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Tsunhua Yang

Yi-Chin Chen

Sheng-Chi Yang

Jui-Yi Ho

Gong-Do Hwang

A STATISTICS-BASED AND AN SIMPLE PHYSICS-BASED MODELS TOWARD AN OPERATIONAL AND EARLY FLOOD WARNING SYSTEM

TSUN-HUA YANG (1), YI-CHIN CHEN (1), YA-CHI CHANG (1), SHENG-CHI YANG (1), JUI-YI HO (1), GONG-DO HWANG (1)

(1): Taiwan Typhoon and Flood Research Institute, National Applied Research Laboratories, 11F, No.97, Sec. 1, Roosevelt Rd., Taipei, 10093, Taiwan

ABSTRACT

Life and property losses because of disasters such as flooding are getting dramatic increases for past years. Frequent extreme weather events have even worsened the damages globally. Given sufficient information in advance, disaster preparedness and management can be well-settled. The damages and losses can be mitigated and even prevented. An early disaster warning system, named TAPEX Expert System - Flooding Potential Quick Look System, has been built in 2013 in Pingtung County, Taiwan to provide enough lead times for decision-makers to take prevented measures and execute cautions. Using ensemble quantitative precipitation forecasts, the system could estimate the flood risk at township level and issue possible threat warnings up to 72 hours in advance. The system is a statistics-based model and rapidly provides information to meet the operational needs. However, further detailed information, such as what exact villages instead of townships are flooded, is no doubt a need to speed up the response process. Therefore a simple physics-based model then is developed to identify possible flooding areas downscale to village level. Three villages (out of 33) in Pingtung County and two typhoon events were applied to test the model. The results were presented against those from a complex model and demonstrated promising potential as a valuable reference for better emergency response to alleviate the loss of lives and property in the future operation practice.

Keywords: Flood Potential Forecasting; Ensemble Quantitative Precipitation Forecast

INTRODUCTION

Taiwan suffers from floods almost every year and flooding exacts huge economic and social costs. The heavy and rapid rainfall cause floods in urban areas due to insufficient and inefficient drainage system. If flooding potential can be determined in the very early stage, this will facilitate reduction of deaths, injuries, and economic losses. To meet the demand, the Taiwan Typhoon and Flood Research Institute (TTFRI), National Applied Research Laboratories (NARLabs) has employed the technical capabilities of relevant agencies in the successful development of the "TAPEX Expert System - Flooding Potential Quick Look System," which can forecast the probability of flooding in the next 1 to 72 hours at township level when torrential rain is approaching [7]. Since it is a statistics-based model, the computing speed is its advantage to meet the real-time operational need. However, the model provided less spatial information in comparison with complex physics-based models. To achieve efficiency and sufficiency, a simple physics-based flood forecasting model was proposed in the study. A complex physics-based flood forecasting model such as Chen *et al.* [1] may provide very detailed information (like time and the exact location of flooding). To obtain the results, complex physics-based models usually need high-powered computers and a big amount of computation time. For real-time operations, timely decision is necessary. The decision-makers would not have timely forecasts without compromise the forecast precision. Thus, a few studies try to find the balance between the simulation precisions and computation time to meet the real-time operational needs by developing simplified physics-based flood routing models. For example, Lhomme *et al.* [4] developed a simplified hydraulic model (RFSM) to keep model runtimes at practical levels. The concept behind the RFSM is to take the total flood volume into floodplain areas and spread the water over the floodplain accounting for the topography. Krupka [2] also considered the speed of simulation which has an impact in the practical implementation. He developed a rapid flood inundation model (RFIM) designed to satisfy this requirement. The RFIM, same as RFSM, takes a single value of volume of inundation to calculate flooding on the floodplain. The slope of terrain is considered to be the main factor of water spreading.

