ARTICLE

Runoff simulation considering the effects of hydraulic structures on agricultural water uses

Sang-Jin Lee · Seung-Jin Maeng · Kyong-Sik Ryoo · Joo-Cheol Kim · Dong-Hyeon Woo

Abstract For the efficient management of water resources in the target basin, this study proposed a method to improve the reliability of a long-term hydrological simulation model by applying to the model agricultural water more approximate to actual water uses (than planned water demands) through their adjustment based on the effects of small-scale hydraulic structures. To verify agricultural water uses estimated using the proposed method, they were applied to a basin management model. And then, simulated runoff at main station points was compared with measured runoff. As a result, there occurred errors with large differences from measured data, mainly, at station points where their dependency on river water was high. To verify simulated return rate, return rate for a test zone was estimated, and then compared with the simulated return rate. Correlations between annual rainfall and runoff errors were analyzed. As a result, it was found that those errors were enlarged in dry years. Long-term runoff simulation analysis showed that simulated runoff came to be negative when a farming season began. This could be significantly improved using water uses adjusted to consider the effects of small-scale hydraulic structures. Also, correlation analysis quantitatively confirmed that simulated runoff after adjustment was more correlated with measured runoff than before adjustment.

Finally, fitness tests for runoff simulations before and after adjustment were carried out through a residual analysis to analyze residual normality and independence. As a result, the fitness of runoff simulation after adjustment was significantly improved.

Keywords Agricultural water · Hydraulic structures · SSARR model · Rainfall-runoff simulation · Return rate · Water use

Introduction

In a situation where lots of researches warn against the impacts of global warming and climate change on water resources (IPCC 2008), scientific basin-wide water resources management beyond conventional, fragmented water management, and operation system have emerged. But long-term runoff models for basin-wide water management generally require the involvement of a large-scale basin. Accordingly, they are exposed to uncertainty related to complex hydraulic and hydrological characteristics, which is not the case with simple water management for sub-basins. Of these hydraulic and hydrological characteristics, agricultural water uses and return rate are very difficult to quantitatively analyze and identify. Especially in Korea like other Asian countries where the agricultural sector occupies the majority of water uses, it is very important to estimate the actual amount of agricultural water uses, although it is very challenging to do so; agricultural water uses in a basin vary depending on diversified water use pattern, uncertainty in arable area, climatic condition, etc.

Generally, the estimation of agricultural water uses requires that of basin-scale planned unit water demands and return rate (based on the analysis of return flow

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reusable in terms of water-use cycles). But agricultural water demands estimated using this method are not the same with actual water uses in a basin. With regard to this, various studies to estimate agricultural water uses and return flow have been carried out.

A study undertaken in Japan developed a multiple regression equation using Volterra integral equation to analyze runoff characteristics in paddy field. The study reported that return rate in paddy field (estimated using the equation and other measured data) was 49.3% (Ito et al. 1980). Also, it was reported in the analysis of field water balance (including soil water) for the Malaysia Muda irrigation area that 46.3% of irrigation water supply was used through evapotranspiration, and that 48.6% was drained (Yashima 1982). In the Euphrates basin in Syria, a study to estimate irrigation return flow in a dry region through the mass-balance analysis of chlorides was undertaken (Kattan 2008). The applicability of a hierarchical model was demonstrated through a case study on Periyar–Vaigai Irrigation System in Tamil Nadu, India. It was found that return flow simulated using the model was consistent with measured return flow. A statistical analysis showed that correlation coefficients for single and double cropping seasons were high (Mohan 2009).

Also in Korea, studies to estimate return rate through choosing a research area in small-scale paddy zone and researching water supply and drainage have been undertaken. Cheong et al. selected small-scale paddy area to measure water balance components during the growing season in 2003. As a result, total irrigation return flow rate was estimated at 53.7%, of which 30.2% was rapid return flow and 23.5% was delayed return flow (Cheong and park 2004; KOWACO 2006).

Agricultural water uses in large-scale basins were estimated using an indirect estimation method such as unit load method (MOCT 2001). This method is useful for estimating municipal or industrial water uses whose unit load shows a spatiotemporally insensitive change. But they are not suitable for estimating agricultural water uses changing in a spatiotemporal, sensitive way due to direct impacts from rainfall, evaporation, basin runoff, etc. Actually, the previous studies attempted to estimate agricultural water uses using, mainly, statistical or regression analysis (based on in situ measured return flow). There have been also studies that employed various methods for inversely estimating agricultural return flow from observed data (using a long-term runoff model). But they had their own limitations in that used simulation data were based on presumed demands for irrigation water, not actual water uses.

Other various attempts to reduce errors in a long-term runoff simulation have been undertaken. In Kansas, the effects of irrigation facilities in Wet Walnut Creek Watershed on river runoff and groundwater flow were assessed; for this assessment, POTYLDR Model was used together with MODFLOW Model to identify river–aquifer interactions in a basin. To minimize errors in a long-term runoff simulation for the Rattlesnake Creek basin, an integrated simulation model known as "SWATMOD" was used (Zhang et al. 2009; Ramireddygari et al. 2000). Zhang et al. (2009) proposed a method to explain modeling uncertainty while regionalizing the parameters of Genetic Algorithms (GA) and Bayesian Model Averaging (BMA) to calibrate SWAT and analyze its uncertainty at the same time. In Japan, these regionalization schemes provided an intuitively simple method to model ungauged basins using measurable catchment attributes. But parameter uncertainty still acted as an obstacle to such modeling. These two methods were explored through a case study on many small-/mid-scale humid basins located in various places (Satish et al. 2008).

The purpose of this study is to enhance the reliability of long-term rainfall-runoff simulation results by proposing relation equations to estimate agricultural water uses through spatiotemporally analyzing the effects of small-scale irrigational hydraulic structures on runoff, and thereby, modifying a rainfall-runoff model based on the proposed relation equations.

Methods and materials

Effects of hydraulic structures and agricultural water uses/return rate estimation equations

In Korea, reservoirs (or dams) occupy the majority of hydraulic structures (54.5%) in terms of the irrigation area of water abstraction sources. The reason for this is that they secure stable water supply to water users against high seasonal variations in rainfall. Other abstraction sources include pumping stations (17.3%), weirs (11.9%), infiltration galleries (2.3%), tube wells (1.7%), etc.

Hydraulic structures in the target basin include dams, reservoirs, pumping stations, pipes, infiltration galleries, and weirs. Most of reservoirs are used to provide irrigation water for downstream area. Each pumping stations used for water abstraction from a main channel or tributaries can be categorized as the 1st, 2nd or 3rd phase one according to direct or indirect water abstraction.

