THE DEVELOPMENT OF RAIN-BASED URBAN FLOOD FORECASTING METHOD FOR RIVER MANAGEMENT PRACTICE USING X-MP RADAR OBSERVATION

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This study developed efficient urban flood alert criteria nomograph that can be used without time delay. The reason for developing the nomograph is the characteristics of small urban watershed such as short concentration time by high impervious area and the localized heavy rainfall. The flood look-up table is based on rainfall information and shows possibility of flood occurrence by the location of average rainfall intensity and rainfall duration on look-up table. Moreover, we used the X-MP radar, which has finer spatial-temporal resolutions with higher accuracy than ever. To evaluate the applicability, we reproduced the flood using developed nomograph with observed gauge and radar rainfall for 9 events. We forecasted the flood occurrence using the nomograph with forecasted radar rainfall using short-term prediction method to secure the lead time. Through the results, we confirmed the developed nomogrpah and radar rainfall is useful for urban flood forecasting.

Key Words **:** *Rain-based, urban flood forecasting, X-MP radar, Toga River*

1. INTRODUCTION

In recent years, occurrences of local and heavy rainfall are increased in small river basin, thus frequency of urban flood occurrence is increased. Urban flash flood is caused by hydrologic phenomenon, which is affected by urban characteristics. One of the characteristics of urban flash flood is that it occurs immediately after rain because of the steep basin slope and drainage system such as Toga River. Rain also abrupt generated localized heavy rainfall. Thus, earlier warning even by 5 to 10 minutes is crucial for saving lives of people enjoying the river side. Numerous studies have been developed the forecasting method that helps to reduce urban flood damages. Most of previous studies have used rainfall-runoff model; however, it is not useful in practical work. Because of it is needed time and expert knowledge for calculation and operation. Therefore, the river management administrator needs simple and practical method. For these reasons, we developed efficient urban flood alert criteria nomograph**,** such as look-up table, which is considering the characteristics of urban watersheds and can be used without time delay. Moreover, we used X-band Multi Parameter radars(X-MP radars) in this study. In order to prevent urban flash flood damages, we have to secure the lead time for evacuation, because rain is occurred locally (within a few kilometers) during short time (less than 1 hour) in urban area. Hence, X-band radar, which has 1 minute time resolution with 250m spatial resolution, is useful for urban flood forecasting.

2. URBAN FLOOD ALERT CRITERIA NOMOGRAPH

The urban flood alert criteria nomograph, such as look up table, is based on rainfall information (average rainfall intensity and rainfall duration). It is developed by analysis of flood discharge and water levels and the rainfall scenarios such as hyetograph. The flow nomograph is assembled by relationship with the flood discharge and level using hydrological model and the various hyetograph from time distribution methods at the specific flood forecasting station like equation (1) (Bae et al., 2012). The equation indicates that a specific rainfall conditions, such as average rainfall intensity and rainfall duration, can induce a specific flood level.

$$WL_i = f(P_i, T_i) \tag{1}$$

Here, i is reference flood levels, P_i is the average rainfall intensity at i, and T_i is the rainfall duration each rainfall scenario. WL_i is isostage each flood forecasting reference which is converted into the flood discharge used H-Q curve. The flood discharge is calculated by pairs of average rainfall intensity and rainfall duration each hyetograph at each flood forecasting reference. It is used to define the flood discharge range at the flood forecasting reference.

The nomograph is drawn as a function of rainfall intensity (y-axis) and rainfall duration (x-axis) that cause a flash flood each reference flood level. The levels are determined considering river character such as cross section. The possibility of the flood occurrence is shown by location of the rainfall intensity and rainfall duration on look-up table such as **Fig. 1(c)**. If the locations of average rainfall intensity and rainfall duration are exceeding the reference flood level on nomograph, it will indicate the possibility of passing over. The exceed means to move from lower left to upper right on the nomograph for over a specific flood level. If the location move to lower left side of the line of flood level on nomograph, river would be safe.

