FloodViz: A Visual-Based Decision Support System for Flood Hazard Warning

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ABSTRACT

Disaster prevention and response is becoming increasingly concerned not only with disaster mitigation, but also with the integration of hazard-related data. Take flood hazards for example, decision makers require precipitation data and the critical threshold value to judge when to evacuate the residents. Therefore, a system that can provide key information in real time is required. We developed a visual-based flood decision support system, called FloodViz, which runs automatically and provides information to help flood mitigation. The aims of the proposed system are to integrate interdisciplinary data from meteorology and hydrology and provide a clear description of the flood situation. We propose a solution that uses Information Technology (IT) to achieve our goal. We first acquire the rainfall forecasts of all the administrative regions. The at-risk regions, whose precipitation exceeds its critical value, can thus be identified using a computational model. To give the decision maker key information, we interpret flood information with visualization. The interface of FloodViz comprises a map of Taiwan highlighting the high-flood potential regions and a data filter for the time sequence. Flood response decision makers can determine if pre-evacuation is necessary based on the domain knowledge and flood information provided by FloodViz. FloodViz was tested in a real case during the strike of Typhoon Fung-wong. The system, which offered early warning information, successfully extended the response time for flood response and rescue, and thus minimized the possible damage induced by floods.

Keywords - flood, early warning system, decision support system, information visualization

1 Introduction

Taiwan is a flood-prone island. The topography drops away steeply from the central mountain, with an altitude of 3000 meters, to the west flatlands in only 50 kilometers. The distribution of rainfall in time and space is uneven, and the runoff flows quickly to the flatlands, which seriously threatens the lives and properties of residents downstream whenever heavy rain falls. Moreover, owing to the occurrence of global climate change, sudden torrential rains have occurred frequently in recent years. Hence, the contemporary system adopted for flood mitigation might no longer be able to prevent flooding from the extreme weather. In 2009, Typhoon Morakot, which led to the most disastrous flooding in the last 50 years, brought an accumulated rainfall of 2777 mm over three days causing nearly 700 deaths and roughly $4.7 billion USD of damage [1]. In other cases, Typhoon Herb (1996) brought 1095 mm daily rainfall, Typhoon Dujuan (2003) brought 1223 mm daily rainfall, and Typhoon Megi (2010) brought 938 mm daily rainfall. During these events, the residents in the affected regions were trapped in their houses or on the road, as shown in Figure 1, because no effective early warning or evacuation commands were issued by the ministerial government. This situation revealed that no reliable system existed for executing disaster prevention and rescue when encountering extreme torrential rain or massive typhoons.

Figure 1. The scene of an urban flood in Taiwan

2 Flood Response Procedure in Taiwan

The National Science and Technology Centre for Disaster Reduction (hereafter referred to as NCDR) is responsible for disaster prevention and rescue in Taiwan. The entire process of disaster prevention and rescue is illustrated in Figure 2 [2].

Analysis and simulation of early warnings: When torrential rain occurs or a typhoon approaches Taiwan, the specialists of NCDR utilize related prediction models, related basic information (such as a flood-prone area map), and historical disaster information to analyze and understand where the flood potential regions are located.

Monitoring: The monitoring information reflects the real-time condition at the site and includes, for example, the water level of the main rivers and the rainfall from each rain gauge station, which can be used as a reference for the decision-making process.