In this study, a simple physics-based flood routing model is proposed to accommodate the real-time operational needs. The model assumes that the floodplain is composed of storage cells. The slope is also the main driven factor for water spreading and a single flood volume is distributed into the floodplain. The purpose of the model is to improve the flood warning level from township to village level. As a consequence, the decision-makers would have enough detailed information and react to the threats in a timely manner. The rest of this paper is organized as follows. The following section contains a brief description of TAPEX-Expert System and its selected forecasts in 2013. Thereafter a section describes the concept of the proposed simple physics-based flood forecasting model. Results and discussion presents are presented at the end.

TAPEX EXPERT SYSTEM – FLOODING POTENTIAL QUICK LOOK SYSTEM

The system assesses inundation potential with a 3-day lead time using an ensemble quantitative precipitation forecast (TAiwan cooperative Precipitation Ensemble forecast eXperiment [TAPEX]). The details of TAPEX are described in Lee *et al.* [3]. Two levels of inundation risk, which are high- and low-potential are issued considering three different aspects: (1) the design capacity of a storm sewer system, (2) a flood inundation potential database, and (3) historical records. A micro-genetic algorithm is applied in the system to assess the inundation risk. The Typhoon Kong-rey in 2013 caused serious flooding in Pingtung County and the study here presents the performance of the system in the typhoon. The system performance evaluation applies the contingency table shown as Table 1 and the following Eq. (1) to (3). Table 2 shows the system performance for Typhoon Kong-rey during August 29-30, 2013.

$$\text{Overall accuracy} = (\text{Hit} + \text{No Event}) / \text{Total townships} \tag{1}$$

$$\text{High-potential accuracy} = \text{Hit} / (\text{Hit} + \text{False Alarm}) \tag{2}$$

$$\text{Low-potential accuracy} = \text{No Event} / (\text{No Event} + \text{Miss}) \tag{3}$$

Where “Hit” means that a flood was observed at a township and the model forecasted. “False Alarm” means that the model forecasted “flooding” at a township without observation record. “Miss” means the observation record showed a flood at a township but the model did not forecast. Finally, “No Event” means that neither the observation nor the model showed flooding at the same township.

Table 1. Contingency table for analyzing flood forecasts

	Observed	Not Observed
Forecasted	Hit	False Alarm
Not Forecasted	Miss	No Event

Table 2. The system performance of TAPEX-Expert System for Typhoon Kong-rey

UTC	**0–24 Hours**			**25–48 Hours**			**49–72 Hours**		
	Overall	**High**	**Low**	**Overall**	**High**	**Low**	**Overall**	**High**	**Low**
082706	1.00	-	1.00	0.67	-	0.67	0.97	-	0.97
082712	1.00	-	1.00	0.70	1.00	0.69	1.00	-	1.00
082718	0.97	0.00	1.00	0.67	-	0.67	1.00	-	1.00
082800	0.76	0.50	0.81	0.91	-	0.91	1.00	-	1.00
082806	0.73	0.63	0.76	0.97	-	0.97	1.00	-	1.00
082812	0.64	0.44	0.71	1.00	-	1.00	1.00	-	1.00
082818	0.67	0.50	0.68	1.00	-	1.00	1.00	-	1.00
082900	0.91	-	0.91	1.00	-	1.00	1.00	-	1.00
Ave.	**0.83**	**0.41**	**0.86**	**0.86**	**1.00**	**0.86**	**0.99**	**-**	**0.99**

The system provides very useful information for relevant government agencies to take prevented measures such as water pump deployment and rescue manpower arrangement. Since the system issues the flooding risk evaluation at township level, there is always a desire to have more precise information in terms of the flooding location. Especially when the extreme storm is approaching, the decision-makers are eager to know what specific areas will be exposed to flooding. For example, the governor of Pingtung County may find the flood risk evaluation at township level useful when the typhoon is still miles away and use it for disaster prevention and mitigation. Since there are a total of 33 townships in the county, the governor needs to make more efficient moves due to limited resources and time as the typhoon is approaching or landing. In that regard, a physics-based flood routing model with simple concept is introduced to meet the needs of efficiency and sufficiency. The next section will describe the details of the simple physics-based model.

