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Design of drainage culverts considering critical storm duration

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A method for designing road-crossing drainage culverts taking into the account critical storm duration is proposed. Based on estimated design floods, a hydraulic design approach is also proposed to optimise the dimensions and hydraulic variables of the culverts. Two small watersheds in Korea (Baran and Banweol) and thirty-five culvert design zones were used in this study. Critical storm durations were determined by applying Huff curves and unit hydrograph models such as the Nakayasu model, the United States Department of Agriculture Soil Conservation Service (USDA SCS) Curve Number model, the Clark model, and the WFRpaddy model. The American Association of State Highway and Transportation Officials (AASHTO) equation was applied to the thirty-five drainage culvert watersheds along segments of Highway No. 39 to define the optimum dimensions and hydraulic variables of the drainage culverts. The selected unit hydrograph models accurately estimated unit hydrographs for the study watersheds. Thus, the models can be considered a useful tool for computing peak runoff rates in Korean watersheds. For the other major watersheds studied, the design floods obtained by standard design were 50% greater than those calculated by the unit hydrograph models, indicating that the rational method, which is often used in culvert designs in Korea, predicts lower values than those of the standard design method. The design floods determined by the unit hydrograph models were higher than those predicted by the rational method applied in this study. Each unit hydrograph model calculated different values for double or triple rectangular-shaped culverts. With the exception of one watershed, the differences compared with the results from the standard design and AASHTO methods ranged from 0 to 10%. Consequently, implementing a design flood based on the critical storm duration is more appropriate than a design flood calculated using only the rational method. Thus, the design method using the concept of critical storm duration can be recommended to estimate a design flood. If the design method for drainage culverts developed in this research is applied to the standard design in Korea, a variety of subjective methods of estimating the design floods can be objectively achieved. Also, through incorporation of a Geographical Information System (GIS), a design which considers anticipated land use changes could be achieved.

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1. Introduction

The design of road drainage facilities require an accurate estimation of discharge–frequency relationships. Some facilities require a momentary peak flow rate while others require a runoff hydrograph that provides an estimation of runoff volumes. Momentary peak flow rates are most often used in the design of bridges, culverts, roadside ditches, and small storm sewer systems. These small-scale engineering works are sensitive to the design flood.

Cross-drainage culverts extend under a roadway and transport runoff across the roadway. Design of road-crossing culverts should take into account the many engineering and technical aspects at the culvert site and the adjacent areas. The engineer must also incorporate personal experience and judgement to determine which criteria must be considered and how to design the final dimension of the culvert.

A drainage culvert design is expected to meet a design standard that can safely drain the design peak flow. According to the Drainage Facility Design Guide (KEC, 2008), the capacity of a drainage culvert is determined by the design flood and hydraulic calculations. Because there are numerous drainage culverts and it would require much time and effort to calculate their precise design flood in practical application, the drainage culvert designs are often based on rough calculations. However, the over- or under-calculation of the design floods significantly affects construction costs and safety. Therefore, there is a need to develop a practical design method for drainage culverts that is based on a scientific design flood assessment.

Traditionally, many calculations of the design flood have employed the rational method, while other methods considered only the peak runoff rate. In order to calculate a more precise design flood, a precise hydrograph-based method is suggested. Further, because of the inadequacy of the frequency-based rainfall method used in the existing standard design method, a method to more accurately estimate design flood is needed to assess the actual rainfall distribution status by taking the rainfall duration distribution into account.

The time factor used in the rational method is simply a period within the total storm duration during which the maximum average rainfall intensity occurs. To date, in most standard designs, the rational method uses the time of concentration at each design point within a drainage basin as the maximum average rainfall intensity. In some cases, however, runoff from a portion of the drainage area that is highly impervious may result in a greater peak discharge than would occur if the entire area was considered (Debo and Reese, 1995; Sim and Jo, 1998).

In order to address these limitations, variations in the time of concentration, calculation and other problems which are associated with the existing rational method and the concept of critical storm duration are considered. The critical storm duration provides the maximum peak discharge. The flood peaks are then plotted against the rainfall duration, and the design peak discharge and critical duration are obtained from the peak of a smooth curve drawn through the plotted points (Maidment, 1992). However, critical storm durations are influenced by the soil type and land uses of a watershed, the rainfall distribution, and the characteristics of the hydrologic models. Because of this, a single approach cannot yield a design procedure or a formula which is applicable to the conditions in all watersheds. In the case of Korea, runoff coefficients are used as the representative values in order to estimate design floods. Because this may result in significant deviations in terms of the critical storm duration, there is a need to examine their effects and to standardise the design procedure. To answer these questions, a drainage culvert design should use the concept of critical storm duration with rainfall distribution types and also be able to implement proper hydraulic calculations after the design flood has been estimated.

The following objectives were considered in order to develop a method to design drainage culvert cross-sections that take into account the rainfall distribution and the critical storm duration; (1) estimating the design flood at ungauged watersheds using the proposed flood design estimation method, (2) determining drainage culvert cross-sections in accordance with hydraulic calculations based on the design flood and the critical storm duration, and (3) evaluating the applicability of the proposed design method.

2. Methodology

2.1. *Study watersheds*

Two gauged watersheds in Korea, HP No. 6 (Balan) and WS No. 1 (Banweol), were selected in order to evaluate the performance of different unit hydrograph models. The hydrologic characteristics of the watersheds are discussed in detail by (Park *et al.*, 1997; Koo, 2001; Kang *et al.*, 2006). In order to evaluate the applicability of various drainage culvert design approaches, ungauged small watersheds were selected from the Balan–Banweol highway expansion and pavement project area, along National Highway No. 39 in Korea (Fig. 1).

