Rainfall Thresholds and Flood Warnings: A Case Study in New Taipei City

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ABSTRACT

High-intensity rainfall of short duration is triggered by mesoscale convective clouds, and remains difficult to forecast with numerical forecasting models. The Water Resource Agency (WRA) in Taiwan has developed a flood alert system that has defined two levels of flood warning based on predefined rainfall thresholds in each township. The system tracks rainfall in real-time through rain gauge stations in specific locations and then issues flood warnings to the corresponding affected townships when the rainfall reaches a predefined threshold. However, the system does not account for temporal–spatial rainfall distribution and the density of rain gauge stations; because of failed alarms that can thus result, some townships are inundated during the heavy rain and typhoon season. To improve the effectiveness of the flood warning system, we have proposed a methodology utilizing data from Quantitative Precipitation Forecasts (QPFs) to examine and revise the rainfall thresholds of the WRA. This procedure has two phases: (1) assess the effectiveness of flood warnings in each township, and (2) adjust the original rainfall thresholds. Taking New Taipei City as the study case, we revised the rainfall thresholds in five townships based on the proposed methodology and rainfall data collected during the invasion of Typhoon SAOLA that attacked Taiwan from July 31 to August 3, 2012. The revised thresholds will be tested in future events to validate their effectiveness with regard to accurate flood warnings.

INTRODUCTION

Flooding induced by typhoons and storms is the most severe hazard in Taiwan. Whenever detects the flood potential, the authority, Water Resources Agency (WRA), should issue a flood warning to the public beforehand and take precautions to minimize loss of life and property caused by the disaster. Experts in both meteorological and hydrological domains have empirically determined the corresponding rainfall thresholds in accordance with historical inundation events for different townships and developed an automatic notification system for issuing flood warnings (Wu and Wang, 2009). The flood warning is divided into two levels—the primary and secondary alarms—which refer to their associated evacuation operations. The primary alarm is established if it is continuing to rain in the flood warning area and there may already be flooding in the villages and roads; if it is continuing to rain in the flood warning area and there may be flooding at villages and roads within three hours, this triggers the secondary alarm.

FLOOD RAINFALL THRESHOLDS

Generally, rainfall thresholds identify precipitation critical values that can be used both in the context of landslides and debris flow hazard forecasting (Annunziati et al., 2000; Crosta and Frattini, 2000) and in flood forecasting or warning (Georgakakos, 2006; Martina et al., 2006), and are in extensive use in the United States (Georgakakos, 2006) and Central America. In Europe, the Integrated Project FLOODSite (http://www.floodsite.net) among other projects aims at assessing the advantages of using the rainfall threshold method as an alternative to traditional approaches in the case of flash floods.

In the context of flood warning, rainfall thresholds have been generally used by meteorological organizations or by civil protection agencies to issue alarms. In Taiwan, the responsibility of issuing warnings or making emergency decisions rests on stakeholders not knowledgeable in hydro- or meteorology such as flood emergency managers or mayors (Martina et al., 2006).

IDENTIFICATION OF THE CRITICAL RAINFALL THRESHOLD IN TAIWAN

Rainfall thresholds are established from surveying historical data of flood events. Experts consequently set the minimum rainfall causing flooding as the threshold of primary alarm separately for each township in all the administrative regions in Taiwan. For example, if seven events caused flooding, the minimum 1, 3, 6, 12, and 24 h rainfall values from among the seven can be set as the rainfall thresholds. A flood warning would be issued even if only one of the five rainfall thresholds was surpassed.

However, when the thresholds were defined, neither the spatial and temporal distributions of rainfall nor the influence of the spacing of the rain gauge stations were been considered. It is overly simplistic to assume that rainfall in the location of a rain gauge is equivalent to that in the surrounding areas. In the past, some townships were inundated when heavy rain or typhoon occurred because the flood warning system failed to detect the potential for flooding, causing serious damage. In addition, the misjudgment of flood potential sometimes happens as well, which can lead to the decision to enact flood responses unnecessarily. Thus, rainfall thresholds should be calibrated in order to improve the correctness of flood warnings in the future.

STUDY AREA

New Taipei City was selected as the study area. It is the largest city in Taiwan, located in the north of Taiwan Island, and has an area of 2052 km^2, 29 townships, and a population of 3.93 million. Affected by the factors of terrain, rainfall, and drainage facilities, some of the townships are prone to flooding whenever a typhoon or heavy rain comes. Among the 29 townships, 20 of them have been classified as flood potential areas; the other 9 townships have been classified as debris flow potential areas, which is outside of our research scope.

RESEARCH GOALS

The aim of this research is to revise the current rainfall thresholds of New Taipei City for the flood warning system in Taiwan. The revised thresholds should be able to provide accurate warnings during times of heavy rain or flooding. We develop a methodology utilizing the data from Quantitative Precipitation Forecasts (QPF) to examine and revise the rainfall thresholds. To validate its performance, we also endeavor to verify the revised rainfall thresholds for in the future when a heavy rain or typhoon occurs.