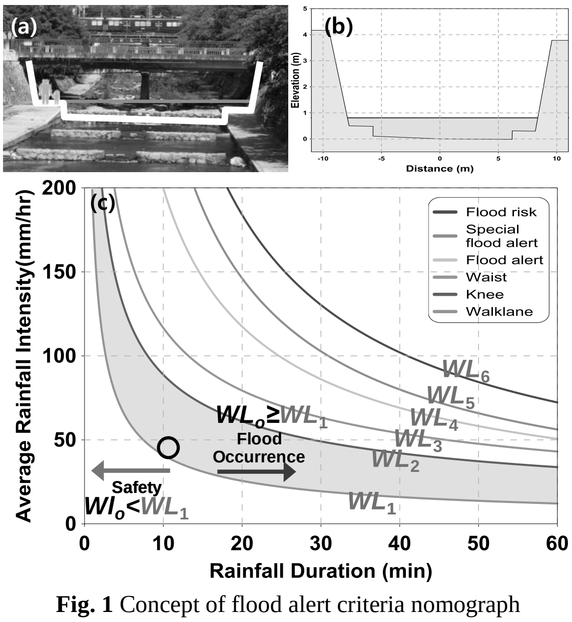

Fig. 1 Concept of flood alert criteria nomograph

3. X-MP RADAR FOR URBAN FLOOD FORECASTING

For evacuation, we have to obtain the lead time before flood occur using forecasted rainfall. However, it is difficult to generate predicted rainfall field using ground rain gauge observation and it is not easy to detect localized rainfall in urban area by C-band radar, which has low resolution in particular. Hence, it is needed to use the radar information, which has high spatial and temporal resolution, for urban flood forecasting. In this study, we also try to apply the X-MP radar information and its applicability. The used X-MP radar information is composited in Kinki area using 4 radar sites (JUUBUSAN, ROKKO, TANOGUCHI, KATSURAGI). The time resolution of composited radar is 1 minute and spatial resolution is 250m. It has also high accuracy of QPE (Quantitative Precipitation Estimation) by dual polarization function. Forecasted radar rainfall is estimated using Translation model with full parameters and without growth decay rate for every 10 minutes (Nakakita et al., 1996). For the application of nomograph, we estimate the mean areal precipitation using radar rainfall value in Toga River such as **Fig.2**.

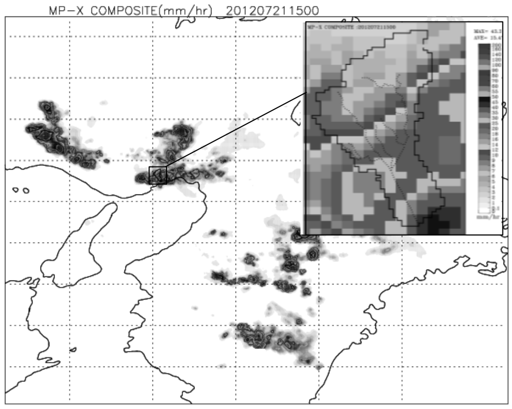

Fig. 2 Composited radar rainfall in Kinki area and Toga River basin

4. DEVELOPMENT OF NOMOGRAPH IN TOGA RIVER BASIN

(1) Hydrological model set up

Toga River is a highly urbanized area and had some flash flood disaster. In 2008, 50 people washed away, among them, 5 people died by a flash flood caused by abrupt generated localized heavy rainfall, therefore, it is needed urban flood forecasting system, which can earlier warning even by 5 to 10 minutes. The lower river basin is mostly urbanized and most of the inland water is conveyed to the main river through pipes or ducts, however, the upper river is mountainous area.

