Storm Runoff Prediction Using Rainfall Radar Map Supported by Global Optimization Methodology

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Abstract. In Tokyo metropolitan area, flood risk is increasing due to social and environmental conditions including concentration of population and industry etc. Small urban watersheds are at a high risk of inundation by river flooding and/or inner water induced by heavy rainfall in a short time. To estimate river water level accurately in urban small rivers, it is critically important to conduct precise runoff analysis by using spatiotemporally distributed rainfall data. In this study, a runoff analysis was conducted with spatiotemporally densely distributed X-band MP Radar (X-band multi-parameter radar) data as input for storm events occurred in upper Kanda River, a typical urban small river in Tokyo. Then, SCE-UA method, one of global optimization methodologies, was applied to identify the parameters of the storm runoff model. The results revealed that urban storm runoff was predicted accurately using X-band MP radar map supported by optimized runoff model.

Keywords: Urban runoff · X-band MP radar · Small urban watershed
SCE-UA method

1 Introduction

In recent years, locally concentrated heavy rainfall, known as guerrilla-type rainstorms, has frequently brought about flood damages in Japan. Especially, Tokyo Metropolis is at an increasing risk of flooding due to its social and environmental conditions such as population and industry concentration, and urbanization or climate change which increase storm runoff. Small urban watersheds are prone to be caused inundation by river flooding or inner water because heavy rainfall even for a short while can bring about a sudden increase in storm runoff volume. Based on these backgrounds, it is expected to conduct precise runoff analysis by using detailed spatiotemporally distributed rainfall data.

X-band MP radar network (XRAIN), deployed by the Ministry of Land, Infrastructure, Transportation, and Tourism of Japan (MLIT), was started its full operation in March 2014 after the trial operation since 2010. The system provides detailed spatiotemporally distributed rainfall data. Earlier studies on the X-band MP radar data

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include; characteristics of the data and precise estimation methods of radar rainfall [1], and the precision evaluation of X-band MP radar rainfall [2].

However, storm runoff prediction using X-band MP radar data has not been carried out for small urban watershed. In addition, there is no method for calibrating urban runoff models. X-band MP Radar data, having sixteen times higher resolution and five times higher frequency compared to conventional radar data, are a large set of rainfall data, so-called big data. To make the best use of these detailed data, it is expected that runoff analysis models convert rainfall into precise storm runoff.

Thus, in this study, the authors built a storm runoff model using X-band MP radar data, and applied a global optimization method, the Shuffled Complex Evolution University of Arizona, SCE-UA, [3] for optimization of the runoff model. With the model, the authors evaluated the hydrograph reproducibility. Storm events in upper Kanda River, one of representing urban small rivers in Tokyo, were selected as the target.

2 Target Watershed and Storm Events

2.1 Target Watershed

The Kanda River, an urban watershed in western Tokyo, Japan, was selected as the target watershed. It originates in Inokashira Pond in Mitaka City and flows into Nakano Ward, then, into Shinjuku Ward after merging with the Zenpukuji River. With the basin area of 105.0 km^2 and the length of 25.48 km, it is one of typical small rivers in Tokyo and is designated as one of Japanese first-class rivers. In this study, Koyo Bridge, shown in Fig. 1, was selected as the site to determine the reproducibility of the model, and upper Kanda River basin, having a catchment area of 7.7 km^2 at Koyo Bridge, was selected as the target basin.

