Hydrologic System for Simulating Reference Flows in the Geum River Basin's TMDL Practices

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Abstract. In South Korea TMDLs are now calculated in the administration boundaries (similar to counties in the U.S.) along the main rivers by multiplying a calculated reference flow times the water quality concentration of different parameters. To model this practice, a hydrologic system was implemented which simulates daily stream flows at the 36 main gauging stations along the streams within the Geum River basin. This computer system uses the DAWAST runoff model to calculate return flows from paddy fields, domestic and industrial uses, and was verified using two years of observed data measured every eight days. This computer system has several modules for estimating daily demands from: paddies, domestic water uses, and industrial water uses. The computer system also simulates daily water storage in reservoirs, and calculates reference flows and total loads. A presentation of the computer system and it application to the Geum River will be presented.

1. Introduction

In South Korea, total maximum daily loads (TMDLs) are determined at stations located along the major rivers within administration areas (areas similar to U.S. counties). The TMDLs are estimated by multiplying a calculated reference flow times the water quality concentration of different parameters. Reference flows are kept within limits determined by previous flows. A reference flow is defined as the 275th lowest daily stream flow averaged for 10 years.

The Geum River, the third longest in South Korea, is approximately 400 km long and has a watershed of 9,959 km^2. In the Korean TMDL practice, the Geum River basin includes the Mankyoung River and the Dongjin River; which means that in calculating the TMDL, the total watershed area is 122,257 km^2. The flow discharge and water quality is monitored at 36 main gauging stations. Two dams are located on the Geum River, the Daechung Dam with a total storage capacity of 1,419 Mm^3 and the Yongdam Dam with a total storage capacity of 815 Mm^3. Part of the water stored in the Yongdam Dam is diverted to the Mankyoung River basin located outside of the Geum River's watershed.

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The stream flows at the 36 gauging stations are largely influenced by the outflows from dams upstream and the return flows from paddy fields, residential and industrial areas. These complicated stream flow behaviors mean that it is necessary to develop a systematic hydrologic simulation tool for applying to the TMDL practice in the Geum River basin of South Korea.

2. System Configuration

Figure 1 shows how this hydrologic system simulation tool is configured. At its center is a daily rainfall runoff simulation module. The tool also includes modules for: simulating daily water requirements for paddies, estimating daily domestic and industrial water use, simulating daily water storages in dams, deriving the relationship between discharge and water quality concentrations, and calculating reference flow and TMDL.

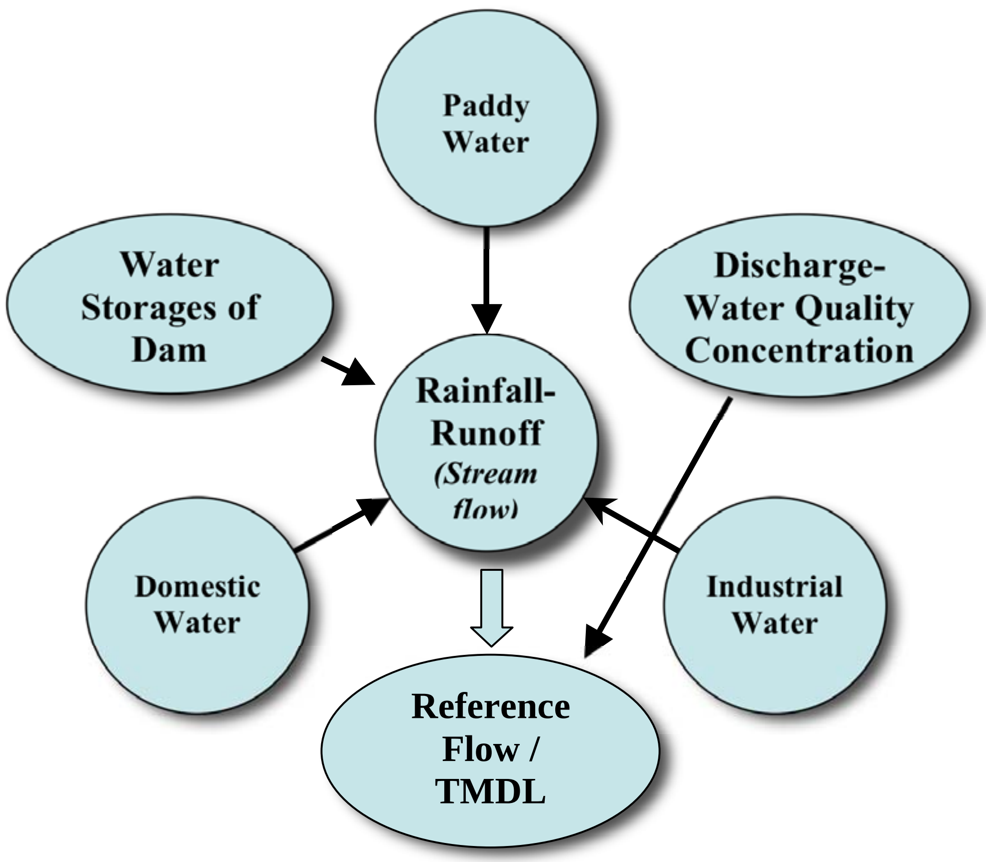

Figure 1. System configuration.

2.1 Rainfall-Runoff Module

Runoffs have been simulated using the Tank model described in “Water Vision 2020” (Ministry of Construction and Transportation 2000) and by the SSARR model detailed in "Development of Real-time Optimal Operating System for Managing Low Flows in the Nakdong River Basin" (Korea Water Resources Corporation 1996). The DAWAST model (Noh 1991) introduced the concept of soil water storage to simulate runoff in Korea. The hyperbolic function was also used in expressing soil water storage in TPHM (Kim 2001). Likewise, curve number (CN) was used in expressing soil water storage in the SWAT model (Kim and Kim 2003). The Tank model was applied to estimate the inflow simulation of the Soyanggang and Chungju Dams, considering the rate of snow accumulation and snow melt (Lee *et al*. 2003). These models are not able to simulate stream flows which include return flows from various water supplies. In contrast, the applicability of the DAWAST model was tested by simulating the inflow to the Daechung Dam after considering return flows from various water supplies (Noh 2003). When return flows were considered, the ratio of the simulated inflows to observed inflows was 97.8%. When return flows were excluded, however, the ratio of simulated inflows to observed inflows was 90.9%. The simulated results were considerably improved by considering return flows in the DAWAST model. The DAWAST model was selected for use as the main module of the rainfall runoff model in which return flows were considered.

2.2 Paddy Water Requirement Module

To estimate the irrigation requirements of paddy fields, evapotranspiration, infiltration, and effective rainfall must be considered. The rate of evapotranspiration is affected by meteorological conditions, such as duration of sunshine, temperature, humidity and wind speed. Infiltration is determined by factors such as soil properties and types and groundwater level. The amounts of water used in cultivating rice and in managing hydraulic facilities are also considered. Paddy water requirements are calculated by multiplying the paddy area, adding decreasing pond depth, subtracting effective rainfall and taking into account additional various losses.

Evapotranspiration was estimated using the modified Penman equation of Doorenbos and Pruitt (FAO 1977). The Penman equation (1) is used mainly in irrigation scheduling by estimating daily evapotranspiration using meteorological data.

$$ETo = C\,[W \cdot Rn + (1 - W) \cdot f(u) \cdot (e_a - e_d)] \quad (1)$$

where ETo represents the potential evapotranspiration (mm/day), W the weighing coefficient on temperature, Rn the net solar radiation (mm/day), f(u) the function of wind speed, e_a - e_d the difference between saturation vapor pressure and mean vapor pressure at average air temperature, and C the coordinating factor according to meteorological conditions.

