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A Study on the Development of the Rain-based Urban Flood Forecasting Method with X-MP Radar in Toga River Basin

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Synopsis

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.

Keywords: 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 abruptly 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 (Andjelkovic, 2001). 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 the relationship with the flood discharge and level using a hydrological model and 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.

$$WL_i = f(P_i, T_i) \quad (1)$$

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.

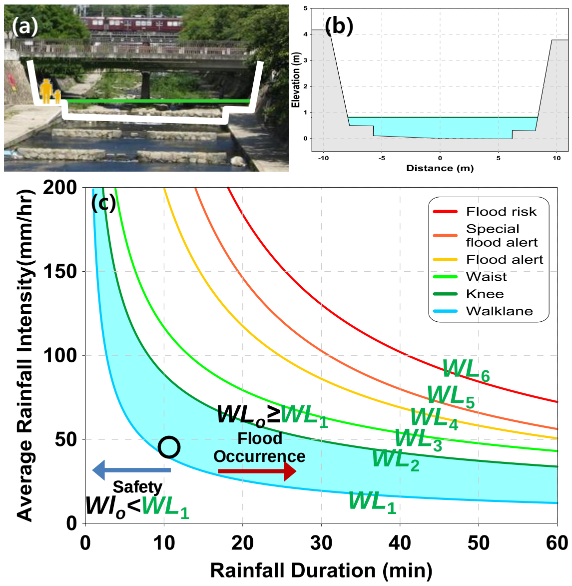

Fig. 1 Concept of flood alert criteria nomograph

3. X-MP radar for urban flood forecasting

For the 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 the 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, TANOGUCHI, ROKKO, 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.

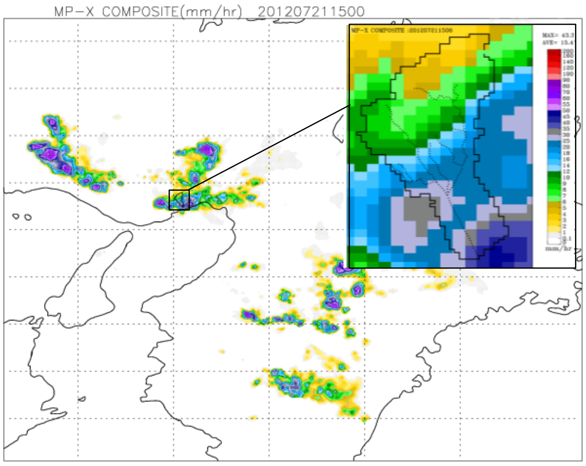

Fig. 2 Composited radar rainfall in Kinki area and Toga River basin

4. Development of urban flood alert criteria nomograph in Toga River basin

4.1 Application area and input data

The application area is Toga River in this study. The main reach of the Toga River is located in Kobe City with two small tributary streams, the Rokko River and the Somatani River. The length of the main river is 1.79km and drainage area is 8.57 km^2 (total area is 10.98km^2 of MLIT). Slope is 1/200 (river mouth), 1/20 (upstream end) and channel cross section is trapezoid with 15m bottom width. The side walls and the bottom are fixed by concrete and side stairs are installed at many locations for improving the accessibility to the riverfront. The lower river basin is mostly occupied by residential houses and paved streets developed up to the foot of the mountainous area. Therefore, a storm drainage system is installed for preventing inland flood. Most of the inland water is conveyed to the main river through pipes or ducts (Fujita and Kunita, 2010). The flood concentration time is about 20 minutes. Hence, Toga River had some flash flood disaster. In 28 July 2008, there was occurred the flash flood caused by abrupt generated localized heavy rainfall. There were several people including children enjoying the river and the weather is fine with no rain. It is apparent that the water depth increases significantly with large water surface undulation. The side walking ways are also covered with water. It has to be mentioned from these images that the sudden increase of water depth occurred almost within two minutes and not in ten minutes. This flow situation continues for more than twenty minutes. There are people who failed to evacuate from the river due to the sudden increase of water depth. Among them ten people were rescued by local residents but five people including three children were drowned to death. In fact, according to the local residents the Toga River had been known to become dangerous once a thunder storm comes to the area and actually a similar flash flood occurred in 1998 with no loss of life at that time. Consequently, it is needed urban flood forecasting system, which cans earlier warning even by 5 to 10 minutes.

