Rapid Flood Evaluation Systems in Taiwan Metropolitan Areas

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Abstract: Hydrological issues in metropolises in Taiwan have become increasingly important because the storm water sewer systems of metropolises are frequently unable to meet the requirements of the existing and future metropolitan development. Typhoons or torrential rains that cause rainfall intensities that exceed the designed capacity of storm water sewers can result in serious flooding. The losses caused by flooding can be reduced if the areas at risk of flooding can be predicted and warnings can be issued to prompt disaster prevention and allow response units and residents to prepare before disasters occur.

The primary purpose of this study is to integrate the quantitative precipitation forecasting technologies [1, 2] developed by the Taiwan Typhoon and Flood Research Institute to establish a rapid, stable, real-time, and automatic metropolitan area flood estimation system for predictive flooding analysis. The objects of this study are metropolitan areas in Taiwan with storm water sewer systems. The standard capacities of storm water sewer systems throughout Taiwan and the geographic information system (GIS) shape files are collected and compiled. Additionally, the potential flooding areas are divided into four levels (high, medium, low, and no flooding) and are compared with the rainfall warning values of the Water Resources Agency. The study combines the results of quantitative precipitation forecasts, establishes an information database (MySQL), processes Google Earth KML files, and designs a WEB GIS display interface to construct a system for estimating the flooding possibility (probability) in metropolitan areas during typhoons or torrential rains. This study subsequently employs the event of Typhoon Kalmaegi for flooding estimation and display; the estimation results are consistent with the flooding survey data, indicating that the estimations made by the flooding estimation system are correct.

Keywords: geographic information system; Rapid Flood Evaluation Systems; Google Earth

Introduction

Taiwan is located in the hub of the western Pacific typhoon path, the topography is steep and the rivers are short with rapid currents. During typhoon season, the converged torrents rushing down from mountainous areas frequently cause severe flooding in downstream flat terrains. Additionally, flooding may occur in cities and villages if the rainfall intensity of typhoons and torrential rain exceeds the designed capacity of the storm water

sewer systems in metropolitan areas, resulting in a substantial loss of lives and properties. The damage caused by flooding can be reduced if warnings for typhoons and torrential rain can be issued through the monitoring, forecasting, and decision-making of flood warning systems.

Generally, the emphases of flood forecasting include the water level of rivers, embankments, and lowland flooding; the relevant predictive information can be obtained by simulating the values of drainage basins using one- or two-dimension flood forecasting models to

predict the water level of rivers or the flooding depth. However, the forecasting models established through the numerical method of solving the flow control formula may be affected by uncertainties, such as precipitation data, topographies, or models, when making real-time predictions, resulting in unstable values. Two-dimensional physical calculations of flooding patterns are also more time-consuming to produce and have problems meeting the urgent response requirements. Thus, issuing flood warnings without requiring the use of physical models can improve the timeliness of early warnings. The Water Resources Agency established flood warning values for each village and township in Taiwan to construct flood warning systems; by comparing actual rainfall and flood warning values, warnings can be promptly issued to areas at risk of flooding [3, 4]. Additionally, Yeh *et al.* [5] analyzed the relationship between the maximum rainfall accumulated

in 1, 3, and 6 h and the flooded number of villages and townships based on survey data of historical flooding events to establish the flood warning values of these villages and townships. Hsu *et al.* [6] deduced the regressions of regional rainfall and flooding using statistical methods, and re-estimated the rainfall warning value of Tainan City using historical typhoon data. Both the studies of Yeh and Hsu assumed a directly proportional correlation between rainfall and flooding degree when determining flooding rainfall warning values. However, besides excessive rainfall being a major cause of flooding, rainfall duration, area topography, and the strength of flood prevention facilities are also crucial factors affecting the degree of flooding.

This study establishes information databases, processes information files, and displays interface designs to construct a rapid, stable, real-time, and automatic flood estimation system for metropolitan areas based on the designed capacity of storm water sewer systems and consistent with the quantitative precipitation forecast technologies developed by the Taiwan Typhoon and Flood Research Institute. The flood estimation system provides a reference for typhoon or torrential rain warnings, disaster-related decisions, and disaster-reduction measures.