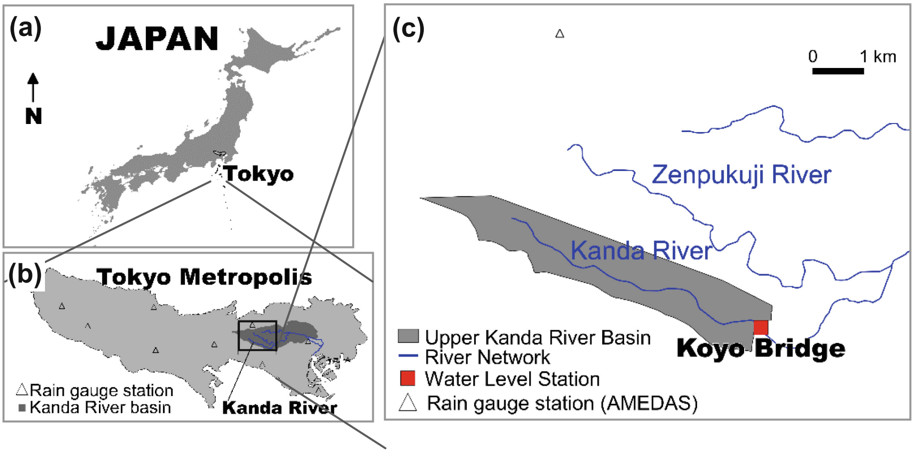

Fig. 1. Index map of (a) Japan, (b) Kanda river basin in Tokyo and (c) target area upper Kanda basin at Koyo Bridge.

2.2 Target Storm Events

Five target events were selected from the ones occurred in 2013. Since heavy rainfalls during a short period are capable of rising water level in small rivers, rainfall over 25 mm in 30 min were selected as the target events [4].

Storm events were defined as sequential rainfalls with no longer than 1 h intervals. Table 1 shows the five target events. In the table, 30 min maximum rainfall, the period of rainfall data used in runoff analysis, and rainfall causes are also listed.

Table 1. Target rainfall events

Rainfall event	Rainfall (mm/30 min)	Period of rainfall data used for runoff analysis	Cause of rainfall
Ev.1	36	9/15 03:20–9/15 17:20 (841 min.)	Typhoon No.18
Ev.2	35	8/12 17:14–8/12 23:39 (386 min.)	Atmospheric instability
Ev.3	31	6/25 11:38–6/25 18:10 (393 min.)	Atmospheric instability
Ev.4	26	9/04 22:51–9/05 14:27 (937 min.)	Low pressure
Ev.5	25	4/06 14:48–4/07 04:53 (846 min.)	Low pressure

2.3 Overview of the Rainfall Data

X-band MP Radar provides detailed rainfall data in every 250 m × 250 m mesh in every 1 min. The target area is only 7.7 km^2 and consisted of as much as 138 mesh data (see Fig. 2). The basin average rainfall applied to the runoff analysis was created from X-band MP Radar data.

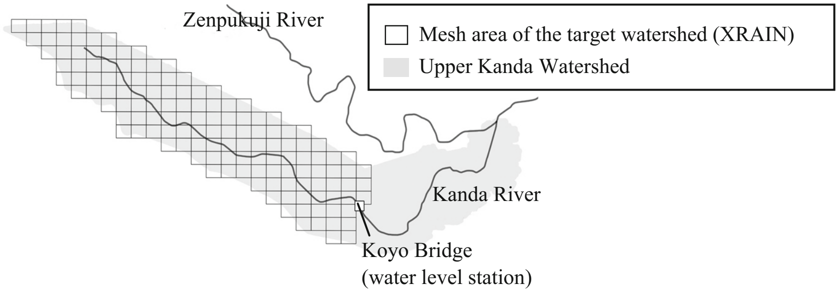

Fig. 2. Mesh area of the target watershed

Figure 3 shows hyetographs and cumulative rainfall by X-band MP Radar. For comparison, ground rainfall observation data, called AMEDAS data, is also shown in Fig. 3. AMEDAS observation stations are deployed by the Japan Meteorological Agency (JMA), and the nearest station from the target basin is located 5 km distant from the target watershed (see Fig. 1). Figure 3 shows the time series of rainfall for events from 1 to 3 out of the five target events.