For development of the nomograph, we collected the hydrological data and GIS data in Toga River basin. The hydrological observation data are collected 5 rain gauges of MLIT such as Fig. 3 and defined the thiessen polygon to estimate the mean areal precipitation. There is only water level observation station (Kabutobash station) in Toga River. The observation time interval is 10 minutes interval and MLIT suggested the H-Q curve as equation (2).

$$Q = 53.889(H - 36.6434)^2 \quad (2)$$

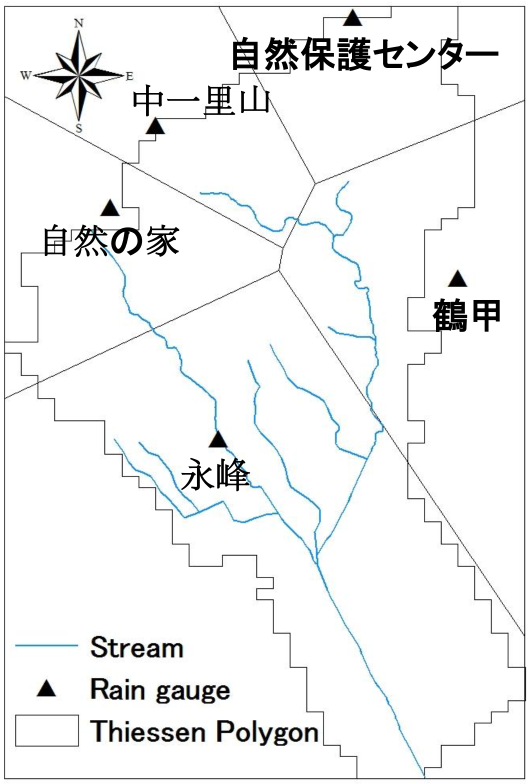

Fig. 3 Thiessen polygon map

4.2 Hydrological model set up

Toga River is a highly urbanized area, especially, the lower river basin is mostly urbanized. However, the upper river is mountainous area such as Rokko Mountain.

For considering these hydrological characteristic of Toga, we used Storm Water Management Model (SWMM) and Storage Function Model (SFM) to 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. 4(a) considering by geographical information such as Digital Elevation Model (DEM), landuse, impervious area, stream line and drainage system. 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. 4(c).

We selected 8 events to optimize the parameter of SWMM and SFM. Fig. 5 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.