For considering these hydrological characteristic of Toga, we used Storm Water Management Model (SWMM) and Storage Function Model (SFM) to

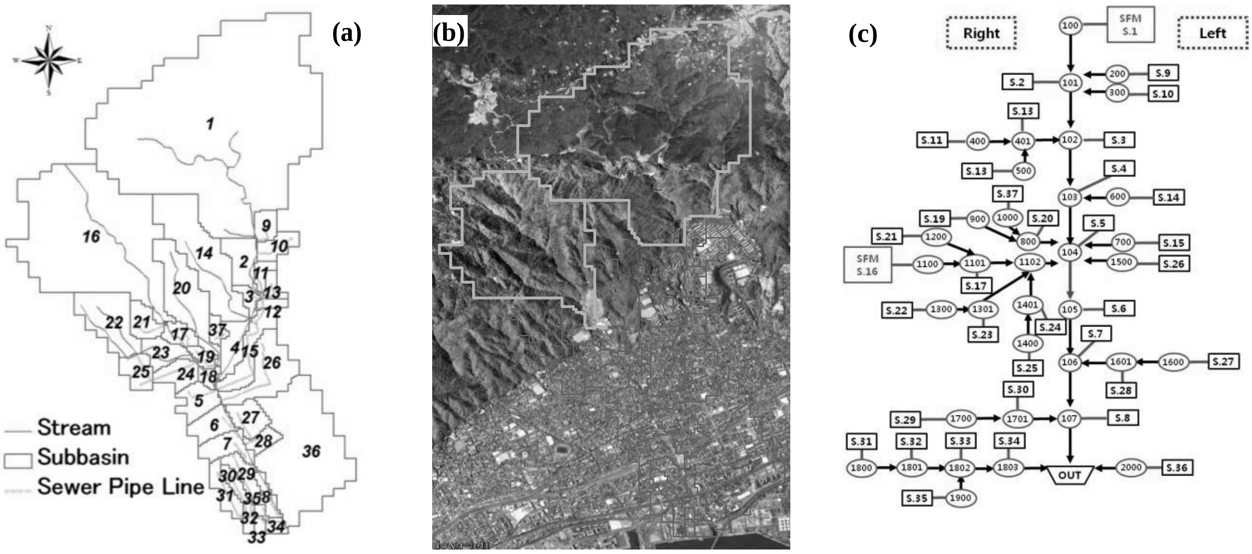

Fig. 3 The divided sub basins and network to construct the connected SFM and SWMM(a) Pipe line(green line) and stream line(blue line), (b) Sub basins(SFM is applied for blue line area), (c) channel network in Toga River

analyze sewer system and storage capacity of mountainous area for flood discharge estimation. SWMM model simulates real storm events on the basis of rainfall and drainage system characterization to predict outcomes in the form of quantity and quality values. SFM was proposed by Kimura in Japan (Kimura, 1961) and it incorporates the nonlinearity of flood runoff in a simple numerical procedure.

Toga basin is divided by 37 sub basin as **Fig. 3(b)** considering by geographical information such as Digital Elevation Model (DEM), landuse, impervious area, stream line and drainage system (**Fig. 3(a)**). To consider the mountainous area in this study, SFM model is applied at 2 sub basins (sub 1 and 16) and its outflows are used the inflows of SWMM as **Fig. 3(c)**. We selected 8 events to optimize the parameter of SWMM and SFM. **Fig. 4** and **Table 1** are calibration and verification results from parameter optimization using observed rain gauge rainfall. It is also found that SWMM could not simulate the depletion curve, however, the adding SFM and SWMM could be considered the depletion curve. The SFM had been developed for mountainous area and flood discharge is estimated using storage functions by amount of discharge and storage. Therefore, it could estimate the amount of storage in mountainous area accurately and could simulate the tail water curve in upper Toga River basin. Through the model calibration and verification, the connected SFM and SWMM are better than only SWMM in C-Corr and RMSE.

(2) Nomograph Development in Toga River

The procedure for the nomograph development can classify into 1) setting up the reference flood level at flood forecasting station, 2) setting up the rainfall hyetographs, 3) estimating the flood discharge using rainfall hyetograph and developed model, and 4) development of flow nomograph.