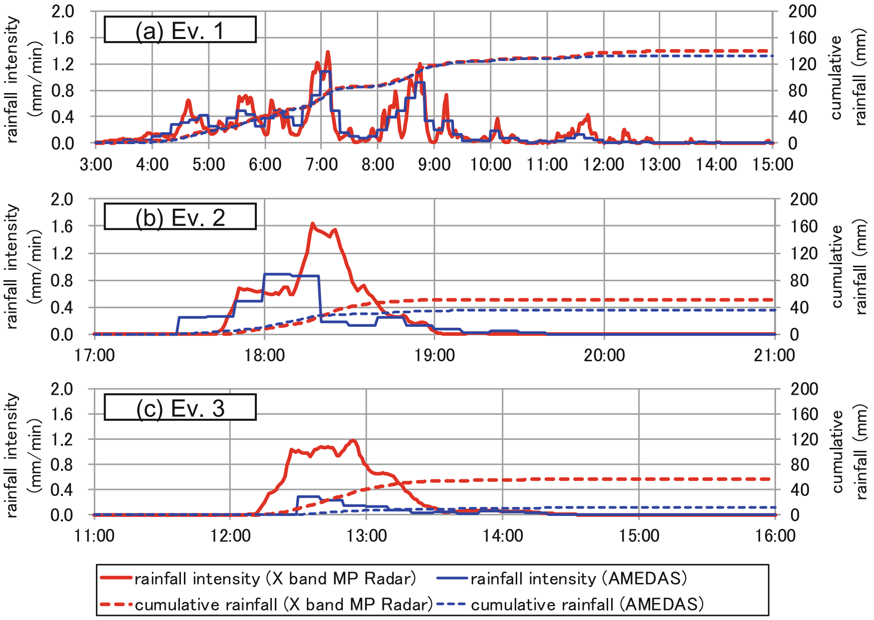

Fig. 3. Hyetographs and cumulative rainfall

In Fig. 3(a), X-band MP Radar and AMEDAS show nearly the same hyetograph and cumulative rainfall. In contrast, these hyetographs seem differences in Fig. 3(b) and (c): cumulative rainfall by AMEDAS is far smaller than X-band MP Radar. The data implies that the AMEDAS observation station, being placed in the distance, did not detect the locally concentrated rainfall, because events 2 and 3 were locally concentrated rainfall due to the atmospheric instability. In addition, since X-band MP Radar provides 1-min data, it seems to detect more detailed temporal variation of rainfall than AMEDAS data.

3 Runoff Analysis Model and Calculated Hydrograph

3.1 Overview of the Runoff Model

The runoff model used in this study is called Urban Storage Function (USF) model (see Fig. 4) with governing Eqs. (1)–(4) [5]. It is a lumped runoff analysis model in which urban runoff mechanism is incorporated. In USF model, users do not have to separate effective rainfall and runoff components, because runoff components are conceptually expressed to incorporate urban-specific runoff mechanism such as outflow to other basins through combined sewer system or leakage from water distribution pipes.

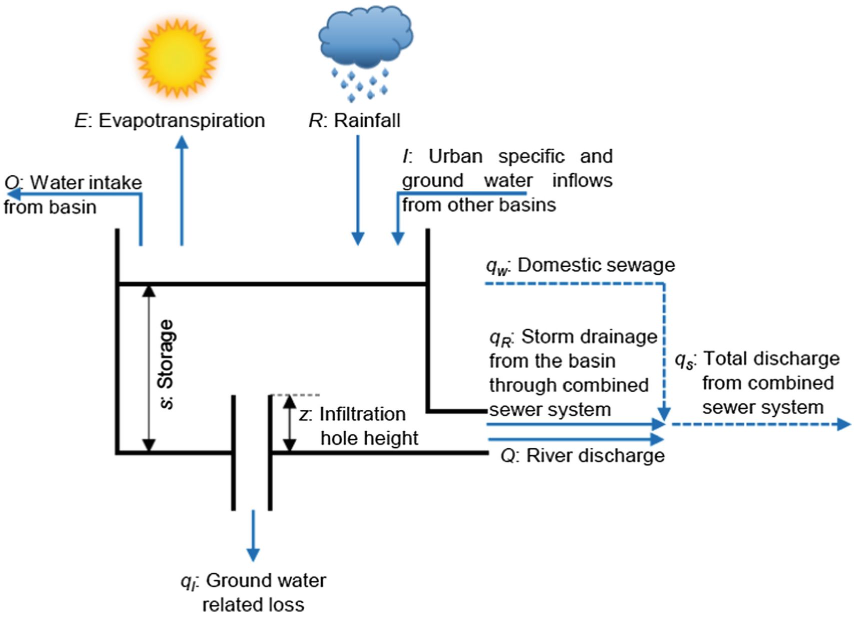

Fig. 4. Schematic diagram of urban storage function model

The Eq. (1) is the relation between runoff from the basin and the total storage within the basin, whose continuous equation leads to the Eq. (2). The Eq. (3) is groundwater-related loss. The Eq. (4) expresses the relation between river discharge and storm drainage to other basins through the combined sewer system.