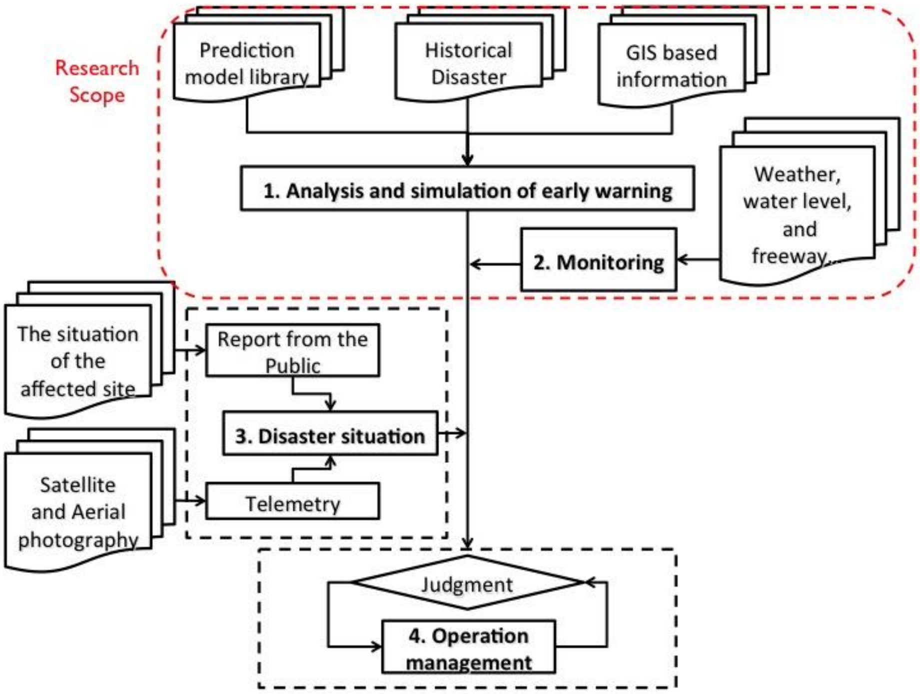

Figure 2. The process of flood response and rescue in Taiwan [2]

Disaster situation: Whenever struck by a typhoon or heavy rain, the local specialists can report only a portion of the disaster situation; the remaining information must come from the reports of residents living in the affected regions. However, the situation of rural areas is often unknown because of the difficulty contacting such remote areas. Therefore, NCDR uses spatial telemetry technologies to obtain the information when weather conditions permit.

Operation management: A consultant team of hydrologists, meteorologists, and a flood response team hold a discussion with the decision makers—the chief of Executive Yuan and the mayor of each county—via an emergency video conference to propose the countermeasures, as shown in Figure 3. The subsequent operations such as evacuation, sheltering, and equipment management is performed in serious situations.

An analysis of early warning signs and monitoring are the key steps to flood prevention and response. A successful decision to evacuate the residents of at-risk areas always relies on reliable flood simulation and a workflow with high efficiency. Much research has examined these parts of the current process in Taiwan; however, the process still needs to be enhanced. Therefore, we focus on analysis and simulation of early warnings as well as disaster monitoring to help improve the entire flood decision process.

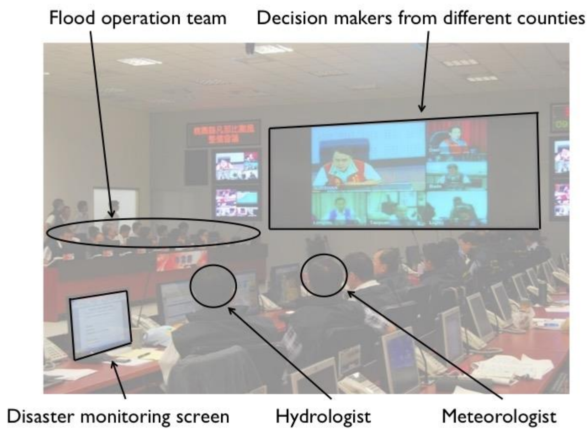

Figure 3. Government video conference to deal with flood response and rescue

3 Flood Warning System

Taiwan's government has been addressing flood risk management issues in recent years. Initially, flood management focused on reducing the frequency of floods, flood extent, and duration. Recently, the main focus has been on managing flood risk. Flood risk is defined as the probability of a flood event occurring and its consequences, in terms of casualties and economic damage [3]. From flood hazard management to flood risk management, the emphasis has shifted to raising flood awareness, flood proofing, and the use of flood forecasting, warning, and response systems [4].