METHODOLOGY

Accurate quantitative precipitation estimates (QPEs) and very short-term quantitative precipitation forecasts (QPFs) are critical to accurate monitoring and prediction of water-related hazards and water resources (Vasiloff *et al.*, 2007). Nowadays, radar QPEs, which are able to provide rainfall measurements corresponding to the grid scale of distributed hydrological models, are commonly used in hydrological applications. The primary advantage of using radar for rainfall estimation is that it provides higher spatial and temporal resolution products and has larger areal coverage compared with traditional rain-gauge-measured rainfall. Despite the scaling advantages in space and time they provide, stand-alone radar systems are not always sufficient for quantitative application. As a result, operational radar QPEs are often based on a combination of both radar and rain gauge information (He *et al*., 2013).

In the research, the QPF data, provided by Quantitative Precipitation Estimation and Segregation Using Multiple Sensors (QPESUMS), serve as input for us to examine and adjust the rainfall thresholds. In QPESUMS, the Taiwan area is split into a 441 x 561 grid with each cell representing an area of 1.25 x 1.25 km and provide real-time 0-3 h QPFs with 10-min update cycle by grids (Chen *et al*., 2006).

Our proposed methodology for the adjustment of rainfall thresholds is divided into two phases, as shown in Figure 1: (1) Assess the effectiveness of flood warnings in each township; and (2) Adjust the original rainfall thresholds.

Phase 1: Assess the effectiveness of flood warnings. In order to examine the current rainfall thresholds, we interpolate the QPF grid data for the surrounding rain gauge stations. We first compare the rainfall calculated from the interpolation with the critical rainfall thresholds of each rain gauge station and take statistics for the occurrence and non-occurrence of flood alarms. The rates are compared with the actual inundation events observed, and the numbers of hits (i.e., successful alarms), false alarms, and miss alarms are subsequently worked out for the assessment of threshold effectiveness.

Assessment of the effectiveness of flood warnings based on predefined rainfall thresholds is performed by using contingency tables. Contingency tables are highly flexible methods that can be used to estimate the effectiveness of a deterministic forecast system (Mason and Graham, 1999). A warning W is defined as the forecast of the occurrence of an event E (in this case, the surpassing of a threshold).

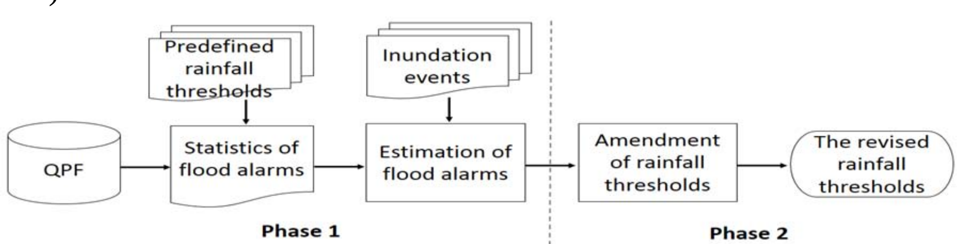

Figure 1. Schematic flowchart of the proposed methodology.

A two-by-two contingency table can be constructed as illustrated in Table 1. From n total observations, one can differentiate the total event occurrences (e) and non-occurrences (*e´*); further, the total warnings are denoted as *w*, and no-warnings as *w'*. The following outcomes are possible: a hit, if an event occurred and a warning was issued (with *h* the total hits); a false alarm, if an event did not occur but a warning was issued (with *f* the total false alarms); a miss, if an event occurred but a warning was not issued (with *m* the total misses); and, a correct rejection, if an event did not occur and a warning was not issued (with *c* the total correct rejections).

Table 1. Two-by-two contingency table for the assessment of a flood warning system.

	Forecasts		
Observations	Warning, W	No Warning, W´	Total
Event, E	*h*	*m*	*e*
Non Event, E´	*f*	*c*	*e´*
Total	*w*	*w´*	*N*

Three statistics can be used to summarize the contingency table. The probability of detection (POD) is the ratio of correctly forecasted events to the total predicted events:

$$\text{POD} = \frac{h}{h + m} \tag{1}$$

where *h* is the total hits, and *m* is the total miss alarms. The range of values for POD goes from 0 to 1, with the latter value being desirable: a POD of 1 one means that all occurrences of the event were correctly forecasted.

The false alarm rate (FAR) is the ratio of false alarms to the total predicted events:

$$\text{FAR} = \frac{f}{h + f} \tag{2}$$

where *f* is the total false alarms, and *h* is the total hits. The range of values for FAR goes from 0 to 1, with the former value being desirable: a FAR of 0 means that in the verification sample, no events forecast to occur were non-occurrences.