For the purpose of this study, a construction site on Highway No. 39 was selected. Generally, hydrologic data for the design were not monitored for the design flood. Monitoring devices were initially intended to install at the study site. Unfortunately, this was not allowed since they could be obstacles for the construction (Kang, J.H., Personal Communication, May 22, 2008).

Thirty-five drainage culverts, twenty-three of which were circular and twelve rectangular in cross-section, were selected along the segments of National Highway No. 39 that under major renovation. The watershed areas of these drainage culverts vary from 1.0 to 223.0 ha. The hydrological parameters of the watersheds were defined using a Geographical Information System (GIS). GIS data were incorporated to create, retrieve, and evaluate the databases for the highway drainage design. The GIS was capable of accurately extracting both the geographic and hydrologic characteristics as an input for hydrologic models from existing databases. For all watersheds, runoff coefficients were obtained by reclassifying the land use map (1/25 000), and Curve Numbers (CNs) were obtained by reclassifying the land uses and attribution of the soils map.

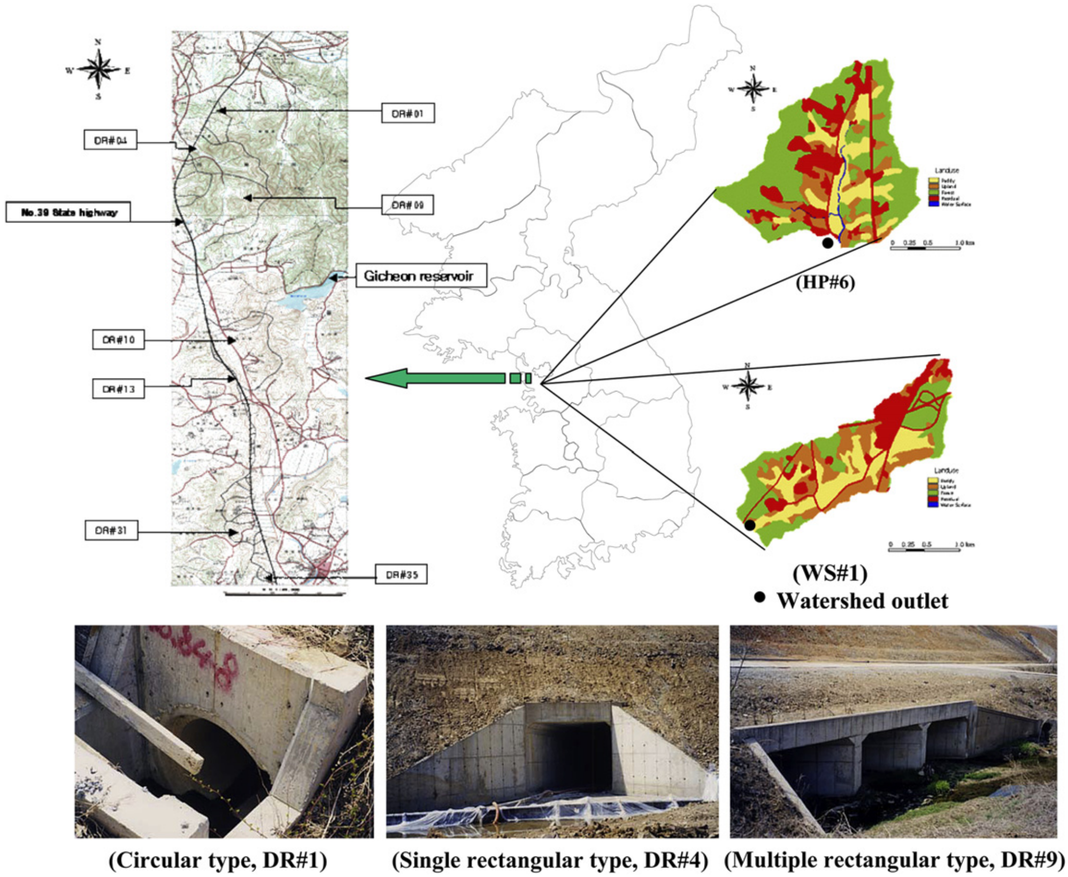

Fig. 1 – Selected watersheds and National Highway No. 39.

2.2. *Critical storm duration*

The concept of critical storm duration is a useful tool to assess the design flood when designing drainage culverts. Further, use of the critical storm duration is appropriate when determining the rainfall duration which influences the maximum peak runoff rate. The method using critical storm duration requires information on the effective rainfall and rainfall distribution, as well as an effective rainfall–runoff model. According to Sim and Jo (1998), the method to select the critical storm duration that is appropriate for the situation in Korea are as follows: (1) effective rainfall calculation in accordance with the USDA Soil Conservation Service (USDA SCS) CN model, (2) rainfall distribution in accordance with the Huff rainfall distribution model (Huff, 1967), and (3) the Clark model (Clark, 1945) which considers maximal topography factors for a watershed.

To determine the critical storm duration, this study calculated the effective rainfall in accordance with the USDA SCS model and used the Huff curves, a rainfall distribution model, which utilises the frequency-based rainfall. Using this approach, and by observing the relationship between the peak runoff rate and the critical storm duration, the critical storm duration was calculated in order to estimate the design flood. In order to estimate design floods with different return periods, mathematically expressed Intensity Duration Frequency (IDF) curves for the city of Suwon were used. The IDF curves are available from the Korea Institute of Construction Technology (KICT, 2000).