A SIMPLE PHYSICS-BASED FLOOD FORECASTING MODEL (SPModel)

Digital elevation model (DEM) consists of a matrix data structure with the topographic elevation of each grid stored in a matrix node. The study proposed a simplified model using DEM as topography reference. Then the flow direction according to the variation of elevation between neighboring grids can be identified. This is the main driven force applied to water movement in the model. In the study, the model applies the D-infinity flow model which was originally proposed by Tarboton [6] to identify the flow direction. It is defined as steepest downward slope on planar triangular facets on a block centered grid (Figure 1). Since the flow direction is defined, the flow accumulation can be calculated for each grid. If the flow direction equals 0, pi/4, pi/2, 3pi/4, pi, 5pi/4, 3pi/2, 7pi/4, the flow drains to one neighbor. If the direction falls between two adjacent neighbors (e.g., the direction in Figure 1), the flow is proportioned between these two cells (3 and 4) according to the flow direction angles ($\alpha_1$and α_2). The flow accumulation records the number of grids that drain into an individual grid. All the grids then can be rearranged in a sequence of descending flow accumulation. The new sequence is called “hydrological sequence” in the study. The grids with higher ranking in the hydrological sequence in which means more water flows. In other words, those grids are also at a higher risk of flooding than others.

The model calculated efficient rainfall using Eq. (4) as follows:

$$I = R - S \tag{4}$$

Where I is the efficient rainfall, R is the total observed rainfall, and S is the sink term which describes any kinds of water loss. In the present study, the water loss (S) is assumed zero which means all the rainfall will be accounted for flooding in the floodplain. The Eq. (4) becomes I=R and the event-based flood volume can be calculated as:

$$\text{Total Flood Volume} = \sum_{i=1}^{n} I \times A_i \tag{5}$$

Where A_i is the area of individual grid and n is the total number of grids in the floodplain.

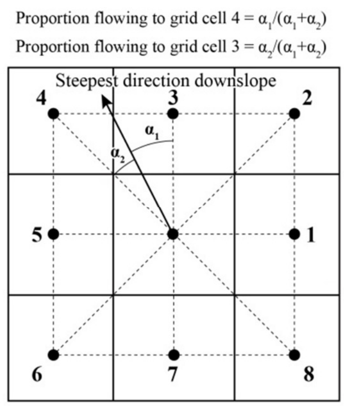

Figure 1. Flow direction using D-infinity flow model [6]

Since the purpose is to find the villages at a high risk of flooding, the SPModel simulates the water spreading using the flat-water assumption and a single event-based flood volume. The volume calculated by Eq. (5) and distributed into the floodplain and spreads over it accounting for the topography. The hydrological sequence is used to choose which grids are filled the water. In the study, the water fills the water staring from the very first 10 percent of the hydrological sequence. For example, there are 2,926 grids at Hengchun Township and the flood volume initially fills into the very first 292 grids following the hydrological sequence. The water fills the grid by 1-cm increment and the total water volume is calculated after every increment. The simulation stops when the total volume reaches the smallest difference with the given even-based flood volume. The water spreading is based on the flat-water assumption. Figure 2 shows an example of water spreading. At beginning, the water fills up at the grid (Z_1) with highest flow accumulation (Figure 2a). The water keeps filling till $Z_1 + \triangle h_1 > \triangle h_2$ (Figure 2b) and then spreads to the grid (Z_1). The water stops spreading when the surface reaches flat, such as $Z_1 + \triangle h_1 = Z_2 + \triangle h_2$ in Figure 2c.