There are two representative dams in the target basin: Yongdam Dam and Daecheong Dam. The Yongdam Dam located most upstream of the Geum River basin is used to provide municipal water for downstream area and release instream flow for the environmental maintenance of the main channel. The Daecheong Dam is used to provide municipal and industrial water for many cities in the Geum

River basin, including Daejeon, Chungju, Cheonan, etc. Table 1 shows arable area and irrigation area in each sub-basin for which agricultural water is supplied by hydraulic structures. Representative irrigation facilities in the target basin include reservoirs, pumping stations, weirs, infiltration galleries, and tube wells. They have direct influences on streamflow variations (F_D). Generally, channel streamflow tends to increase in a region where a reservoir is the main source of irrigation water supply (W_S). This is because outflow from the reservoir increases return flow (R_S). If pumping stations or weirs are the main sources of irrigation water supply, channel streamflow tends to decrease. This is because irrigation water consumptions (W_L) decrease return flow (R_L). But tube wells and infiltration galleries used to supply irrigation water (W_G) do not significantly affect channel streamflow. This is because groundwater stage is determined and compensated by streamflow level. It means that the effects of tube wells and infiltration galleries on channel streamflow are not significant enough when compared with those of other irrigation facilities. Therefore, this study determined channel streamflow variations caused by various hydraulic structures as:

$$F_S = F_N - F_D \tag{1}$$

$$F_D = (W_L + W_G) - (R_S + R_L + R_G) \tag{2}$$

where F_S and F_N refer to simulated-channel streamflow and natural-channel streamflow, respectively; F_D means streamflow variations caused by small-scale hydraulic structures; R_L and R_G refer to the return flow of water supplied by pumping stations and weirs, and tube wells and infiltration galleries, respectively.

Different hydraulic structures have different influences on channel streamflow. For the efficient management of water resources in a basin, the estimation of water supply and return flow according to the share of water supplied by hydraulic structures in each sub-basin is required. But it is very difficult to identify water supplied by hydraulic structures in each sub-basin. In addition, relevant data are almost unreliable. Therefore, this study proposed the following relation equations to estimate agricultural water uses and return rate, in which the effects of various hydraulic structures were took into account:

$$U_W = \frac{A_T - A_S}{A_T} \times S_W \tag{3}$$

$$R_W = \frac{A_T}{A_T - A_S} \times \frac{I}{E + I} \quad (if; \ A_T \neq A_S) \tag{4}$$

where U_W, A_T, A_S, and S_W refer to water uses (m³/s) (adjusted by benefited area that is used in a basin management model), total benefited area (ha) (covered by small-scale hydraulic structures), benefited area (covered by reservoirs), and planned water demands in total (m³/s), respectively; R_W, I, and E refer to return rate (%), water infiltration (mm) and water evaporation (mm), respectively.

Target basin and long-term runoff modeling

The Geum River basin, one of four major rivers in Korea, is a target area in this study, and its catchment area and channel length are 9,810.4 and 395.9 km, respectively. The target basin does not interact with other basins in terms of inflow and outflow exchanges; actually, hydraulic structures in this basin function to distribute water resources to the water users of the basin. This is why the basin was chosen to identify the effects of hydraulic structures on water balance and streamflow.

Table 1 Arable area and irrigation area in each sub-basin for which agricultural water is supplied by hydraulic structures

| Basin no.	Total area (km²)	Arable area (km²)	Reservoir (km²)	Pumping (km²)	Weir (km²)	Infiltration gallery (km²)
B.01	279.51	26.72	22.12	0.67	3.71	0.22
B.02	165.59	4.57	3.41	0.00	1.16	0.00
B.03	477.31	12.31	8.41	0.11	3.50	0.30
B.04	595.12	10.79	5.63	0.30	4.82	0.04
B.05	389.52	19.19	8.18	4.81	5.18	1.02
B.06	1062.31	71.58	42.71	13.80	12.69	2.38
B.07	1209.11	76.94	50.02	13.58	11.37	1.97
B.08	753.02	24.33	6.33	3.67	13.42	0.91
B.09	1853.12	139.64	102.30	21.83	14.70	0.82
B.10	605.21	9.66	1.75	3.49	3.34	1.09
B.11	999.12	109.28	45.52	32.63	31.11	0.02
B.12	467.11	84.12	69.57	5.62	7.79	1.15
B.13	562.61	197.9	24.17	170.67	2.32	0.70
B.14	527.12	83.19	65.07	17.34	0.14	0.64
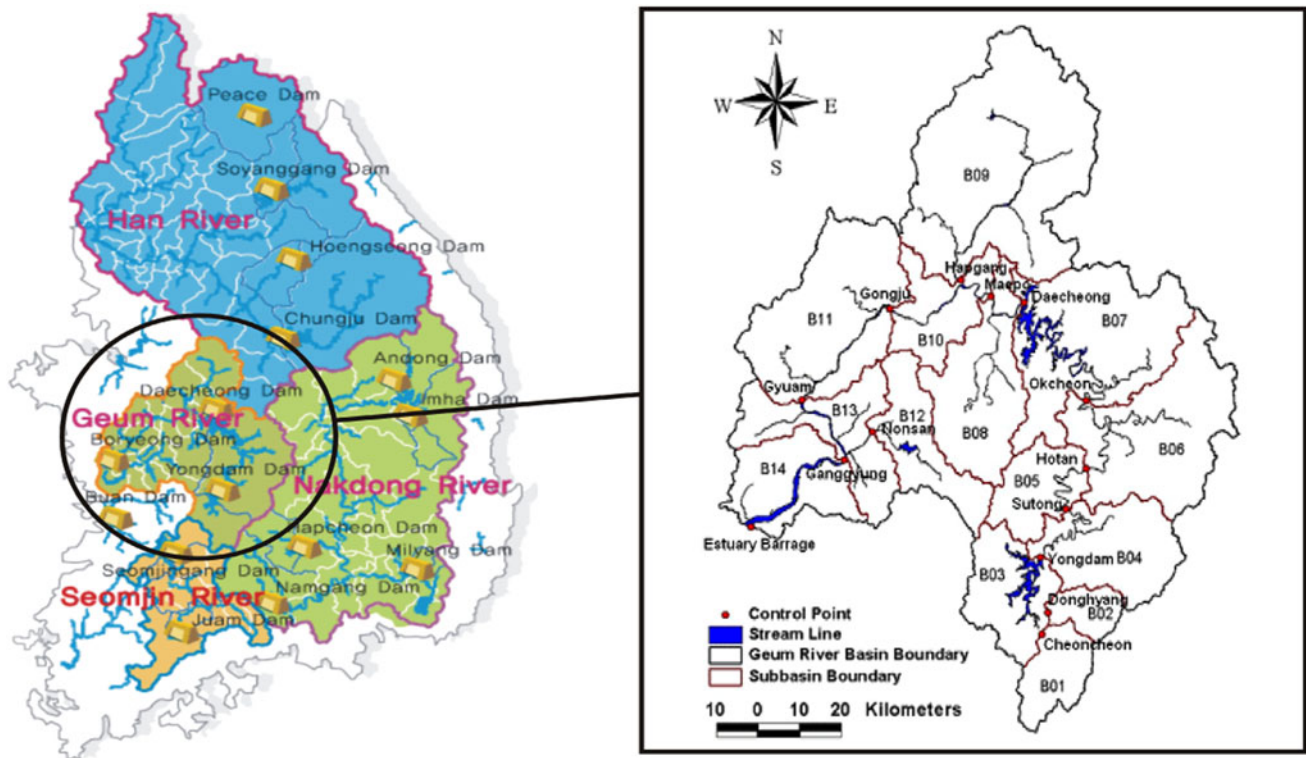
Fig. 1 Location of the Geum River and shape of sub-basins