The Huff curves (Huff, 1967) provide an effective method of characterising storm mass curves (Bonta, 2001, 2004). For the Huff model, hourly rainfall records for the period from 1964 to 2000 were obtained and analysed from the Suwon Weather Bureau, Korea. For the Huff curves a period was defined as dry if it lasts at least 6 h.

The Clark model, taking into account the maximal topography factor, was used to determine the critical storm duration. The critical storm duration was estimated by subdividing the rainfall duration into 0.1 h interval. The rationale for this was that, according to Sim and Jo (1998), only an approximate value is obtained when using a time unit of 1.0 h to assess the critical storm duration.

2.3. *Hydrology and hydraulic models*

The design flood was calculated by applying the rational method, which calculates the peak runoff rate, and by applying several different unit hydrograph models takes into account the critical storm duration. The rational method and the unit hydrograph models were applied for rainfall–runoff relationships which are applicable to ungauged watersheds for estimating the peak runoff rate. The unit hydrograph models used in this study included; the Nakayasu model (Horner and Flynt, 1936; Jung and Moon, 2001; Lee *et al.*, 2004), the USDA SCS CN model (USDA SCS, 1985, 1986), the Clark model (Clark, 1945), and the watershed flood routing model considering paddies (WFRpaddy model, Kim *et al.*, 2000). The models were applied using hydrological parameters defined by using GIS. Details of the hydrological models used in this study are found in many references (Horner and Flynt, 1936; Clark, 1945; USDA SCS, 1985, 1986; Maidment, 1992; Jung and Moon, 2001).

To select possible methods for this study, a survey was conducted to recommend methods from local civil engineers and hydrologists (Chun, J.C.; P.E.; Hyun, C.H.; Shin, S.H., personal communication, May 10 and May 17, 2008). The models used for this study were selected by recommendation from civil engineers. More models can be used for the flood designs in other countries (e.g. Europe including the United Kingdom) but were not considered here.

The WFRpaddy model was proposed by Kim *et al.* (2000) to estimate flooding from small watersheds containing rice paddy fields. The WFRpaddy model adopted the rainfall excess and hydrologic flood routing components of the USDA SCS model, and includes a paddy runoff routine that represents the special runoff characteristics of irrigated paddies, such as inundation, retention storage, and drainage. The hydrologic cycle within a paddy field is explained in terms of a water balance (Kim *et al.*, 2000; Kang, 2002; Kang and Park, 2003; Kang *et al.*, 2006).

The runoff from a paddy can be calculated using a weir formula as follows:

$$Q_p = c_p W H_p^{3/2} \tag{1}$$

where Q_p, c_p, W, and $H_p^{3/2}$ represent runoff ($m^3 s^{-1}$) from the paddy field, the outlet runoff coefficient, the drainage outlet width parameter (m), and the overflow depth (m) from the drainage outlet, respectively.

The American Association of State Highway and Transportation officials (AASHTO, 1991, 2000) method was applied for determining the dimensions of the culverts for the hypothetical design storms resulting from changes in the topography and land uses at the thirty-five culvert drainage watersheds in this study. Hydraulic calculations for the culvert design can be seen in detail in the AASHTO model drainage manual.

3. Results and discussion

3.1. *Time of concentration*

Hourly and daily precipitation data were obtained from the weather stations located within the Balan (HP No. 6) and Banweol (WS No. 1) watersheds and from the Suwon Weather Bureau. Hydrological monitoring stations equipped with two float- and pressure-type water level gauges were located at the outlets of the watersheds. The constant-slope method, which connects the minimum value prior to the beginning of the storm hydrograph to the inflection point on its recession limb, was used for baseflow separation. The details of these watersheds monitoring method were discussed by Koo (2001) and Kang *et al.* (2006).

In the USDA SCS method the change in CN is based on an antecedent moisture condition (AMC) determined by the total rainfall in the 5-day period preceding a storm. Three levels of AMC are used: AMC-I is the lower limit of moisture, AMC-II is the average, AMC-III is the upper limit of moisture (USDA SCS, 1985). Because the design flood is the maximum runoff expected due to the frequency-based rainfall, the CN values were obtained for AMC-III. The CN for the HP No. 6 watershed was 89, and 90 for the WS No. 1 watershed. A period of 25 years was used for the recurrence period using the standard design method of for culvert drainage used in Korea. The critical storm duration was calculated by estimating the peak runoff rate and Huff curves for a period of more than 25 years.

The collected data showed that the watershed areas of the studied drainage culverts ranged from 0.01 to 2.23 km^2, the channel lengths ranged from 0.06 to 2.74 km, the watershed slopes ranged from 1.69 to 4.92 $m\,km^{-1}$, the runoff coefficients ranged from 0.73 to 0.84, and the CN ranged from 71 to 86. The DR No. 09 was the largest watershed in area, and the DR No. 13 watershed was the smallest. The time of concentration was obtained using the Kirpich equation (Kirpich, 1940). The time of concentration for the watersheds varied from 5 to 88 min. Table 1 shows the geomorphological and hydrological characteristics of the drainage culvert watersheds.

3.2. *Design flood by the rational method*

The 35 drainage culverts were already installed in the project area. The rational method was used to calculate the design flood for each culvert using the frequency-based rainfall of the design recurrence interval. A recurrence period of 25 years was used for design for the 35 drainage culverts. However, in this research the design flood was calculated based on a recurrence frequency of 2, 5, 10, 25, 50, 100, and 500 years.

