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Rainfall-Runoff Analysis of Flooding Caused by Typhoon RUSA in 2002 in the Gangneung Namdae River Basin, Korea

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ABSTRACT

Gangneung City on the east coast of the Korean Peninsula was devastated by flooding from August 31 to September 1, 2002 caused by Typhoon Rusa. The purpose of this study was to clarify the magnitude of the 2002 flooding caused by that typhoon in the Gangneung Namdae River Basin. The peak discharge observed at Gangneung was compared to the maximum peak discharge predicted empirically based on parameters for the climatically similar Tohoku district of Japan. The observed peak discharge from the Gangneung Namdae River exceeded the maximum peak discharge predicted for the Tohoku district. In addition, a rainfall-runoff analysis of the storm showed that the total areal rainfall in the basin, estimated from the discharge recorded at Gangneung, for the storm may have exceeded 1,000 mm, considerably more than the 898 mm reported for the observed rainfall at Gangneung during that period.

1. INTRODUCTION

From August 31 to September 1, 2002, the entire Korean Peninsula suffered from extensive flooding and landslides on being hit by Typhoon Rusa. Gangneung, a city on the east coast of the peninsula, was one of the most devastated areas, 870 mm/d being recorded on August 31, 2002 - the highest historical record - and a total rainfall of 898 mm recorded from August 31 to September 1. The heavy rainfall caused severe flooding in the region, inundating the entire urban area of Gangneung.

The purpose of this study was to clarify by two methods the magnitude of the flooding in 2002 caused by Typhoon Rusa in the Gangneung Namdae River Basin. One was to compare the magnitude of flooding in Gangneung with flooding that occurred in Japan. The other was to estimate the actual areal rainfall in the Gangneung Namadae River Basin by rainfall-runoff analysis.

The magnitude of the flooding in Gangneung was analyzed by means of equations of enveloping curves used to assess regional flood peaks in the Tohoku district of Japan. The equations used in Japan were applied to the Gangneung Namdae River Basin because the east coast area of the Korean Peninsula is considered to have climatic conditions similar to those of the Tohoku.

Areal rainfall in the basin was reevaluated in order to examine the possibility of there have been much more rainfall than was recorded at observatories. This could be assessed by analysis of the water balance during the storm, as well as from analysis of radar rainfall data. In addition, rainfall-runoff was analyzed by means of a kinematic runoff model, and the calculated discharge estimated from observed rainfall data compared to the observed discharge. In another approach, areal rainfall throughout the Gangneung Namdae River Basin was estimated by means of a power-type Tank Model from discharge data recorded in Gangneung.

2. RIVER BASIN AND DATA

2.1 Gangneung Namdae River Basin

The Gangneung Namdae River rises in the Taebaek Mountain Range, runs through the city of Gangneung after joining the Wangsan River, and then flows into the Japan Sea (**Fig. 1**). The basin area is 258.7 km^2, and length of the main channel is 32.9 km (Ministry of Construction and Transportation, Korea, MOCT). In this study, the area of focus was the region upstream of the urban area of Gangneung City, an area of 171.1 km^2.

This area is separated into two parts; upstream and downstream of the Gangneung Reservoir. The upstream area consists of two sub-basins; the Namdae River and the Wangsan River basins.

The terrain of the study area is very steep with a elevation range of as much as 1,400 m, and the main channel is only 32.9 km long. Landuse in the area is mainly for agriculture and forestry.

2.2 Hydrological Data

Rainfall and runoff data for flooding in the basin are available for August 30 to September 4, 2002. The Korea Meteorological Administration (KMA) has installed two rain gauges at Gangneung and Daegwallyeong, and the MOCT has observed water levels at Gangneung. Water level data was converted to observed discharge by means of two rating curves determined by the MOCT (see Section 3.2).

KEY WORDS: Typhoon RUSA, Gangneung, Korea, flood magnitude, rainfall estimation

Fig. 1 Physiographical map of the Gangneung Namdae River Basin.

