Predicted Rainfall Evaluation Method to Prevent Underestimation of Predicted Small River Flooding

Takaaki FUKUHARA Kazuya TAKAMI Yasushi KAMATA
Meteorological Disaster Prevention Laboratory, Disaster Prevention Technology Division

A train disaster prevention system is currently being studied, with a view to preventing small river flooding disasters. In this system, synthetic precipitation volumes obtained by radar are input as past rainfall, while blended precipitation predictions obtained by combining numerical meteorological simulations and Nowcast, are input as future precipitation. Rainfall used for input was examined, to find a way to prevent underestimation of immersion depths predicted by calculation, due differences in precipitation volumes caused by the falling of raindrops or by the displacement of precipitation areas. As a result, we found out that it is necessary to input the synthetic rainfall obtained two minutes before the measurement time concerned as the past precipitation amount, and the maximum value of predicted precipitation amount of blending in the area within a radius of 1 km ~ 5 km from the measurement point concerned as the future precipitation amount.

Keywords: inundation prediction, flooding in small rivers, synthetic rainfall

1. Introduction

Meteorological disasters of railroads such as the collapse of embankments and railroad slopes, inundation due to river increase, railway flooding, pier scouring are caused by heavy rains. To prevent the train from encountering these disasters, when rainfall observed by the rain gauge installed every several kilometers along the railway line, or when the value of the river water exceeds the predetermined threshold, train operation control such as speed restrictions and operation suspension are carried out.

Since inundation floods and railroad floods due to river increase are brought by rainfall not only along the railway but also around of the river, it is necessary to have rainfall information other than that along railroad tracks on the upstream side of the river in order to prevent the train from encountering these disasters. In recent years, weather radars capable of acquiring precipitation intensity have been deployed, and it has become possible to acquire precipitation every minute with a grid interval of about 250 meters.

In the case of heavy rain, especially localized torrential rain, drainage speed cannot keep up with water accumulation in small rivers in urban areas: this often leads to excessive discharge and flooding. In some cases, damage occurs only minutes after rainfall: for example the Toga River disaster in Kobe City, Hyogo Prefecture [1], and the Zoshigaya disaster, in Tokyo [2]. In these cases, even if a flooding risk is detected from the observation data collected by rain gauges or weather radars, there is a possibility that damage will occur before there is time to complete the calculation. Therefore, in order to reduce the railroad disasters caused by such localized torrential heavy rains, securing lead time is an issue when analyzing inundation and flooding. Therefore, in addition to acquiring the observation results of precipitation, especially that of a short time rainfall, it is important to predict the possibility of flooding and inundation using the forecast data.

Methods to predict the occurrence of inundation, flooding and sediment-related disasters using rainfall data provided by external institutions are being developed in order to reduce disasters caused by localized heavy rain in small rivers in urban areas. In addition, safety zones around potential disaster areas were analyzed to optimize the stopping position of trains, to prevent them entering disaster-hit zones, as part of a “railway disaster prevention system for localized heavy rain,” which can also be used to assess passenger evacuation areas [3]. Here, since the catchment area of the small-scale river is narrow, the prediction error of the short heavy downpours has a large influence on the estimation result of the immersion depth. In some cases, the result of the inundation / flooding analysis gets smaller than the actual evaluation, which in turn suggests the possibility that a potential flood might go undetected.

In order to avoid leaving undetected or underestimating the possibility of flooding, this study also developed a method to convert and process precipitation data from external institutions to data that could be used as input for the inundation/ flooding analysis (hereinafter referred to as the preprocessing method).

2. Outline of the railway disaster prevention system for localized heavy rain

Figure 1 shows the flow of the railway disaster prevention system for localized torrential heavy rainfall. In this system, as shown in Fig. 2, planar rainfall data for the preceding 2 hours and subsequent 2 hours, making a total of 4 hours, were acquired in relation to reference time ($t_0$). Next, from the acquired data, the input precipitation amount for the inundation / flooding analysis [4] was set. Using this input rainfall as an initial value, an inundation / flooding analysis was performed to find the immersion area along the railroad track, and then train stopping positions were analyzed, to determine where the trains could stop to avoid the flooding.