Since the rational method is generally often used in culvert designs in Korea, a comparison was made between the design floods calculated using the rational method and those for the standard design method (Fig. 2). The design floods obtained by the standard design method ranged between 0.4 and 95.6 $m^3 s^{-1}$, compared to between 0.3 and 29.6 $m^3 s^{-1}$ by the rational method. On average, the design flood predicted by the standard design method was higher than that for the rational method. When using the largest design flood for the DR No. 09 watershed, the standard design method was 323% greater than that calculated by the rational method. This shows that the standard design method substantially over-estimated the design flood.

Taking the recurrence interval of 25 years used by the standard design method as a standard, the standard design method yielded a higher design flood frequency than the rational method. Moreover, it also showed that the flood calculated for the 25-year frequency by the standard design method yielded a much higher value than that for the 500-year frequency using the rational method (Fig. 2). As shown in Fig. 3, the design flood increased as the watershed area increased.

3.3. *Applicability of the unit hydrograph models*

To evaluate the performance of the different unit hydrograph models, the models were tested with the measured field data. The model performance was evaluated using metrics such as

Table 1 – Hydrological characteristics for each drainage culvert watershed

Drainage culvert name	Area (km^2)	Flow length (km)	C	CN
DR No. 01	0.0381	0.259	0.79	72
DR No. 02	0.2815	0.811	0.80	74
DR No. 03	0.0908	0.545	0.79	77
DR No. 04	1.1426	2.014	0.77	76
DR No. 05	0.0297	0.184	0.81	74
DR No. 06	0.0927	0.353	0.80	72
DR No. 07	0.3829	0.939	0.80	77
DR No. 08	0.1035	0.559	0.80	77
DR No. 09	2.2304	2.738	0.78	77
DR No. 10	1.8627	2.243	0.76	76
DR No. 11	0.0213	0.087	0.81	80
DR No. 12	0.0183	0.112	0.82	77
DR No. 13	0.0077	0.061	0.80	75
DR No. 14	0.0117	0.070	0.80	75
DR No. 15	0.0165	0.087	0.80	86
DR No. 16	0.0222	0.105	0.83	85
DR No. 17	0.0129	0.165	0.84	82
DR No. 18	0.0123	0.116	0.83	77
DR No. 19	0.0238	0.169	0.77	75
DR No. 20	0.0221	0.156	0.80	75
DR No. 21	0.0103	0.144	0.80	75
DR No. 22	0.0101	0.088	0.80	75
DR No. 23	0.0258	0.179	0.81	75
DR No. 24	0.0082	0.110	0.80	76
DR No. 25	0.0130	0.177	0.80	73
DR No. 26	0.0489	0.327	0.80	75
DR No. 27	0.1613	0.705	0.78	71
DR No. 28	0.2882	0.727	0.75	76
DR No. 29	0.1048	0.555	0.75	74
DR No. 30	0.0189	0.181	0.82	84
DR No. 31	0.2958	0.829	0.78	80
DR No. 32	0.0410	0.379	0.81	80
DR No. 33	0.0717	0.406	0.81	79
DR No. 34	0.1505	0.659	0.77	80
DR No. 35	0.0888	0.484	0.73	81

the root mean squared error (RMSE), the Nash efficiency criterion (NEC) (Nash and Sutcliffe, 1970), and the coefficient of the determination (R^2) for time to peak and peak runoff rates for all 41 selected storm events at the two gauged watersheds, HP No. 6 and WS No.1.

The model estimations were accurate (NEC and R^2 were greater than 0.90 for the peak runoff rate) for all 41 data sets for the selected unit hydrograph models (Table 2). The results from the model applications indicated that the computed runoff parameters were statistically in close agreement with the observed data. Thus, the selected models appear to be applicable to various watersheds in Korea for estimating peak runoff rates.

3.4. *Design floods based on the critical storm duration*

In order to determine the design flood for drainage culverts based on the critical storm duration, the peak runoff rates for various frequencies were obtained by applying the Huff curves in accordance with the critical storm duration. Among the thirty-five drainage culverts watersheds along the National Highway No. 39, only the major drainage culverts (based on the watershed size) for DR No. 4, DR No. 7, DR No. 9, DR No. 10

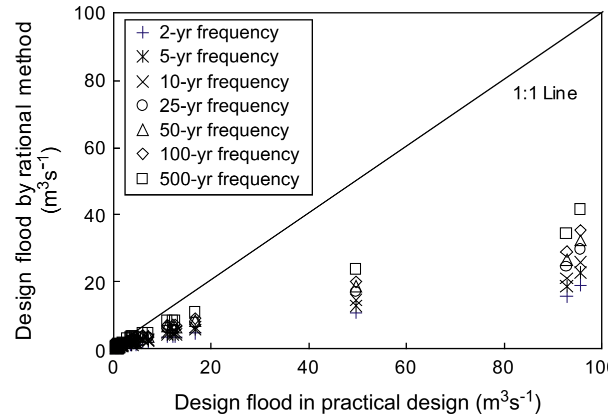

Fig. 2 – Comparison of the results for the calculated design flood from the rational method and from the standard design method.

and DR No. 31 were selected. This is because the drainage culvert design was the same for all drainage culvert watersheds for rainfall events with duration of less than 10 min.

On the basis of the frequency-based rainfall data provided by the Suwon Weather Bureau, the effective rainfall was obtained with respect to AMC-III condition. In order to estimate this design flood at each recurrence interval, the Huff rainfall distribution model that yielded the greatest peak runoff rate was chosen for the recurrence intervals of 5, 25 and 50 years. Since the watershed areas for the drainage culverts were small and the rainfall durations were set at intervals of 0.1 h for 24 h, a total of 240 time slots were defined. In this study, the Clark model was selected as the model for estimating the peak runoff rate.