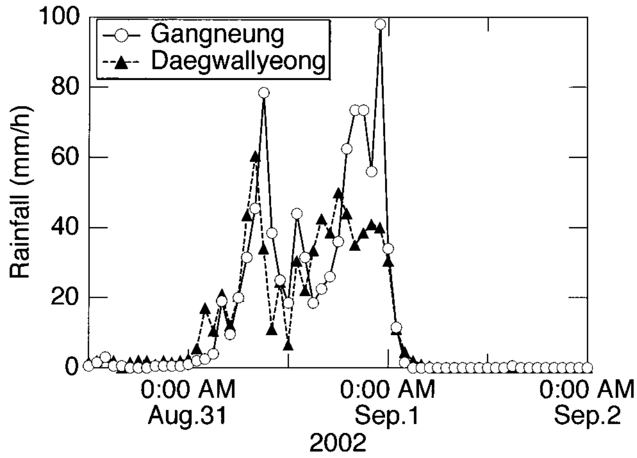

Fig. 2 Hyetographs at Gangneung and Daegwallyeong.

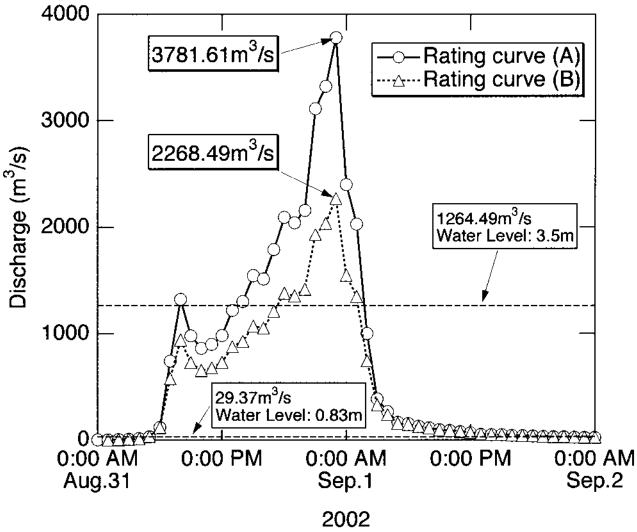

Fig. 3 Hydrograph at Gangneung.

3. MAGNITUDE OF FLOODING CAUSED BY TYPHOON RUSA

3.1 Rainfall

Fig. 2 shows variation in rainfall recorded at Gangneung and Daegwallyeong from August 31 to September 1. At Gangneung, the maximum hourly rainfall was 98 mm/h, and the maximum daily rainfall 870 mm/d; both recorded maximums.

The waveform of rainfall variation has two peaks. The cumulative rainfall from the onset of precipitation exceeded 200 mm when the first peak occurred. Therefore, it is likely that the soil of the basin would have been almost saturated when the second peak occurred. Moreover, with saturation of the soil surface adversely affecting rainwater infiltration, almost all of the precipitation would have become surface water and caused severe flooding.

3.2 Discharge

Variations in discharge at the Gangneung gauging station during the storm were estimated by converting water level data by means of two different rating curves derived by the MOCT at that station (equations (A) and (B)). **Fig. 3** shows those variations. Here, equation (A) was mainly used to calculate discharge because the usable water level range for equation (A) is greater than that of equation (B). Hereafter, discharge calculated by means of equation (A) is referred to as "observed" discharge. The upper limit of the range for equation (A) was closer to the highest water level than was that of (B), but the water levels around the time of peak discharge during the flooding were beyond the usable ranges of the equation (A) and equation (B). The highest water level on the staff gauge was 5.34 m, whereas the respective upper limits of the usable ranges of equations (A) and (B) are 3.5 m and 0.83 m.