The water requirements of rice in paddy fields are estimated using Equation (2):

$$Req(t) = ET(t) + I - Re(t) \quad (2)$$

where Req(t) is the water requirements of paddy fields, ET(t) is the evapotranspiration, I the infiltration, Re(t) is the effective rainfall, and subscript t is the day.

Water requirements of paddy fields are estimated on a daily basis by pond depth and effective rainfall. Pond depths in paddy fields are calculated using the water balance equation (3). Effective rainfall is calculated using Equation (4).

$$D(t) = D(t-1) + Re(t) + Req(t) - U(t) \qquad (3)$$

$$Re(t) = D(t) - D(t-1) - Req(t) + U(t) \qquad (4)$$

where D(t) is the pond depth in paddy fields, Re(t) the effective rainfall, Req(t) is the irrigation requirement, and U(t) is the water consumption out of actual evapotranspiration and infiltration. Subscript t denotes time.

The rate of return flow from paddy water is estimated to be 35% on an average in Korea.

2.3 Domestic and Industrial Water Use Module

Domestic water use is estimated by multiplying the number of persons who reside within a sub-watershed by the amount of water used per day per person. This calculation includes a coefficient for monthly variations in water use.

Industrial water use is estimated by multiplying the number of workers or the area of an industrial complex within a sub-watershed by the amount of water used per person or per unit area. As with the domestic water use equation, the calculation for industrial water use also considers the monthly variations in water use.

The rate of return flows from domestic and industrial water use is estimated to be 65% on an average in Korea.

2.4 Water Storage Simulation in Dam Module

To model the impacts of dams along the Geum River, the daily Yongdam-Daechung dam cascade model was developed (Noh 2000). This model, shown in Figure 2, is used in this study as an external module.

2.5 Discharge-Water Quality Concentration Relation Deriving Module

Water quality items selected are Biochemical Oxygen Demand (BOD), Chemical Oxygen Demand (COD), Suspended Solids (SS), Total Nitrogen (TN), and Total Phosphorus (TP). The module for deriving the relationship between stream discharges and water quality concentrations has been designed as an integral part of the hydrologic system simulation tool. The water quality simulation results are shown graphically on a daily basis.

2.6 Reference Flow Calculating Module

Reference flow is now defined as the 275^{th} lowest flow averaged for 10 years at the selected stream station. The reference flow is required to make an analysis of flow duration. In the hydrologic system simulation tool, frequency is also analyzed to help decision makers. This module will be constructed and put directly into the hydrologic system simulation tool. After calculating reference flow and deriving the relationship between flow and water quality, a module will also be developed that will calculate TMDL at each station and display it graphically.

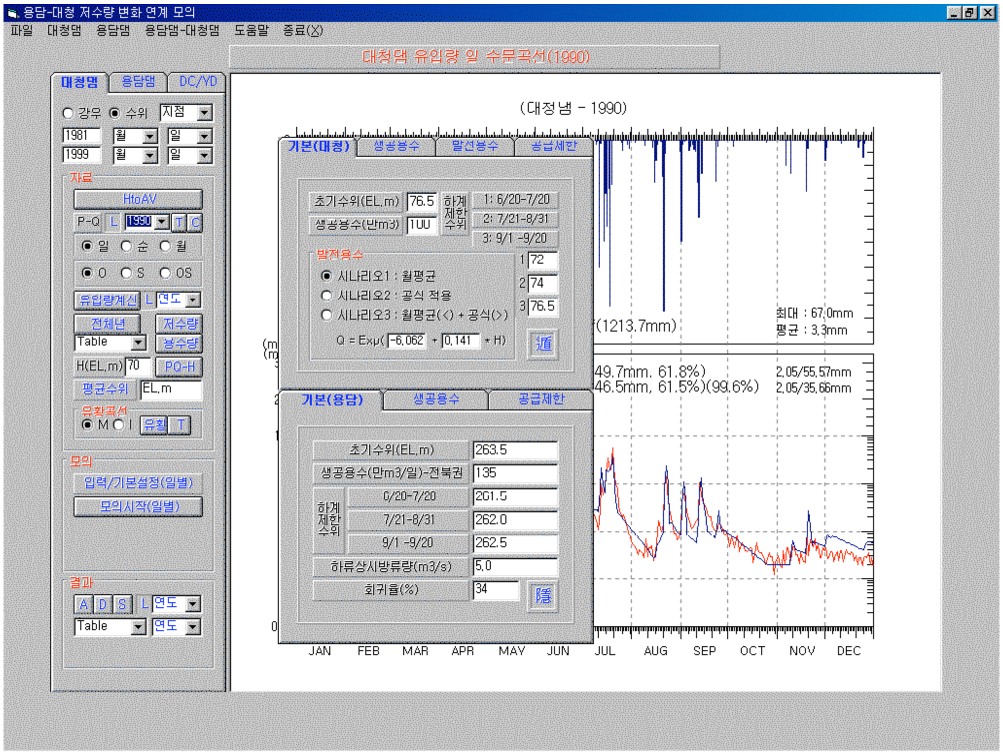

Figure 2. Yongdam-Daechung dam cascade model.

3. System Implementation

Visual Basic 6.0 was used to combine all the modules into one graphical user interface form. This single form is intended to make the system user friendly. The tool's menus and captions are written in Korean only as the likely user of this tool will be Korean. However, they can be translated into different languages for use in other parts of the world.

Figures 3 to 7 show some of the modules that have been developed. Figure 3 shows the daily paddy requirements being simulated. The graphic at the top of the screen shows the rainfall, followed by pan evaporation, evapotranspiration, ponding depth, and paddy water requirements.

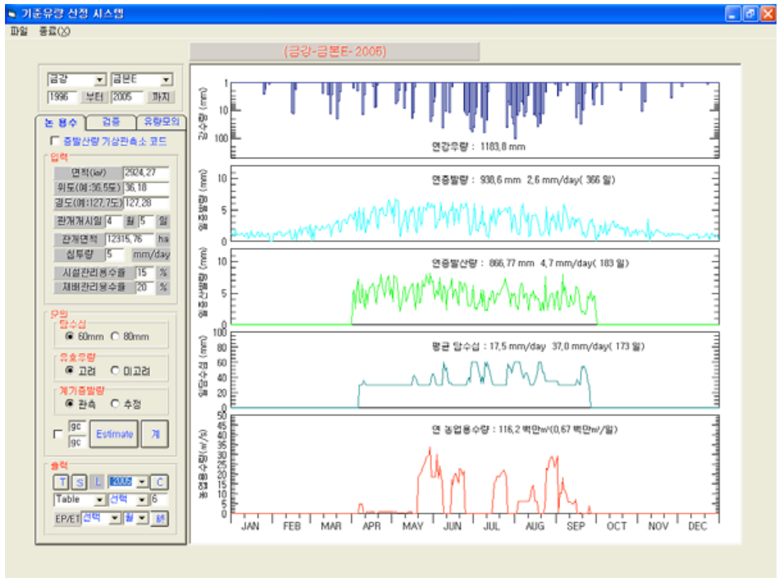

Figure 3. Daily paddy water requirement module.

Figure 4 shows daily stream flows being simulated. The graphs from top to bottom display rainfall, paddy water use, domestic water use, industrial water use, and runoff from the above.