In the subdivision of the target basin into sub-basins based on the Water-Resource Unit Map, Long-term Water Supply Plan and Basin-wide Master Development Plan (which are among national water resource plans) were taken into account (MOCT 2001; KOWACO 1999). As shown in Fig. 1, the target basin was subdivided into 14 sub-basins in total: the basin upstream of the Yongdam Dam was subdivided into 3 sub-basins; the area covering the Yongdam Dam to the Daecheong Dam was subdivided into 4 sub-basins; and the area covering the Daecheong Dam to its river mouth was subdivided into 7 sub-basins. A model for long-term runoff simulations in the sub-basins was framed. This framed model loaded with SSARR Model (US Army Corps of Engineers 1991) as its engine was designed to support object-oriented, universal GUI so that it can be used for similar simulations in other basins. Based on the SSARR model, the authors developed a new runoff simulation model [i.e., ESP (Ensemble Streamflow Prediction)-Based Rainfall Runoff Forecasting System (RRFS)] that would enable the simulation and prediction of long-term runoff in a basin (KOWACO 2006). The SSARR Model has been used in water-resource practices since its development in 1956 (US Army Corps of Engineers 1991). The model successfully proved its own usability, e.g., in the Columbia River (Rockwood 1961) and the Mekong River (Rockwood 1968). Also in the Yongdam basin in Korea, the model was used to simulate

the streamflow change scenario for the projection of flood risk (Kang et al. 2007).

Figure 2 shows a schematic diagram of SSARR Model for the target basin (i.e., the Geum River). A runoff simulation model developed in this study was so designed that parameters may be approximate to actual values through calibrating them based on the comparative analysis of observed and simulated values. This process corresponds to the phase of parameter calibration which precedes that of runoff simulations, which, in turn, can be seen in the flowchart showing the process of this study (Fig. 3). The flowchart also shows a process where errors in agricultural water uses are checked before runoff simulations are continued.

Rainfall and water use

Of rainfall gauging stations operated by the MLTMA (Korea Ministry of Land Transport and Marine Affairs), the KWRC (Korea Water Resources Corporation), the KMA (Korea Meteorological Administration), and the KRCC (Korea Rural Community Corporation), the ones whose measured daily precipitation data are relatively reliable were selected: 37 (1983–1988 in data coverage), 45 (1989–1992 in data coverage), 39 (1992 in data coverage), 40 (1994–1995 in data coverage), 41 (1996–1999), and 53 (2000 to the current year in data coverage). For the calibration of missing long- or short-term data or any other
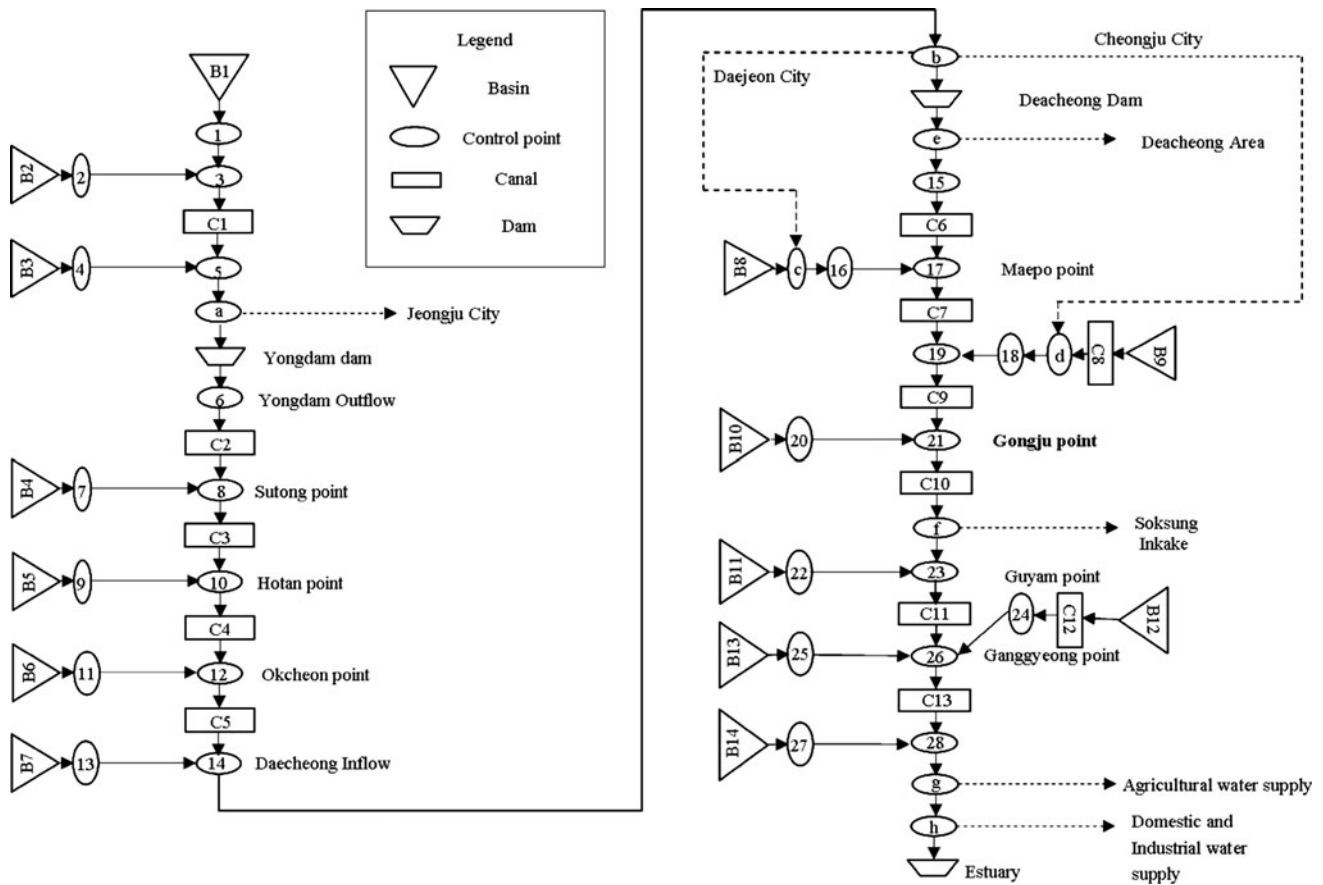
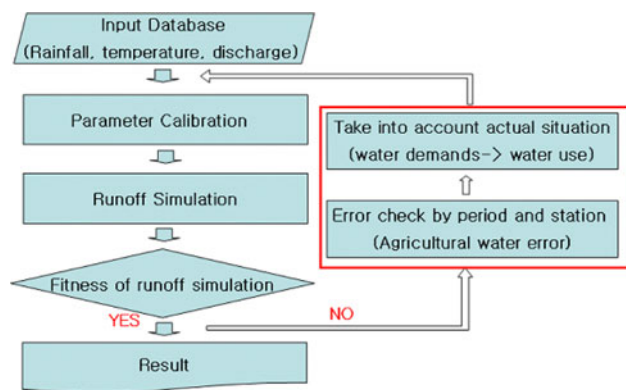Fig. 2 Runoff flowchart of Geum River basin

Fig. 3 Flowchart of study process

data questionable in terms of reliability, reciprocal distance squared (RDS) method, one of methods to calibrate precipitation data was used.

