 May 2014 according to the actual measurement data. The hourly measured water-level data of the Dangsan irrigration main canals for the 9 days from 7 a. m., 5 May 2014 to 7 a.m., 14 May 2014 were extracted. For the hydraulic simulation, the SWMM dynamic wave was applied and the coefficient of roughness was 0.020 based on a concrete canal. The amount of water passing the start point of Dangsan Main Canal was used as the input data, and the time interval for the measurement was 1 h. To compare the result of the simulations, we collected measurement data from the water-level gauges at (a) the start point of Dangsan Main Canal, (b) the Dangsan 1st Main Canal, and (c) the Dangsan 2nd Main Canal.

As a result of the comparison between the simulation results at each point and the actual measurement data (Figure 6), although there is a 3 cm difference between actual data and the simulation result at the starting point of the Dangsan Main Canal, a 5 cm difference in the Dangsan 1st Main Manal, and an 8 cm difference in the Dangsan 2nd Main Canal, the simulation results of the water-level changes after irrigation follow the tendency of the actual measurements. Root mean square equation (RMSE) analysis was implemented to determine the correspondence between the actual measurement and the simulation of the water-level curve. RMSE results of the starting point of the Dangsan Main Canal, Dangsan 1st Main Canal and Dangsan 2nd Main Canal were 0.001, 0.062 and 0.004, respectively. Consequently, the simulation data provided similar results to the actual measurement considering the water loss in irrigation canals.

CONCLUSION

In this study, we developed a hydraulic analysis model for agricultural irrigation networks by adding the functions of irrigation canal network analysis and hydraulic analysis for the sluice gate controls by using the SWMM module. We used a GIS engine to develop an input file creation module including the irrigation block data, such as area, soil and crop characteristics, and the facilities and irrigation canals were converted to a network model with nodes and links. The developed model was applied to Daesan District located in the western part of South Korea. The irrigation canal network analysis function, the hydraulic analysis function of the sluice gates, the water balance function for paddies and the input file creation function using GIS were developed and used to create an irrigation canal network model with nodes and links for Daesan District. We verified that the changes of water level, amount of flow and velocity of each canal were simulated accurately based on a time series.

The analysis of the irrigation canal flow network should be considered for reasonable operation and planning concerning optimized irrigation and water allocation. Therefore, this study successful overcame some of the limitations of canal network flow analysis currently carried out in South Korea, which is only based on canal flow simulation. This hydraulic model can assist with accurate irrigation scheduling based on its simulation results, such as flow travel time, water level, and flow amount depending on sluice gate control. Thus, we recommend the model for control of the water supply from the start to the end points of irrigation canals to prevent invalid discharge and water waste.

It is worth pointing out that some limitations of this hydraulic model remain and deserve further study. First, substantial manual operations for the model set-up of canal network modelling are needed. Second, water diversion and pumping data are critical model inputs, but they usually have low spatial and temporal resolution and involve significant uncertainty. Third, since water quality issues are interrelated with irrigation water resource issues in South Korea, future studies may consider developing a module to extend an integrated water quality model.

ACKNOWLEDGEMENTS

This study is supported by the Korea Institute of Planning and Evaluation for Technology in Food, Agriculture, Forestry and Fisheries as the Technology Development Project for Export Strategy (Project No. 312067–3).

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