Fig. 4 shows the changes in the peak runoff rates according to the rainfall duration for determining the design flood and the critical storm duration at the selected drainage culvert watersheds. The bold dotted line on each graph indicates the peak runoff at the critical storm durations. Thus, the peak runoff rates at the critical storm durations are the design

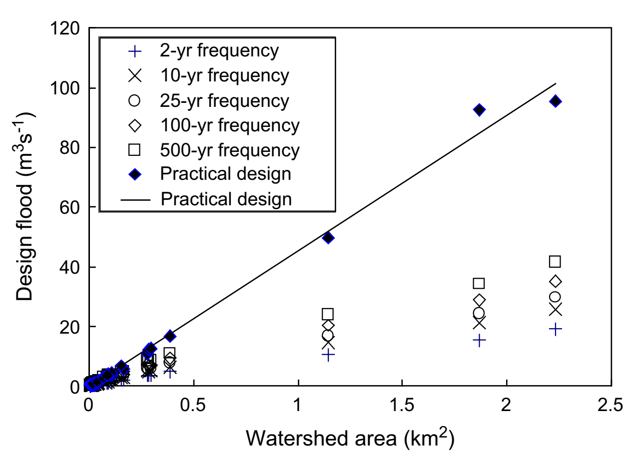

Fig. 3 – Changes in the design floods predicted by the rational method and by the standard design method for thirty-five drainage culverts.

Table 2 – Performance parameters of the different unit hydrograph models for time to peak and peak runoff rates for 41 recorded storm events at the two study watersheds

Model	Time to peak			Peak runoff rate		
	RMSE (min)	NEC	R^2	RMSE ($m^3 s^{-1}$)	NEC	R^2
USDA SCS CN	2.73	0.8687	0.8711	1.95	0.9531	0.9561
WFRpaddy	2.61	0.8799	0.8819	2.59	0.9170	0.9385
Clark	2.49	0.8913	0.8997	2.04	0.9484	0.9721
Nakayasu	2.60	0.8810	0.8858	2.38	0.9298	0.9698

floods for the frequency interval. Note that a recurrence period of 25 years is normally used by the standard design method for drainage culverts design in Korea. The DR No. 09 watershed, which had the largest area, also had the largest design flood of 25.6 $m^3 s^{-1}$. The design flood also increased as the recurrence interval increased (Table 3).

3.5. *Hydrographs obtained by the different models*

The different unit hydrograph models were used to estimate hydrographs based on the critical storm duration and the frequency intervals and frequency-based hydrographs for the drainage culverts were estimated by the Clark model. The