Peak discharge recorded at the Gangneung gauging station was compared with the maximum peak discharge computed by means of enveloping curve equations that often are used to design flood control measures in Japan. The enveloping curves were drawn from regional flood-peak data for each district in Japan. Because the climate on the east coast area of the Korean Peninsula is considered to resemble that of the Tohoku district in Japan, calculation of maximum peak discharge at Gangneung is assumed to be derivable by the use of the enveloping curve equations for the Tohoku district.

In Japan, the following enveloping curves generally are used:

(1) Creager Enveloping Curves

The general form of the Creager equation is:

$$Q = CA^{(A^{-0.05})-1} \tag{1}$$

Table 1. Comparison of observed and estimated probable maximum peak discharges in the Namdae River basin.

Estimated or observed	Type of equation	Coefficient	Peak specific discharge ($m^3/s/km^2$)
Estimated	Enveloping curve eq. (1) (Creager's equation)	C=34 (Tohoku Dist.)	10.6
		C=80 (Max. in Japan)	24.9
	Enveloping curve eq. (2)	K=26 (Tohoku Dist.)	12.7
		K=49 (Max. in Japan)	24.0
Observed	Rating curve (A)	—	22.1
	Rating curve (B)	—	13.3

Table 2. Water balance during the storm period.

(a) Total rainfall

Observation point	Rainfall (mm)
Gangneung	898.0
Daegwallyeong	761.5

(b) Total runoff depth at Gangneung

Rating curve	Runoff depth (mm)
Eq. (A)	789.3
Eq. (B)	544.4

where Q is the peak discharge ($m^3/s/km^2$), C a coefficient dependent on the location of the objective drainage basin, and A the drainage area (km^2). The value of C is 34 for the Tohoku district of Japan and 80 for the southern Shikoku, southern Kyushu, and Okinawa islands, the largest peak values for flood discharge in Japan.

(2) Kadoya's Enveloping Curves

Kadoya and Nagai (1979) presented the enveloping curve equation:

$$Q = KA^{-0.06} \exp\left(-0.04A^{0.45}\right) \quad (2)$$

where Q is the peak discharge ($m^3/s/km^2$), K a coefficient dependent on the location of the objective drainage basin, and A the drainage area (km^2). The value of K is 26 for the Tohoku district of Japan and 49 for the southern Kii Peninsula of Honshu Island, southern Shikoku Island and Kyushu Island where the equation gives the largest values for peak discharge in Japan.

A comparison of peak discharges estimated from the enveloping curves and observed discharges is shown in **Table 1**. The observed discharge exceeds the maximum peak discharge predicted for the Tohoku district. The observed peak discharge was calculated as 22.1 $m^3/s/km^2$ by means of the rating curve (A), whereas the peak discharge for a basin in the Tohoku district of Japan with the same area as that of Gangneung Namdae River Basin was estimated as 10.6 $m^3/s/km^2$ by enveloping curve equation (1) and 12.7 $m^3/s/km^2$ by equation (2). The observed discharge also was comparable to the maximum peak discharges predicted for Japan, 24.9 $m^3/s/km^2$ by enveloping curve equation (1) and 24.0 $m^3/s/km^2$ by equation (2). These results indicate how large the magnitude of the flood was.

3.3 Water Balance during the Storm

Table 2 shows the total runoff depth at Gangneung and total amount of rainfall at Gangneung and Daegwallyeong during Typhoon Rusa. The two values for total runoff depth shown in this table were derived from water level data by means of rating curves (A) and (B).

The estimate for total observed runoff depth (calculated by rating curve (A)) appears inordinately large given the total rainfalls at Gangneung and Daegwallyeong. Moreover, the ratio of observed runoff depth to observed rainfall at Gangneung was as high as 88 % even though the basin probably was dry before the storm. The amount of rainfall for the ten days preceding the storm (August 21 - 30) was as little as 4 mm at Gangneung and 18.9 mm at Daegwallyeong. The high ratio is due to a water imbalance between the observed rainfall and runoff. The reason is that the observed discharge calculated by a rating curve was greater than the actual discharge and/or the observed rainfall was in fact less than the actual amount that fell in the basin.