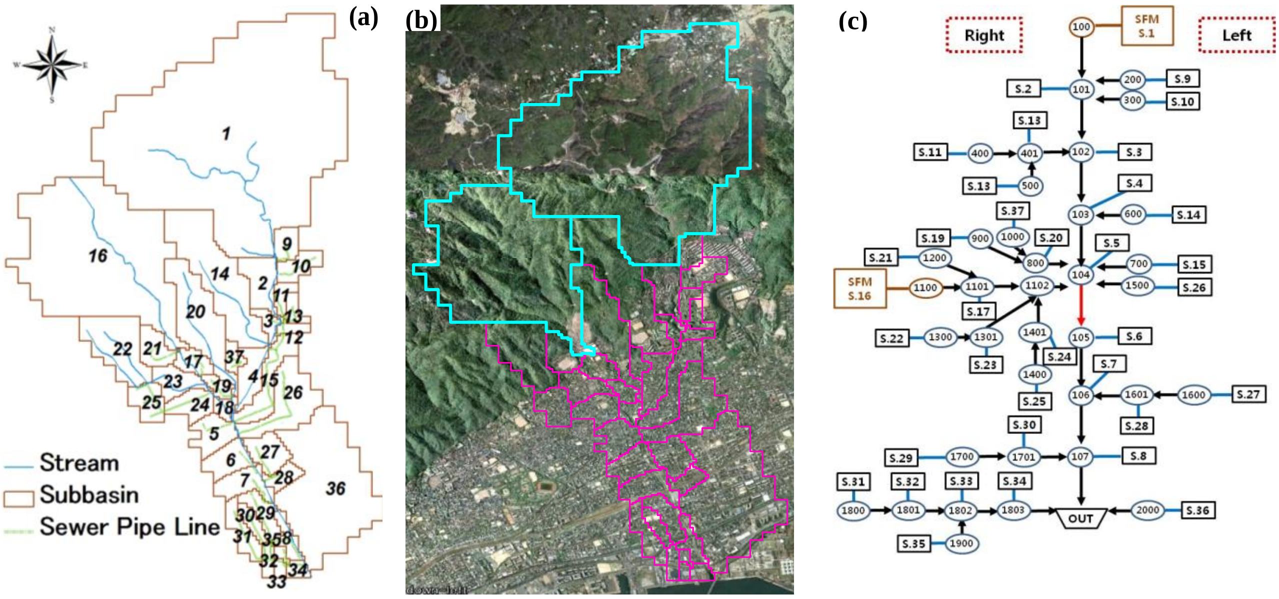

Fig. 4 The divided sub basins and network to construct the connected SFM and SWMM(a) Pipe line(green line) and stream line(blue line), (b) Sub basins(SFM is applied for blue line area), (c) channel network in Toga River

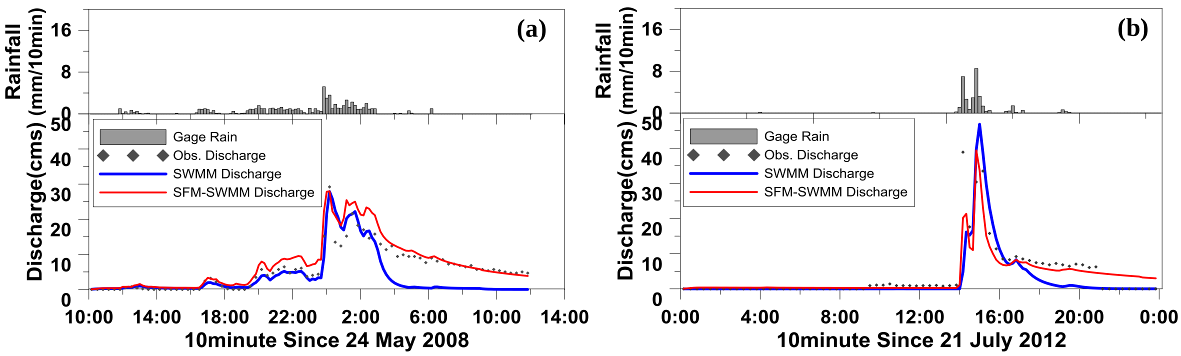

Fig. 5 The results of model parameterization (a) Calibration result (24-25 May 2008), (b) Verification result (21 July 2008)

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 Correlation Coefficient (C-Corr) and Root Mean Square Error (RMSE).

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

4.3 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 such as Fig. 6.

(1) 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 through the In-situ survey (Fig. 7). 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. 8, 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, the knee level, and the 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 the 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 as shown Table 2.