A flood warning system can play a key role in mitigating flood risk by noticing the abnormalities before they happen and providing real-time information during flood events. Many flood protection systems have been developed in the last few years. Some of them use electronic sensors to monitor infrastructure and to understand when a dangerous situation might occur. Delft-FEW, for example, used real-time sensor information coupled with water level, precipitation, meteorological, and radar data to provide a hydrological forecast, as well as a flood warning system [5]. UrbanFlood used sensor networks and Artificial Intelligence to immediately calculate the probability of dam failure in addition to developing a decision support system for assisting flood response managers during flood events [6]. In 2010, Windarto developed a flood early warning system, which records rainfall and water level using a gauge placed upstream and a recorder placed in a downstream location. A server located in a government office receives the data from the recorders to predict a flood and sends flood status information to managers and stakeholders via Short Message Service (SMS) [7].

Many flood warning systems highlight the performance of their predictive mechanisms, while neglecting the significance of making the outcome more understandable. Take Taiwan for example, the flood response is conducted by the executive institute, the premier of which makes decisions according to the reports given by metrological and hydrological experts. In other words, the decision maker has insufficient knowledge to understand the computational results. To solve this problem, the domain experts should express their prediction using a comprehensive format.

Integrating the flood forecast model with a Geographic Information System (GIS) web application would be one solution to provide stakeholders with clear information about the flood situation. In 2004, Hulchy et al. integrated meteorology, hydrology, and hydraulic models with a web-based grid computing approach to present flood forecasting for a river basin [8]. In 2005, Cate et al. provided a web-based GIS service with an interface by which a user can directly run the hydrological model. The tool was connected to a spatial and non-spatial database server as well as an application server depositing hydrological models [9]. In 2009, Jia et al. described a web-based rainfall runoff prediction system using a distributed conceptual model [10]. Thus, many decision-making tools based on GIS have been developed in the past. However, the stakeholders still have to run the model themselves whenever they need to access flood forecasting information. Besides, some plugins have to be installed in specific computers before using the GIS services. The stakeholders may run into the problem of obtaining the information when they are out of the office.

In this study, we attempt to provide a web-based decision support system for urban flooding. The system runs a meteorological model in the background to forecast the flood potential. The mechanism is initiated and the flood risk is updated automatically every time precipitation data is provided. The at-risk areas are visualized and presented on the web page belonging to the flood response and prevention team to facilitate the decision-making process. The stakeholders can access this service from their computers or mobile devices to make decisions accordingly.

4 Rainfall Threshold Setting

In this study, issuing an early flood warning is based on the methodology of rainfall threshold, which has already proved to be useful in mitigating the effects of flooding [11]. The Water Resources Agency has, therefore, adopted the rainfall threshold methodology to issue the flood alarm to the 19 cities in Taiwan. Historical data including the set of available flood events and non-events were used to extrapolate the critical value for each rain gauge station. Each gauge station is responsible for the surrounding township. Once the value of the rainfall forecast surpasses the critical value, the ministerial government department will issue a flood warning to the corresponding townships. We use Table 1 to illustrate the setting of the rainfall threshold. We take Houanliao rain gauge station, located in Yunlin county, and the settings of 1-, 3-, 6-, 12-, and 24-hour rainfall thresholds as an example. Wu et al. collected data on the previous events and non-events of flooding and accumulated rainfall to obtain minimum rainfall inducing floods. As a minimum 6-hour rainfall accumulation did not make sense, because it was lower than the minimum 3-hour rainfall accumulation, they considered the reasonableness of the 3-hour and 12-hour values and made an adjustment. After receiving the minimum, they subtracted a value from the minimum to define the rainfall threshold. The value was decided according to their specialized knowledge, and the purpose of the adjustment was to reserve the response time. In order to prevent flash floods, another threshold 10 mm higher than the previous one was set to ensure sufficient response time [12]. Hence, for a flood warning, there are two different levels. Level one indicates that the region has a very high probability of flood risk; level two indicates that the region should be on alert because of its existing flood potential. The threshold values of level one are higher than those of level two, because if more rainfall occurs in the same duration, the situation will become more dangerous. The authority concerned is now able to issue a flood warning to the potential regions. To keep this solution reliable, the defined rainfall threshold is revised every year according to the latest occurrences of flood events.