In Korea, rainfall occurs mainly during the summer (June to September); 2/3 of annual precipitation occurs during the 4 months, while as little as 1/5 during the 6 months of November to April. However, the majority of agricultural water uses occur during April to June;

generally, April is the month when agricultural activities begin. Surplus water stored using a reservoir during the wet season is supplied during the dry season. Accordingly, as high as 80% of paddy field depends on hydraulic structures (e.g., reservoir) for water supply. In this regard, it is inevitable to carry out the status survey of the hydraulic structures for the quantitative analysis of agricultural water uses.

Results and discussion

Status of water uses in each sub-basin

Figure 4 shows the dependency of water uses on river water in each sub-basin; the ratio of arable area benefiting from the direct use of river water in each sub-basin was estimated to identify the level of such dependency. For this estimation, the ratio of area benefiting from the use of water from each hydraulic structure was used. As seen in the figure, it was found that Sub-basin 13 where the ratio of arable area depending on river water supply through pumping stations was very high showed the highest

Fig. 4 Water supply area and dependency on river water in each sub-basin
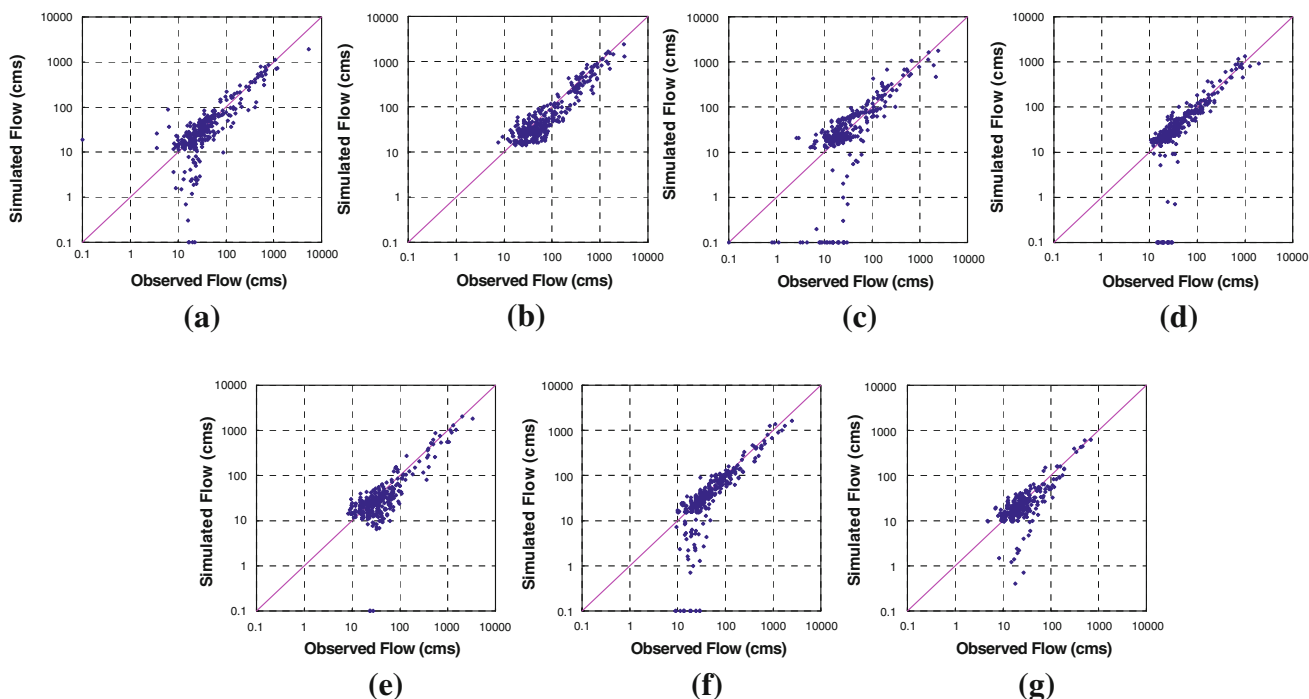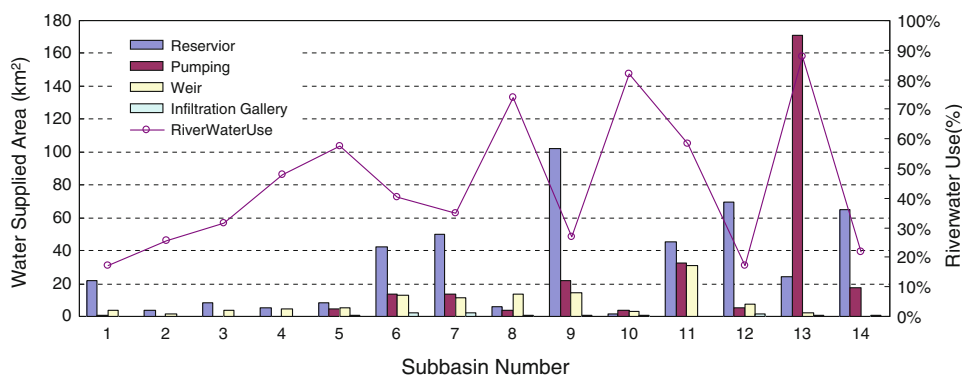

Fig. 5 Annual comparison of daily simulated runoff at the Daecheong Dam point (small-scale irrigation facilities not considered). **a** Year 2002, **b** year 2003, **c** year 2004, **d** year 2005, **e** year 2006, **f** year 2007, and **g** year 2008

dependency on river water. Also in Sub-basins 5, 8, and 10 where there are many pumping stations with few irrigation reservoirs, the rate of dependency on river water was estimated at as high as 60% or higher. In Sub-basins 1, 2, and 3 located upstream of the Yongdam Dam, and Sub-basins 7, 9, 12, and 14 located upstream of the Daecheong Dam, where their catchment area is extensive and there are many mid-scale or larger irrigation reservoirs, the rate of dependency on river water was found to be relatively low.

Runoff simulation results

This study assumed that one of the main reasons why runoff simulation results were inaccurate as mentioned above was that the effects of small-scale hydraulic

structures in a basin were not taken into account. To validate this assumption, two cases of basin runoff simulations (i.e., the ones that take into account and does not take into account such effects) were undertaken using Eqs. 1–4.