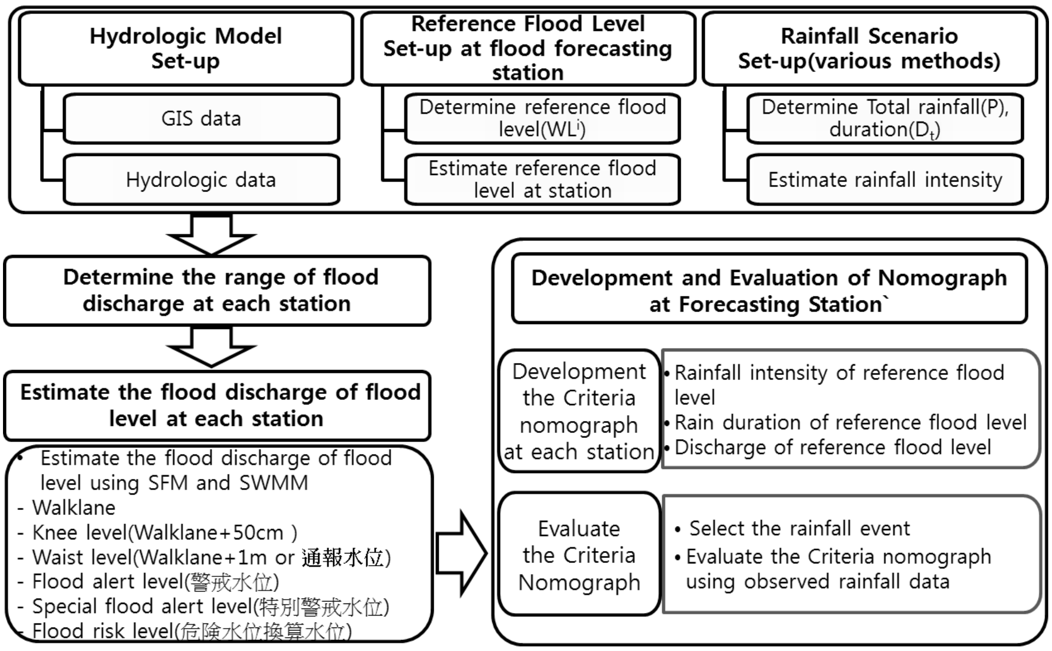

Fig. 6 The procedure of the flow nomograph development

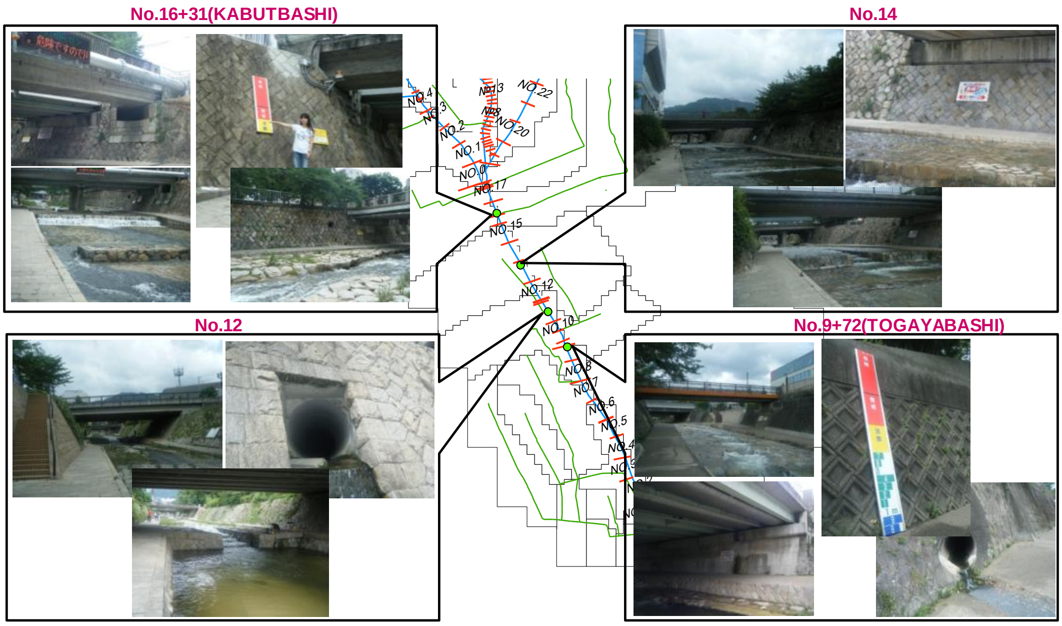

Fig. 7 In-situ survey of Toga river basin for determine the flood forecasting station