Table 1. Illustration of the setting of the rainfall threshold using Houanliao rain gauge station as an example

Accum. Rainfall (hour (s))	Event A (mm)	Event B (mm)	Event C (mm)	Event D (mm)	Event E (mm)	Min. (mm)	Min. inducing flooding	Defined threshold
1	13	18	56	24	55	13	55	30
3	36	36	108	50	89	36	89	70
6	64	69	141	60	146	60	100*	90
12	113	86	146	82	226	82	113	100
24	160	105	186	131	321	105	160	130
Flooding	Yes	No	Yes	No	Yes			

* After making reasonable adjustments

5 System Architecture of FloodViz

The flood decision support system, FloodViz, is developed based on web technologies. The operational environment is Microsoft Window server 2008 using Internet Information Service (IIS) 7.5 and .NET framework 4.5 with RAM 4G and 100G of hard disk space. MariaDB is used for data inquiry. FloodViz is available to authorized users at the URL, http://wraflood.colife.org.tw/Flood.aspx. The architecture of the system is presented in Figure 4.

As shown in Figure 4, the system acquires the rainfall forecast data from the Centre Weather Bureau (CWB), Taiwan. The data is produced using either the Ensemble Typhoon Quantitative Precipitation Forecasts (ETQPF) model or the Quantitative Precipitation Estimation Segregation Using Multiple Sensors (QPESUMS) system. During typhoons, we use the output from ETQPF as the data source; when encountering a torrential rainfall, we use QPESUMS.

The ETQPF model was developed to provide typhoon rainfall forecasts for Taiwan. The rainfall forecasts are obtained using the ensemble prediction method, which gives typhoon forecast tracks. The predicted rainfall can thereby be obtained based on statistics [13]. The QPESUMS model integrates Doppler radars (WSR-88D), numerical models, satellites, lightning, and surface sensors to make reasonable Quantitative Precipitation Forecasts (QPF), which are applicable to both water resource management and flash flood warnings [14]. The QPF data are formatted to a grid coordinate with a spatial resolution of 0.0125° (approximately 1.25 km) in both longitude and latitude, and a temporal resolution of 10 minutes. Both models can provide rainfall forecasts for the next 72 hours. For Taiwan, 20367 grids are provided in each forecast and each grid is given a value of rain intensity. Take the result of rainfall forecast conducted on September 21, 2014, at 0:00 UTC+8 for example. The grids with an intensity higher than 0 millimeters per hour are shown on the map in Figure 5. As you can see, by using ETQPF, we can understand the intensity and distribution of accumulated rainfall for the next six hours.

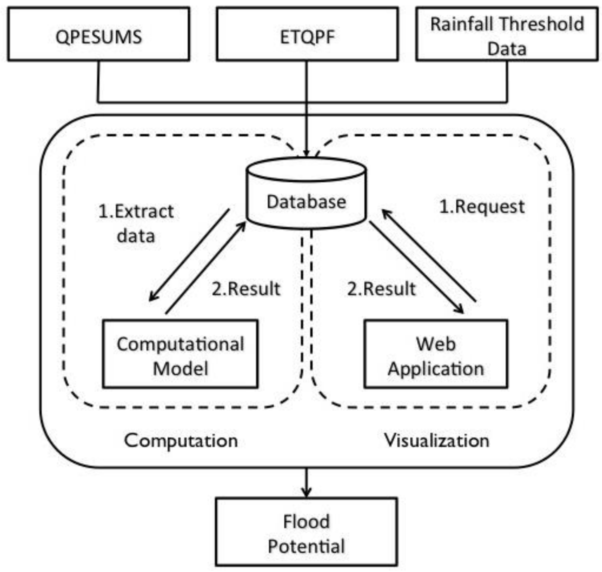

Figure 4. FloodViz Architecture

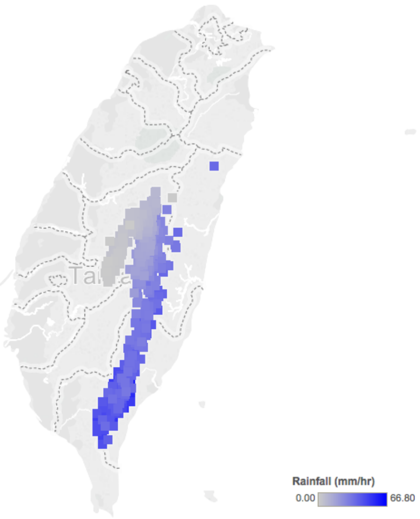

Figure 5. Example of a 6-hour rainfall forecast using ETQPF on September 21, 2014, at 0:00 UTC+8

FloodViz extracts the rainfall forecast data once an hour, if there is precipitation, and stores it in the local database. The computational model then starts to check whether the provided rainfall exceeds its corresponding critical value. If this statement is true, the township is identified as “at-risk.” After completing the calculations, the at-risk townships are visualized on the web page. Hence, the disaster response team in both central and local governments can log on to the platform and obtain the latest situation.

