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Assessment of sewer flooding model based on ensemble quantitative precipitation forecast

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SUMMARY

Short duration rainfall intensity in Taiwan has increased in recent years, which results in street runoff exceeding the design capacity of storm sewer systems and causing inundation in urban areas. If potential inundation areas could be forecasted in advance and warnings message disseminated in time, additional reaction time for local disaster mitigation units and residents should be able to reduce inundation damage. In general, meteorological–hydrological ensemble forecast systems require moderately long lead times. The time-consuming modeling process is usually less amenable to the needs of real-time flood warnings. Therefore, the main goal of this study is to establish an inundation evaluation system suitable for all metropolitan areas in Taiwan in conjunction with the quantitative precipitation forecast technology developed by the Taiwan Typhoon and Flood Research Institute, which can be used for inundation forecast 24 h before the arrival of typhoons.

In this study, information for the design capacity of storm sewer throughout Taiwan was collected. Two methods are proposed to evaluate the inundations: (a) evaluation based on the criterion of sewer capacity (CSC), and (b) evaluation based on the percentage of ensemble members (PEM). In addition, the probability of inundation is classified into four levels (high, medium, low, and no inundation). To verify the accuracy of the proposed system, Typhoon Megi and Typhoon Nanmadol were used as test cases. Four verification indices were adopted to evaluate the probability of inundation for metropolitan areas during typhoons. The inundation evaluation results basically match the observed data on flooding, which demonstrate that this flood evaluation system has an effective grasp on the probability of inundation for storm sewer systems.

1. Introduction

Taiwan is geographically located directly in the path of northwest Pacific typhoons. Previously determined statistics (1958–2010) show that an average of 29.2 typhoons form each year, 3.4 of which affect Taiwan, and 76% of the cases occur during the months of July to September. The swift socio-economic development in recent years has enlarged the area covered by urban growth. Urban storm sewer systems are often incapable of withstanding and satisfying the current and future demands of urban development. Therefore, when typhoons or torrential rains arrive, severe inundations occur if the incoming rainfall exceeds the design rainfall intensity of the storm sewer system. For example, the torrential rain accompanying Typhoon Kalmaegi in 2008 caused widespread damage in the coastal townships of Pingtung County (the maximum accumulated rainfall was 706 mm within 42 h). In 2009, Typhoon Morakot brought record-breaking precipitation, the maximum total accumulated rainfall was 3060 mm within the whole affecting period – 6 days, the maximum observed daily rainfall for 8 August and 9 August were both more than 1000 mm, which caused widespread inundation damage from continuous rainfall. The main inundation area encompassed three cities and nine counties in Taiwan. In 2011, Typhoon Nanmadol (the maximum accumulated rainfall was 1117 mm within 84 h) reached southern Taiwan and caused heavy inundation in the regions surrounding Pingtung and Kaohsiung. In the same year, Typhoon Nalgae also caused disastrous damage in Yilan, although it

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did not make landfall to Taiwan and the typhoon center was far from the terrain. The circulation of Typhoon Nalgae interacted with the northeasterly monsoon flow, and the convergence flow enhanced and locked by the topographical lifting. It also produced continuous heavy rainfall (the maximum accumulated rainfall was 1621 mm within 72 h).

Taiwan encounters increasingly damaging typhoons in recent years (Emanuel, 2005; Liu et al., 2009). However, the protection offered by existing flood prevention engineering is limited. To reduce the overall damage from typhoons, torrential rain, and floods, appropriate non-structure damage mitigation methods must be adopted in addition to currently available engineering solutions. There are many non-structure approaches, such as: (1) establishing flood prone area restrictions to avoid high-density developments in potential flood areas; (2) developing flood forecast or early warning systems so that residents living in potential flood areas can evacuate in time to reduce flood damage and loss; (3) emphasizing knowledge and education of the potential threat of floods to reduce residents and mitigate losses; (4) establishing flood insurance to share or allocate risks; and (5) conserving soil and water in the watershed to reduce surface runoff during storms. One of the most effective methods among the non-structure solutions is the disaster warning and response measures (Reed, 1984; Yu and Chen, 2005). By controlling and understanding typhoon and torrential rain movements beforehand, timely inundation warnings and initiation of preventive measures in potential disaster areas should significantly minimize the losses from disasters.