4. RAINFALL-RUNOFF ANALYSIS USING KINEMATIC RUNOFF MODEL

To clarify the reasons for the water imbalance described above, discharge at Gangneung was simulated in a kinematic runoff model. The simulated discharge at Gangneung, derived from the observed rainfall, was compared to the observed discharge calculated by rating curve (A).

4.1 Model of Gangneung Namdae River Basin

Three sub-basins make up the Gangneung Namdae River Basin, two upstream of the Gangneung Reservoir and one downstream. Each sub-basin could be expressed as a combination of two rectangular planes and one channel in the kinematic runoff model. The Gangneung Reservoir was expressed by a Power-type Tank Model which considers the retardation effect of the reservoir. The upstream and downstream parts of the basin are connected by

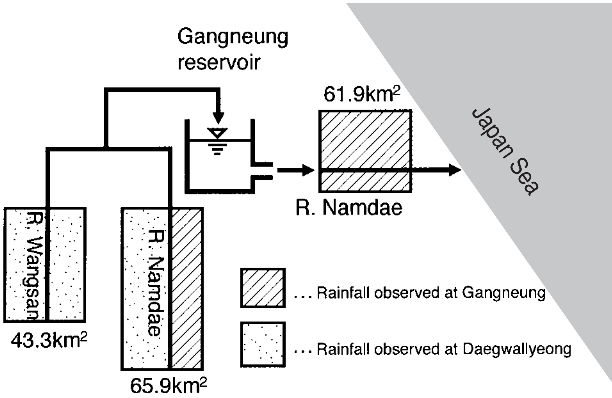

Fig. 4 Schematic illustration of the kinematic wave runoff model for the Namdae River basin.

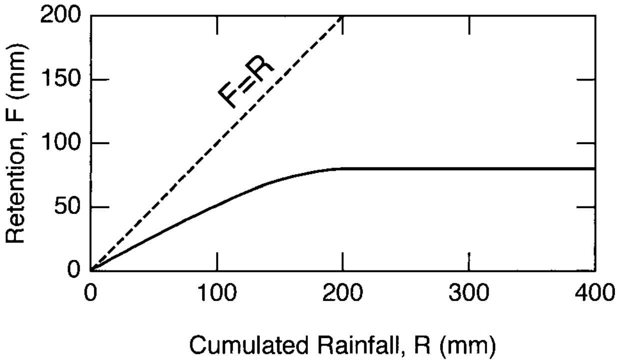

Fig. 5 Retention curve for mountainous area. The solid line shows the relationship between cumulated rainfall and rainwater that did not contribute to direct runoff. The dashed line shows the case in which no rainfall contributes to direct runoff.

the reservoir. A schematic illustration of the rainfall-runoff model for the Gangneung Namdae River Basin is shown in **Fig. 4**. The area of the planes and the channel length of each sub-basin are given in **Table 3**.

Rainfall distribution was assumed to be as shown in **Fig. 4**, which considers the distance between each sub-basin and each rain gauge station. Effective rainfall was calculated by means of the cumulated rainfall-retention relationship (**Fig. 5**) which is based on rainfall and runoff data observed in Japanese forests.

4.2 Basic Equations and Parameter Calibration

(1) Surface flow parameters

The momentum equation for surface flow is

$$h = kq^p$$

where h is the flow depth (m), q the flow discharge per unit width of a slope (m^2/s), and k and p are parameters. Parameter p was set at 0.6 based on Manning's law. The initial value for k was set at 1.0 because k was found to range from 1.0 to 2.0 in Japanese forests (Nagai et al., 1988). Parameter k subsequently was calibrated and the hydrograph calculated fitted to the observed one. Parameter k, used to calculate runoff in each sub-basin, is shown in **Table 3**.