6 Flood Computation

After obtaining the rainfall forecasts, we can assess the flood potential by applying the rainfall threshold approach described in Section 4. We have to calculate the average rainfall at the rain gauge station located by the provided grid rainfall data to correct the regional error. The rainfall forecasts can then be mapped with their corresponding critical value to check whether the area has flood potential. We run the computational model on the web server to automatically extract rainfall forecasts and perform flood computation. The result provides the following information: the current date and time, the affected counties, and the flood warning level. The affected townships and the flood warning level of each county are also provided for a more detailed judgment. The computational results are formatted in JSON and stored in MariaDB database system.

The database collects the results of at-risk regions after the calculation is conducted by the model. As shown in Figure 6, each column stores the at-risk counties, and the new data will be continually imported every hour if at-risk regions are identified. For each row, the leftmost cell indicates the time that the set of results were inputted, and the remaining cells from left to right show the at-risk counties calculated based on 6-, 12-, 24-, and 48-hour rainfall forecasts.

7 Flood Visualization

To give the decision maker the best user experience, we developed a web-based interface visualizing the flood computational results. When users request to browse the latest situation of flood potential, FloodViz will ask the server to display the information in response to the user’s demand. To achieve this, we construct the web service using ASP.NET, and we use Hypertext Preprocessor (PHP) scripts to perform data extractions from the database according to the requirement.

To visualize the affected regions, we used the open source Google Maps API [15] to create map views on our website and present the at-risk counties as polygon layers over the basic map, as shown in Figure 7. The level-one alert counties are coloured red and the level-two alert counties are coloured orange to emphasize the level of danger. To structure the polygon layers for each county, we obtained the maps in ESRI shapefile (.shp) format from the Institute of Transportation, transferring the format from shapefile format to JSON. The polygon can, hence, be plotted as a layer above the default map using TopoJSON [16], and the detailed information such as the at-risk townships in certain counties can be understood when the user moves their mouse over the corresponding polygon, as shown in Figure 8.

PredictTime	AlertCounty_6HR	AlertCounty_12HR	AlertCounty_24HR	AlertCounty_48HR
2014092100	[ ]	[{"Countycname":"台東縣", "Level":2, "Descriptio...	[{"Countycname":"南投縣", "Level":2, "Descriptio...	[{"Countycname":"南投縣", "Level":1, "Descriptio...
2014092101	[ ]	[{"Countycname":"台東縣", "Level":2, "Descriptio...	[{"Countycname":"南投縣", "Level":2, "Descriptio...	[{"Countycname":"南投縣", "Level":1, "Descriptio...
2014092102	[ ]	[{"Countycname":"台東縣", "Level":1, "Descriptio...	[{"Countycname":"屏東縣", "Level":1, "Descriptio...	[{"Countycname":"台東縣", "Level":1, "Descriptio...
2014092103	[ ]	[{"Countycname":"台東縣", "Level":1, "Descriptio...	[{"Countycname":"屏東縣", "Level":1, "Descriptio...	[{"Countycname":"台東縣", "Level":1, "Descriptio...
2014092104	[ ]	[{"Countycname":"台東縣", "Level":1, "Descriptio...	[{"Countycname":"台東縣", "Level":1, "Descriptio...	[{"Countycname":"台東縣", "Level":1, "Descriptio...
2014092105	[ ]	[ ]	[{"Countycname":"南投縣", "Level":2, "Descriptio...	[{"Countycname":"南投縣", "Level":2, "Descriptio...
2014092106	[ ]	[ ]	[{"Countycname":"南投縣", "Level":2, "Descriptio...	[{"Countycname":"南投縣", "Level":2, "Descriptio...
2014092107	[ ]	[ ]	[{"Countycname":"南投縣", "Level":2, "Descriptio...	[{"Countycname":"南投縣", "Level":2, "Descriptio...
2014092108	[ ]	[{"Countycname":"花蓮縣", "Level":2	[{"Countycname":"花蓮縣", "Level":2	[{"Countycname":"高雄市", "Level":2