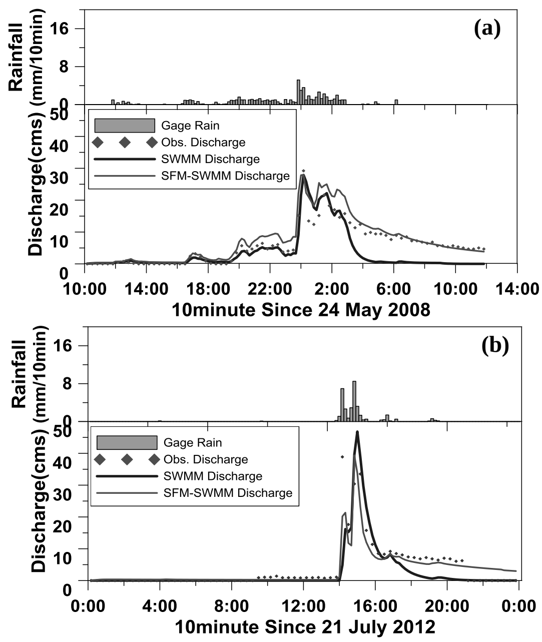

Fig. 4 The results of model parameterization (a) Calibration result (24-25 May 2008), (b) Verification result (21 July 2008)

Table 1 Calibration and verification results

Event	C-Corr		RMSE	
	SWMM	SFM+ SWMM	SWMM	SFM+ SWMM
2008/05/24-25	0.81	0.97	4.41	2.48
2008/08/23	0.90	0.98	2.97	1.60
2011/09/02-05	0.85	0.91	5.66	8.09
2011-05/28-31	0.80	0.92	5.56	4.05
2008/06/21	0.78	0.88	2.54	1.47
2008/07/28	0.87	0.97	5.90	3.33
2012/7/10	0.85	0.93	4.24	3.02
2011/09/19-22	0.81	0.93	8.56	7.42

a) Decision of the reference flood water level

In this study, Kabutobashi water level station as the main flood forecasting station was selected to secure the disaster safety in Toga River. The reasons why we selected the Kabutobashi are that it has water level observation station and has possibility of flash flood occurrence by the inflow from connected pipes and upper streams. We determined the 7 reference flood levels like **Fig. 5**, respectively. The flood alert, special flood alert, flood risk, and design flood level among them are referred to the standard of MLIT (http://www.river.go.jp). The walklane, knee, and waist level are determined according to degree of disaster by the cross-section. Here, we determined that the knee level is over 50cm and the waist level is over 70cm from the walklane. The corresponding discharge of reference flood level is estimated of water level-discharge relationships (H-Q curve). We considered the error tolerance of ±5% of H-Q curve for discharge range.

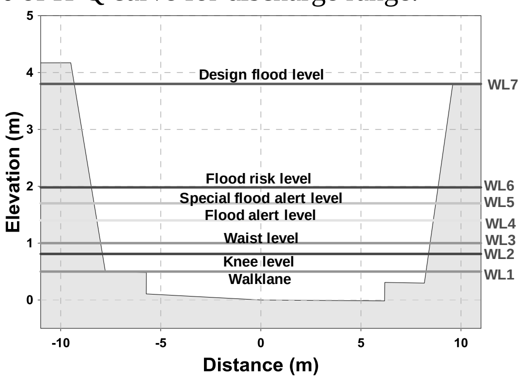

Fig. 5 Reference flood waterlevel of Kabutobashi

Table 2 Water depth and discharge of each reference flood level

Flood level		Water depth(m)	Discharge (cms)	Discharge range (cms)
WL1	Walklane	0.31	17.3	16.4~18.2
WL2	Kneel	0.81	61.31	58.2~64.4
WL3	Waist	1.01	85	80.8~89.3
WL4	Flood alert	1.4	152	144.4~159.6
WL5	Special flood alert	1.7	214	203.3~224.7
WL6	Flood risk	1.98	284	269.8~298.2
WL7	Design flood	3.8	944	869.8~991.2