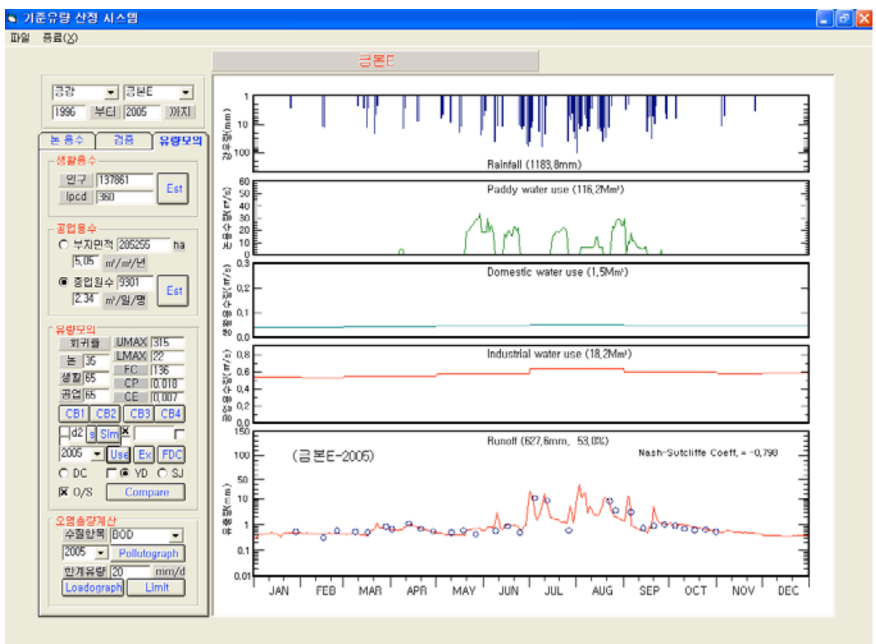

Figure 4. Daily stream flow simulation module.

Figure 5 shows an example of deriving the relationship between discharge and BOD concentration. Other water quality parameters for which relationship are derive include COD, SS, TN, and TP.

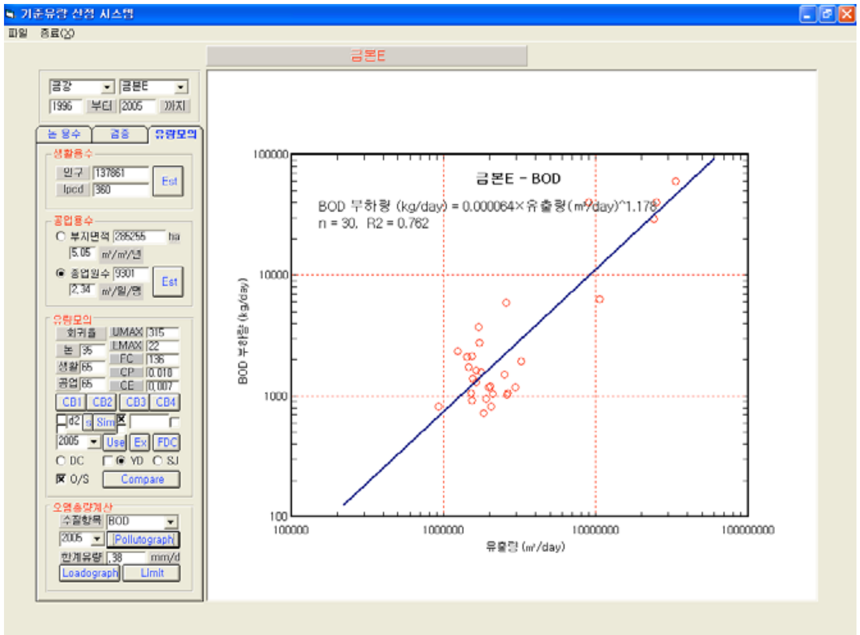

Figure 5. Discharge-water quality concentration module.

Figure 6 shows an example of calculating reference flow in which flow duration analysis is taken every year for 10 years and the sorted flows are averaged everyday. Then, the 1st value of 1,676.45 m^3/s, the 10th value of 37.20 m^3/s, the 95th value of 20.44 m^3/s, the 275th value of 12.73 m^3/s, and the 355th value of 10.70 m^3/s are selected. Finally, the 275th value of 12.73 m^3/s is determined to be the reference flow at the given station. In the graph, the red line shows the mean value, and the other 3 blue lines show the 2-yr, 3-yr, and 5-yr frequency flows, respectively.

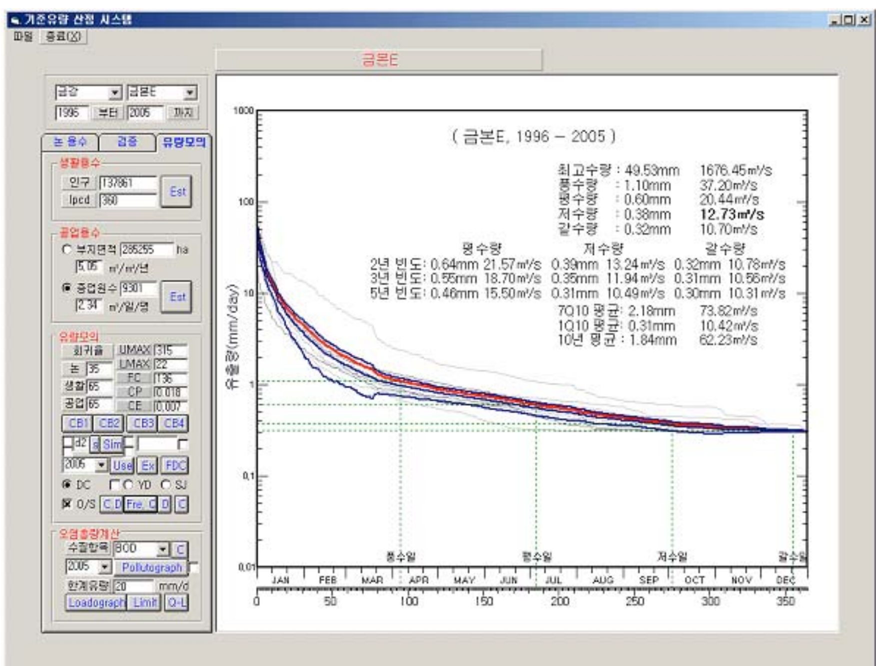

Figure 6. Reference flow calculating module.

Figure 7 shows an example of a load graph expressed on a daily basis. The upper graph shows a stream flow with a mean flow of 1.72 mm/day, a minimum of 0.31 mm/day, a maximum of 40.32 mm/day, and an annual flow of 627.6 mm/yr. The dark part is below the calculated reference flow, which shows an annual flow of 133.1 mm/yr or 22 % of the total flow. The lower graph is the water quality load which was produced by using the stream flow in the load equation derived in Figure 5. The BOD load shown has a mean of 6,188 kg/day, a minimum load of 663 kg/day, and a maximum load of 205,090 kg/day, the annual load is 2,258 ton/yr. The dark part is below the calculated reference flow, which shows an annual of 306.26 kg/yr or 13.6 % of total.

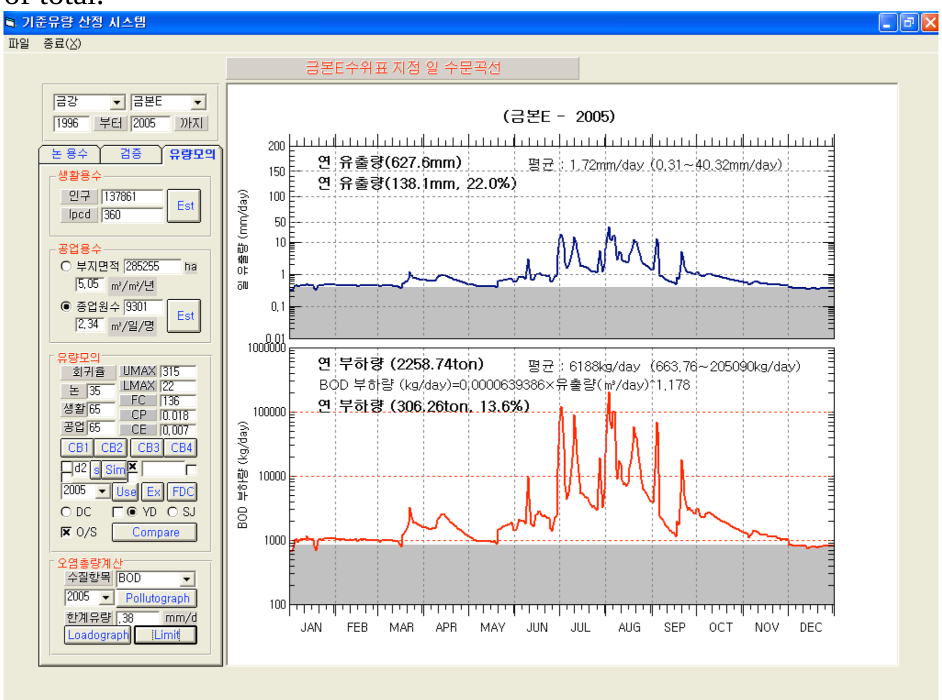

Figure 7. TMDL calculation module.