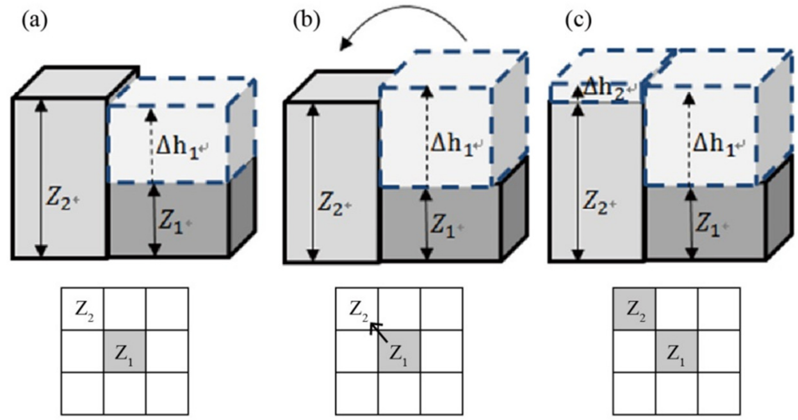

Figure 2. Flat-water assumption for water spreading in the SPModel

CASE STUDY

Pingtun County, located at southern Taiwan, has flood hazards during typhoon season (May to October) frequently (Figure 3), especially in the Pingtung City, Linbian Township, and Hengchuen Township. In the 3 township, there are flood hazards induced by heavy rainfall by the Typhoon Fanapi in 2010 and the Typhoon Nanmadol in 2011. We selected the three townships as the study areas to test the performance of the SPModel.

The flood volume corresponding to the townships for simulation is listed as Table 3. The models were built using a 200 m × 200 m DEM, from Aerial Survey Office of Taiwan's Forestry Bureau. To test the model performance, the results of SPModel were, then, compared with that of WASH123D, a complex physics-based flood routing model [5]. Table 4 shows the variable number of grids using in the SPModel.

RESULTS

Comparisons in flooding between SPModel and WASH123D are shown in Figure 4 and 5. Figure 4 shows that the comparison of simulated results for Pingtung City and Linbian Township during Typhoon Fanapi. Figure 5 shows that the comparison of simulated results for Hengchun Township during Typhoon Nanmadol. In figures, the SPModel's results showed "light gray" color and the WASH123D's results were "gray" color. The overlapped results were in black. The forecasts with inundation depth less than 0.3 m were not plotted in the figures. As a preliminary study, the SPModel's results were acceptable at village level, although some underestimations appeared. For example, SPModel did not forecast flooding in the downtown area but WASH123D did in Pingtung City. It is explained that the downtown area is comparatively lower than other areas. The water would not fill in those areas since they are not at the top of the hydrological sequence. The details will need further investigation. Table 5 shows the analysis in terms of overlapped flooded forecasts. Since the SPModel aims to provide forecasts at township level, the comparison shows the rate of overlapped forecasts is in a good agreement. The highest overlapped rate, 100%, occurred in Linbian Township. The lowest rate happened in Hengchun County which is 86%. In terms of computation time, the WASH123D took average 5 to 10 minutes to simulate the flooding based on the domain size of 300 to 3,000 grids while SPModel only finished within a minute. The SPModel satisfies the operational needs in terms of efficiency if the level of forecasting details is expected.

Table 3. The township names and related rainfall stations

Township Name	Rainfall Station	Typhoon Event	Total Rainfall (mm)
Pingtung City	C1R170	Fanapi	730
Linbian Township	C1R230	Fanapi	401
Hengchun Township	467590	Nanmadol	615

Table 4. Comparison of overlapped villages between SPModel and WASH123D

Township Name	Overlapped Villages/ WASH123D's Forecasts
Pingtung City	64/71
Linbian Township	7/7
Hengchun Township	12/14