The precipitation forecasting plays a crucial role in developing a flood warning system. Hydrological forecasting models and meteorological forecasting models are two approaches to forecasting rainfall (Yu et al., 2004). The hydrological forecasting models (for example, Burlando et al., 1993; Luk et al., 2001) are focused on short duration precipitation forecasts (1–3 h), which are suitable for real-time flood forecast operations. The meteorological forecasting models (for example, Docine et al., 1999) emphasize predicting precipitation potential and belong to long-duration precipitation forecasts (24 h or more). Hydrologists usually employ statistical methods to conduct short-duration precipitation forecasts. Probabilistic models and stochastic models are frequently applied. The Markov-chain model is the most representative probabilistic model, which uses statistical probability to describe the hereditary effect for before- and after-periods during precipitation (Klatt and Schultz, 1983; Zevin, 1986). However, statistical models generally require numerous samples that satisfy the assumption of historic precipitation events sharing the same statistical characteristics with the precipitation event being forecast. Since the short lead-time is considered insufficient for pre-disaster warning, this has driven the development of meteorological forecasts in recent years.

In long-duration precipitation forecasts, quantitative precipitation forecasts (QPF) using numerical weather models are usually applied. The Fifth Generation Penn State/NCAR Mesoscale Model (MM5) developed by Pennsylvania State University (PSU) and the National Center for Atmospheric Research (NCAR) is widely used for precipitation forecasts (Dudhia, 1993; Grell et al., 1994). Recently, the next generation of mesoscale Weather Research and Forecasting Model (WRF) developed by NCAR and supporting organizations has gradually replaced the MM5 model (Skamarock et al., 2005). The WRF model provides various atmospheric physical parameter methods for use in atmospheric research and practical organizations. Since different assumptions are involved in each physical parameter method, they can also be used in various weather types, geographical regions, and specific conditions.

Regarding ensemble forecasts, a real-time MM5 forecasting system was established in 1996 by Cliff Mass and his research group at the University of Washington in Seattle. The main region of forecast was the northwestern US (Colle et al., 2000). The data from the forecasts can be used not only for academic research but also for providing operational reference to the local National Weather Service (NWS). The University of Washington further developed a real-time ensemble forecast system which can manage multiple sets of simulation simultaneously to improve forecasting capability of the mesoscale ensemble forecast method (Grimit and Mass, 2002). Yang and Ching (2005) used the MM5 model to simulate Typhoon Toraji in 2001. Results from the ensemble modeling experiments revealed that selecting proper physical parameters can improve the modeling of typhoon paths and precipitation distribution. Jankov et al. (2005) conducted QPF verifications for case studies using alternative physical parameter method combinations in the WRF model. Chien et al. (2006) designed 12 sets of sensitivity tests to evaluate the precipitation forecast capability of the WRF model. They also determined the optimal combination of the physical parameters for precipitation simulations in Taiwan and the South China region during the plum rains.

Numerous experts in recent years have actively pursued establishing a flood early warning system to reduce damage from disasters. Cunge et al. (1980), Chen et al. (2005) and Chen et al. (2006) developed warning systems that integrated precipitation, watershed runoff, one-dimensional flood routing, and two-dimensional inundation modeling. These kinds of systems combined hydraulic models and geographic information system techniques and have effectively improved the precision of inundation forecasts. Tanguy et al. (2005) developed the French Flood Forecasting Service, SCHAPI, for assessing the evolution of floods and for daily publication of the French flood vigilance chart. Some studies investigated the use of the Flash Flood Guidance (FFG) method and improved the accuracy of flash flood forecasts (Sperfslage et al., 2004; Georgakakos, 2006; Norbiato et al., 2008). More recently, by incorporating the weather forecasts from the German Weather Service (DWD) and the European Centre, Thielen et al. (2009) and Bartholmes et al. (2009) developed the European Flood Alert System (EFAS) to provide early warning information for floods in Europe with a lead time up to 10 days. Versini et al. (2010) proposed a distributed hydrological model for a road inundation warning system and investigated flash flood prone areas in the Gard region of south of France.

To reduce frequent losses due to urban inundation in Taiwan, the authorities are urgently developing an integrated meteorological–hydrological forecast models for inundation evaluation. However, general watershed hydrological modeling is unable to simulate runoff for flooding warning for entire Taiwan because of the complexity in model input and the lengthy computing time of the model. Therefore, developing a fast inundation evaluation system based on statistical or conceptual models is considered required. Based on the results of ensemble QPF designed by the Taiwan Typhoon and Flood Research Institute (TTFRI), the main task of this study is to develop a system that can effectively evaluate inundation and provide warning message for townships throughout Taiwan. Two methods for evaluating storm sewer inundations are proposed: (a) evaluation based on the criteria of sewer capacity (CSC), and (b) evaluation based on the percentage of ensemble members (PEM). The main concept of the CSC method is to multiply the design rainfall intensity of the storm sewer by different factors to classify four levels of inundation probability (high, medium, low, and no inundation). The PEM method involves using the percentage of ensemble members whose forecast precipitation exceeds the storm sewer design criterion. To verify the accuracy of the proposed inundation system, the observed inundation data are compared with the evaluation results by using four evaluation indices for Typhoon Megi and Typhoon Nanmadol. Inundation evaluations based on the CSC and PEM methods were also analyzed detailed.