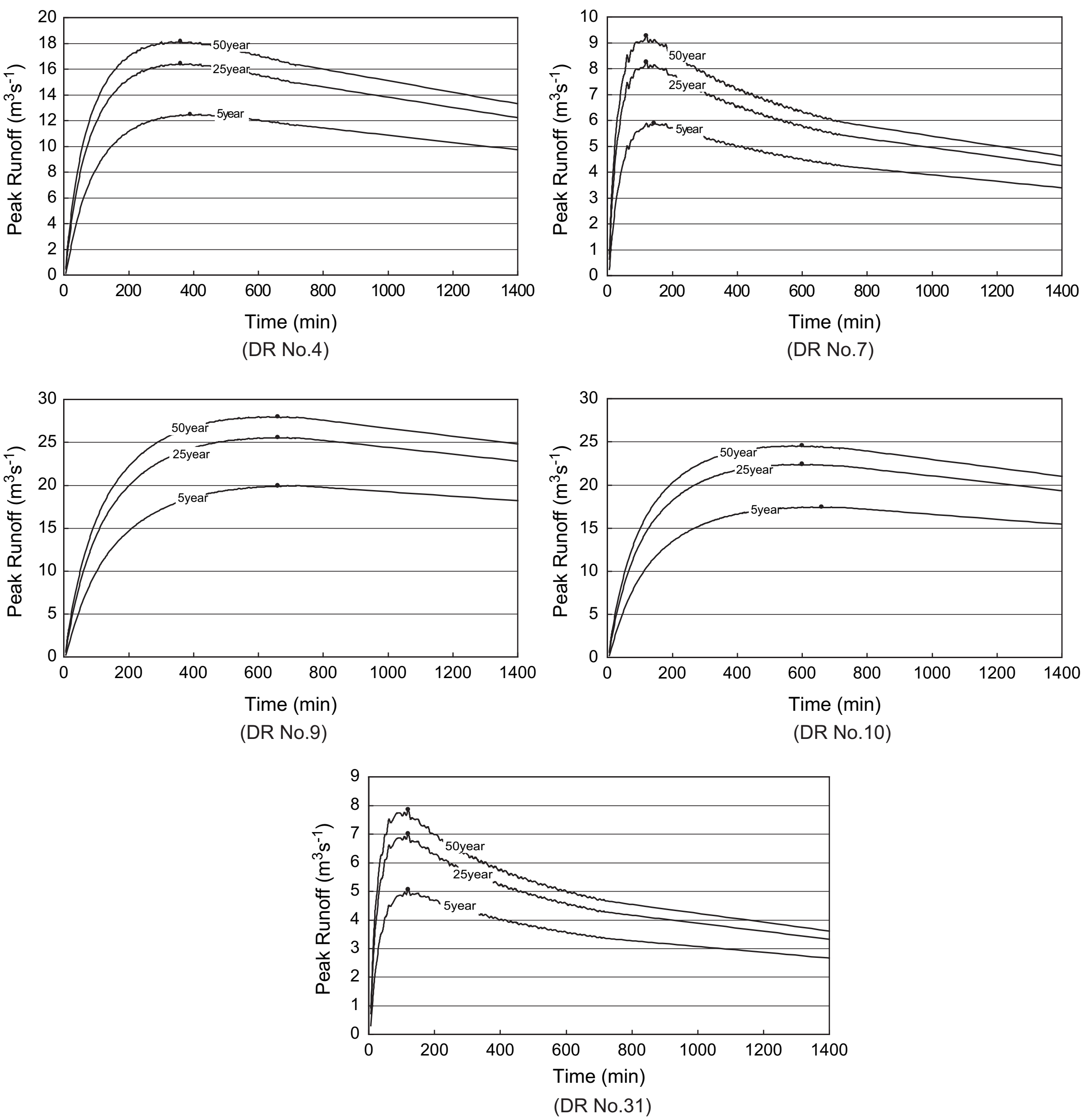

Fig. 4 – Changes in the peak runoff rates with rainfall duration for determining the design flood and the critical storm duration for the drainage culvert watersheds.

Table 3 – Design floods based on the critical storm duration and peak runoff according to frequency

Drainage culvert	Frequency item	5 years	25 years	50 years
DR No. 4	Critical storm duration (min)	390	360	360
	Design flood ($m^3 s^{-1}$)	12.5	16.4	18.2
DR No. 7	Critical storm duration (min)	144	120	120
	Design flood ($m^3 s^{-1}$)	5.9	8.3	9.3
DR No. 9	Critical storm duration (min)	660	660	660
	Design flood ($m^3 s^{-1}$)	19.9	25.6	28.0
DR No. 10	Critical storm duration (min)	660	600	600
	Design flood ($m^3 s^{-1}$)	17.5	22.4	24.6
DR No. 31	Critical storm duration (min)	120	120	120
	Design flood ($m^3 s^{-1}$)	5.1	7.0	7.9

Huff curves from the calculated rainfall storm durations were applied to each drainage culvert, and the effective rainfall was then calculated by applying the USDA SCS CN model for each 0.1 h time interval. The USDA SCS CN, WFRpaddy, Clark and Nakayasu models were applied to the calculated effective rainfall, the hydrograph was predicted, and the peak runoff rate was determined.

For DR No. 9, the largest watershed area, the estimated design floods at the recurrence interval of 25 years were 34.1 $m^3 s^{-1}$, 34.1 $m^3 s^{-1}$, 27.1 $m^3 s^{-1}$, and 32.2 $m^3 s^{-1}$ using the USDA SCS CN model, the WFRpaddy model, the Clark model, and the Nakayasu model, respectively. As shown in Table 4, the UDSA SCS CN model gave the largest design flood; and the smallest value by the Clark model. Regarding the drainage culverts DR No. 4, DR No. 7, DR No. 9, DR No. 10 and DR No. 31, the order of peak runoff rates predicted by the models was the Clark model, the Nakayasu model, the WERpaddy model, followed by the USDA SCS CN model. These were no significant differences in the peak runoff rate among the watersheds and models.

Other than the Clark model application, the hydrographs estimated from the rainfall distribution with respect to the critical storm duration for all unit hydrograph models were similar. The reason for this is that the lines of equal travel time were taken into consideration for each watershed shape in the Clark model application (Fig. 5).

The design floods estimated by unit hydrograph models that take into account the rainfall distribution and the critical storm duration were compared with those predicted by the standard design method (Table 5). For all major culvert watersheds in this study, the estimated design floods obtained by the standard design were 50% greater than those of other tested methods by

Table 4 – Critical storm duration and peak runoff according to frequency (Huff)

Model	Frequency (years)	Item	DR No. 04	DR No. 07	DR No. 09	DR No. 10	DR No. 31
SCS	5	T_p (h)	3.5	1.5	5.7	5.7	1.3
		Q_p ($m^3 s^{-1}$)	15.8	6.2	26.9	22.7	4.9
	25	T_p (h)	3.3	1.3	5.7	5.2	1.3
		Q_p ($m^3 s^{-1}$)	20.7	8.3	34.1	29.5	6.8
	50	T_p (h)	3.3	1.3	5.7	5.2	1.3
		Q_p ($m^3 s^{-1}$)	22.8	9.3	37.1	32.1	7.6
WFRpaddy	5	T_p (h)	3.5	1.5	5.5	5.5	1.3
		Q_p ($m^3 s^{-1}$)	15.7	6.2	26.9	22.8	4.6
	25	T_p (h)	3.3	1.3	5.5	5.0	1.3
		Q_p ($m^3 s^{-1}$)	20.7	8.3	34.1	29.5	6.4
	50	T_p (h)	3.3	1.3	5.5	5.0	1.3
		Q_p ($m^3 s^{-1}$)	22.7	9.3	37.1	32.1	7.2
Clark	5	T_p (h)	3.7	1.4	6.3	6.1	1.1
		Q_p ($m^3 s^{-1}$)	13.7	6.7	21.3	18.7	5.7
	25	T_p (h)	3.4	1.2	6.3	5.7	1.1
		Q_p ($m^3 s^{-1}$)	17.8	9.3	27.1	23.8	7.9
	50	T_p (h)	3.4	1.2	6.3	5.7	1.1
		Q_p ($m^3 s^{-1}$)	19.6	10.4	29.6	26.0	8.8
Nakayasu	5	T_p (h)	3.5	1.4	5.7	5.7	1.2
		Q_p ($m^3 s^{-1}$)	14.4	5.3	25.5	21.5	4.3
	25	T_p (h)	3.2	1.3	5.7	5.2	1.2
		Q_p ($m^3 s^{-1}$)	18.9	7.2	32.2	27.8	5.9
	50	T_p (h)	3.3	1.3	5.7	5.2	1.2
		Q_p ($m^3 s^{-1}$)	20.8	8.1	35.1	30.3	6.7

