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Flash flood warnings using the ensemble precipitation forecasting technique: A case study on forecasting floods in Taiwan caused by typhoons

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SUMMARY

A flash flood is an event that develops rapidly. Given early warnings with sufficient lead time, flood forecasting can help people prepare disaster prevention measures. To provide this early warning, a statistics-based flood forecasting model was developed to evaluate the flooding potential in urban areas using ensemble quantitative precipitation forecasts (the Taiwan Cooperative Precipitation Ensemble Forecast Experiment, TAPEX). The proposed model uses different sources of information, such as (i) the designed capacity of storm sewer systems, (ii) a flood inundation potential database, and (iii) historical flooding observations, to evaluate the potential for flash flooding situations to occur. Using 24-, 48- and 72-h ahead precipitation forecasts from the TAPEX, the proposed model can assess the flooding potential with two levels of risk and at the township scale with a 3-day lead time. The proposed model is applied to Pingtung County, which includes 33 townships and is located in southern Taiwan. A dataset of typhoon storms from 2010 to 2014 was used to evaluate the model performance. The accuracy and threat score for testing events are 0.68 and 0.30, respectively, with a lead time of 24 h. The accuracy and threat score for training events are 0.82 and 0.31, respectively, with a lead time of 24 h. The model performance decreases when the lead time is extended. However, the model demonstrates its potential as a valuable reference to improve emergency responses to alleviate the loss of lives and property due to flooding.

1. Introduction

For years, Taiwan has suffered losses of life and property from disastrous floods triggered by typhoons. Improved flood forecasting would serve an important role in preparing disaster prevention measures. Flood forecasting is a nonstructural method for reducing flood damage. Given early warnings with sufficient lead time, civil protection authorities and the public can exercise caution and take preventive measures to mitigate the impacts of flooding. In terms of cost effectiveness, some studies, such as those undertaken by Multihazard Mitigation Council (MMC, 2005) and United Nations Development Programme (UNDP, 2012), have found that the money spent on emergency response is far more effective and less costly than money spent on recovery efforts. Their findings apply to floods as well as other disasters; early warnings are effective in decreasing the loss of life and property resulting from floods. A well-built early flood warning system would provide decision makers and local response teams with sufficient information as to the source of flooding and local characteristics in addition to additional lead time to prepare preventive measures.

More than 100 countries have been affected by flash floods (WMO, 2008). Hong et al. (2013) defined a flash flood as a rapid flooding of water over land caused by heavy rain or by the release of impounded water within minutes or up to several hours. A high-intensity rainfall event in a short period of time can overwhelm the capacity of drainage systems and can cause a flash flood. A significant proportion of flooding in the UK in 2007 was a result of such surface runoffs rather than as a result of the overtopping of river channels (Aronica et al., 2012). Certain area-oriented characteristics, such as low-lying land, allow the land to collect water easily but prohibit draining smoothly (Jha et al., 2012). A dangerous combination of the aforementioned factors deteriorates the flood-resisting capacity of flood-prone areas and creates even worse floods. The failure of hydraulic structures, such

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Nomenclature

μGA	micro-genetic algorithm
1D	one-dimensional
2D	two-dimensional
m	meter
AI	artificial intelligence
CWB	Central Weather Bureau
EFAS	European Flood Alert System
FEMA	Federal Emergency Management Agency
FFG	flash-flood guidance
GA	genetic algorithm
LST	Local Standard Timemm
	millimeter
NCDR	National Science and Technology Center for Disaster Reduction
NCHC	National Center for High-Performance Computing
NCU	National Central University
NTNU	National Taiwan Normal University
NTU	National Taiwan University
NWP	numerical weather prediction
CCU	Chinese Culture University
RTFAS	Real Time Flood Alert System
TAPEX	Taiwan cooperative precipitation ensemble forecast experiment
TTFRI	Taiwan Typhoon and Flood Research Institute
UNDP	United Nations Development Programme
UTC	Coordinated Universal Time
WRA	Water Resources Agency, Ministry of Economic Affairs

as pumps and drainage systems, can cause floods, but this aspect is not included in this study due to its complexity and unpredictability. Regardless, the total amount of rainfall remains the most severe threat for generating floods.