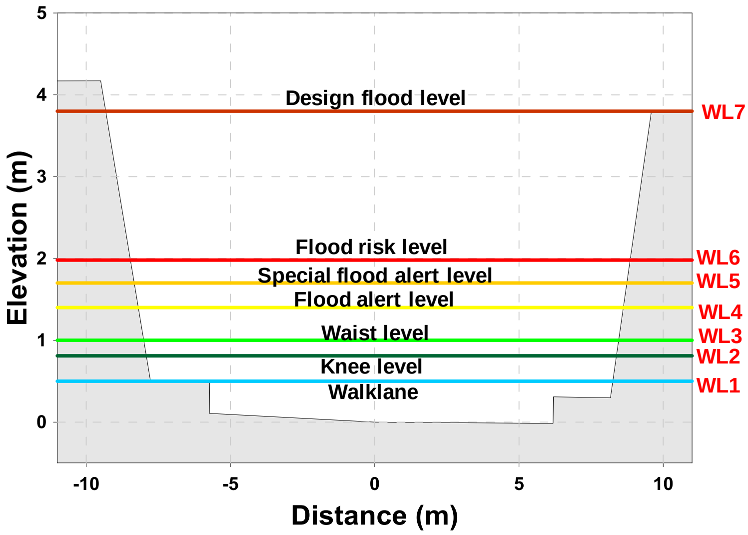

Fig. 8 Reference flood waterlevel of Kabutobashi

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

(2) 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.

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

Total Rain (mm)	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.

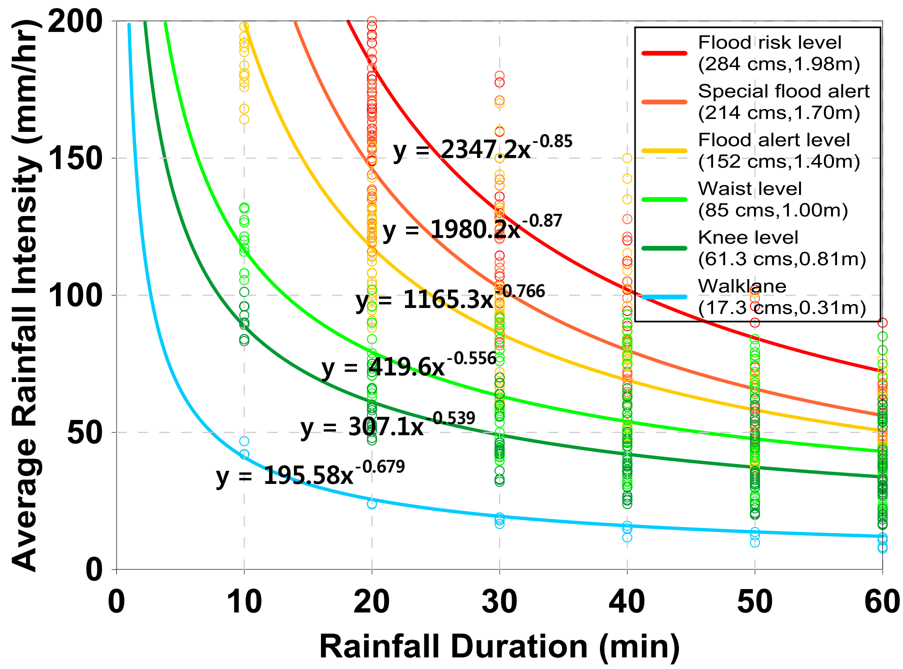

Fig. 9 Developed criteria nomograph and regression equation

(3) 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.

(4) Development of optimal nomograph using regression analysis

The average rainfall intensity and the 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. 9.

5. Applications 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. 10(a)-1 and 11(a)-1 for 9 events. The X-MP rainfall radar (Radar QPE) as shown in Figs. 10(a)-2 and 11(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. 10(a)-3 and 11(a)-3. The Figs. 10(b) and 11(b) are reproduced flood using gauge expressed by orange bar in Figs. 10(a)-1 and 11(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. 10(c) and 11(c) are reproduced flood using radar QPE expressed by orange bar in Figs. 10(a)-2 and 11(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.