b) Set up the rainfall hyetograph

For the flow nomograph development, many kind of rain events are required as an input data, however, observed rainfall data are not enough to consider various rainfall situations. We have utilized various rainfall events based on the synthetically generated hyetograph using the Yen-Chow and Keifer-Chu and Mononobe method. The location of peak rainfall during rainfall duration was set as 1) forward (at 1/4 time of the event), 2) centered (at 2/4 time of the event), and 3) backward (at 3/4 time of the event). The total rainfall amounts of the event were assumed as varying from 2mm to 100mm with 2 mm interval. The rainfall durations were set from 10 minutes to 60 minutes with every 10 minutes interval. Based on these conditions, totally 900 synthetic rainfall events were generated and utilized as the input data of the hydrologic model.

c) Estimation of corresponding peak discharge and average rainfall intensity for reference flood level

The flood discharge is estimated using the connected SWMM and SFM in Toga River and the peak flood discharge is determined from flood discharge at each hyetograph. We only considered the rainfall information of the event when the peak discharge is included the discharge range of **Table 2** for nomogrpah development. Average rainfall intensity (P_i) and rainfall duration (T_i) causing the flood are determined through the estimated results at each reference flood level like **Table 3**.

Table 3 Flood discharges of various hyetographd by Yen-Chow method (centered) at Kabutobashi

Total rain	Value	Rainfall Duration (T_i)					
		10	20	30	40	50	60
10	Peak discharge (Q_i)	23.97	17.90	13.75	11.01	8.99	7.48
	Rainfall intensity (P_i)	90.00	37.50	23.33	16.88	13.20	10.83
20	Peak discharge (Q_i)	77.84	59.26	46.33	37.90	31.61	27.02
	Rainfall intensity (P_i)	180.00	75.00	46.67	33.75	26.40	21.67
30	Peak discharge (Q_i)	137.65	108.46	87.21	72.39	62.16	53.88
	Rainfall intensity (P_i)	270.00	112.50	70.00	50.63	39.60	32.50
40	Peak discharge (Q_i)	203.38	156.09	127.44	105.70	91.62	81.71
	Rainfall intensity (P_i)	360.00	150.00	93.33	67.50	52.80	43.33
50	Peak discharge (Q_i)	276.52	212.05	173.56	145.03	125.32	108.38
	Rainfall intensity (P_i)	450.00	187.50	116.67	84.38	66.00	54.17
60	Peak discharge (Q_i)	365.39	276.09	223.68	189.47	164.02	143.29
	Rainfall intensity (P_i)	540.00	225.00	140.00	101.25	79.20	65.00
70	Peak discharge (Q_i)	452.38	344.82	275.51	229.94	200.15	177.04
	Rainfall intensity (P_i)	630.00	262.50	163.33	118.13	92.40	75.83

*Rainfall intensity means average rainfall intensity.

d) Development of optimal nomograph using regression analysis

The average rainfall intensity and rainfall duration, and results of flood water level according to reference flood discharge for average rainfall intensity from the simulated hyetographs were used to develop the criteria nomograph in the Toga River. The nomograph was made through the regression analysis at 6 reference flood water levels except for WL7 such as shown in **Fig. 6**.