$$s = k_1(Q + q_R)^{p_1} + k_2 \frac{d}{dt}\{(Q + q_R)^{p_2}\} \tag{1}$$

$$\frac{ds}{dt} = R + I - E - O - Q - q_R - q_l \tag{2}$$

$$q_l = \begin{cases} k_3(s - z) & (s \geq z) \\ 0 & (s < z) \end{cases} \tag{3}$$

$$q_R = \begin{cases} \alpha(Q + q_R - Q_o) & (\alpha(Q + q_R - Q_o) < q_{R\max}) \\ q_{R\max} & (\alpha(Q + q_R - Q_o) \geq q_{R\max}) \end{cases} \tag{4}$$

Where s: total stored height (mm), t: time (min), Q: river discharge (mm/min), q_R: storm drainage to other basins through the combined sewer system, q_{Rmax}: maximum storm drainage, q_l: groundwater-related loss (mm/min), R: rainfall intensity (mm/min), I: urban-specific and ground water inflows from other basins (mm/min), E: evapotranspiration (mm/min), O: water intake (mm/min), z: infiltration hole height for

q_l (mm), Q_o: initial river discharge (mm/min), α: sewage discharge constant, k_1, k_2, k_3, p_1, and p_2: model parameters.

The value of q_{Rmax}, I, E, O, Q_0 were given by observed data.

3.2 Hydrograph Reproducibility by Standard Parameter Values

The USF model has seven-parameters: k_1, k_2, k_3, p_1, p_2, z, and α. Based on the parameter values used in existing studies [5], standard values shown in the Table 2 were used to predict storm runoff.

Table 2. Standard values for USF model's parameters

Parameter	k_1	k_2	k_3	p_1	p_2	z	a
Value	40	1000	0.02	0.4	0.2	10	0.5

Figure 5 shows the observed and calculated hydrographs for the events 1 to 3. Respective rainfall hyetographs given as the input are also shown. The time of peak discharge were mostly reproduced in each event, but the calculated peak discharge is greater than observed data. Especially in Fig. 5(b) and (c), calculated peak discharge is greater by almost twice. The reproducibility of hydrographs is insufficient because rainfall or runoff characteristics, which are different in each event, were not expressed appropriately.

4 Optimization of the Storm Runoff Model by Global Optimization Methodology

4.1 Procedure to Setting Parameters of Storm Runoff Analysis Model by SCE-UA Method

In this section, SCE-UA method was applied to optimize USF model's seven parameters.

SCE-UA method is a global search method with an algorithm based on the synthesis of four concepts: competitive evolution, controlled random search, simplex method, and complex shuffling. It is an effective and efficient automated optimization method for calibrating model parameters [3, 6–8].

According to Kanazuka's study [9], in which he compared the effectiveness of parameter identification between USE-UA method, Particle Swarm Optimization (PSO), and Cuckoo search, it was found that SCE-UA method was the most effective in applying to USF models.

So, the authors applied SCE-UA method for parameter estimation of the USF models for the five selected storm events in the target watershed. Root mean square error (RMSE) was used as the objective function in evaluating the reproducibility of the model. The model parameters are identified by calibration using the average watershed rainfall compiled from X-band MP Radar and the observed river discharge. SCE-UA method requires a number of runs and generations for optimizing parameters to be converged.