4. System Verification

The modules whose verification are described here are the paddy water requirement module and the runoff module. Irrigation water use data from wide paddy fields are not available because the water use in these paddies is complicated and difficult to measure. Therefore, the paddy water module was verified by comparing observed reservoir storages with simulated reservoir storages using a dam where data on its operation was available. The runoff module was verified by applying it to stations with observed stream flow data, but in this study, we show the result of only one station, the G monitoring station of the Geum River. This station is located 20 km downstream of the Daechung Dam.

4.1 Study Area

The Damyang Dam was selected to verify the module for estimating irrigation water requirements in wide paddy fields. This reservoir was constructed in 1976 to irrigate paddy fields. The dam is situated in Cheonnam province in Korea. The reservoir's water is used to irrigate an area of 5,011 ha. The effective capacity of the reservoir is 64.8 Mm^3, and the watershed area is 65.6 km^2. Figure 8 shows the watershed that drains into this reservoir.

The relationships between the elevation, water surface area, and storage volume are shown in Figure 9. Full water level is EL.119.5 m above sea level, and the dead water level is EL.80.0 m.

The Geum River basin's watershed area measures 9,959 km^2, which increases to 122,257 km^2 if the watersheds of the Mankyoung River and the Dongjin River are included. Within this river basin, the Geum River has 26 monitoring stations, and the Mankyoung and Dongjin rivers each have 5 monitoring stations for a total of 36 monitoring stations within the area of interest. Figure 10 shows the locations of these monitoring stations. The Daechung Dam, constructed in 2001, and the Yongdam Dam, constructed in 2002 are located in the upstream area of the Geum River (Table 1).

Figure 8. Watershed of the Damyang Dam.

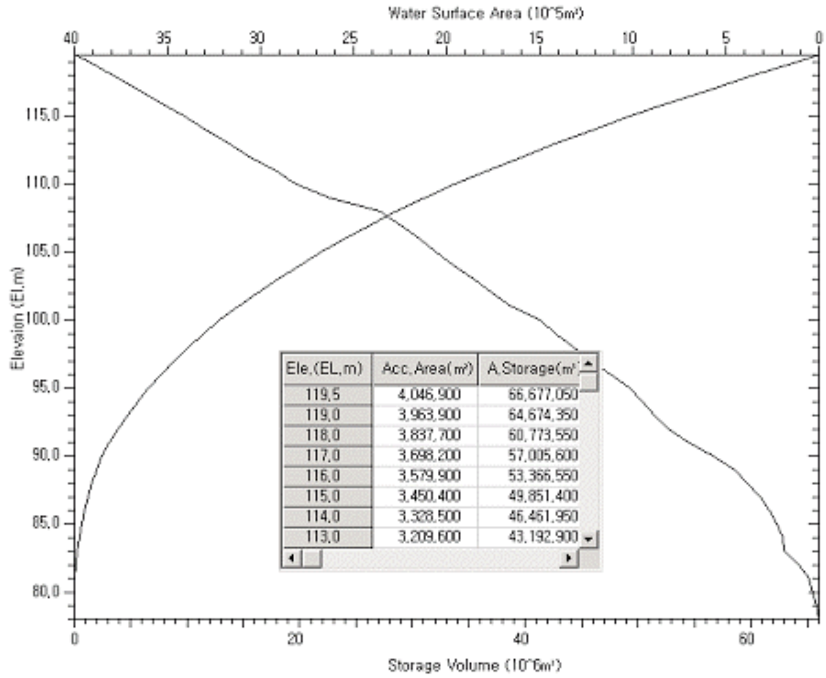

Figure 9. Area-capacity curve of the Damyang Dam.

Table 1. Specifications of the Daechung, Yongdam Dam.

Item	Daechung Dam	Yongdam Dam
Ponding Year	1981	2001
Watershed Area	4,134.0	930.0
Flood Water Level (EL.m)	80.0	265.5
Full Water Level [EL.m]	76.5	263.5
Limited Water Level [EL.m]	72.0	261.5
Low Water Level [EL.m]	60.0	228.5
Total Water Storage [Mm^3]	1,490	815.0
Effective Water Storage [Mm^3]	790.0	672.0

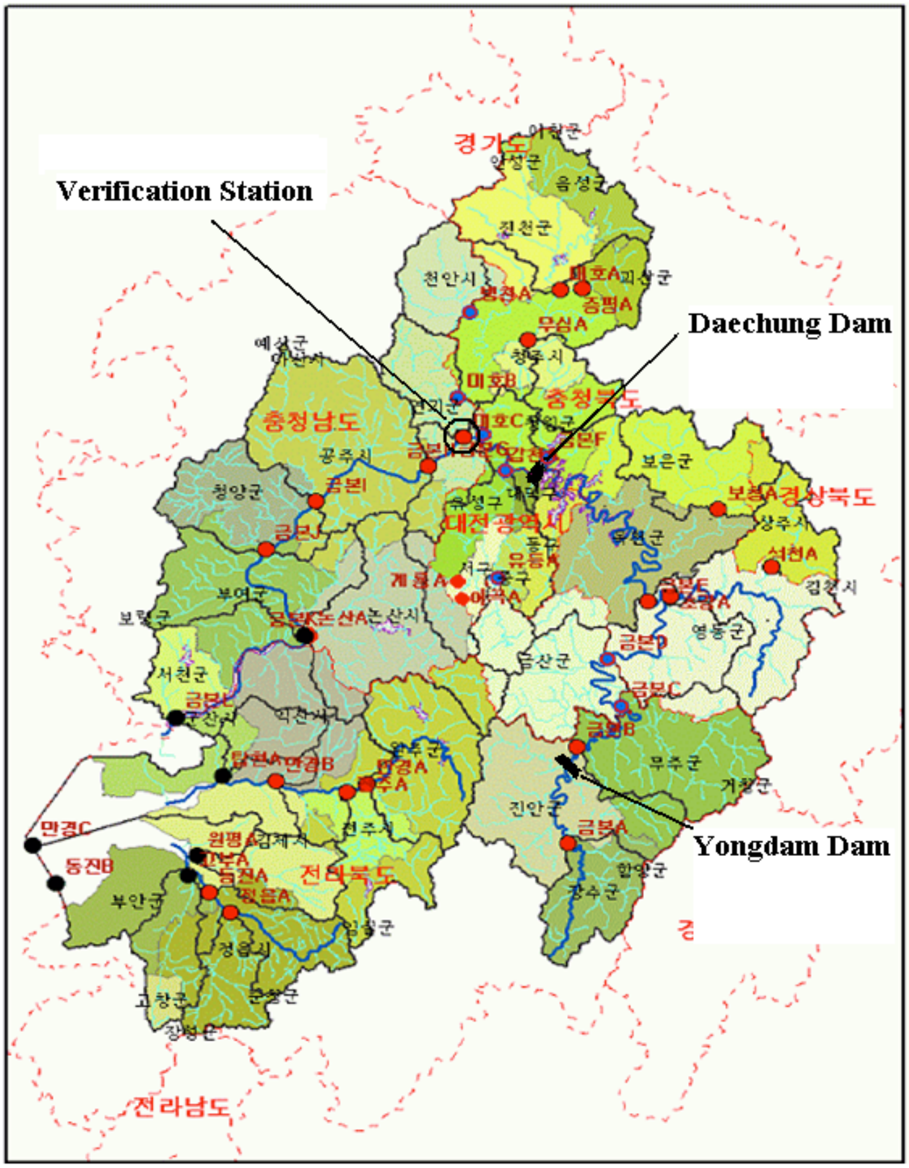

Figure 10. Locations of 36 monitoring stations within the Geum River basin.