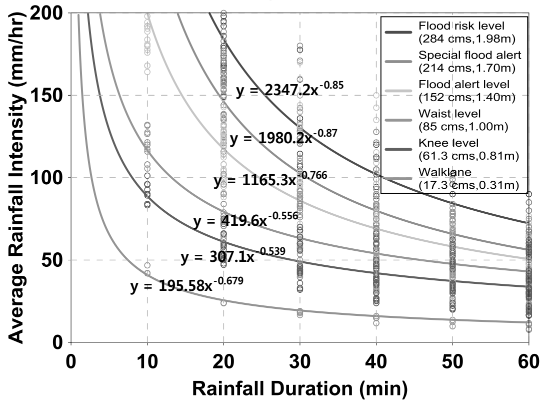

Fig. 6 Developed criteria nomograph and regression equation

5. APPLICAIONS AND RESULTS

To evaluate the applicability of flood forecasting using the developed nomograph, we reproduced the flood using the developed nomograph with observed gauge rainfall (Gauge) such as **Figs. 7(a)-1** and **8(a)-1** for 9 events. The X-MP rainfall radar (Radar QPE) as shown in **Figs. 7(a)-2** and **8(a)-2** are being used for the evaluation of radar rainfall usefulness. Using the nomograph and rain data, we can forecast the flood occurrence when at least locations of circles are positioned over the flood level of nomograph. The circles are drawn by the average rainfall intensity and rainfall duration. Furthermore, we forecasted the flood occurrence using the nomograph with forecasted X-MP radar rainfall (Radar QPF) using short-term rainfall prediction method (Translation model) to obtain the lead time such as **Figs. 7(a)-3 and 8(a)-3**. The **Figs. 7(b)** and **8(b)** are reproduced flood using gauge expressed by orange bar in **Figs. 7(a)-1** and **8(a)-1**, respectively, for applicability evaluation. The basin averaged rainfall of gauge was estimated by Thiessen method. The average rainfall intensity for each rainfall duration is estimated by moving average from current time to 60 minutes before. The **Figs. 7(c)** and **8(c)** are reproduced flood using radar QPE expressed by orange bar in **Figs. 7(a)-2** and **8(a)-2**. The basin averaged rain of radar was estimated by arithmetic average method. The estimation method of average rainfall intensity is same as rain gauge case.