Figure 6. The database fields storing the results of the flood computation

Figure 7. The web-based map shows each county in Taiwan using a layer of polygons

Figure 8. The functional module shows the detailed flood situation of a county

8 Results and Discussion

FloodViz realizes the automation of analysis and simulation of early flood warnings, using visualization to present the decision-aided information more intuitively. In the current process, shown in Figure 9, the response team first acquires the monitoring data such as rainfall and discharge from the gauge stations. The team manually runs the model by inputting the data and formatting the results to report the flood situation to the decision makers. Based on the provided documents, they discuss the situation with the domain specialist and make judgments for the subsequent response.

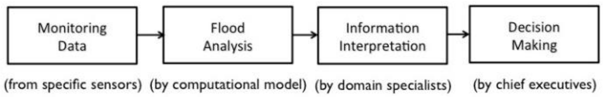

Figure 9. The current flood response process

By using FloodViz, the manpower that originally ran the models and made the reports is released. As shown in Figure 10, FloodViz automatically acquires the required data at fixed intervals, performs the flood computation, and stores the results in the database. When decision makers require information on the flood situation, they are able to obtain the latest updates, using our visual platform. The advantages of FloodViz are reducing the operating time of the entire process and presenting the situation directly, without losing or misunderstanding any of the information.

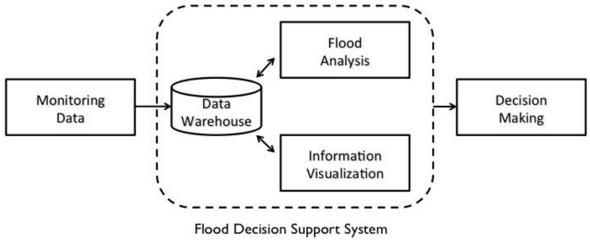

Figure 10. Implementing FloodViz in the flood response process

9 Case study: Typhoon Fung-wong striking Taiwan on Sep. 2014

We used a typhoon event to validate the performance of FloodViz. Typhoon Fung-wong attacked Taiwan between September 19 and 22, 2014, causing flooding in the majority of counties in South Taiwan. The maximum daily rainfall of 721.5 mm occurred in Pingtung County.

Figure 11 displays the operation of FloodViz. From 5 a.m. to 7 a.m. on September 21, 2014, the decision makers saw the three situations illustrated from left to right, indicating the affected regions. For the regions showing a level-one flood warning (red), the neighborhood magistrates were asked to evacuate and shelter the residents and put all the rescue equipment on standby; for the regions indicating a level-two flood warning, the decision makers consulted the response team for the disaster situation, arranged manpower, and prepared equipment.

According to FloodViz at 2 a.m. on September 21, 2014, the 24-hour flood early warning system for Taitung

County was level one, while Nantou County, Kaohsiung County, Kaohsung city, and Pingtung County were level two. By mapping these forecast results with the statistics of flood events provided by the Water Resource Agency, shown in Table 2, FloodViz successfully predicted the flooding in both Taitung and Pingtung County.

In this event, 3329 residents were evacuated to shelters successfully according to the executive command; only one person was killed and five people were injured.