This study applied XRAIN (eXtended RAdar Informa-
tion Network, provided by Ministry of Land, Infrastructure and Transport) synthetic rainfall for each past rainfall as input to railway disaster prevention system. Blending predicted precipitation amount [5], by the National Research Institute for Earth Science and Disaster Resilience (NIED), were prepared from high resolution data Nowcast of Japan Meteorological Agency and numerical prediction data based on a numerical model and distributed.

Blending predicted precipitation amount were calculated using two methods widely used as short precipitation prediction methods (methods for predicting rainfall based on kinematic extrapolation of rain clouds (Nowcast) and numerical calculation), where the predicted precipitation volumes obtained from both methods are weighted and synthesized [6]. It was confirmed that predicted rainfall volumes obtained using this method were smaller than the prediction error found when using only Nowcast or only numerical prediction [7].

![Fig. 3 River A catchment area and blending prediction area](Map based on white map from Geospatial Information Authority of Japan)

influence on the inundation / flooding analysis result. As shown in Fig. 3, the catchment area of river A is narrow in the north and south directions with 12 km in the east-west direction and 5 km in the north-south direction. Therefore the influence is particularly large if the precipitation area shifts in the north-south direction.

There are two types of possible deviation between precipitation amount input to the railway disaster prevention system and precipitation amount observed on the ground:

- Past rainfall amount: The difference between synthetic rainfall data (XRAIN) and ground rainfall (the value obtained from ground rain gauges)
- Forecast rainfall amount: Deviation of the rainfall area of blending predicted rainfall amount from that of rainfall actually observed afterwards

XRAIN synthetic rainfall obtains rain density from the state of the raindrops observed in the sky by radars, and it can be considered that there will some deviation with the precipitation and the precipitation area observed on the ground due to the falling and evaporation of raindrops and the movement of rain clouds.

In addition, the blending precipitation volume prediction is obtained from Nowcast precipitation data and rainfall amount from numerical predictions as described above. Nowcast is based on kinematically extrapolating the movement of rain clouds: immediate prediction accuracy is therefore high, but it is difficult to accurately predict newly occurring rain clouds that appear during the prediction period. In numerical prediction, it is possible to predict newly generated rain clouds during the prediction period, since the atmospheric state is reproduced in the weather model, however rain clouds are generated after a certain period of time from when calculations begin. For this reason, blended prediction combines the advantages of both approaches, but there may be a shift in the precipitation area and amount between precipitation prediction results and observed values.

Fig. 1 Railway disaster prevention system for localized heavy rain

![Fig. 2 Conceptual diagram for input of precipitation data to inundation / flooding analysis system](A) Program for obtaining precipitation volume

- Obtained from NIED Blending predicted precipitation amount
- XRAIN synthetic rainfall

(B) Rainfall preprocessing system

- Preprocessed precipitation amount
  - Past predicted precipitation amount

(C) Flooding/inundation analysis system

(D) Evacuation guidance display system

3. Difference between input and actual precipitation

A small river in an urban area (hereinafter “river A”) which had suffered flooding in the past was used as a model. The catchment area of river A is shown in Fig. 3 together with the distribution area of the blending precipitation prediction described in Section 2. If accurate values are found for all points in the target river basin, planar rainfall as the input value for inundation / flooding analysis will produce the most reliable results. In the case of short heavy downpours, the spatial scale and time scale are about 10 km and about one hour, respectively, but as mentioned in Section 1, for small rivers, the catchment area is narrow, so a difference in the precipitation area has a significant

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For this reason, precipitation preprocessing was examined (1) in Fig. 1 to avoid resulting estimations from flooding/inundation analyses being underestimated due to these two types of deviation. The results of this investigation are shown below, divided into past precipitation and predicted precipitation.

4. Preprocessing method of past rainfall

4.1 Method for evaluation deviation between XRAIN synthetic rainfall and ground rainfall

XRAIN synthetic rainfall to be input as past precipitation data was obtained at intervals of about 250 meters from where the state of raindrops in the sky was obtained by weather radar. XRAIN synthetic rainfall data was compared with actual precipitation amount observed on the ground.