Table 3. Parameters used in the kinematic runoff model for the Gangneung Namdae River Basin.

Sub-basin	Slope				Channel		
	Left – side		Right – side				
	k	Area (km^2)	k	Area (km^2)	K	P	Length (m)
1	0.5	9.160	0.5	52.714	1	0.7	4753.6
2	0.5	16.445	0.5	26.856	1	0.7	7380.5
3	0.5	33.327	0.5	32.583	1	0.7	11839.2

The continuity equation is

$$\frac{\partial h}{\partial t} + \frac{\partial q}{\partial x} = r_e$$

where t is the time (s), x the distance (m), and r_e the effective rainfall (m/s).

(2) Channel flow parameters

The momentum equation for channel flow is

$$W = KQ^P$$

where W is the cross section of channel flow (m^2), Q the discharge in a channel (m^3/s), and K and P are parameters. Initial values for K and P respectively were set at 1.0 and 0.7 based on findings of a Japanese study (Kadoya and Fukushima, 1976). These parameters were calibrated, then the hydrograph calculated was fitted to the observed hydrograph.

The continuity equation is

$$\frac{\partial W}{\partial t} + \frac{\partial Q}{\partial x} = q$$

where q is the total discharge per unit channel length from the slopes adjoining both sides of the channel (m^2/s).

(3) Retardation effect of the Gangneung Reservoir

Discharge from the upstream areas of the basin flows into the Gangneung Reservoir, before being released downstream. To account for the retardation effect of the reservoir, discharge from it was expressed by means of a one-layer Power-Type Tank Model. The discharge estimated with this model is expressed as

$$q = a(h - z)^{5/3}$$

where q is the runoff depth of the tank (mm/h), h the water depth (mm), z the height of the runoff (side) hole, and a the runoff coefficient. Parameters of the tank model, a and z, were calibrated by trial and error, and respectively set as 0.05 and 700.

A simulated hydrograph is shown in **Fig. 6**. This "observed" hydrograph represents the discharge calculated by rating curve equation (A). This figure shows that the observed discharge tends to be greater than the calculated one, especially about the time of the second peak. The total observed discharge volume is considerably larger than the total calculated discharge. If the discharge value calculated by rating equation (A) is assumed to be true then the actual amount of rainfall exceeded the observed rainfall amount because the observed discharge attributed to actual rainfall was greater than the calculated discharge of the observed rainfall at Gangneung or Daegwallyeong.

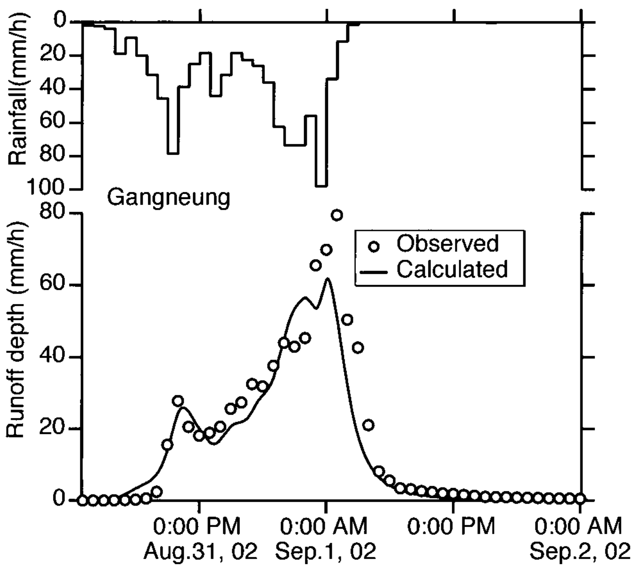

Fig. 6 Calculated hydrograph with the kinematic runoff model

5. RAINFALL-RUNOFF ANALYSIS WITH THE POWER-TYPE TANK MODEL AND INVERSE ESTIMATION OF AREAL RAINFALL FROM DISCHARGE DATA

An imbalance between the observed rainfall and discharge has been shown, and the probability suggested that the actual rainfall in the Gangneung Namdae River Basin was greater than the recorded amount.