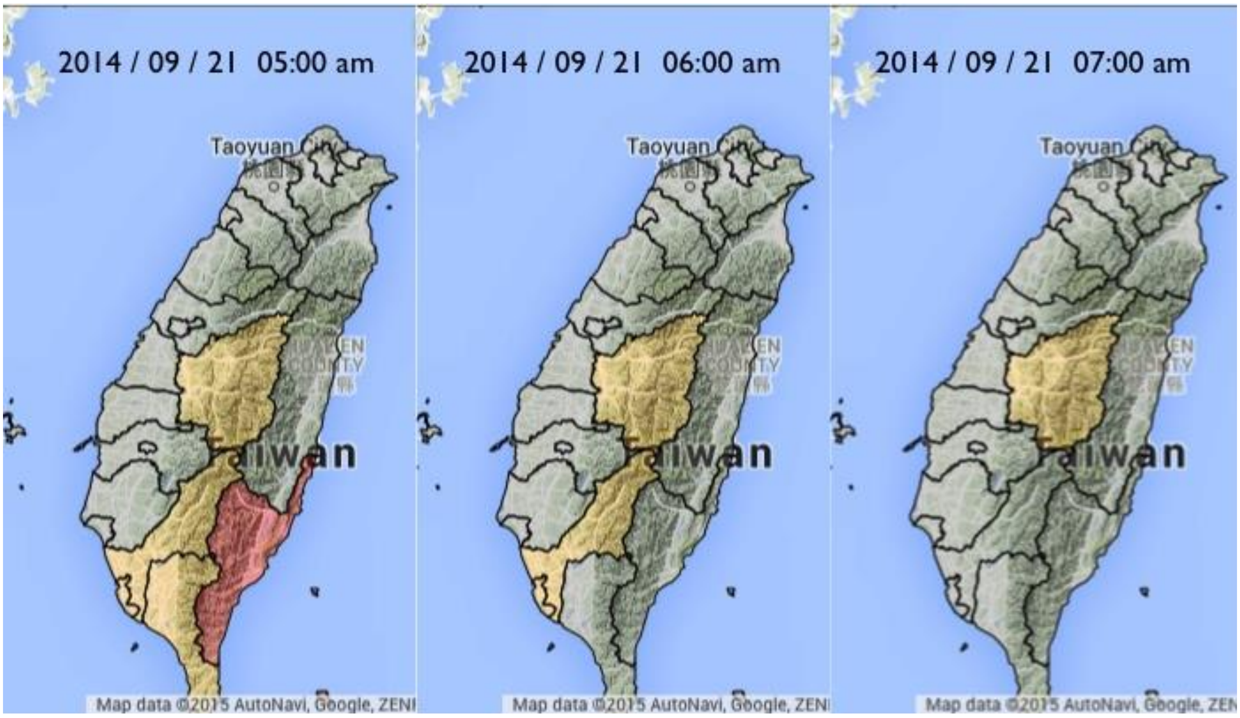

Figure 11. The flood warning simulation for the next 24 hours on September 21, 2014, at 05:00 UTC+8 (left), at 06:00 UTC+8 (middle), and at 07:00 UTC+8 (right)

Table 2. Statistics of flood events during Typhoon Fung-Wong

County	Township	Location	Flooding begin	Flooding end	Flood depth
Pingtung	Hengchun	Nanwan Rd.	Sep 21 16:27	-	0.3 m
Pingtung	Hengchun	Dehe Rd.	Sep 21 14:48	-	0.5 m
Pingtung	Hengchun	Chikan Rd.	Sep 21 14:57	-	0.5 m
Taitung	Taitung	Sec. 2, Zhongxing Rd.	Sep 21 11:25	Sep 21 19:10	0.5 m
Taitung	Taitung	Fuyu Rd.	Sep 21 10:30	Sep 21 19:10	0.3 m
Taitung	Taitung	Xichang St.	Sep 21 09:20	Sep 21 19:25	0.2 m
Taitung	Guanshan	-	Sep 21 11:42	Sep 21 17:10	0.5 m

10 Conclusion

We developed the flood decision support system, FloodViz, which provides a region-based flood warning simulation with a graphic and direct manipulation interface. Benefitting from recent advances in computer technology, we overcame several technical challenges and implemented a more effective system to help flood emergency operations. FloodViz can seamlessly communicate with the rainfall forecasting engine on a fixed interval. A real-time computational model is embedded in FloodViz to analyze the flood potential. FloodViz is internet-accessible and stakeholders can access flood situations on any internet-enabled device, which can therefore increase the available response time. The case of Typhoon Fun-wong is a real case that validates the applicability and performance of FloodViz. The results show that FloodViz can provide reliable information to assist in the decision-making process of flood response and rescue.

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