Table 2 shows input data to estimate paddy water use, domestic water use, and industrial water use at the G monitoring station of the Geum River.

4.2 Paddy Water Requirement Module

Water storages in the irrigation reservoir are balanced using equation (5). Stored water is only used when water in the reservoir measures between the full storage level and the dead storage level. If the water is over the full storage level, it overflows. And if water is below the dead storage level, the water supply is zero. Inflows to the reservoir were simulated by the DAWAST model. Water demands are paddy irrigation water requirements which are estimated by the developed module. Outflows are stream minimum flows to be used to maintain water quality in streams at an appropriate level. An objective function to minimize storage errors is shown in equation (6), (7) which are used to parameterize the inflow model (Noh 2000). Simulation results are evaluated through Nash-Sutcliffe model efficiencies and equal value lines.

$$Ss(t+1) = Ss(t) + I(t) - E(t) - D(t) - O(t), \tag{5}$$

where I(t) is inflow to reservoir, E(t) water surface evaporation, D(t) water demand, O(t) outflow, t is the daily time interval.

$$\text{Min } S_e = \sum(S_o - S_s) \tag{6}$$
$$\text{Min } S_e = \sum(S_o - S_s)^2 \tag{7}$$

where S_e is the reservoir water storage error, S_o is observed water storage, and S_s is simulated water storage.

The DAWAST model's parameters were determined as UMAX of 343 mm, LMAX of 29 mm, FC of 127 mm, CP if 0.0216, and CE of 0.0080 using the Simplex optimization method as shown in Figure 11.

In the calibration year of 1999, the daily inflow to the Damyang Dam was simulated. In that year, 1,324 mm of rain produced 787.4 mm of runoff. As shown in Figure 12, the simulated storage very closely fitted the observed storage in the Damyang Dam. The Nash-Sutcliffe's model efficiency was shown to be 0.986, a very high value. Similarly, the value line between the observed storage and the simulated storage was very close to a 45˚ line as shown in Figure 13.

Table 2. Input data for estimating water uses of the G monitoring station watershed of the Geum River.

Watershed Area [km^2]	Sub watershed	166
	Accumulated watershed	5,027
Paddy Field Area [ha]	Sub watershed	2,161
	Accumulated watershed	7,733
Population [person]	Sub watershed	129,357
	Accumulated watershed	1,208,181
Industrial Complex Area [m^2]	Sub watershed	52,694
	Accumulated watershed	585,520
Employee [person]	Sub watershed	12,794
	Accumulated watershed	126,536

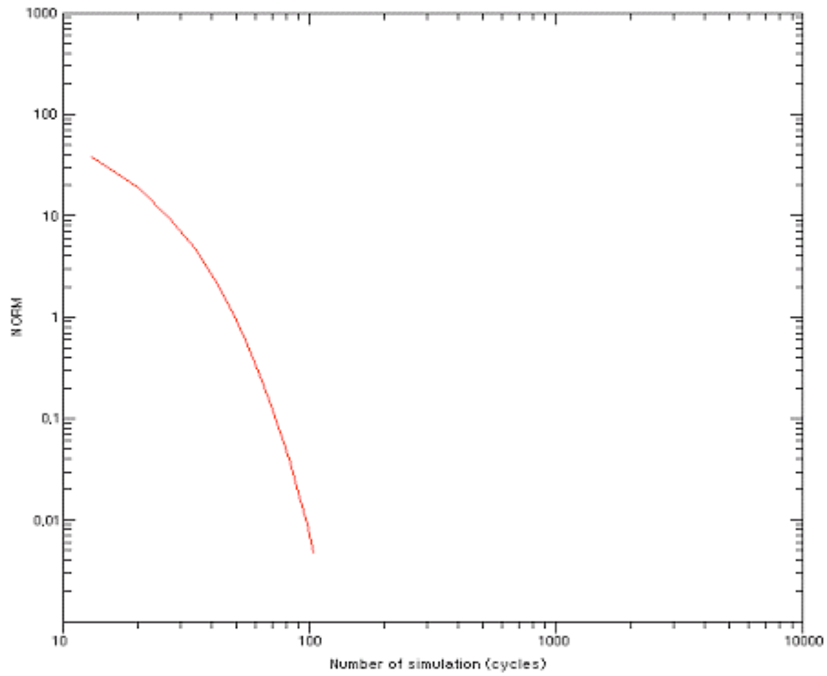

Figure 11. Paramater optimization of the DAWAST model using objective function with minimization of reservoir storage error.

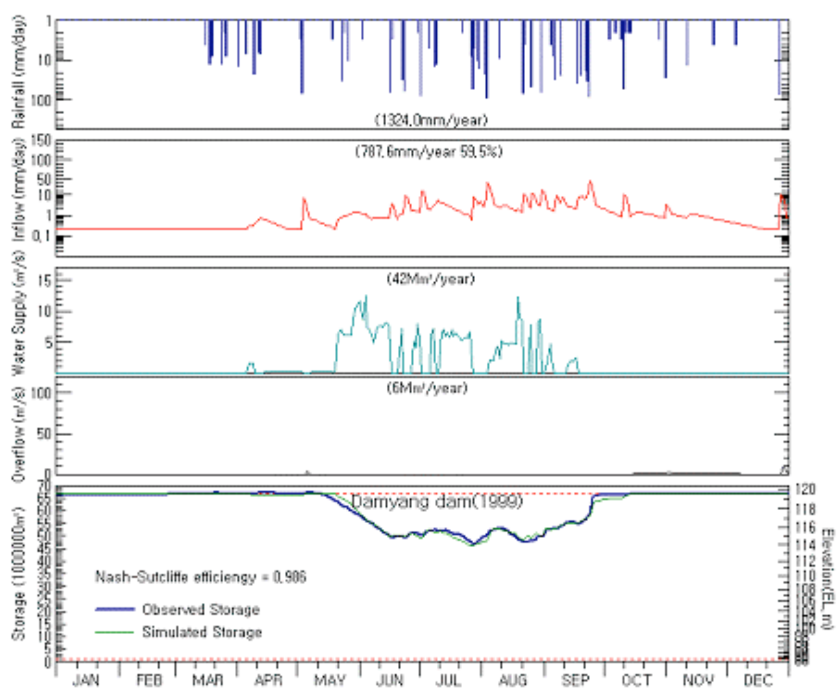

Figure 12. Comparison of the observed and simulated storage in the Damyang Dam for calibration year 1999.