Neither POD nor FAR can give a complete picture of forecasting success; it is therefore desirable to include a statistic that incorporates both POD and FAR. This is the critical success index (CSI) (Schaefer, 1990; Wilks, 1995). The CSI is the ratio of correctly forecast events to the total forecasts that either were made (*h* + *f*) or should have been made (*m*):

$$\text{CSI} = \frac{h}{h + m + f} = \frac{1}{\text{POD}^{-1} + (1-\text{FAR})^{-1} - 1} \tag{3}$$

where POD is the probability of detection, and FAR is the false alarm ratio.

For either a zero POD or a unit FAR, CSI uniquely equals zero, since there are no hits. The range of values for CSI goes from 0 to 1, the latter value being desirable.

In this research, the cases of correctly issued alarms (*h*), miss alarms (*m*), and false alarms (*f*) are computed for the 1 and 3 h thresholds of the primary and secondary alarm levels in each township in the case of flood, and the three indices above—POD, FAR, and CSI—are consequently derived.

Phase 2: Adjust the rainfall thresholds. After the examination in Phase 1, the rainfall thresholds that led to high numbers of false or miss alarms should be adequately adjusted, and the basis of this judgment is CSI. If CSI is equal to or higher than 0.5, the performance of that threshold is recognized as adequate, whereas if CSI is lower than 0.5, this indicates the original threshold should be adjusted. We defined two parameters, Δ_{POD} and Δ_{FAR}, as correction values. As described above, POD is the probability of detection for flood alarms. The situation that reduces the thresholds is when townships are inundated without an early warning, which indicates the threshold is too high to detect the potential for flooding. Thus, the correction value Δ_{POD} is incorporated to lower the threshold: the lower the value, the more the threshold is reduced. On the other hand, FAR is the false alarm rate. A false alarm means a township was not inundated after an early warning was issued, which indicates the threshold is so low that the system sends the warning unnecessarily. Thus, the correction value Δ_{FAR} is incorporated to raise the threshold: the higher the value, the more the threshold is increased. Correction values vary according to observed POD and FAR as shown in Table 2.

Table 2. Correction values and operating ranges for revised threshold calibration

POD Range	Δ_{POD}	POD Range	Δ_{POD}
POD ≥ 0.75	-5 mm	POD ≥ 0.75	-5 mm
0.75 > POD ≥ 0.5	-10 mm	0.75 > POD ≥ 0.5	-10 mm
0.5 > POD ≥ 0.25	-15 mm	0.5 > POD ≥ 0.25	-15 mm
POD < 0.25	-20 mm	POD < 0.25	-20 mm

The revised threshold T_j can thus be determined:

$$T_j = T_i + \Delta_{POD} + \Delta_{FAR} \quad (4)$$

where T_i represents the original threshold, Δ_{POD} represents the correction due to the POD, and Δ_{FAR} represents the correction due to the FAR.

The revised thresholds of each township will be validated in the future when another typhoon or heavy rain strikes New Taipei City. Likewise, if the CSI in the townships fails to reach expectations for flood warning performance, the proposed methodology will be iteratively executed to calibrate the rainfall thresholds.

PROPOSED THRESHOLDS

Typhoon SAOLA hit Taiwan on July 31, 2012 and caused the most serious damage in New Taipei City, where two people dead, nine people were injured, and six districts—Sansia, Wugu, Sindian, Wulai, Yonghe, and Danshuei—were inundated. It is obvious that the flood warning system was insufficiently effective in protecting the inhabitants of the city from flooding. To address this deficiency, we use the proposed methodology to revise the thresholds based on Typhoon SAOLA in the inundated townships. Table 3 presents five examples of the revised rainfall thresholds.

Table 3. Revised rainfall thresholds after Typhoon SAOLA.

Rain gauge station name	Township name	1-hour rainfall threshold		3-hour rainfall threshold	
		Level 2 alarm	*Level 1 alarm*	*Level 2 alarm*	*Level 1 alarm*
Banciao	Tucheng	35 mm	45 mm	100 mm	110 mm
	Banciao	40 mm	50 mm	90 mm	110 mm
	Sinjhuang	25 mm	35 mm	75 mm	95 mm
	Shulin	35 mm	45 mm	100 mm	110 mm
Danshuei	Danshuei	40 mm	50 mm	85 mm	110 mm

CONCLUSION

The research proposed a two-phase methodology to revise rainfall thresholds for the townships in New Taipei City. In the first phase, Quantitative Precipitation Forecast (QPF) data and predefined rainfall thresholds were used to assess the effectiveness of the current flood warning system by using contingency tables for comparison. The probability of detection (POD), false alarm rate (FAR), and critical success index (CSI) were thus derived by the end of this phase. If the CSI fell under its median value, revised thresholds for each township were determined by adding correction values based on the range of the POD and FAR. The research thus provides revised rainfall thresholds based on the proposed methodology and the rainfall data collected during the invasion of Typhoon SAOLA. The performance of these new values will be validated in the future in terms of their effectiveness in issuing accurate flood warnings.

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