Figure 5 shows a scatter graph in which daily simulated runoff data at the Daecheong Dam point estimated (or collected) using long-term runoff simulations with 2002–2008 in coverage period were plotted against the corresponding observed data. In the figure, it can be seen that, in most of the covered years (including 2002 and 2004), abnormal data (i.e., errors) referring to simulated runoff data with large differences from observed data are scattered around along x-axis. This suggests that simulated runoff (along y-axis) was lower than observed runoff (along x-axis); actually, it is judged that this resulted from
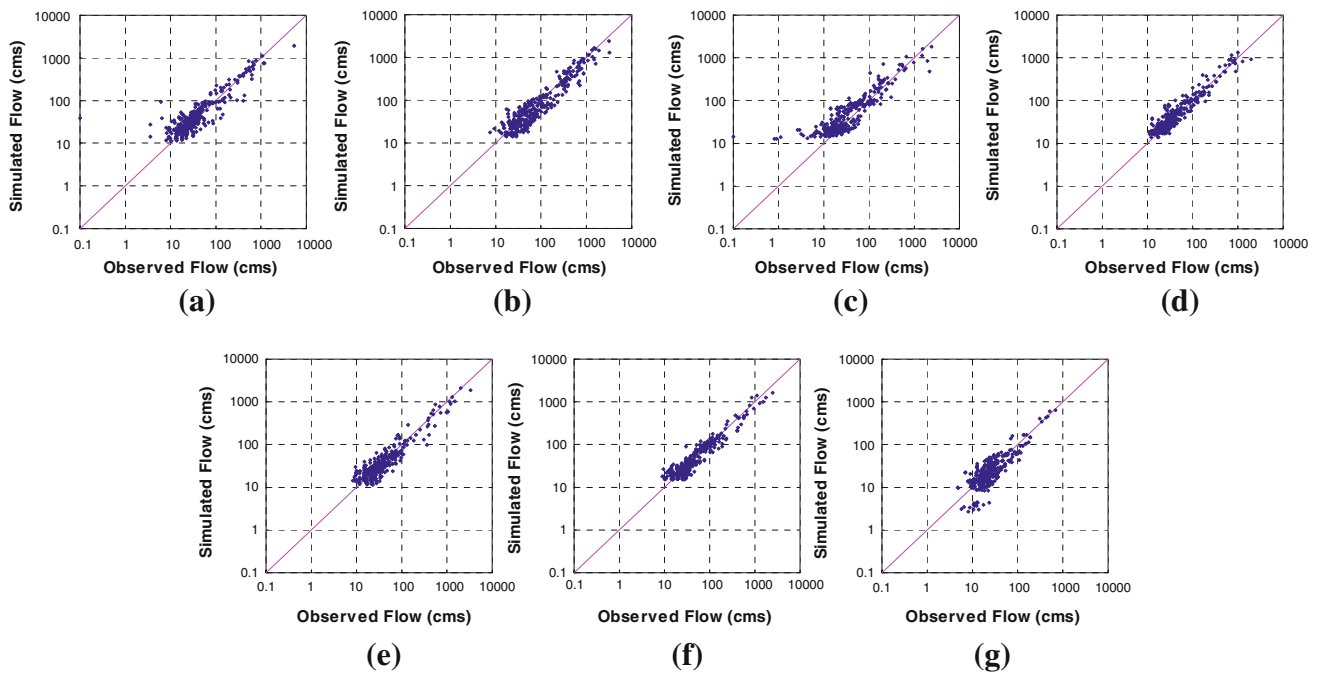
Fig. 6 Annual comparison of daily simulated runoff at the Daecheong Dam point (small-scale irrigation facilities considered). **a** Year 2002, **b** year 2003, **c** year 2004, **d** year 2005, **e** year 2006, **f** year 2007, and **g** year 2008
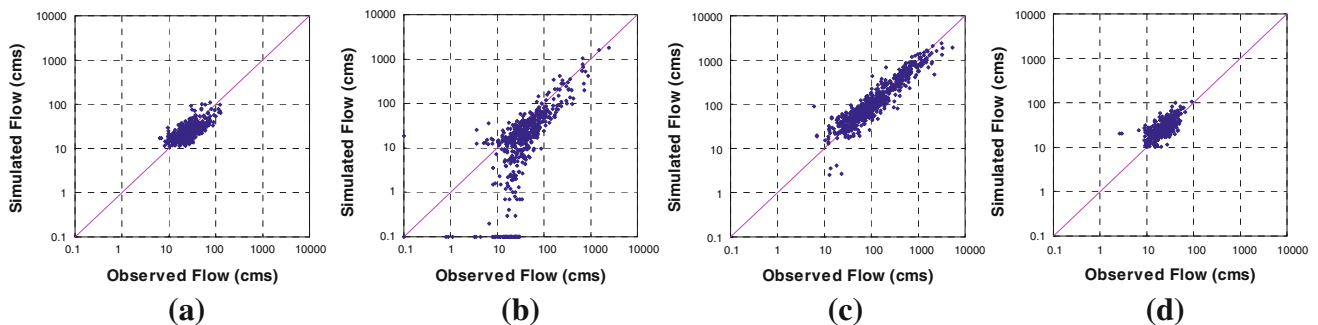

Fig. 7 Comparison of quarterly simulated runoff at the Daecheong Dam point (small-scale irrigation facilities considered). **a** 1st quarter, **b** 2nd quarter, **c** 3rd quarter, and **d** 4th quarter

the overestimation of water uses since such characteristics as water uses and return flow attributable to small-scale reservoirs or any other small-scale hydraulic structures were not taken into account. Figure 6 shows that runoff simulations were significantly improved using the equations to estimate agricultural water uses as mentioned earlier in this study. In the figure, it can be seen that most of abnormal data were removed.

Since water demands vary according to each season, runoff data with 2002–2008 in coverage period (i.e., 7 years in total) were quarterly classified and analyzed. The values of simulated runoff at the Daecheong Dam point were plotted against observed data on a quarterly basis. As a result, notable characteristics were revealed during the 2nd quarter corresponding to the farming season; most of

irrigation water uses occur in this season. In Fig. 7, it can be seen that, in runoff simulations using normal planned agricultural water demands, abnormal low discharge (approximate to 0.1 in y-axis) appeared.