Research Area

This study selects Taiwan's metropolitan areas with storm water sewer systems as the research areas for developing a rapid flood estimation system. In modern cities, storm water sewer systems are indispensable public facilities that rapidly transport and remove accumulated water through drainage channels, storm water sewers, pumping stations, and water gates. These systems not only solve water accumulation problems and reduce losses of life and property, but they also improve environmental sanitation and promote appropriate development of cities.

Because of rapid developments to metropolitan areas and the economy, the government has progressively initiated various storm water sewer system projects in urban areas since the 1960s and 1970s. The planned length of the storm water sewer channel is 6,858.50 km, 4,337.56 km of which was completed by the end of 2008. Of the storm water sewer channel, Taiwan Province has completed 3,433.69 km, Taipei City completed 521.60 km, and Kaohsiung City completed 382.27 km. The project implementation ratio is 63.24 %, wherein the ratio of Kaohsiung City is the greatest (96.84 %) and followed by that of Taipei City (96.6 %). The implementation ratio of Taiwan Province is the lowest (57.96 %) and the progress must be accelerated. [7]

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Dr. **Hsin-Ya Ho** is presently as the Deputy Director of Taiwan Typhoon and Flood Research Institute, since January 2010. His professional fields of expertise are focus on Hydraulics & Flood Mitigation. Dr. Ho has been the Executive Secretary of the National Science & Technology Program for Hazards Mitigation in Taiwan, from November 1997 to December 2006; and, was the Executive Secretary of National Science & Technology Center for Disaster Reduction in Taiwan, from July 2003 to February 2007; and the Secretary General of Disaster Management Society in Taiwan from January 2007 to October 2008. Dr. Ho has relatively in-depth study and professional expertise on the disaster prevention systems, and typhoon & flood mitigation that are in Taiwan.

Figure 1. Procedures of this study.

Methodologies

This study first collects related information, such as the standard capacities of storm water sewer systems and the GIS shape files of metropolitan areas. Subsequently, the flooding probabilities are divided into four levels (high, medium, low, and no flooding), and the results of quantitative precipitation forecasts are combined for rapid comparison of rainfall intensities to estimate the flooding possibility (probability) of Taiwan metropolitan areas under the forecasted rainfall of a typhoon. Finally, the estimated results (timing and probability of flooding) are displayed using the Google Earth display interface as a reference for flooding warnings. Figure 1 shows the procedures of this study.

The detailed steps and methods of this study are as follows:

1. Collection of Information Regarding the Rainfall Intensity of Storm Water Sewer Systems

Storm water sewers have a certain protection standard. However, as land use increases because of urbanization, the runoff flows are enlarged and the concentration time is decreased in metropolitan areas. The existing storm water sewers cannot process torrential rains within a short period, resulting in overflows from manhole covers and flooding in metropolitan areas. Therefore, this study adopts a more direct approach and compares the standard rainfall intensity designs of the storm water sewer system in various metropolitan areas and the rainfall forecast

information to determine flooding probabilities.

This study compiles the latest information of storm water sewer systems and the formula of the rainfall intensities of 314 villages and townships in Taiwan provided by the Construction and Planning Agency, Ministry of the Interior. Table 1 shows the formulae for the storm water sewers and rainfall intensities of each village and township in Yilan County. Figure 2 shows the rainfall intensity duration curve of Taipei City, Keelung City, and Tainan City. Furthermore, because of the short concentration time of storm water sewer systems in metropolitan areas, this study focuses on short rainfall durations, using rainfall intensities of 1- and 2-h rainfall durations as the references for estimating flood probabilities.

Figure 2. The rainfall intensity duration curves of Taipei City, Keelung City, and Tainan City.

Table 1. Archive of the storm water sewer capacities for rainfall intensity of each city and township in Yilan County.