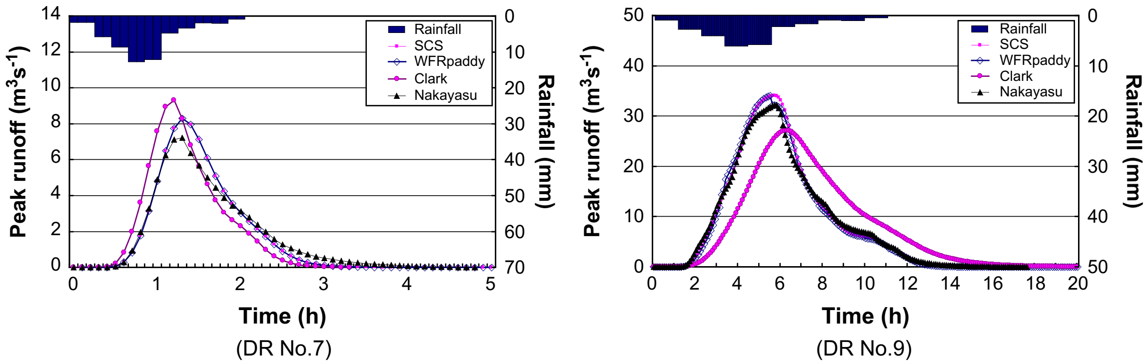

Fig. 5 – Examples of the observed and the simulated hydrographs at 25-year frequency.

Table 5 – Comparison of the design floods predicted by the standard design, rational, and hydrologic models (unit; $m^3 s^{-1}$)

Station	Standard design	Rational method	Unit hydrograph models			
			USDA SCS CN	WFRpaddy	Clark	Nakayasu
DR No. 04	49.7	16.9 (34.1%)[a]	20.7 (41.7%)	20.7 (41.6%)	17.8 (35.8%)	18.9 (38.0%)
DR No. 07	16.6	7.7 (46.2%)	8.3 (50.0%)	8.3 (50.0%)	9.3 (56.0%)	7.2 (43.6%)
DR No. 09	95.6	29.6 (31.0%)	34.1 (35.7%)	34.1 (35.6%)	27.1 (28.4%)	32.2 (33.7%)
DR No. 10	92.8	24.3 (26.2%)	29.5 (31.7%)	29.5 (31.8%)	23.8 (25.6%)	27.8 (29.9%)
DR No. 31	12.7	5.9 (46.9%)	6.8 (54.0%)	6.4 (50.7%)	7.9 (62.1%)	5.9 (46.9%)
Mean (%)		36.9	42.6	41.9	41.6	38.4

a % of the standard design method.

Table 6 – Comparison of the sizes of the drainage culverts determined using the standard design method and AASHTO method

Station	Method	Culvert number and size (m)	HW_i (m)	HW_o (m)	Control HW (m)	Outlet velocity ($m s^{-1}$)
DR No. 04	P	2 at 3.5 × 3.5[a]	2.52	1.75	2.52	8.0
	A	3 at 2.5 × 2.0	2.57	4.51	4.51	2.4
DR No. 07	P	2.5 × 2.5	2.4	1.63	2.4	6.8
	A	2 at 2.0 × 1.5	1.88	2.87	2.87	2.1
DR No. 09	P	3 at 3.0 × 2.5	3.6	1.56	3.6	4.2
	A	3 at 3.0 × 2.5	3.56	3.38	3.56	4.4
DR No. 10	P	2 at 3.0 × 3.0	4.8	4.1	4.8	5.5
	A	2 at 3.0 × 3.0	4.57	4.82	4.82	5.3
DR No. 31	P	2.5 × 2.0	2.1	2.03	2.1	4.9
	A	2 at 1.5 × 1.5	1.91	2.38	2.38	2.6

P; standard design method, A; AASHTO method, HW_i; inlet head water, HW_o; outlet head water, HW; head water.
a Number of culverts with a given width (m) × height (m).

the models. The table shows that the rational method, which is often used in culvert designs, resulted in lower values than those of the standard design method.

Furthermore, the design floods calculated by the unit hydrograph models, that took into account the critical storm duration with respect to the rainfall distribution model, yielded a greater peak runoff rate than that predicted by the rational method applied in this study. Consequently, a design flood based on the critical storm duration is a more appropriate guideline to use when selecting a suitable drainage culvert than the design flood calculated by the rational method.

3.6. *Hydraulic design of drainage culverts*

The AASHTO method defines the dimensions and hydraulic variables of the optimal culverts of a selected type for a given design runoff. The AASHTO method was applied in this study

Table 7 – Comparison of culvert sizes by the standard design and the AASHTO methods

Station	Q_d ($m^3 s^{-1}$)	Culvert number and size		Cross-sectional area (m^2)		(b)/(a), %
		Standard method	AASHTO method	Standard method (a)	AASHTO method (b)	
DR No. 04	49.70	2 at 3.5 × 3.5[a]	3 at 2.5 × 2.0	24.50	15.00	61.2
DR No. 07	16.60	2.5 × 2.5	2 at 2.0 × 1.5	6.25	6.00	96.0
DR No. 09	95.60	3 at 3.0 × 2.5	3 at 3.0 × 2.5	22.50	22.50	100
DR No. 10	92.83	2 at 3.0 × 3.0	2 at 3.0 × 3.0	18.00	18.00	100
DR No. 31	12.67	2.5 × 2.0	2 at 1.5 × 1.5	5.00	4.50	90

a Number of culverts with a given width (m) × height (m).

to determine the dimensions of culverts to meet the hypothetical design storms that would result from changes in topography and land uses in the selected five drainage culvert watersheds. The AASHTO method was incorporated with GIS data to help design roads through areas that have development plans in the near future.