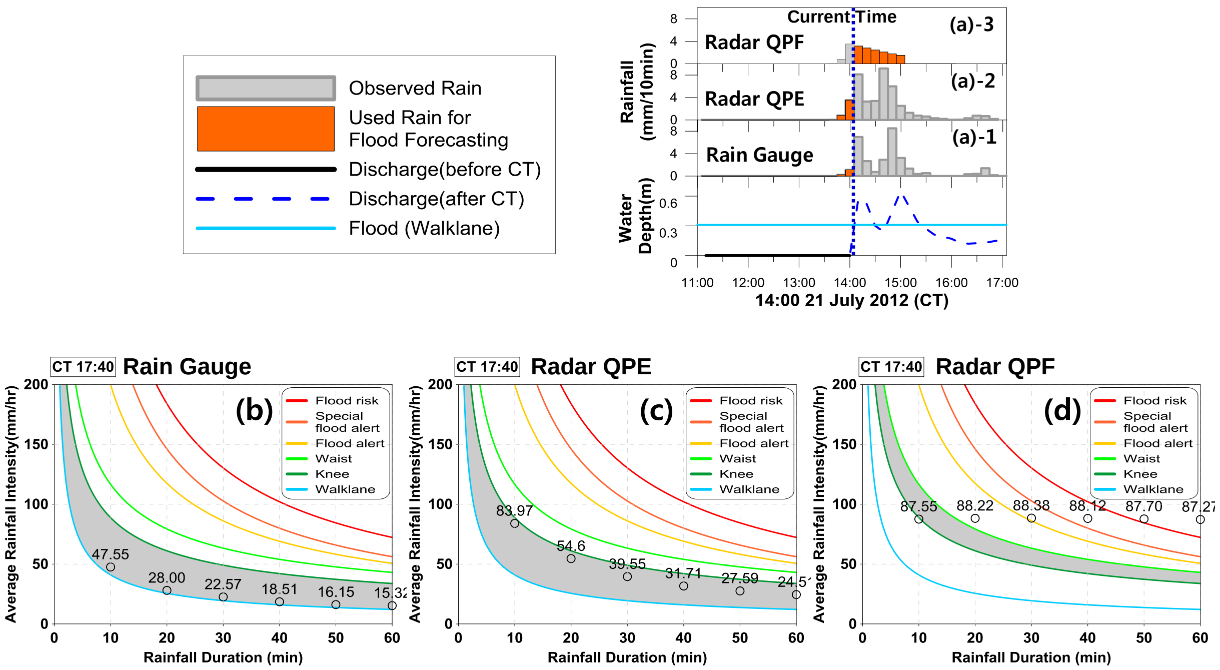

Fig. 10 Flood forecasting using nomograph at 14:00 21 July 2012 (a) time series used rainfall and water level, (b) observed gauge rainfall, (c) observed radar rainfall (QPE) and (d) forecasted radar rainfall (QPF)

Fig. 10 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 10(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. 11 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 11(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 10(d) and 11(d) is predicted flood using Radar QPF expressed by orange bar in Figs 10(a)-3 and 11(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. 10(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. 11(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. 10(a)-3 and 11(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. 10 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. 11, 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.