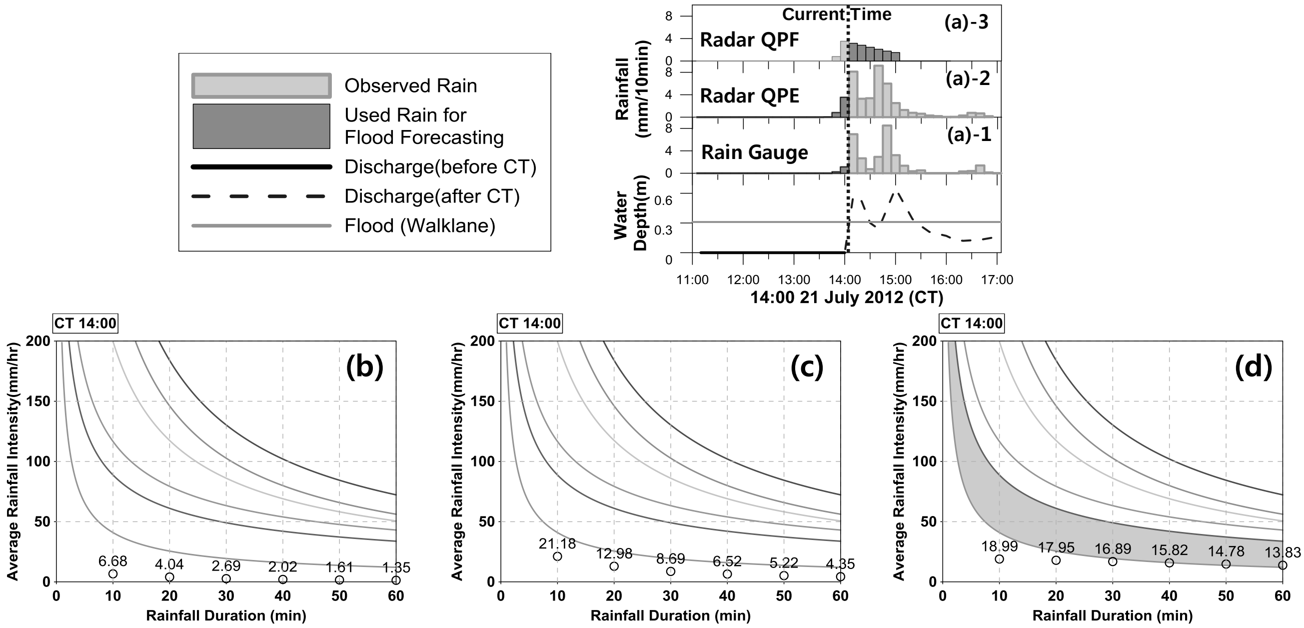

Fig. 7 Flood forecasting using nomograph at 14:00 21 July 2012 (a) time series used rainfall and water level (b) observed gauge rainfall, (c) observed radar rainfall (QPE) and (d) forecasted radar rainfall (QPF)

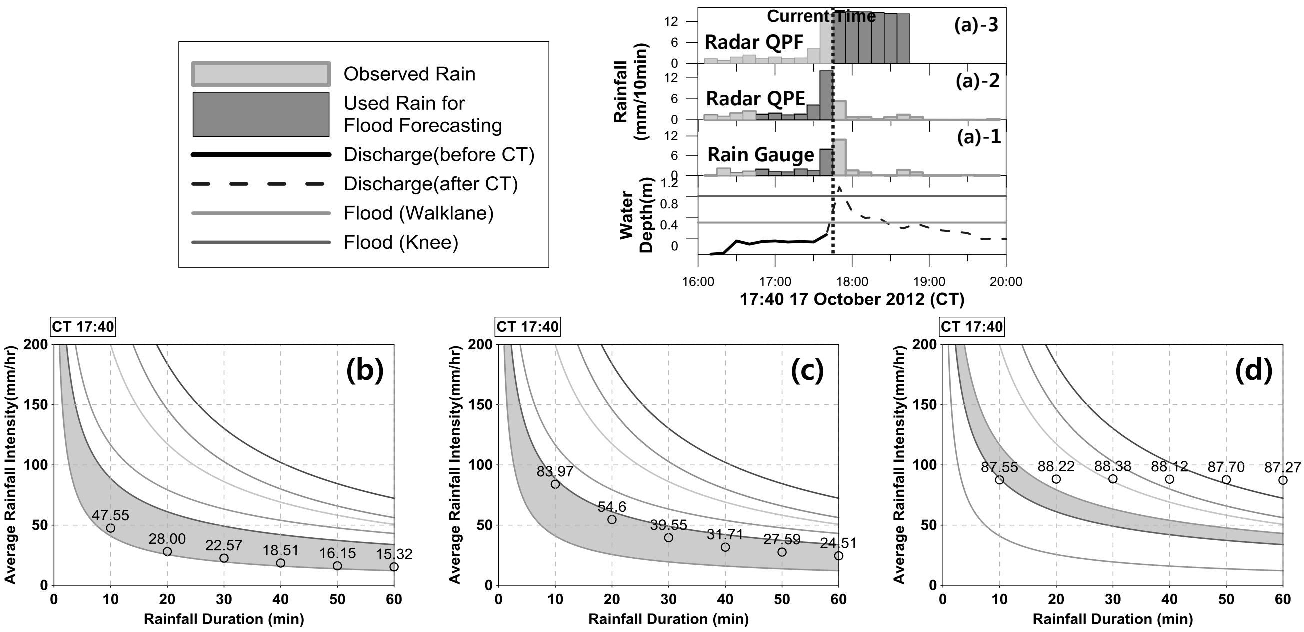

Fig. 8 Flood forecasting using nomograph at 17:40 17 October 2012 (a) time series used rainfall and water level, (b) observed gauge rainfall, (c) observed radar rainfall (QPE), and (d) forecasted radar rainfall (QPF)

Fig. 7 shows the application results for the event at 14:00 21 July 2012. At this event, flood (0.57m) occurred at 14:10 in real. **Figs 7(b)** and **(c)** show that the circles on the nomograph are located in lower left side of the line of the walklane when using observed gauge rainfall and radar rainfall. Hence, observed gauge and radar rainfall cannot forecast the flood. **Fig. 8** shows the application results for the event at 17:40 17 October 2012. At this event, peak flood (0.98m) occurred at 17:40 in real. According to **Figs 8(b)** and **(c)**, observed gauge rainfall and radar rainfall can forecast the flood over the walklane, however, the water level is underestimated because the real flood occurred over the knee level.