As seen above, simulation results at the Daecheong Dam point significantly improved when the effects of small-scale hydraulic structures were taken into account. But small-scale hydraulic structures at each station point of the target basin vary in terms of their characteristics. Accordingly, daily simulated runoff at main station points in the Geum River basin was estimated; in this estimation, coverage period ranges from 2002 to 2008. Figures 8 and 9 show results using a scatter graph. Runoff simulation results were improved on the whole when the effects of small-scale hydraulic structures were taken into account.
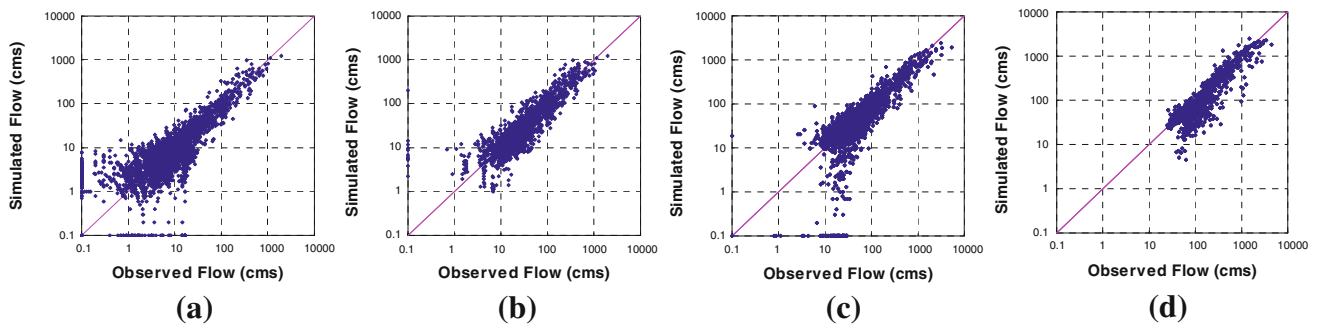
Fig. 8 Comparison of simulated runoff at each point (small-scale irrigation facilities not considered). **a** Yongdam, **b** Hotan, **c** Daecheong, and **d** Gongju
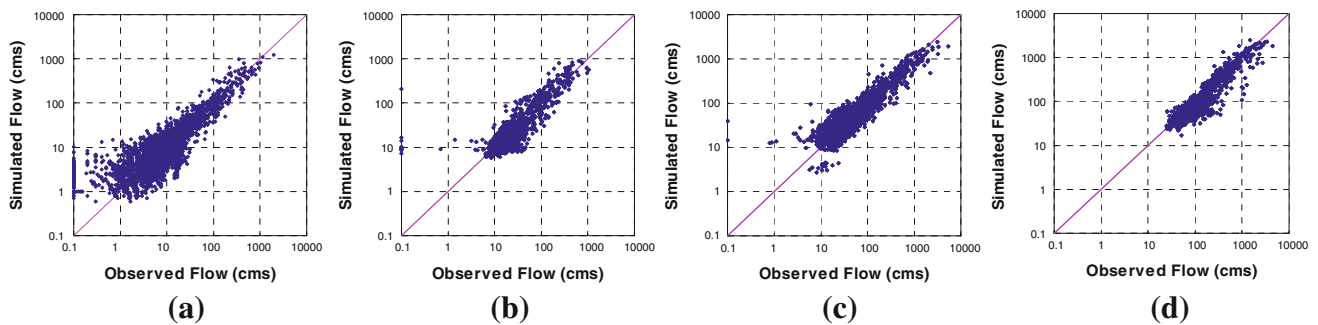

Fig. 9 Comparison of simulated runoff at each point (small-scale irrigation facilities considered). **a** Yongdam, **b** Hotan, **c** Daecheong, and **d** Gongju

Since runoff at each station point is affected by sub-basins located upstream, it was compared with the corresponding data in Fig. 4 showing the dependency of each sub-basin on river water and hydraulic structures. As mentioned earlier, it can be seen that the existence of many small-scale reservoirs at the Daecheong Dam point lowered the dependency of sub-basins on river water and many low discharge errors, and that basin runoff simulation results were significantly improved by taking into account the effects of small-scale hydraulic structures. Runoff simulation results at the Hotan Station point or the Gongju Station point were found to be relatively good. The two station points are affected by Sub-basins 5 and 10 with a relatively high level of dependency on river water. At the Yongdam Dam point, there appeared many errors (approximate to 0.1 in x- and y-axes) as shown in Fig. 8. Of these errors, the ones approximate to 0.1 in y-axis are correlated with the fact that the dependency of Sub-basins 1, 2 and 3 affecting discharge at the Yongdam Dam point is relatively low.

These errors were improved by taking into account the effects of small-scale hydraulic structures located at the same point, which finding was similar to the case of the Daecheong Dam point. But there was not any change in errors approximate to 0.1 in x-axis even after such effects were taken into account. It is judged that this resulted from missing or inaccurate measured data.

Return rate of agricultural water

To verify the results of simulated return rate, this study examined return rate at a test zone belonging to Sub-basin 8 in 2004 and compared it with the corresponding ones as mentioned earlier. This zone whose water source traces back to the Geum River is not so large in irrigation area. In addition, it enables the easy measurement of pumped water and drainage flow, and consequently, return rate. To calculate return rate at this zone, irrigation water, drainage flow, and infiltration flow was measured. The measured drainage flow and infiltration flow was considered as rapid return flow and delayed return flow, respectively. As shown in Table 2, rapid return rate, delayed return rate, and total return rate were estimated at 45.37, 61.51, and 16.41%, respectively, while simulated return rate estimated using Eq. 4 was estimated at 45.62% as shown in Table 3.

These results are judged to be related to effective rainfall. To remove impacts related to rainfall, rainfall period was excluded in estimating return rate through an in situ sample survey. But some rainfall gradually returning through deep percolation causes delayed return flow or soil moisture, and consequently, overestimated return flow. Therefore, the identification of more accurate return rate requires an inclusive method to analyze water balance, including rainfall and evapotranspiration.

Table 2 Return rate at the Daecheong Dam point in the Geum River basin (non-rainy)

Month	A third of month	Irrigation water (mm)	Drainage flow (mm)	Infiltration flow (mm)	Rapid return rate (%)	Delayed return rate (%)	Total return rate (%)
5	Last	46.59	27.84	7.37	59.76	15.82	75.58
6	First	182.27	66.06	14.72	41.24	13.11	54.35
	Mid	110.51	29.76	14.02			
	Last	31.71	37.99	13.80			
7	First	15.83	19.84	3.68	57.82	17.27	75.05
	Mid	19.40	31.28	5.71			
	Last	205.10	87.84	32.11			
8	First	111.57	48.43	17.44	42.27	17.91	60.18
	Mid	96.05	41.70	12.61			
	Last	98.29	39.18	24.75			
9	First	128.04	41.37	18.19	35.30	17.48	52.78
	Mid	7.47	6.47	5.50			
Total		1,052.83	477.66	169.9	45.37	16.14	61.51

Table 3 Return rate of Basin 8 in the Geum River basin by Eq. 4

Month	May	June	July	August	September	Average
Return rate (%)	66.25	37.54	33.39	46.12	44.80	45.62

The monthly comparison of return rates in Tables 2 and 3 shows that there are large differences among them in June, July, and August. This indicates that return rate based on the in situ sample survey was affected by rainfall; as shown in Fig. 10, the comparison of return rate based on the in situ sample survey and total monthly rainfall indicates that measured return rate was affected by rainfall.

This study may enable the outlined identification of the return flow of agricultural water in the Geum River basin as well as at each station point. But the verification of the results requires long-term researches on the return flow of agricultural water at various station points.

Residuals analysis

It is general that, in a dry year, little rainfall and dry atmosphere accompany a relatively high amount of evaporation. This is why planned agricultural water demands estimated using the concept of net water consumption increase when compared with normal agricultural water uses. But actual water uses are less than normal water uses since water demands cannot be met due to, for example, a decrease in runoff. Accordingly, it is expected that the results of runoff simulations using planned agricultural water demands will be exposed to more errors in a dry year than otherwise. This is judged to have resulted from a lack of water supply due to drought,