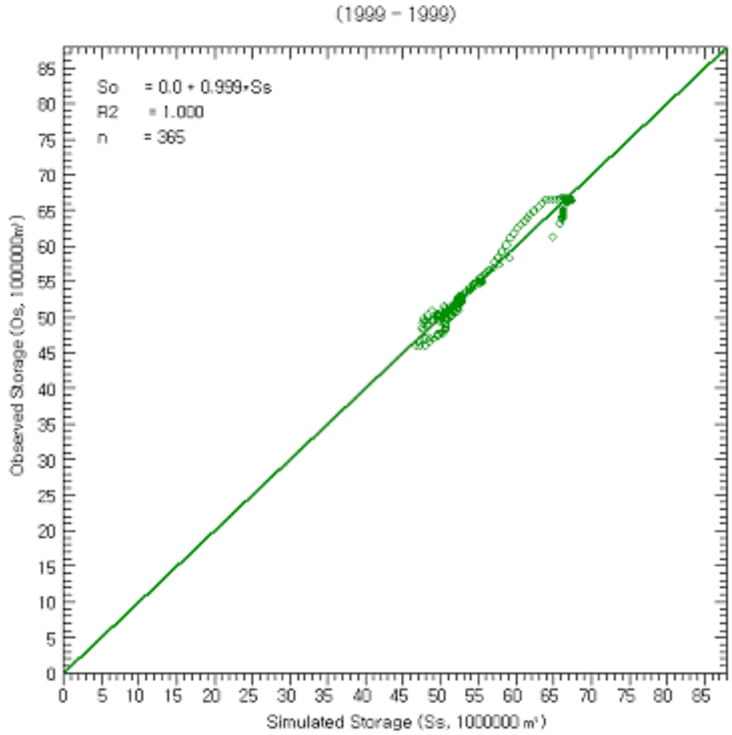

Figure 13. Equal line value comparison of the observed and simulated storage in the Damyang Dam for calibration year 1999.

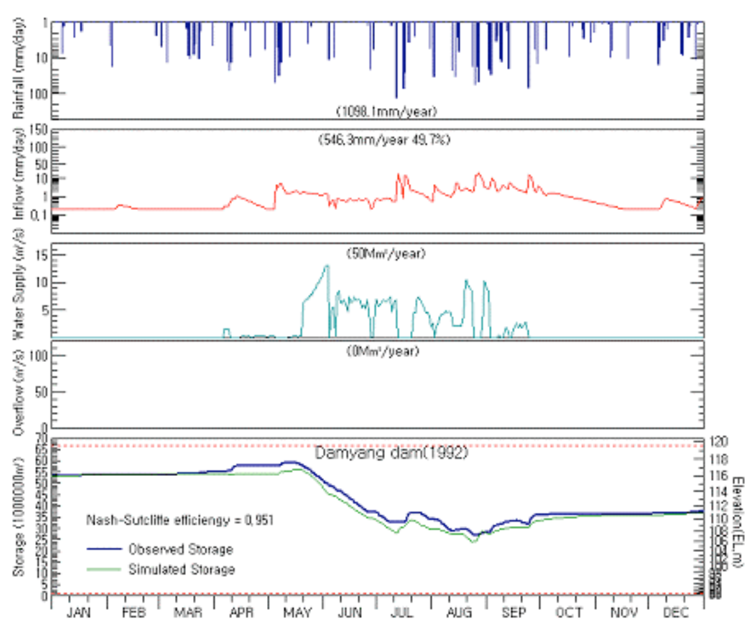

Figure 14. Comparison of the observed storage and the simulated in the Damyang Dam for verification year (1992).

The year 1999 was selected as the verification year. Figure 14 shows the simulation of the daily inflow to the Damyang Dam in which rainfall of 1,098.1 mm produced 546.3 mm of runoff. The observed storage and simulated storage in the Damyang Dam were very closely fitted. The Nash-

Sutcliffe's model efficiency was very high at 0.951. The line showing the simulated storage closely matched the observed storage line as shown in Figure 15. Consequently, the module was judged to be able to estimate daily paddy irrigation water requirements at a reasonable level.

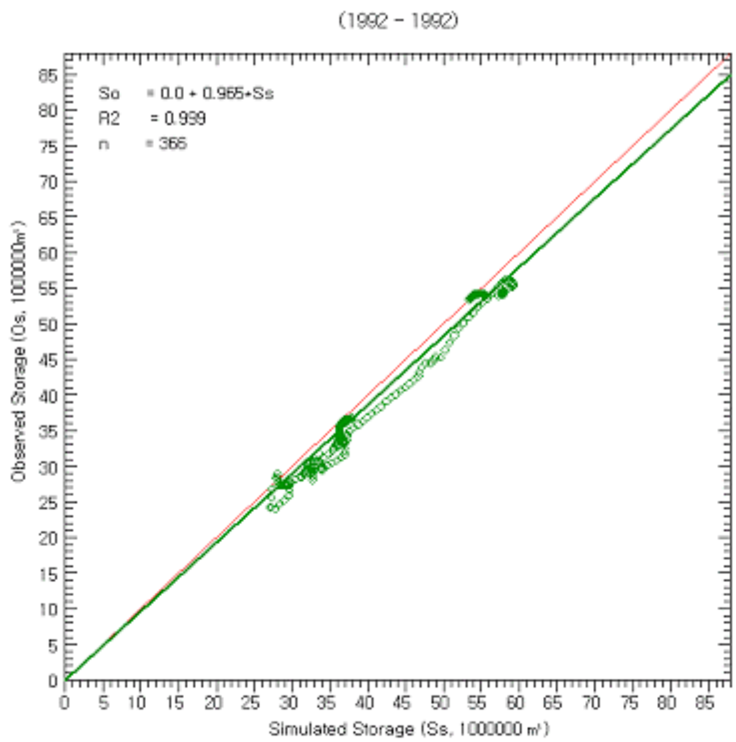

Figure 15. Equal line comparison of the observed storage and the simulated in the Damyang Dam for verification year (1992).

4.3 Runoff Module

Stream flows at 31 of the 36 monitoring stations within the Geum River basin have been monitored every 8 days since September, 2004. Only data from 2004 and 2005 were used to verify the runoff module. Based on the nonlinear Simplex method, the parameter optimization module of the DAWAST model was implemented to determine 6 parameters: ratios of return flows from paddy water use, domestic water use, and industrial water use using a daily time step as well as a time step which only used the data from the 8-day measurements. To simplify the procedure and maintain consistency, the return flow ratios were fixed. In this study, the parameters of the DAWAST model were determined using only the operational data of the Daechung Dam. The model was then applied to all monitoring stations within the Geum River basin. Only the results of the G monitoring station are presented here.

Figure 16 shows the daily water demands within the Daechung Dam watershed. Applying return flow ratios to domestic water of 65%, industrial water of 65%, and paddy water of 35%, the DAWAST model's parameters were determined. Figure 17 shows an example of the simulation of the daily

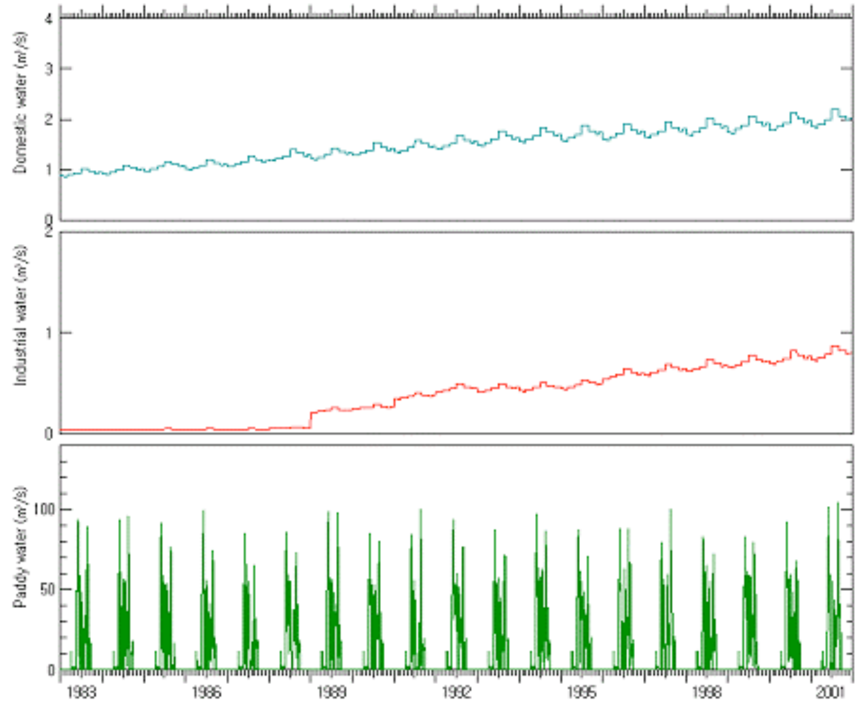

Figure 16. Daily water demands within the Daecheong Dam watershed.