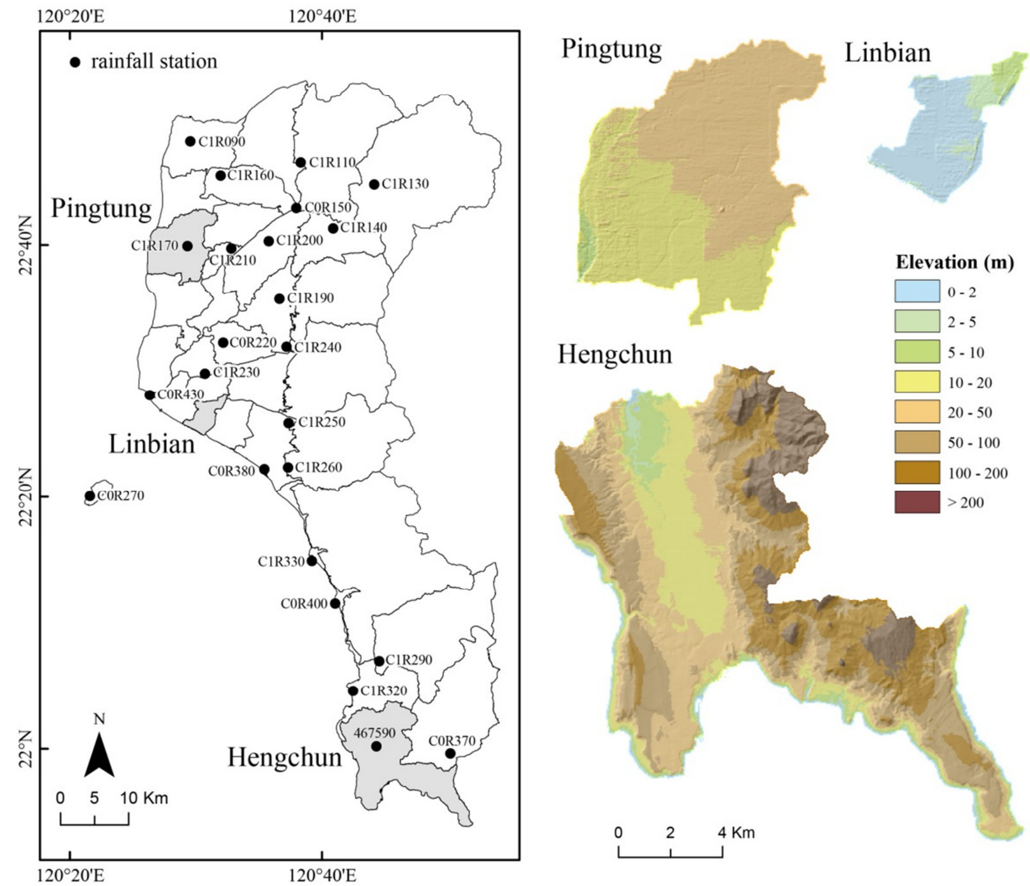

Figure 3. Map of Pingtung County and three selected townships, Pingtung City, Linbian Township, and Hengchun Township

Table 5. Number of overlapped flooded villages

Township Name	Total Grid Number
Pingtung City	1,442
Linbian Township	308
Hengchun Township	2,926