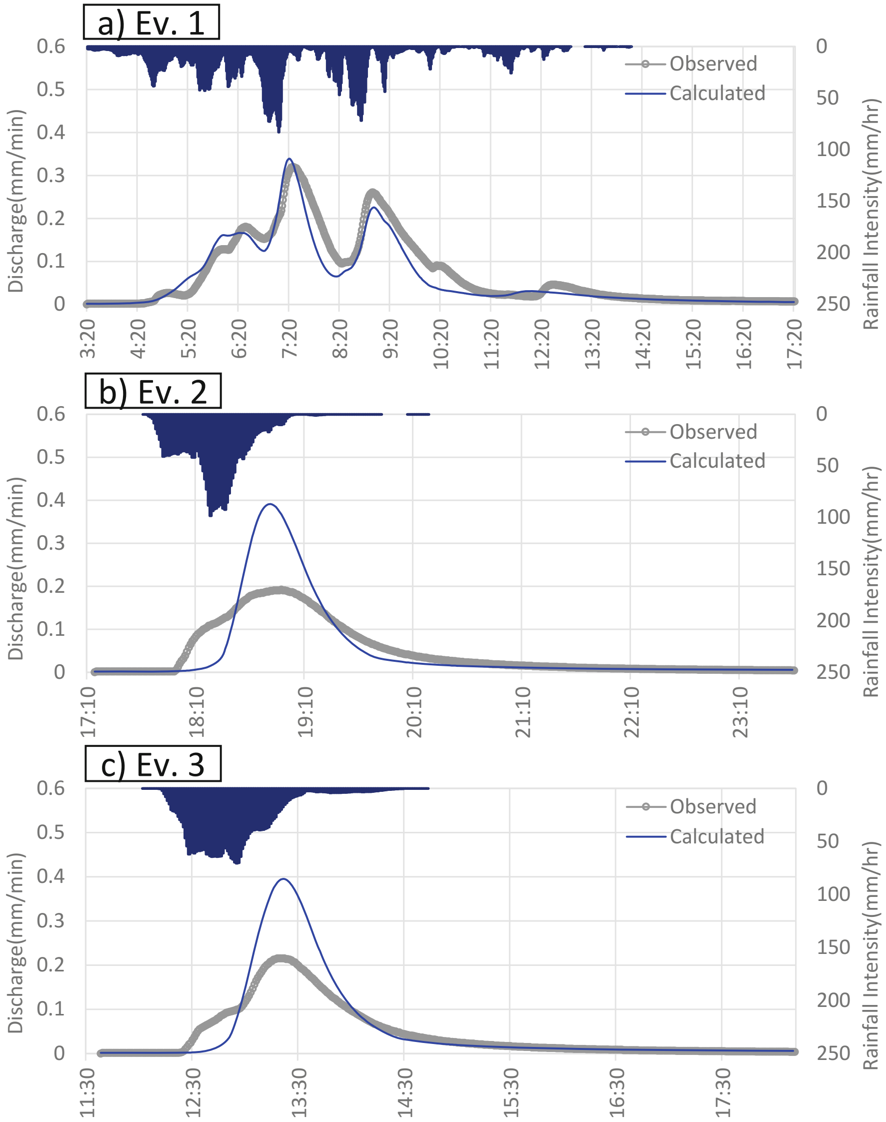

Fig. 5. Reproducibility of hydrograph by standard parameter values

4.2 Reproducibility of Runoff Hydrographs by Optimal Parameters

Figure 6 shows runoff analysis results of events 1–3 from 1st generation to 40th generation by SCE-UA method. RMSE values for each generation and event are shown in Table 3.

Calculated runoff hydrographs shown in Fig. 6 indicates that, for each event, the calculated hydrographs reproduces the shape of the observed hydrograph more precisely as generation numbers increase. Also, as shown in Table 3, the RMSE values