Since there were no rainfall observation points in the river A catchment area, cases where the hourly precipitation volume reached 30 mm or more at observation points of the Japan Meteorological Agency around river A were targeted. Since the main focus of this railway disaster prevention system is localized heavy rain, 20 heavy rainfall cases where 1-hour of rainfall exceeded 30 mm (Table 1) were extracted, excluding typhoons that cause heavy rain that is observed over a wide area.

In each case, 10-minute precipitation (ground precipitation, unit mm) observed at each observation point of the Japan Meteorological Agency and 10-minute precipitation at each lattice point of the XRAIN synthetic rainfall in the vicinity of the observation point of the Meteorological Agency (unit mm) were compared. However, the XRAIN synthetic rainfall is given the precipitation intensity (unit mm/h) for every minute. Therefore, assuming that the rain with the precipitation intensity obtained each time continued for 1 minute, based on XRAIN synthetic rainfall, the estimated precipitation amount is obtained by dividing synthetic rainfall by 60 to set the rain for 1 minute, and integrating it over 10 minutes.

The past precipitation amount preprocessing method was examined using the time correlation and root mean squared error (RMSE) between the obtained ground rainfall amount and estimated precipitation amount.

4.2 Results of past rainfall preprocessing tests

Figure 4 shows time series of ground precipitation and the estimated precipitation amount at the lattice points for XRAIN synthetic rainfall including the observation points for 120 minutes (0 is set to the time when the maximum during the 10-minute downpour was observed) in Event 5 and 18. Figure 4 shows that the estimated precipitation volume almost reproduces the same ground precipitation volume as in Event 5, however, there are a few events showing a deviation between the two volumes, e.g. Event 18. The surface distribution of the simultaneous correlation coefficient for 2 hours in Event 5 is shown in Fig. 5. This figure shows the extent to which the time series of estimated rainfall at each lattice point for XRAIN synthetic rainfall reproduces that of ground precipitation. Figure 5 shows that the point where the highest correlation coefficient appears is a lattice point slightly away from the weather station on the ground. Such a shift was also seen in other cases.

| Table 1 | Events extracted as localized heavy rainfall events |
|---------|-----------------------------------|
| Event | Observation point | Peak of 1-hour rainfall |
|       |                    | Amount | Time of occurrence |
| 1     | Saitama            | 49.5mm | 2016/08/18 23:40 |
| 2     | Koshigaya          | 34.0mm | 2016/08/03 02:17 |
| 3     | Tokorozawa         | 30.5mm | 2016/07/14 19:00 |
| 4     | Nerima             | 35.5mm | 2016/07/14 15:47 |
| 5     | Hachioji           | 33.0mm | 2016/08/20 15:58 |
| 6     | Fuchu              | 46.5mm | 2016/07/14 19:17 |
| 7     | Setagaya           | 32.0mm | 2016/07/14 19:35 |
| 8     | Setagaya           | 38.0mm | 2016/08/20 10:45 |
| 9     | Tokyo              | 47.5mm | 2016/08/20 10:37 |
| 10    | Abiko              | 53.5mm | 2016/07/20 05:31 |
| 11    | Sakura             | 54.5mm | 2016/08/24 12:59 |
| 12    | Chiba              | 55.0mm | 2016/09/13 11:03 |
| 13    | Sagamihara-chuo   | 86.5mm | 2016/08/10 18:08 |
| 14    | Sagamihara-chuo   | 36.0mm | 2016/08/20 11:38 |
| 15    | Hiyoshi            | 43.0mm | 2016/07/14 19:51 |
| 16    | Hiyoshi            | 42.5mm | 2016/07/15 12:53 |
| 17    | Hiyoshi            | 36.5mm | 2016/08/02 06:27 |
| 18    | Ebina              | 52.5mm | 2016/08/10 17:27 |
| 19    | Yokohama           | 47.0mm | 2016/07/14 19:44 |
| 20    | Yokohama           | 81.0mm | 2016/07/15 13:15 |

![Fig. 4](image)

**Fig. 4** Time series of ground rainfall and XRAIN synthetic rainfall (Events 5 and 18)

![Fig. 5](image)