Yilan County									
Serial number	City and township	Proposal or project titles	Frequency and rainfall patterns	Formulas	Depth of various rainfall durations (mm)				Remarks
					30 min	60 min	90 min	120 min	
1	Yilan City	Storm water sewer system proposal of Yilan County Government	Rainstorm ntensity formula of once every (5) year is adopted for the pipe system design	$i = \frac{815.8}{(t + 18)^{0.56006}}$	46.66	71.10	88.89	103.32	Established by the Construction and Planning Agency, Ministry of the Interior in October, 2002
2	Zhuangwei Township	Storm water sewer system proposal of Zhuangwei Township, Yilan County	Rainstorm ntensity formula of once every (2) year is adopted for the pipe system design	$i = \frac{280}{t^{0.3838}}$	37.95	58.17	74.79	89.16	Established by the Bureau of Housing and Urban Development, Taiwan Provinceial Government in March, 1980
3	Yuanshan Township	Storm water sewer system proposal of Yuanshan Township, Yilan County (urban planning of Yuanshan Township)	Rainstorm ntensity formula of once every (5) year is adopted for the pipe system design	$i = \frac{846.275}{(t + 23.738)^{0.5595}}$	45.55	71.10	89.85	105.00	Established by Yilan County Government in May, 2009
4	Toucheng Towhship	Storm water sewer system proposal of Toucheng Township, Yilan County	Rainstorm ntensity formula of once every (2) year is adopted for the pipe system design	$i = \frac{280}{t^{0.3838}}$	37.95	58.17	74.69	89.16	Established by the Bureau of Housing and Urban Development, Taiwan Provinceial Government in February, 1980
5	Jiaoxi Towhship	Storm water sewer system proposal of Jiaoxi Township, Yilan County (Sicheng area)	Rainstorm ntensity formula of once every (2) year is adopted for the pipe system design	$i = \frac{280}{t^{0.3838}}$	37.95	58.17	74.69	89.16	Established by the Bureau of Housing and Urban Development, Taiwan Provinceial Government in August, 1991
6	Luodong Township	Storm water sewer system proposal (review) of Luodong Township, Yilan County	Rainstorm ntensity formula of once every (3) year is adopted for the pipe system design	$i = \frac{841.977}{(t + 17.5)^{0.6033}}$	41.00	61.02	75.12	86.36	Established by the Construction and Planning Agency, Ministry of the Interior in August, 2004

2. Establishing Flood Probability Categories

Storm water sewer systems may be affected by factors such as blockages, damage, or inappropriate management of manhole pipelines, reducing their tolerance to the standard rainfall intensity. Therefore, flooding predictions that resemble actual conditions more accurately can be achieved by multiplying the designed standard values with different coefficients to determine the flooding probability; this value is subsequently compared with the forecasted rainfall values.

This study formulates the following four categories of flooding probabilities:

- (1) No flooding: lower than 55 % of the designed standard value.
- (2) Low probability: between 55 % and 85 % of the designed standard value.
- (3) Medium probability: between 85 % and 115 % of the designed standard value.
- (4) High probability: greater than 115 % of the designed standard value.

This study compares the rainfall intensity warning values with the rainfall warning values issued by the Water Resources Agency to determine whether the 55 %, 85 %, and 115 % standards are reasonable. The rainfall warning values issued by the Water Resources Agency were established according to the rainfall records of

Figure 3. A comparison of the rainfall warning values determined by this study with the experience data value build by Water Resources Agency.

Figure 4. The layers of 314 cities and townships in Taiwan.

locations that flooded during previous typhoons and torrential rain. Thus, the flooding probability for 421 cities, villages, and townships can be evaluated. This study selects 43 warning values to calculate the probability of the rainfall warning values estimated by the system falling into wrong flooding probabilities indicated by the Water Resources Agency's system (Figure 3). The calculation results show that the chances for wrong estimation rates the highest is the *low probability* category, indicating that the flooding estimations of the system developed in this study are more conservative compared to the experience values build up by Water Resources Agency. Regarding the probability of *no flooding* in Figure 3, it is the probability of the no flooding estimated result which on the contrary did flood according to the Water Resources Agency's system; the lower this *no flooding* probability the better.

Comparative analysis proves that the three coefficients proposed by this study conform to the rainfall warning values of actual conditions.

3. Editing Layers of Metropolitan Areas and Establishing a Database

ArcGIS [8] is used to edit 314 layers of metropolitan areas for subsequent display on a WEB GIS interface. Figure 4 shows the layers of 314 cities and townships in Taiwan. Additionally, we established an associative database, including the inquiry and development of multi-language corresponding encodings and a high, medium, and low flooding probability database. In summary, this study used three coefficients, 314 villages and townships, and two durations, comprising a total of 1,884 pieces of data ($3 \times 2 \times 314 = 1884$).