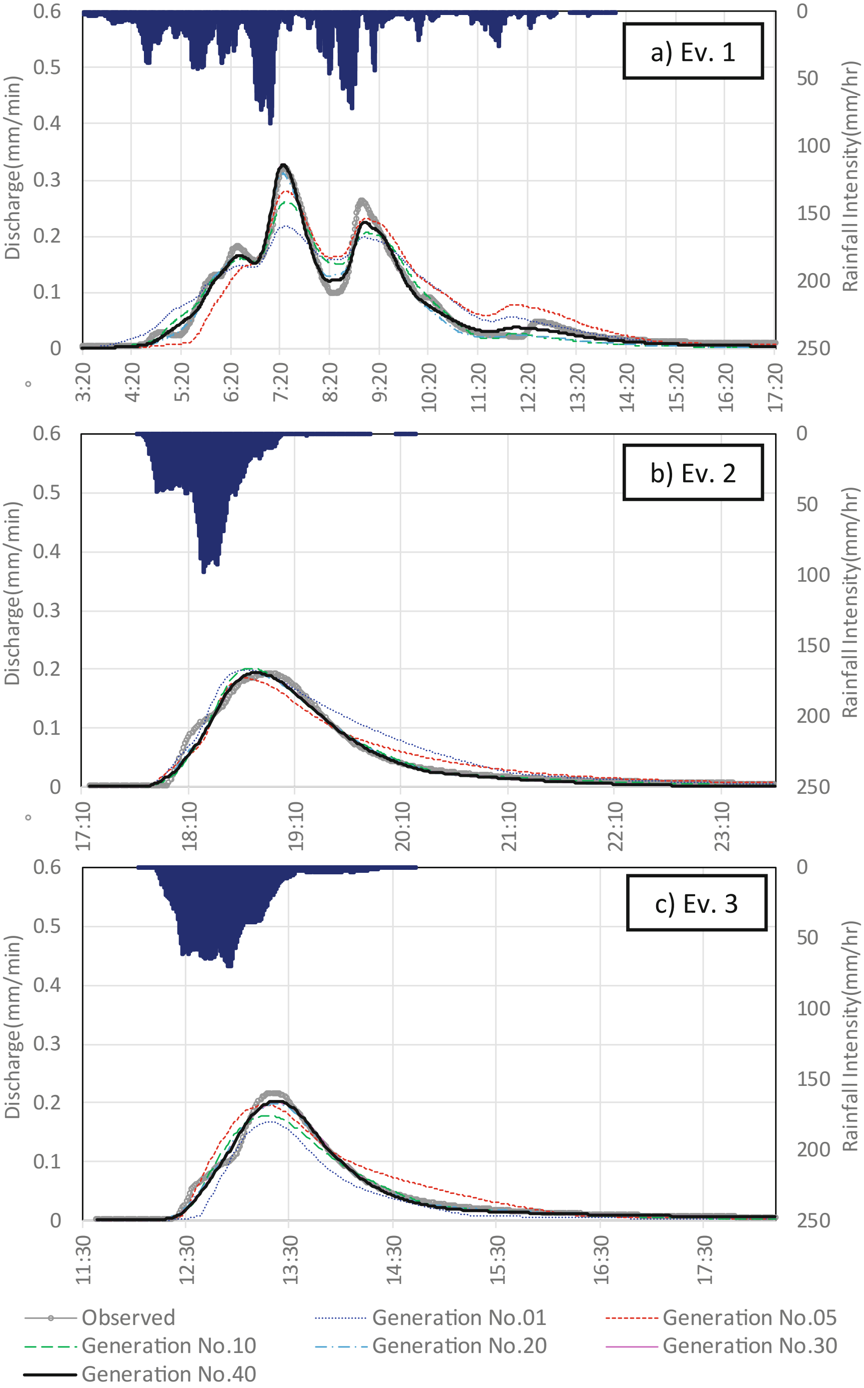

Fig. 6. Reproducibility of hydrograph of each generation

Table 3. RMSE for each generation

	Generation No.01	Generation No.05	Generation No.10	Generation No.20	Generation No.30	Generation No.40
Ev.1	0.029	0.028	0.019	0.012	0.011	0.011
Ev.2	0.013	0.010	0.006	0.005	0.004	0.004
Ev.3	0.013	0.012	0.008	0.005	0.004	0.004
Ev.4	0.020	0.018	0.013	0.010	0.008	0.008
Ev.5	0.033	0.032	0.026	0.024	0.024	0.024

decrease with the increase of generation numbers. They converge mostly to the minimum value when the calibration was proceeding between 30th to 40th generations.

Percentage errors in peak discharge, PEP, are shown in Table 4. The data depicts a similar trend as RMSE; PEP values become lower, closer to zero, as generation numbers increases, and become the closest to zero at 40th generation.

Table 4. PEP for each generation

	Generation No.01	Generation No.05	Generation No.10	Generation No.20	Generation No.30	Generation No.40
Ev.1	−32%	−13%	−18%	−3%	2%	2%
Ev.2	4%	−3%	6%	0%	1%	1%
Ev.3	−22%	−9%	−17%	−8%	−6%	−5%
Ev.4	−46%	−20%	−20%	−5%	−6%	−4%
Ev.5	−48%	−57%	−34%	−37%	−37%	−37%

In this section, USF model's seven parameters were optimized by SCE-UA method with X-band MP Radar data and observed river discharge. The result revealed that the calculated discharge nearly reproduces the observed hydrograph, which implies that the hydrograph reproducibility of USF model with optimal parameters is sufficiently high.