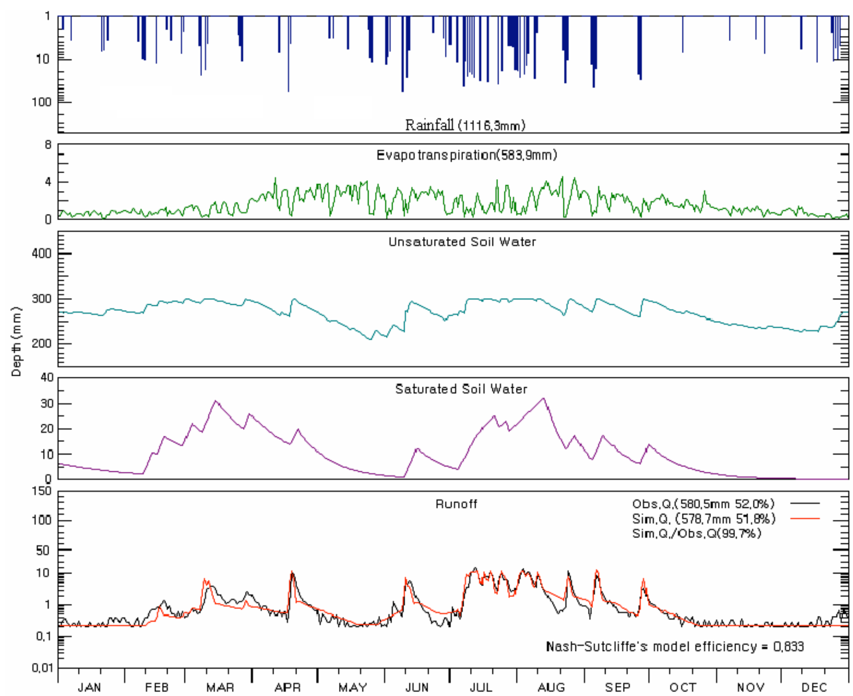

Figure 17. Example of simulating daily inflow to the Daechung.

inflow to the Daechung Dam. Figure 18 is the equal value line between 10-day observed and simulated inflows during the calibration period from 1989 to 1991. Figure 19 is the same for the verification period from 1983 to 2001. Both of them were shown to fit a 45° line closely. From this, it was concluded that the parameters used were able to be applied to other stations

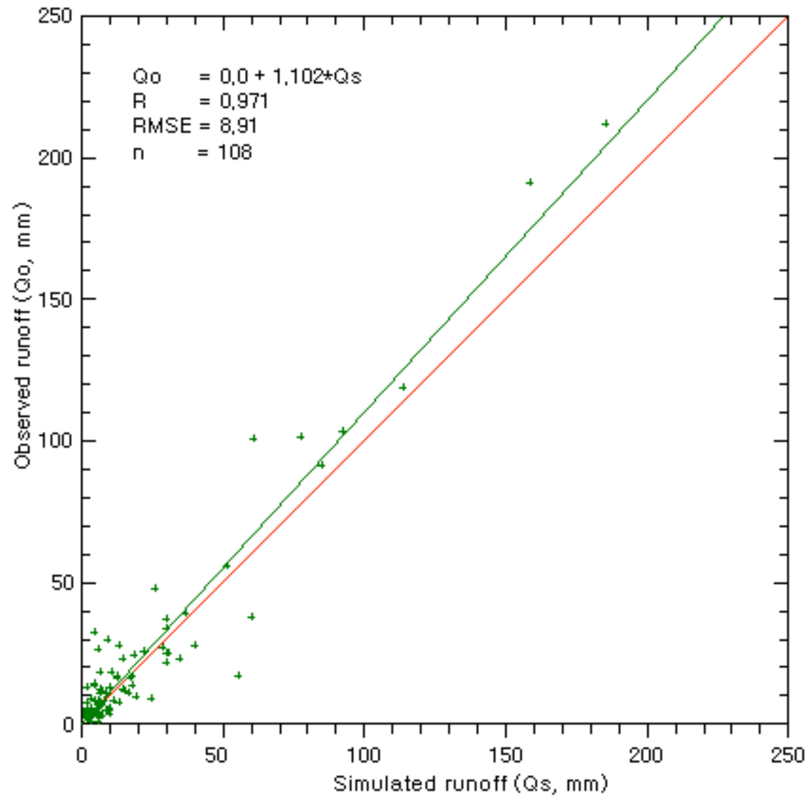

Figure 18. Comparison of 10-day equal value line for the calibration period (1989-1991, Daechung Dam).

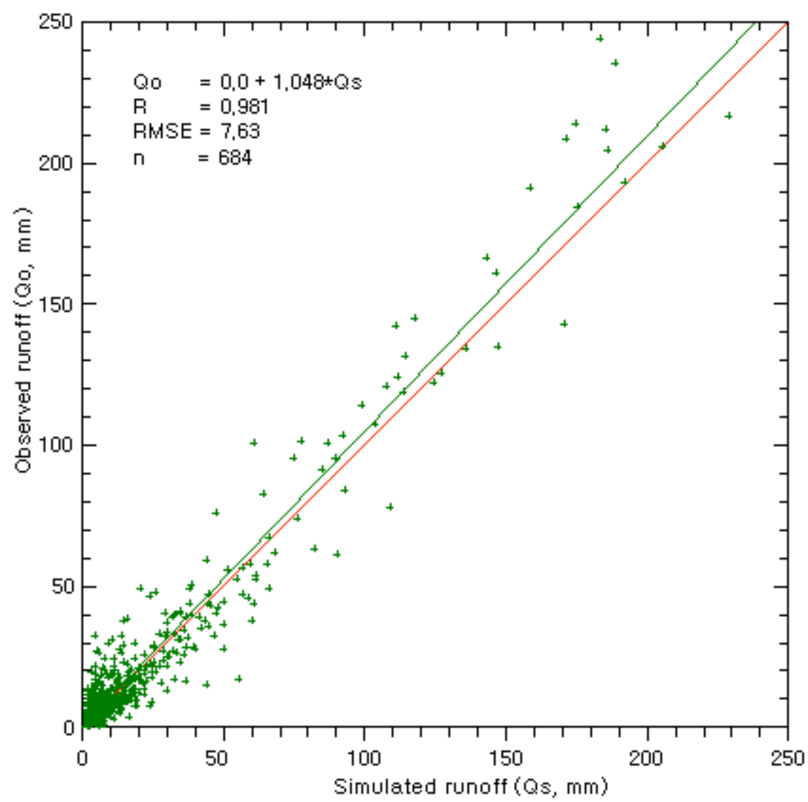

Figure 19. Comparison of 10-day equal value line for the verification period

(1983-2001, Daechung Dam).

Stream flows of the downstream dam are affected by the outflow of any upstream dams. Using the dam water storage simulation module of Figure 2, dam outflows are able to be generated for various dam operation scenarios. Figure 20 shows an example of simulating water storages in the Daechung Dam, which was affected by outflow from the Yongdam Dam upstream.

Figure 20 and Figure 21 show the results of comparing the observed stream flows of each 8 days with the simulated stream flows at the G monitoring station of the Geum River, in which model parameters were used with the same values applied to simulate the inflow to the Daechung Dam as shown Figure 17. Water uses were estimated by applying data shown in Table 2. Outflow from the Daechung Dam was used, which was the values from the Daechung regulating pond. The simulated results showed very good agreement to the observed data, in which the Nash-Sutcliffe's model efficiencies were 0.970, and 0.353, respectively. The results were very good in spite of using sparse stream flow data.