To determine how rainfall was balanced with the observed discharge, rainfall-runoff was simulated with a Power-Type Tank Model. The tank model for the Gangneung Namdae River Basin was calibrated, and an areal rainfall hyetograph estimated from the observed hydrograph by means of this model.

5.1 The Power-Type Tank Model

The model was composed of two tanks in series (**Fig. 7**). Runoff was defined as the sum of the discharges from the side holes of tanks q_1 and q_2. Infiltration, f_1, and percolation, f_2, were defined as discharges from the bottom holes of the tanks. As shown, runoff from the upper tank was a non-linear function (power form function) of the water depth in the upper tank, h_1, whereas that from the lower tank was a linear function of the water depth in that tank, h_2. Infiltration and percolation were both linear functions of water depth in a tank. The lag time of runoff, T, was used to account for runoff propagation in the basin in the calculation of runoff.

5.2 Calibration of the Model

The eight parameters of the Power-type Tank Model: a_1, a_2, b_1, b_2, z_1, z_2, lag time of runoff, T, and the initial value of h_2, were calibrated by the Rosenbrock optimization method. The initial value for h_1 was assumed to be zero. In the calibration, areal rainfall was the weighted sum of the observed rainfall. Discharge data simulated with the kinematic runoff model were used instead of the dis-

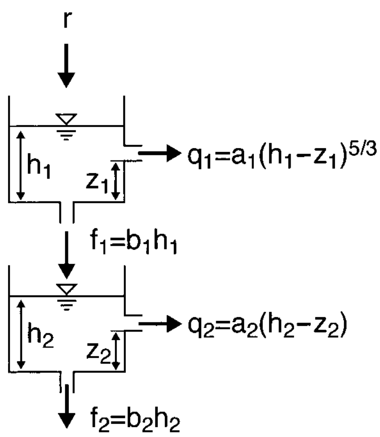

Fig. 7 Power-type tank model.

charge data based on the observed water level, given the requirement for calibrating a rainfall-runoff model using rainfall and runoff data that are balanced in terms of the water budget. As earlier shown, the discharge calculated from the observed water level by means of rating curve equations does not balance with the observed rainfall. The values of the calibrated parameters were a_1=0.00973, b_1=0.028, z_1=82.7, a_2=0.0481, b_2=0.0580, z_2=28.6, h_1=0., h$_2$=0.000730, T_1=0.497.

5.3 Rainfall Estimation Based on Discharge

In the calibrated Power-type Tank Model, the estimated areal rainfall in the Gangneung Namdae River basin was derived from the observed discharge by means of rating curve equation (A). Rainfall then was estimated by correcting the water depth in the upper tank.

The estimation procedure was as follows:

1) Calculation of discharge at a discrete time step k.

For the upper tank:

$$h_1' \leftarrow h_1(k-1) + r_{obs}(k)\Delta t$$
$$q_1(k) \leftarrow a\left(h_1' - z_1\right)^{5/3}$$
$$f_1(k) \leftarrow b_1 h_1'$$
$$h_1(k) \leftarrow h_1' - \left(q_1(k) + f_1(k)\right)\Delta t$$

For the lower tank:

$$h_2' \leftarrow h_2(k-1) + f_1(k)\Delta t$$
$$q_2(k) \leftarrow a_2\left(h_2' - z_2\right)$$
$$f_2(k) \leftarrow b_2 h_2'$$
$$h_2(k) \leftarrow h_2' - \left(q_2(k) + f_2(k)\right)\Delta t$$
$$q_{cal}(k) \leftarrow q_1(k) + q_2(k)$$

where $r_{obs}(k)$ is the areal rainfall calculated from the observed rainfall at time step k; $h_1(k\text{-}1)$ and $h_2(k\text{-}1)$ are the respective water depths of the lower and upper tanks; Δt is the time increment; z_1 and z_2 the side hole heights; $q_1(k)$ and $q_2(k)$ the respective runoff