4.3 Comparing Best Parameters Between Events

In the last section, the optimal parameters of USF model were identified for each storm event. As shown in Fig. 7, the parameter values in 40th generation fluctuates substantially among different events, for k_1 ranges from 40 to 190, k_2 from 300 to 2800, k_3 from 0.007 to 0.022, p_1 from 0.1 to 1.4, p_2 from 0.2 to 1.5, z from 3 to 105, and α from 0.2 to 0.9. It implies that, by giving different parameter values to different events, the model incorporates the event-based characteristics of observed X-band MP Radar and river discharge. Thus, RMSE is minimized, and the reproducibility of USF model's runoff analysis is highly accurate.

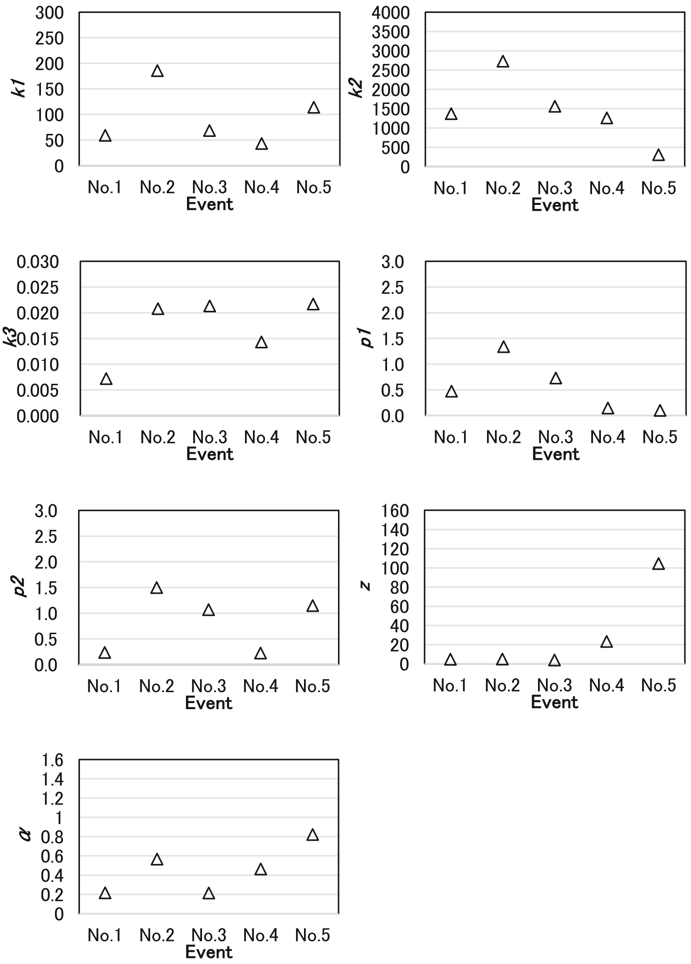

Fig. 7. Optimal parameter values of USF model for each storm event

5 Conclusion

X-band MP radar data, which has high spatiotemporal resolution, was used to predict storm runoff in urban watershed in upper Kanda river basin, western Tokyo, Japan. SCE-UA Global Optimization method was applied to optimize USF model parameters for urban storm events. The results revealed that, although the hydrograph reproducibility was not sufficient with standard parameter values, urban storm runoff was predicted accurately with parameters optimized by SCE-UA method.

It implies that the SCE-UA method successfully identified the optimal values for USF model's seven parameters. In addition, it is concluded that, at least, 30 generations of SCE-UA method were enough to identify parameters of required preciseness.

In runoff prediction in urban small watersheds, practical use of X-band MP Radar data and USF model is one of a future challenge. It is important to improve reproducibility of runoff analysis models by optimizing multiple parameters by global optimization method such as SCE-UA with detailed rainfall information provided by X-band MP Radar.

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