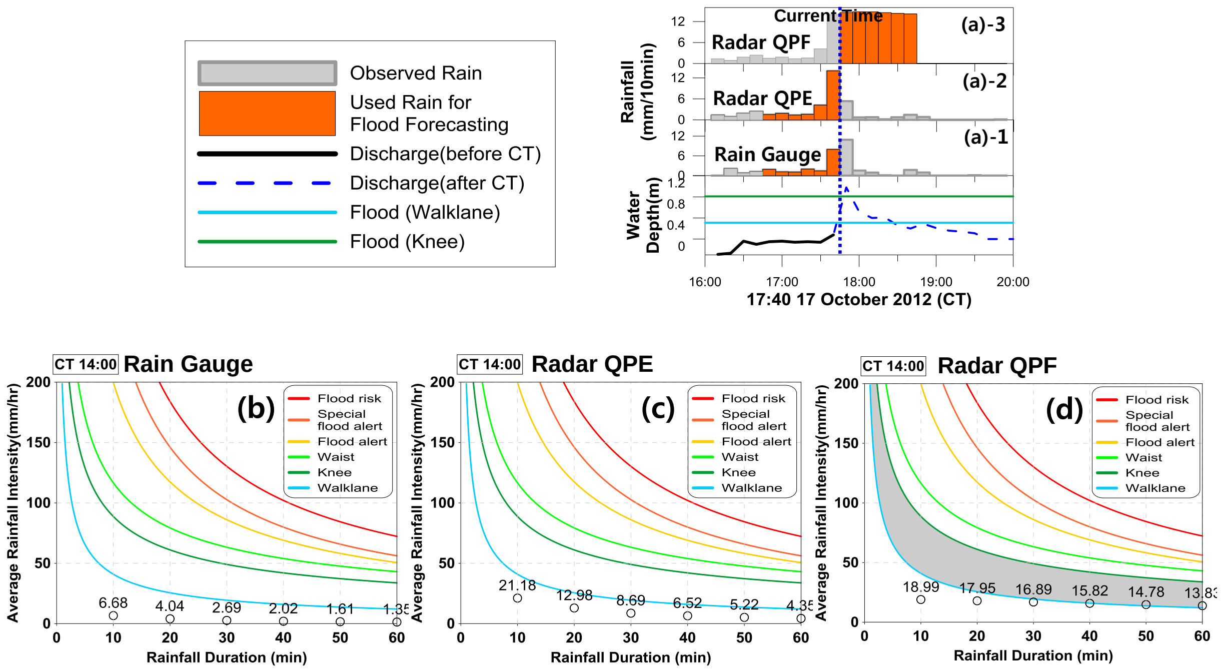

Fig. 11 Flood forecasting using nomograph at 17:40 17 October 2012 (a) time series used rainfall and water level, (b) observed gauge rainfall, (c) observed radar rainfall (QPE), and (d) forecasted radar rainfall (QPF)

Table 4 Performance of flood forecasting using gage observed rainfall and radar forecasted rainfall

Events	Warning Issued	Gauge	Radar QPE	Radar QPF	Actual flood
3 Sep. 2011	Initial Warning Time	20:30	20:00	20:00	20:40
	Initial Warning Level	Walklane	Walklane	Walklane	0.39 m
3 July 2012	Initial Warning Time	Missed	08:40	05:10	05:30
	Initial Warning Level	Missed	Walklane	Walklane	0.37 m
7 July 2012	Initial Warning Time	00:50	00:20	00:10	00:40
	Initial Warning Level	Walklane	Walklane	Walklane	0.35 m
	Peak Warning Time	03:40	03:30	03:10	03:20
	Peak Warning Level	Knee	Knee	Knee	0.86 m
12 July 2012	Initial Warning Time	05:40	05:30	05:20	05:40
	Initial Warning Level	Walklane	Walklane	Walklane	0.39 m
21 July 2012	Initial Warning Time	14:10	14:10	14:00	14:10
	Initial Warning Level	Walklane	Walklane	Walklane	0.57 m
14 Aug. 2012	Initial Warning Time	Missed	06:00	05:10	06:10
	Initial Warning Level	Missed	Walklane	Walklane	0.39 m
1 Sep. 2012	Initial Warning Time	07:00	06:40	06:30	06:50
	Initial Warning Level	Walklane	Walklane	Walklane	0.35 m
30 Sep. 2012	Initial Warning Time	15:30	Missed	Missed	15:50
	Initial Warning Level	Walklane	Missed	Missed	0.32 m
17 Oct. 2012	Peak Warning Time	17:40	17:40	17:40	17:50
	Peak Warning Level	Walklane	Walklane	Knee	0.98 m

Table 5 The accuracy and timeliness of developed nomograph

	Data Type	Warning Issued	Actual flood level			Accuracy (%)	Timeliness (min)
			No flood	Walklane	Knee		
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

This study forecasted the flood for all 10 flood peak such as Table 4. Table 5 is summarized the evaluation results. Here, we counted the flood peak separately, even if there are two peaks in the same flood event. The number in Table 5 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.

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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