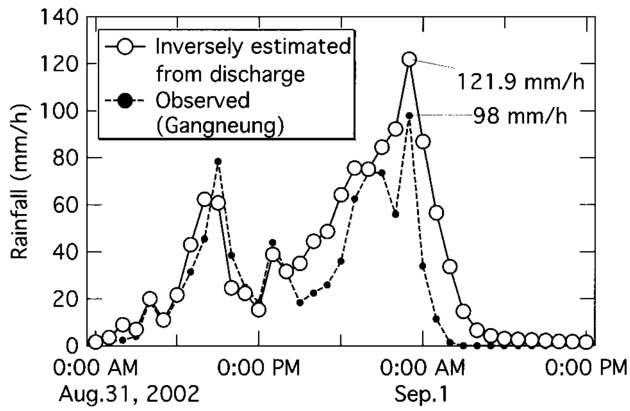

Fig. 8 Inversely estimated rainfall from discharge observed at Gangneung

depths from the upper and lower tanks; $f_1(k)$ and $f_2(k)$ the respective infiltration rate from the upper to the lower tank and the percolation rate from the lower tank; $q_{cal}(k)$ is the calculated runoff depth. Areal rainfall, $r_{obs}(k)$, was calculated as the weighted sum of the observed rainfall. Weight computation was based on the percentage of the area for each sub-basin slope to the total basin area. Correspondence between the observed rainfall and each sub-basin slope is shown in **Fig. 4**.

2) Let $q_{obs}(k)$ be the observed discharge at time step k, then areal rainfall over the basin is

$$h_{1,mod}(k) \leftarrow \left\{\left(q_{obs}(k) - q_2(k)\right) / a_1\right\}^{3/5} + z_1$$
$$r_{est}(k) \leftarrow h_{1,mod}(k) - h_1(k-1)$$
$$h_1(k) \leftarrow h_{1,mod}(k).$$

where $r_{est}(k)$ is the rainfall estimated from the observed discharge.

Fig. 8 shows an areal rainfall hyetograph estimated from discharge. By 0:00 PM on August 31, there was no significant difference between the observed and estimated rainfall. The first peak of the estimated rainfall at 9:00 AM is below that for the observed rainfall, but after 2:00 PM the estimated rainfall exceeded the observed rainfall. The second peak of the estimated hourly rainfall is 121.9 mm/h, far higher than the observed hourly rainfall of 98 mm/h at Gangneung. The total estimated rainfall, 1256.4 mm also is far higher than the 898 mm recorded at Gangneung.

These findings indicate that much more rain fell in the basin during the storm than was previously thought. The rating curve equation used to calculate discharge needs to be reexamined for accuracy, in particular for water levels outside of the usable range. Furthermore, other approaches, such as radar rainfall data analysis, are needed to clarify the range of the rainfall distribution.

6. CONCLUSION

The magnitude of the flooding in the Gangneung Namdae River Basin from August 31 to September 1, 2002 was examined from several hydrological standpoints. The results of the analyses can be summarized:

1) The total observed discharge was more than expected given the amount of rainfall recorded at Gangneung. The reasons for this were that the observed discharge, calculated by means of a rating curve, was greater than the actual discharge and/or the observed rainfall was, in fact, less than the actual amount that fell in the basin.

2) The peak discharge observed at Gangneung was comparable to maximum peak discharges estimated by the commonly used enveloping curve equations in Japan, evidence of how large the magnitude of the flooding was.

3) The maximum hourly rainfall estimated by rainfall-runoff analysis based on the observed discharge was 121.9 mm/h. The estimated total rainfall during the storm, based on the observed discharge, was 1251.4mm.

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