**Fig. 5** Cross correlation coefficient between ground precipitation and estimated precipitation (Event 5)

(White circle : Ground precipitation observation point)
XRAIN synthetic rainfall is a value obtained from the state of raindrops in the sky. Therefore, there is a time lag between the observation of raindrops in the sky by radars and its observation of the raindrops as precipitation on the ground. Consequently, the displacement shown in Fig. 5 may occur due to the rain cloud moving during the time that lapses between the moment raindrops are observed by radars and the time they are observed as rainfall on the ground. We considered the error between the past precipitation estimated and the actual past ground precipitation becomes small if we use estimated rainfall observed a few minutes before the current time. Therefore, we investigated the time difference between the current time and the time when the precipitation at the current time can be estimated in such a way as to represent ground rainfall more accurately by using RMSE between the two rainfall amounts.

In this study, the time difference between calculating ground precipitation and estimating precipitation was set in minutes. For example, the time difference “3 minutes” means that the estimated precipitation volume corresponding to ground precipitation from 10:10 to 10:20 is precipitation from 10:07 to 10:17.

For each of 20 extracted events, changing the time difference from 0 minutes to 9 minutes, we obtained the RMSE between ground precipitation and estimated precipitation at lattice point including ground observation point obtained. RMSE was obtained for 2 hours-worth of data, i.e. 90 minutes before, and 30 minutes after the reference time (rounding up to the nearest 10 minutes). The results are shown in Fig. 6. Figure 6 shows that RMSE is smallest when the time difference is 2 minutes, therefore it is considered that the estimated precipitation will reflect actual ground precipitation more accurately if the time difference is set to 2 minutes.

It was therefore decided that the input to the inundation / flooding analysis would be previous 2-hour rainfall XRAIN synthetic rainfall data collected from 2 hours 2 minutes to 2 minutes before the current time.

In the preprocessing of the predicted precipitation amount in this system, it is necessary to reduce the calculation load in order to input the precipitation data as quickly as possible to the inundation / flooding analysis while satisfying this condition. Therefore, a simple preprocessing method was adopted where the maximum value of the precipitation amount for an area several kilometers around the lattice point is set as the predicted precipitation amount at the lattice point. A conceptual diagram of this method is shown in Fig. 7. This prevents areas of heavy precipitation being missed. If the precipitation area is made too large, heavy areas of precipitation will not be missed, however, the area of flooding will be overestimated. The following section describes the results of investigating the areal range in which the maximum value of precipitation for this preprocessing is extracted will be described. This study also investigated river levels obtained through inundation / flooding analysis to use as indicators so that the calculation results could be compared even when flooding did not occur according to the inundation / flood analysis.

**Fig. 6** Difference between ground rainfall and estimated rainfall with time lag (Average of 20 events)

5. Predicted rainfall preprocessing method

5.1 Concept of predicted precipitation preprocessing method

As described in Section 3, there is a deviation between predicted precipitation area and the actual precipitation area in short-term precipitation prediction. Considering this deviation, rainfall data must be input to the inundation / flooding analysis in a way that avoids underestimation.

The effect of differences in input precipitation amount on the inundation / flooding analysis result was investigated to examine the predicted precipitation preprocessing method.

In order to make the calculation result obtained from input only observed precipitation data the reference for comparison (Ref), all inundation / flooding analyses were conducted with XRAIN synthetic rainfall data used as input data. River levels were then obtained and examined to see if they exceeded riverbank height. If they did, the time at which they exceeded this height was obtained (hereinafter referred to as “overflow time”) along with the location where this occurred. Then, as in the “railway disaster prevention system,” inundation / flooding analyses were performed using both XRAIN synthetic rainfall amount and blending predicted precipitation amount as input rainfall amount.

The minimum radius of the area where the maximum
value of the predicted precipitation volume at each lattice point extracted was then calculated so that the the water level at the overflow occurrence point and at the time of occurrence of overflow in the reference calculation would be on the safe side (the side where the water level does not fall below).