The **Figs 7(d)** and **8(d)** is predicted flood using Radar QPF expressed by orange bar in **Figs 7(a)-3** and **8(a)-3**. The average rainfall intensity using forecasted radar rainfall for each rainfall duration is estimated by moving average from current time to 60 minutes ahead. As shown in the **Fig. 7(d)**, we can guess the possibility of flood occurrence within 10 minutes in advance when using forecasted radar rainfall. The reason is that more than one circle are located in upper right side of the line of the walklane 10 minutes before real flood occurred. **Fig. 8(d)** shows the circles are located in upper right side of the line of the knee level when using radar forecasted rainfall. In general, the radar rainfall forecasting method cannot exactly forecast the rainfall time distribution of high-precision, however, it can forecast the rainfall amount of low-precision due to uncertainty of the method as shown in **Figs. 7(a)-3** and **8(a)-3**. The total rainfall amount, which causes a flood, is more important than rainfall time distribution while using the nomograph for flood forecasting. Thus, it was possible to perform accurate flood forecasting by using Radar QPF in this study. **Fig. 7** indicates that total rainfall amounts of 60 minutes from current time are 25.26mm (Gauge) and 13.83mm (Radar QPF), which corresponding with the walklane flood level. In **Fig. 8**, can be that total rainfall amounts of 10 minutes from the current time are 15.17mm (Gauge) and 14.59mm (Radar QPF), which corresponding with the Knee flood level. Hence, the radar forecasted rainfall could forecast flood level range more accurate than observed gauge rainfall and observed radar rainfall in this event.

Table 4 is summarized the evaluation results of 10 flood peak. Here, we counted the flood peak separately, even if there are two peaks in the same flood event. The number in Table 4 shows the frequency when computed flood level corresponds to each flood level. The accuracy means relative frequency. Timeliness is refers to the time necessary to evacuate before flash flood. The accuracy is 60% when using gauge rainfall data, while the accuracy when using observed radar rainfall is 80%, which is higher than when using gauge rainfall. Because the radar has higher spatial and temporal resolutions and also has higher QPE accuracy than rain gauge rainfall. The accuracy is 90% when using radar QPF and it is higher than radar QPE. Regarding the timeliness, it is less than 10 minutes when using observed radar rainfall and gauge rainfall, while the timeliness is between 20 and 30 minutes when using radar QPF. Hence, the time to prepare for evacuation may insufficient when using observed rainfall, while we can obtain preparing time to evacuate when using radar QPF, because the timeliness of radar QPF is longer than timeliness of observed rainfall.

Table 4 The accuracy and timeliness of developed nomograph

	Data Type	Warning Issued	Actual flood level: No flood	Walk lane	Knee	Accuracy (%)	Timeliness (min)
Computed flood level	Gauge	No flood	0	2	0	60	T<=10
		Walklane	0	5	1		
		Knee	0	1	1		
	Radar QPE	No flood	0	1	0	80	T<=10
		Walklane	0	7	1		
		Knee	0	0	1		
	Radar QPF	No flood	0	1	0	90	10<T=30
		Walklane	0	7	0		
		Knee	0	0	2		

*Yellow means corrected the flood forecast, pink means overestimated, blue means underestimated

6. CONCLUSIONS

This study developed efficient urban flood alert criteria nomograph in Toga River basin and evaluated the applicability using observed gauge rainfall, observed radar rainfall and forecasted radar rainfall using X-MP radar. Through the evaluation results of flood situations, we came to conclusion that the nomograph is useful for urban flood management practice. Also, flood forecasting using forecasted radar rainfall is accurate and can be obtaining the lead time.

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