Fig. 10 Observed return rate of selected point and precipitation of basin 8th (year 2004)
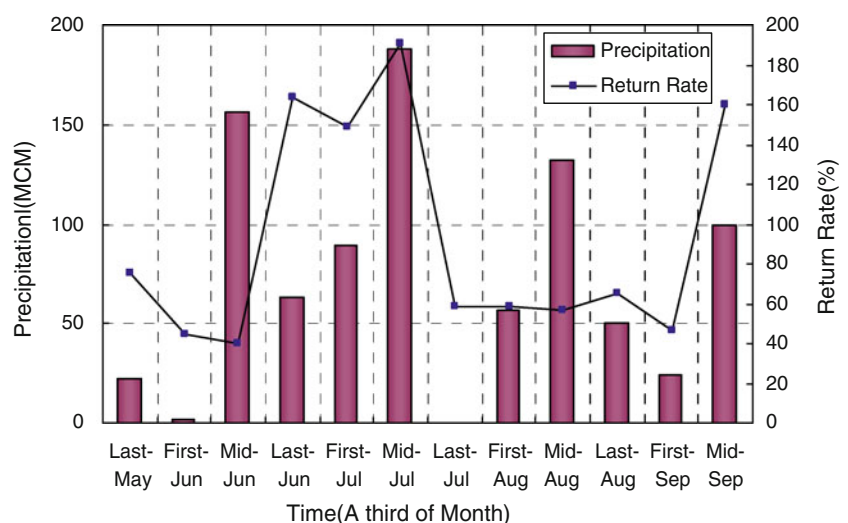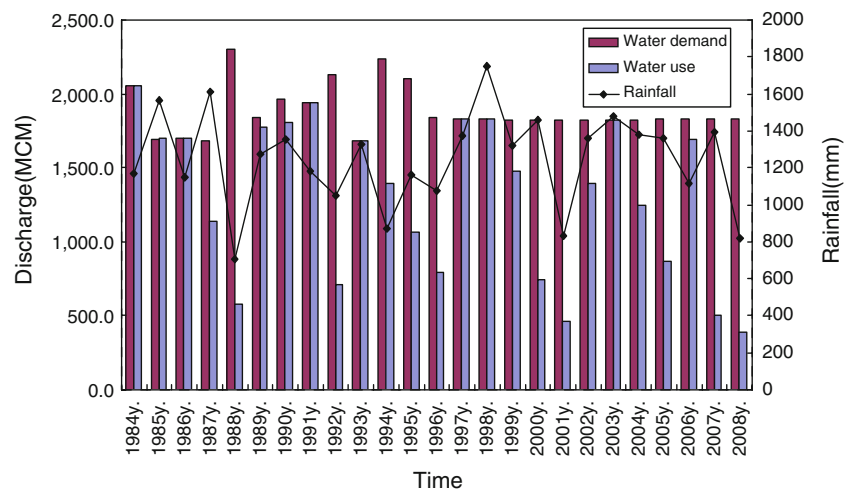
Fig. 11 Yearly water demands and water uses in the Geum River basin

and supported by Fig. 11 showing both planned water demands (estimated through a water demand survey using unit load method) and water uses (adjusted through taking into account small-scale hydraulic structures); in dry years (including 2001 and 2008 when there occurred many errors as mentioned earlier), agricultural water uses were significantly less than actually used agricultural water. This indicates that errors occurring during the runoff simulations resulted from the use of planned water demands estimated through unit load method, not actually used agricultural water. Actual agricultural water uses in dry years are definitely smaller than the estimated amount. In this regard, the method proposed in this study is expected to show a significant improvement.

To verify this, long-term runoff simulations for the year 2008 (classified as a dry year due to the little occurrence of rainfall) were carried out at the Daecheong Dam. The results can be seen in Fig. 12a with b that show the comparison of measured discharge with simulated discharge before and after adjustment based on the effects of small-scale hydraulic structures. In Fig. 12a in which water uses estimated using unit load method were used to simulate discharge, it can be seen that simulated runoff since May (in which the farming season begins) is negative. On the other hand, Fig. 12b shows that runoff simulation results were significantly improved. Pearson coefficient between observed discharge and simulated discharge before and after adjustment (based on the effects of small-scale hydraulic structures) was estimated. As shown in Table 4, correlation between observed discharge and simulated discharge after adjustment was found to be higher than before adjustment. Therefore, it is judged that the estimation method proposed in this study is more approximate to actual water uses than the unit load method.

To assess differences between measured and simulated discharge more quantitatively, discrepancy ratio as defined

by Cheong and Seo (2003) was used as an error indicator. Discrepancy can be expressed as:

$$R_D = \log(Q_p/Q_m) \qquad (5)$$

where Q_p refers to predicted discharge from a rating curve and Q_m refers to measured discharge. If discrepancy ratio is 0, predicted discharge is identical to measured discharge. If discrepancy ratio is larger than 0, predicted discharge is overestimated, while, if discrepancy ratio is smaller than 0, it is underestimated.

Equation 5 shows discrepancy ratio between measured and simulated discharge at the Daecheong Dam point and the Yongdam Dam point. It can be seen that runoff simulation results after adjustment are more approximate to 0 in discrepancy ratio than before adjustment. Table 5 shows that, of all simulations, 80% or higher lied within −0.5 (−50%) to 0.5 (50%) in discrepancy ratio. That is, runoff simulations after adjustment occupied the smaller range of discrepancy ratio. With regard to planned water demands before adjustment, especially at the Daecheong Dam point, the discrepancy ratio of 75 errors corresponding to 3% of all errors lied within −2 (−200%) to −2.5 (−250%). These errors were improved using water uses after adjustment as mentioned in Sect. 'runoff simulation results' and 'return rate of agricultural water'. On the whole, the Yongdam Dam point showed distribution more spread due to low discharge errors and inaccurate measured data than the Daecheong Dam point.

Since discrepancy ratio (R_D) refers to residuals between measured data ($\log Q_m$) and simulated data ($\log Q_p$), fitness tests for runoff simulations before and after adjustment at the Daecheong Dam point were carried out through residual analysis. In the residual analysis, it is analyzed whether residuals are independent of one another and normally distributed. To test whether they are independent, Durbin–Waston (DW) tests through auto-correlation analysis were undertaken. A value for DW statistic ranges from 0 to 4; as
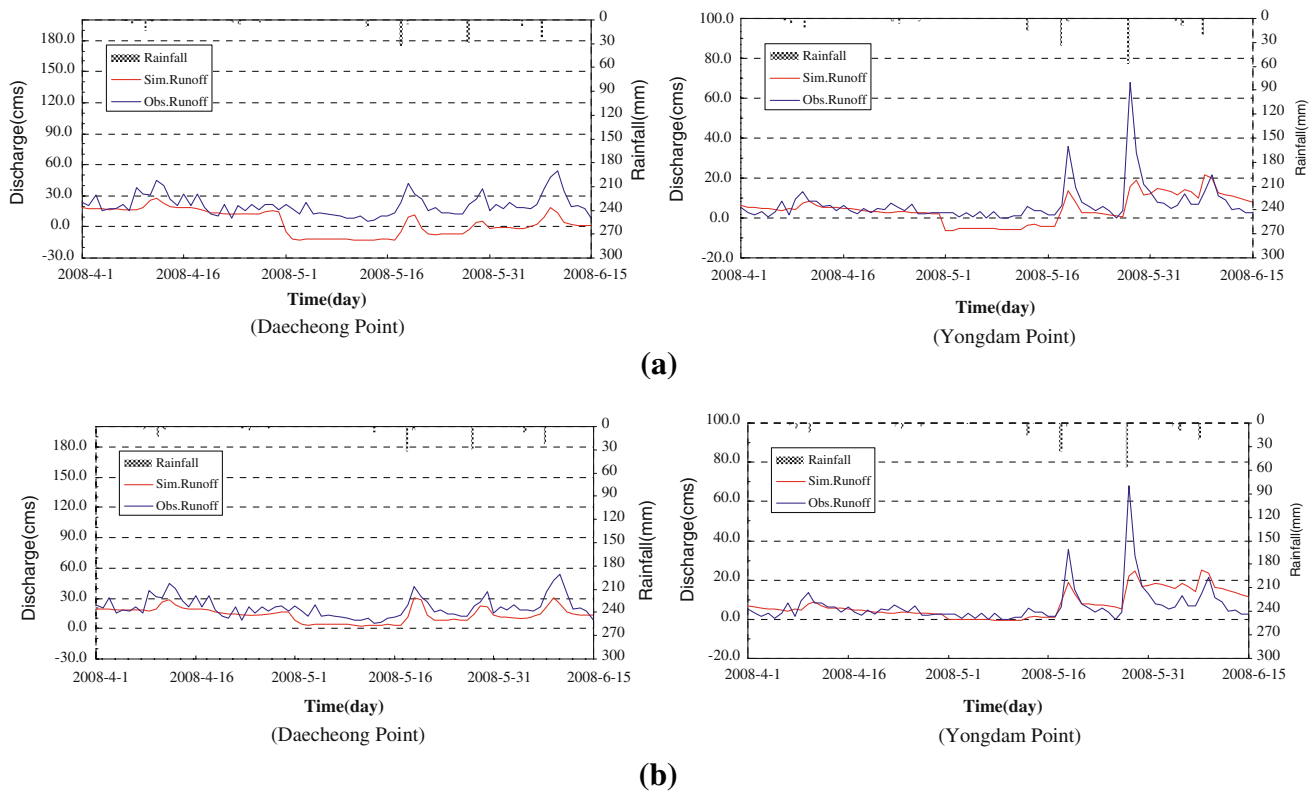
Fig. 12 Comparison of measured discharge with simulated discharge (year 2008, Daecheong). **a** Before and **b** after adjustment