The railway disaster prevention system can also be used to determine train stopping positions and passenger evacuation areas in case of localized heavy downpours, where lead time to determine these is important. Based on the assumption evacuation requires over 20 minutes, the preprocessing of 5 patterns were examined to ensure none underestimated inundation / flooding that occurred 20 minutes, 30 minutes, 40 minutes, 50 minutes, and 60 minutes after the current time. We investigated the preprocessing method that does not cause the inundation / flooding analysis result to be underestimated based on the river water level at the time when the overflow occurred in the reference calculation (hereafter, $t_0$) corresponding to the current time ($t_1$ in Fig. 2) at times $t_1$ - 20 min, $t_1$ - 30 min, ..., and $t_1$ - 60 min, respectively.

### 5.3 Extraction of case studies and adjustment of precipitation area

Localized heavy downpours were extracted from XRAIN synthetic rainfall data for the period July 10, 2016 to December 31, 2016 in the southern area of the blending prediction area shown in Fig. 3 and based on a previous study [4], using the method described below:

1. Maximum precipitation amount in the past 1 hour was 50 mm or more.
2. The area of the region enclosed by a closed curve where the point of the maximum value of (1) was located and where 1 hour precipitation is 30 mm or more was 100 km² or less.
3. Cases where the precipitation in the past 3 hours was 150 mm or less and in the past 24 hours was 200 mm or less.
4. Cases extracted based on (1) to (3), and occurring at the same time in an area of about 110 km × 110 km (1 degree × 1 degree) with the point of peak precipitation for the preceding 1 hour at its center, were regarded to be the same.

As a result, seven cases of localized heavy rain were extracted and are shown in Table 2. All seven cases occurred outside the river A catchment area. The following adjustments were therefore made to associate rainfall to the river A catchment area. First, for each case of heavy rain, a distribution was obtained of the maximum values of the previous 1 hour rainfall and the point was located (local maximum point) where hourly rainfall was greatest. Next, the entire precipitation region obtained through blended prediction was shifted to make the maximum point pass through the central point of the river A catchment area at the time when the peak hourly rainfall occurred (Fig. 8). Based on the local short-time strong rain given in this way, the preprocessing method in which the inundation / flooding analysis result described in Section 5.2 is obtained on the safe side was examined.

### 5.4 Results of predicted precipitation preprocessing method evaluation

An inundation / flooding analysis was performed on each pattern in which the input start time ($t_0$ in Fig. 2) of the predicted precipitation amount was changed as described in Section 5.2, and then the river level when overflowing occurred was obtained. Figure 9 shows the comparison of results of the inundation / flooding analyses with results obtained with the reference calculation, which used un-preprocessed predicted precipitation data. In Fig. 9, the horizontal axis shows the distance from the estuary (the smaller the value, the closer the point to the ocean; the value of the axis is reversed since this river flows from west to east), the vertical axis shows the water level (the value 0 m being the upper end of the river bank). Therefore, if the water level becomes positive, there is a possibility of overflow that may lead to flooding. From this figure, it is found that in the reference calculation, the water level exceeded 0 m at about the 19.7 km (black circle in the figure) from the estuary causing the river to overflow. In the case of the input start time of $t_1$ - 20 minutes (the orange solid line in the figure), the water level was higher than the reference calculation at the time of overflow and the river overflowed. However, in the other cases, the calculated water level fell below 0 m regardless of the distance from the estuary, and the river did not overflow. This means that if preprocessing is not performed, the calculated water level will be lower than the reference calculation, and overflow may be undetected.

Therefore, in order to determine the minimum range for extracting maximum predicted precipitation amount,
to avoid missing a possible overflow during preprocessing, maximum values were found within areas of 1 km, 3 km, 5 km, and 10 km radii from each lattice point, and then used as input data for inundation / flooding analyses. As an example, the calculation result for case 6 where the start time was set to \( t_1 - 40 \) min is shown in Fig. 10. In this figure, when the input rainfall was set to maximum values within a 1 km radius from each lattice point (the gray solid line in the figure), the river level was higher or lower than the water level obtained through the reference calculation, depending on location, which indicates that the risk of missing overflow remained. When input rainfall was set to use maximum values within a 3 km or more radius from each lattice point (yellow, blue and green solid lines in the figure), the river levels exceeded those obtained through the reference calculation, resulting in no underestimations. Therefore, for case 6 where the predicted time began at \( t_1 - 40 \) minutes, a safe side evaluation was possible by performing preprocessing that the predicted precipitation amount used the maximum values found within a 3 km radius from each lattice point.