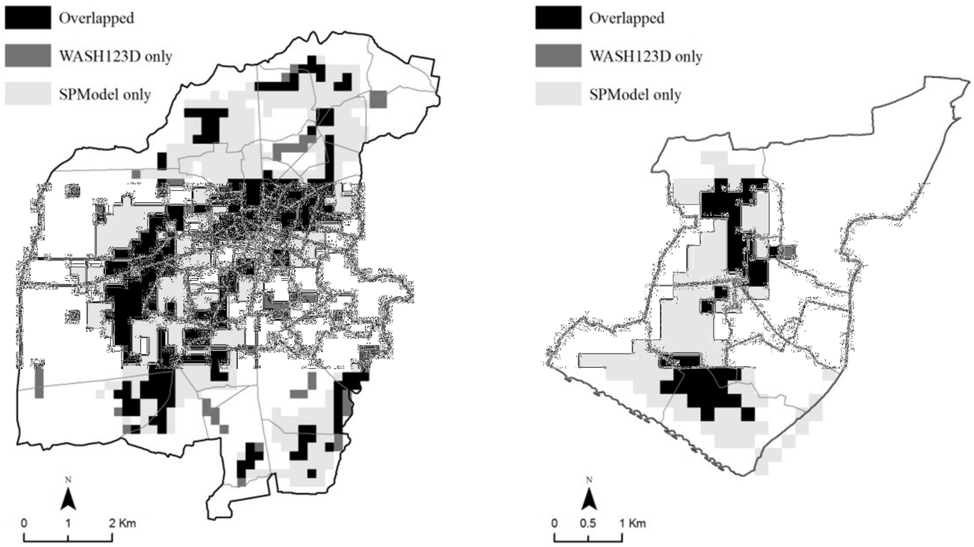

Figure 4. Comparisons of simulated flooded villages in Pingtung City (left) and Linbian Township (right) for Typhoon Fanapi (2010)

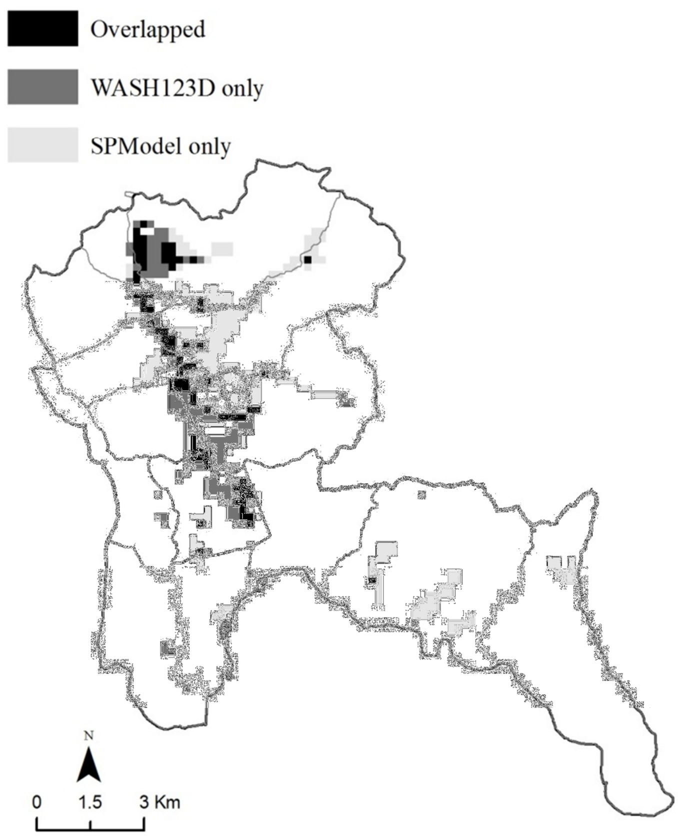

Figure 5. Comparisons of simulated flooded villages in Hengchun Township for Typhoon Nanmadol (2011)

DISCUSSION

As a result of simple physics-based hydraulics, the overall model performance of the SPModel was found to be acceptable, regardless of some underestimated predictions. Compared with the complex physics-based model, the model is more efficient in calculation time. The calculation speed is about 10 times faster. The tradeoff between computing speed and the level of forecasted details should be carefully considered while using the simple physics-based model. In other words, the SPModel is recommended for the use when response time is limited and forecast accuracy is expected. If detailed forecasts or complex evaluation is desired, a complex physics-based model such as WASH123D is recommended instead. Future works are adding water loss term like water pump in the simulation process and applying forecasted rainfall information to extend the applicability of SPModel in the operational decision. For a faster decision process, the statistics-based model will corporate with SPModel to prioritize the township by flooding risk.

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