Table 4 Correlation analysis between observed and simulated discharge

Irrigation water	Daecheong				Yongdam			
	Correlation coefficient	Coefficient of determination	*P* value	Significance (α = 1%)	Correlation coefficient	Coefficient of determination	*P* value	Significance (α = 1%)
Before adjustment	0.580	0.336	0.000	Regard	0.569	0.324	0.000	Regard
After adjustment	0.788	0.621	0.000	Regard	0.634	0.402	0.000	Regard

Table 5 Discrepancy ratio analysis

Station point	Based on the effects of hydraulic structures	Discrepancy ratio (%)				
		±(0– 10)	±(0–30)	±(0–50)	±(0–100)	Beyond ±100
Yongdam	Before adjustment	35.8	67.0	82.9	93.1	6.9
	After adjustment	36.7	68.7	85.9	95.2	4.8
Daecheong	Before adjustment	56.4	84.6	91.9	95.8	4.2
	After adjustment	63.2	93.7	99.0	99.8	0.2

the value approximates 2, the independence of residuals gets high. Its approximation to 0 or 4 represents positive or negative auto-correlation. DW tests showed that a value for DW statistic before and after adjustment was 0.30 and 1.12, respectively. This suggests that the independence of residuals after adjustment was higher.

It is possible to roughly test normality based on the bell-shaped distribution. But a normal probability plot enables the more accurate test of normality. If the normal probability plot for residuals gives distribution approximate to linearity, they are normally distributed. On the other hand, if it gives curved distribution, an assumption that they are

Fig. 13 Normal probability plot for residuals (year 2002–2008, Daecheong). **a** Before and **b** after adjustment

(a)

(b)
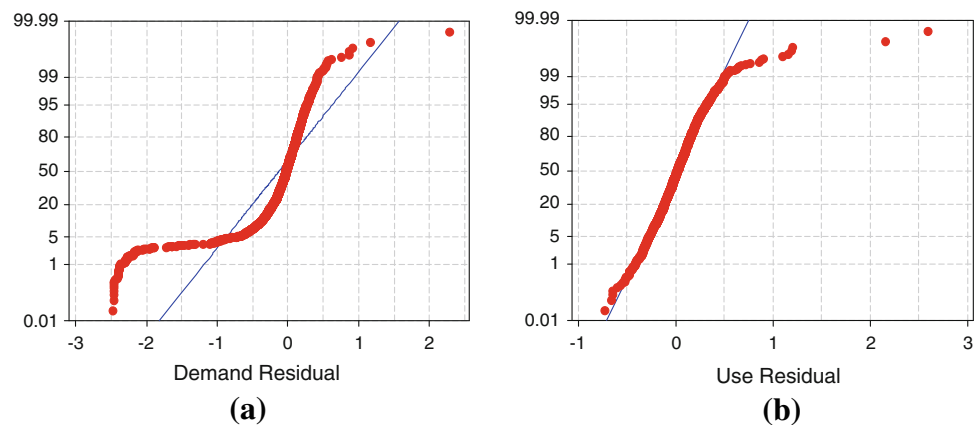
normally distribution is not acceptable. Figure 13 shows that the residuals of runoff simulations after adjustment at the Daecheong Dam point are more normally distributed on a normal probability plot than before adjustment. This indicates that the fitness of runoff simulations after adjustment was significantly improved.

Conclusion

For the efficient management of water resources in a basin, this study proposed a method to improve the reliability of a long-term hydrological simulation model by applying to the model agricultural water more approximate to actual water uses (than planned water demands) through their adjustment based on the effects of small-scale hydraulic structures, and consequently, attempted to enhance the practicality of the model.

Simple equations for the estimation of agricultural water uses and return rate by assessing the effects of small-scale hydraulic structures on river flow were proposed to improve the practicality of long-term runoff simulations that take into account water uses. To verify agricultural water uses estimated using the proposed method, they were applied to a basin management model in which the Geum River basin was a target basin. And then, simulated runoff at main station points was compared with measured runoff. As a result, there occurred errors with large differences from measured data, mainly, at station points where their dependency on river water was high in the 2nd quarter of a year when agricultural water demands were high. To verify simulated return rate, return rate for a test zone belonging to Sub-basin 8 was estimated, and then compared with the simulated return rate. Correlations between annual rainfall and runoff errors were analyzed. As a result, it was found that those errors were enlarged in dry years (e.g., 2001 and 2008) when actual water uses were not met. Long-term runoff simulation analysis showed that simulated runoff

came to be negative in May when a farming season began. This could be significantly improved using water uses adjusted through taking into account the effects of small-scale hydraulic structures. Also, correlation analysis quantitatively confirmed that simulated runoff after adjustment was more correlated with measured runoff than before adjustment. Discrepancy ratio (R_D) analysis at main station points revealed that runoff simulations after adjustment occupied the smaller range of discrepancy ratio. With regard to planned water demands before adjustment, especially at the Daecheong Dam point, the discrepancy ratio of 3% of all errors lied within −2 (−200%) to −2.5 (−250%). These errors resulted from the overestimation of water uses by not taking into account the effects of small-scale hydraulic structures. They all were improved using the method proposed in this study. Finally, fitness tests for runoff simulations before and after adjustment at the Daecheong Dam point were carried out through a residual analysis to analyze residual normality and independence. As a result, the fitness of runoff simulation after adjustment was significantly improved.

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