Following the same method, the minimum area for finding maximum values for preprocessing, that would prevent any underestimation, was determined for each case and each prediction start time. Table 3 shows the results of the minimum areas expressed in terms of radius. From this, it is understood that the area for extracting maximum values expands as the prediction time increases. However, when input precipitation amount was the maximum value obtained in the areas within 5 km radius from each lattice point, the results of the inundation / flooding analysis did not lead to the underestimation of the possibility of inundation or flooding.

![Fig. 9 Result of inundation/flooding analysis without preprocessing input rainfall data (case6)](image)

Table 3 The radius of area where the maximum value of rainfall is taken for the preprocessing predicted rainfall

| Start time of prediction (min) | \( t_1-20 \) | \( t_1-30 \) | \( t_1-40 \) | \( t_1-50 \) | \( t_1-60 \) |
|-------------------------------|-----------|-----------|-----------|-----------|-----------|
| 1                            | 0km       | 0km       | 0km       | 5km       | 3km       |
| 2                            | 1km       | 3km       | 1km       | 0km       | 5km       |
| 3                            | 0km       | 1km       | 3km       | 3km       | 3km       |
| 4                            | 0km       | 0km       | 1km       | 3km       | 1km       |
| 5                            | 0km       | 0km       | 0km       | 3km       | 1km       |
| 6                            | 0km       | 1km       | 3km       | 3km       | 1km       |
| 7                            | 0km       | 0km       | 3km       | 0km       | 3km       |

Maximum range 1km 3km 3km 3km 5km 5km

Therefore, the preprocessing method under which the precipitation after the prediction start time was set based on the maximum value in the areas within 5 km radius from each lattice point was applied.

6. Conclusions

This study examined a method for preprocessing precipitation amount to be input to a railway disaster prevention system, designed for localized heavy rainfall. The system uses XRAIN synthetic rainfall as past precipitation data and blending predicted precipitation as future rainfall. Therefore, the difference between precipitations observed through XRAIN and observed rainfall on the ground, and the shift in rainfall area in relation to predicted precipitation was examined.

As a result, to prevent underestimations from inundation / flooding analyses, it was found that input precipitation data was below:

- For past precipitation, input data was XRAIN synthetic rainfall data obtained two minutes before the reference time.
- For future precipitation, input data was maximum values of blending predicted precipitation amount in areas within 5 km radius from each lattice point.

Note that this system was mainly intended for small rivers with narrow river basin areas, and that this preprocessing cannot always be applied to large rivers with wide catchment areas.

For short-term precipitation predictions, including blending prediction, the deviation in the precipitation area is small immediately after the prediction start time, and the deviation tends to increase gradually. Therefore, although the results of inundation / flooding analyses from precipitation data obtained through preprocessing do not underestimate the possibility of inundation / flooding, there is a possibility that overestimated rainfall amount may be input. Consequently, it is considered that the results of the inundation / flooding analysis can be brought closer to reality, by making the area where the maximum value is extracted smaller during a short period of time after the prediction start time, and larger as time elapses. Future work includes plans to construct methods to dynamically...
set the area for extracting maximum predicted rainfall volumes, and to establish preprocessing methods that prevent inundation / flooding analysis results from deviating excessively from the reality while generating safe side results.

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Authors

Takaaki FUKUHARA
Assistant Senior Researcher, Meteorological Disaster Prevention Laboratory, Disaster Prevention Technology Division
Research Areas: Meteorological Disasters

Kazuya TAKAMI
Researcher, Meteorological Disaster Prevention Laboratory, Disaster Prevention Technology Division
Research Areas: Meteorological Disasters

Yasushi KAMATA
Senior Chief Researcher, Meteorological Disaster Prevention Laboratory, Disaster Prevention Technology Division
Research Areas: Glaciology