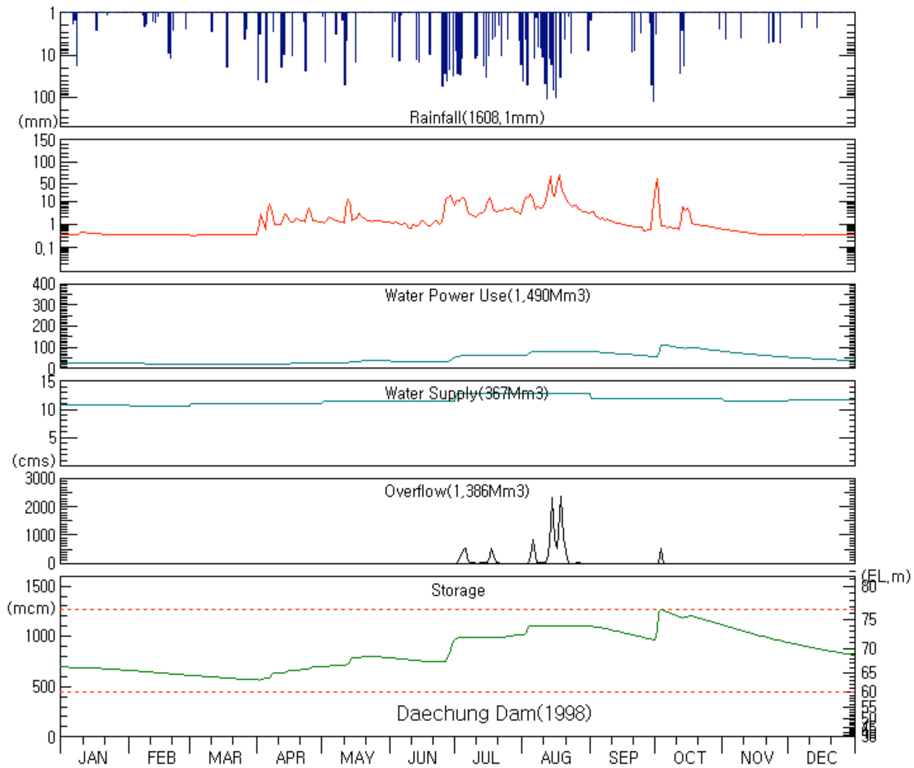

Figure 20. An example of simulating water storage in the Daechung Dam.

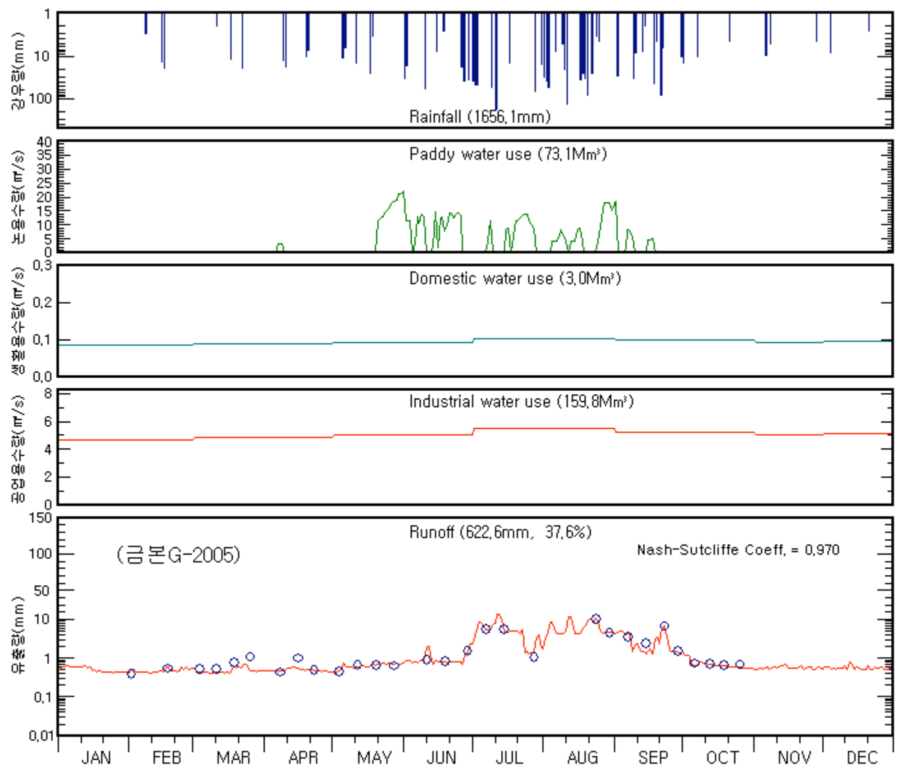

Figure 21. Comparison of the observed and simulated flows at the G monitoring station of the Geum River (2005).

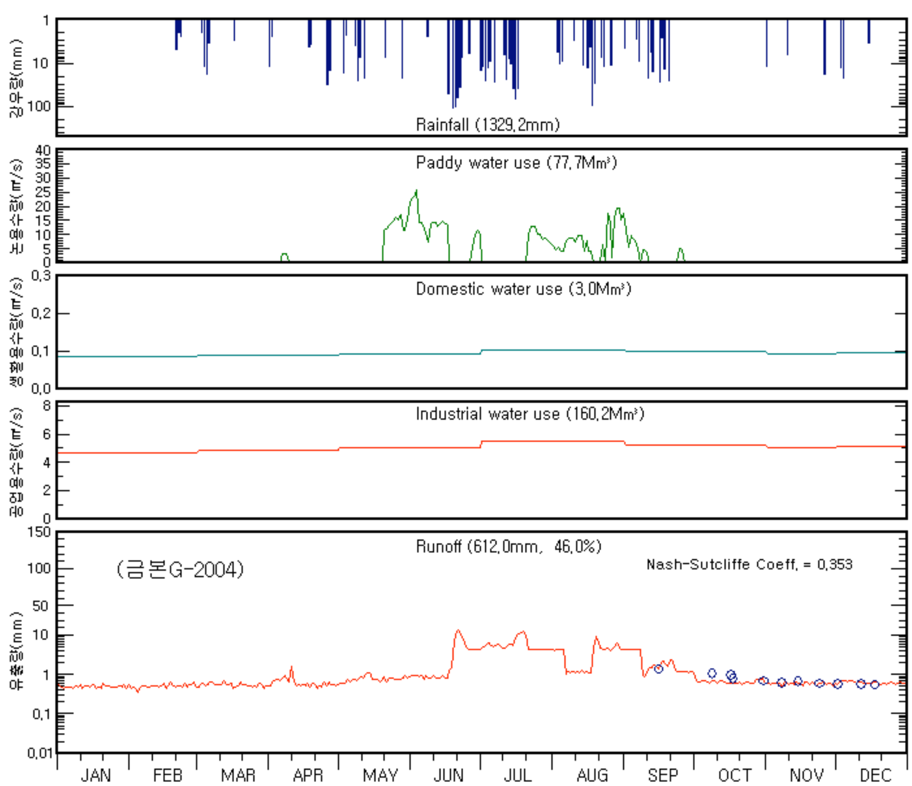

Figure 22. Comparison of the observed and simulated flows at the G monitoring station of the Geum River (2004).

5. Conclusion

In order to calculate reference flows to be applied when determining the TMDL of the Geum River in South Korea, a hydrologic modeling system was developed. The DAWAST runoff model was selected as the key module in the simulation tool. Modules for estimating paddy water, domestic water and industrial water were developed to reflect the impacts of return flows. A module to calculate reference flow was also developed, and a module for deriving the relationship between stream flow and water quality concentration was developed. In addition a module for calculating TMDLs was developed. The runoff module and the paddy water module were verified in this study.

Using the systematic hydrologic simulation tool described in this study, it was possible to determine reference flows in a more rational and rapid way at the 36 monitoring stations located within the Geum River basin in South Korea.

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