Early flood warning systems would not be successful without a proper method of estimating the total amount of rainfall during an event. There are direct and indirect approaches to estimating the expected amount of precipitation. A direct approach is to use onsite observation instruments to measure rainfall. For example, Puerto Rico's Real-Time Flood Alert System (RTFAS) uses observation networks and radar (López-Trujillo, 2010) to transmit flood-related information, such as accumulated precipitation, stream heights, and reservoir water levels. The system enhances the ability of emergency managers to rapidly and accurately anticipate floods, thereby increasing the lead time available to address the emergency. The RTFAS can forecast floods with a high degree of accuracy using *in situ* measurements to observe real-time precipitation. Observation networks and radar can only provide short-term flood forecasts up to 1 to 24 h ahead of the storm (Wu and Wang, 2009). Equipment failure or problems in data transmission often cause interference in flood forecasting during extreme events (Cloke and Pappenberger, 2009). If local characteristics, such as Taiwan's steep slopes, are included, the average lag between observed peak precipitation and flooding is between 2 and 10 h (Jang et al., 2012). Considering the time for emergency evacuation and pump deployment, a warning of one day or longer is imperative to fully execute the disaster preventive measures; hence, the observed data for the short lead time flood forecast (1–3 h) are insufficient to execute the measures. The failure of observation networks is another concern during an extreme event.

An indirect approach is applied to extend the forecast lead time, namely, numerical weather predictions (NWPs) are used to forecast the rainfall and estimate the quantity of precipitation. The ensemble technique of NWPs is widely used instead of a single deterministic model to capture rainfall forecasting uncertainties (Cloke and Pappenberger, 2009). One well-known flood warning system applying the NWPs is the European Flood Awareness System (EFAS). The EFAS was established to provide local authorities with flood forecasting information 3–10 days in advance (Thielen et al., 2009). Combining rainfall-runoff and flood routing models, the EFAS can forecast discharge levels and inundation maps (Pappenberger et al., 2005). The EFAS covers transnational river basins in Europe and monitors flooding due to an increase in river stages. However, heavy rainfall can generate a flash flood in local areas simply because of regional issues, such as an insufficient storm drainage capacity (e.g., Coulthard et al., 2007; Aronica et al., 2012). These rainfall-induced flood events are frequently observed in Asia's highly populated cities, such as Manila, Bangkok, and Taipei (e.g., Gilbuena et al., 2013; Hung et al., 2009; Chou et al., 2013). A typhoon is a phenomenon that generates high-intensity rainfall, and its average impact duration is 73.68 h (Huang et al., 2012). A system such as the EFAS, which emphasizes medium-range forecasting (48–240 h) and covers transnational areas, may not be fully applicable to those cities and events. Several studies (e.g., Alfieri and Thielen, 2012; Alfieri et al., 2014) applied an indicator, the European Precipitation Index (EPIC), and incorporated it into the EFAS for flash flood detection. Those studies demonstrated that the combination of a rainfall-related indicator and NWP can be effective for flash flood warning.

To forecast flooding, hydrologists can use one-dimensional (1D) or two-dimensional (2D) physics-based models to forecast river stages or the extent and depth of inundation (e.g., Hsu et al., 2003; Chen et al., 2005). The numerical instabilities in physics-based models are issues that arise while performing real-time forecasts. They may result from solving water continuity and momentum equations with inadequate precipitation data, local topography, and the model's initial condition setting. In addition, computations in 2D models are often time consuming and less suitable for the needs of emergency response. Considering these restrictions, the timeliness of warnings can be greatly enhanced if inundation warnings are provided without the use of physics-based models. For example, Pan et al. (2011) and Lin et al. (2013) applied neural networks and used a potential inundation database to forecast rainfall-induced flooding. The neural networks were trained using a synthetic potential database from the results of a 2D overland-flow model, and the flood warnings are issued according to rainfall observations. The causes of flooding are complex and difficult to identify correctly. However, flooding is often a function of the amount of rainfall that falls on the land. Thus, many studies (e.g., Norbiato et al., 2008; Wu and Wang, 2009 Diakakis, 2012; Gourley et al., 2012; Seo et al., 2013; Clark et al., 2014) have attempted to link the accumulated rainfall to flooding. The National Weather Service (NWS) has used a similar concept, flash flood guidance (FFG), to monitor and forecast flash floods (Clark et al., 2014). FFG is typically defined as the threshold rainfall to initiate flooding on small streams over durations of 1, 3, or 6 h. Seo et al. (2013) considered the situation in which the threshold is highly dependent on the local hydrological state of the watersheds. Therefore, a suitable systematic approach to evaluating the localized rainfall thresholds is necessary.

This study uses the Taiwan Cooperative Precipitation Ensemble Forecast Experiment (TAPEX) to provide short-range forecasts (less than 72 h). To provide rainfall forecasts with additional lead time, this study includes the following three tasks to develop a