The sizes of the drainage culverts determined by the existing design standards, including the use of graphs, and by the AASHTO method were compared. Both circular and rectangular culverts are commonly used in culvert design, but rectangular culverts were used in this study. The design floods used the values from the USDA SCS CN model that were the largest values for the major watersheds. The results showed very similar values for the large watershed areas and large design floods at the DR No. 09 and DR No. 10 culvert watersheds (Table 6).

Generally, the dimensions calculated by the two methods disagreed about the need to use double or triple rectangular culverts (Table 7). With the exception of the DR No. 04 watershed, whose rectangular culvert size differed by 40%, the differences ranged from 0 and 10% dimensions of cross-sectional area of the required culverts between the two methods (Table 7). Table 8 represents a comparison of culvert sizes by the standard design and the AASHTO methods for the major drainage culvert watersheds.

Climate change is producing higher intensity storms. This needs to be factored into future designs. Thus, it is recommended that further studies should reflect the effect of climate change on the design flood.

Table 8 – Culvert sizes for each design flood by different methods and models at 25-year frequency

Design method	Station	Q_d ($m^3 s^{-1}$)	Culvert number and size
Standard design	DR No. 04	49.7	3 at 2.5 × 2.0[a]
	DR No. 07	16.6	2 at 2.0 × 1.5
	DR No. 09	95.6	3 at 3.0 × 2.5
	DR No. 10	92.8	2 at 3.0 × 3.0
	DR No. 31	12.7	2 at 1.5 × 1.5
Rational method	DR No. 04	16.9	2 at 2.0 × 1.5
	DR No. 07	7.7	1.5 × 1.5
	DR No. 09	29.6	3 at 2.0 × 1.5
	DR No. 10	24.3	3 at 2.0 × 1.5
	DR No. 31	5.9	1.5 × 1.5
SCS	DR No. 04	20.7	2.5 × 2.5
	DR No. 07	8.3	2.0 × 1.5
	DR No. 09	34.1	2 at 2.5 × 2.0
	DR No. 10	29.5	2 at 2.5 × 2.0
	DR No. 31	6.8	2.0 × 1.5
WRFpaddy	DR No. 04	20.7	2.5 × 2.5
	DR No. 07	8.3	2.0 × 1.5
	DR No. 09	34.1	2 at 2.5 × 2.0
	DR No. 10	29.5	2 at 2.5 × 2.0
	DR No. 31	6.4	1.5 × 1.5
Clark	DR No. 04	17.8	2 at 2.0 × 1.5
	DR No. 07	9.3	2.0 × 1.5
	DR No. 09	27.1	3 at 2.0 × 1.5
	DR No. 10	23.9	3 at 2.0 × 1.5
	DR No. 31	7.9	2.0 × 1.5
Nakayasu	DR No. 04	18.9	2 at 2.0 × 1.5
	DR No. 07	7.2	2.0 × 1.5
	DR No. 09	33.2	2 at 2.5 × 2.0
	DR No. 10	27.8	3 at 2.0 × 1.5
	DR No. 31	5.9	1.5 × 1.5

a Number of culverts with a given width (m) × height (m).

4. Conclusions

An approach to estimating design floods by taking into consideration of the critical storm duration for designing drainage culverts was proposed. Based on the estimated design floods, the hydraulic design of the drainage culverts was used to determine the dimensions and hydraulic variables of the optimal culvert sizes for the design floods.

The results obtained from the unit hydrograph models applied in this study indicated that the computed runoff parameters were statistically in close agreement with the observed data. The result obtained by the Clark model revealed some changes in the critical storm durations for a range of recurrence intervals, although there was a small increase in the design flood as the recurrence interval increased.

For the major culvert watersheds in this study, the values from the standard design method yielded 50% higher design floods than those of other methods. The results also showed that the rational method, which is commonly used in culvert designs in Korea, resulted in a lower value than the standard design method. The design floods predicted by the unit hydrograph model, that takes into account the critical storm duration, yielded higher values of the peak runoff rates than that obtained from the rational method. Consequently, the design flood based on the critical storm duration is a more appropriate method for culvert designs than the design flood calculated by the rational method. The values calculated by the unit hydrograph models also showed differences between the numbers of double or triple rectangular culverts needed. With the exception of the DR No. 04 watershed, whose rectangular culvert size differed by 40%, the average difference ranged from 0 to 10% when comparing the standard design and AASHTO methods.

Several design methods are available for use in determining the design flood and optimum drainage culvert size. Based upon the government requirements and appropriate engineering judgement regarding the particular watershed and drainage culverts, the engineers need to carefully select the most appropriate design method for designing new and renovating roads. Upon completion of a drainage facility design, careful consideration should also be given to the proposed installation procedures for the drainage culverts.

If the design method for drainage culverts used in this research was to be applied as a standard design method, a variety of subjective methods of estimating the design flood can be objectively achieved. Also by incorporating a GIS, an advanced design can be achieved for anticipated future land use changes such as urbanisation and industrialisation. The effects of climate change on the intensity of storms will need to be investigated.

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