4. Establishment of Methods for Estimating Flooding Probabilities

The following estimation procedures were established according to the study procedure 2, with rainfall intensities of 1- and 2-h durations:

(1) First, the estimation of 1-h duration is conducted.

$$\begin{aligned} &\text{If } R_{i,t}^{\text{Prediction}} > 1.15R_{i,d=1}^{\text{Design}}, \\ &\quad E_{i,t}^{d=2} = \text{High}. \\ &\text{If } 0.85R_{i,d=1}^{\text{Design}} < R_{i,t}^{\text{Prediction}} < 1.15R_{i,d=1}^{\text{Design}}, \\ &\quad E_{i,t}^{d=2} = \text{Medium}. \\ &\text{If } 0.55R_{i,d=1}^{\text{Design}} < R_{i,t}^{\text{Prediction}} < 0.85R_{i,d=1}^{\text{Design}}, \\ &\quad E_{i,t}^{d=2} = \text{Low}. \\ &\text{If } R_{i,t}^{\text{Prediction}} < 0.55R_{i,d=1}^{\text{Design}}, \\ &\quad E_{i,t}^{d=2} = \text{None}. \end{aligned}$$

Wherein i represents each city and township, t represents the time of the present estimation, d represents the duration, $R_{i,t}^{\text{Prediction}}$ represents the quantitative precipitation forecast of a city or township i at time t , $R_{i,d=1}^{\text{Design}}$ represents the rainfall intensity of a city or township i under 1-h duration, and $E_{i,t}^{d=1}$ represents the estimated flooding probability of a city or township i under a 1-h duration at time t .

(2) Subsequently, the estimation of 2-h duration is conducted.

For the estimation of 2-h duration, the rainfall values at time t and at the previous time, $t-1$, must be added together and divided by 2 to obtain the rainfall intensity of 2-h duration.

$$\begin{aligned} &\text{If } 0.5(R_{i,t-1}^{\text{Prediction}} + R_{i,t}^{\text{Prediction}}) > 1.15R_{i,d=2}^{\text{Design}}, \\ &\quad E_{i,t}^{d=2} = \text{High}. \\ &\text{If } 0.85R_{i,d=2}^{\text{Design}} < 0.5(R_{i,t-1}^{\text{Prediction}} + R_{i,t}^{\text{Prediction}}) < 1.15R_{i,d=2}^{\text{Design}}, \\ &\quad E_{i,t}^{d=2} = \text{Medium}. \\ &\text{If } 0.55R_{i,d=2}^{\text{Design}} < 0.5(R_{i,t-1}^{\text{Prediction}} + R_{i,t}^{\text{Prediction}}) < 0.85R_{i,d=2}^{\text{Design}}, \\ &\quad E_{i,t}^{d=2} = \text{Low}. \\ &\text{If } 0.5(R_{i,t-1}^{\text{Prediction}} + R_{i,t}^{\text{Prediction}}) < 0.55R_{i,d=2}^{\text{Design}}, \\ &\quad E_{i,t}^{d=2} = \text{None}. \end{aligned}$$

Within the formula, $R_{i,d=2}^{\text{Design}}$ represents the designed rainfall intensity in city or township i under a 2-h duration, and $E_{i,t}^{d=2}$ represents the estimated flooding probability of city or township i under a 2-h duration at time t .

(3) Next, the estimated values of 1-h and 2-h durations are combined.

Select the maximum flooding probability of $E_{i,t}^{d=2}$ and $E_{i,t}^{d=1}$, and treat the value as the final estimation $E_{i,t} = \max(E_{i,t}^{d=1}, E_{i,t}^{d=2})$ at time t .

Figure 5. (a) An overlaid image of the quantitative precipitation point output of each city and township. (b) Image of the Thiessen method-controlled area of each point rainfall.

5. Converged Quantitative Precipitation Forecast Results

The flood estimation system required rainfall information as an index for determining flooding probabilities. We used the research results of the Taiwan Typhoon and Flood Research Institute, the typhoon quantitative precipitation value simulation model and the forecasting experimental platform, as the rainfall information in this study. Academia (including 10 professors from National Taiwan University, National Central University, Chinese Culture University, and National Taiwan Normal University), the Central Weather Bureau, and the National Science and Technology Center for Disaster Reduction were invited to participate in conducting quantitative typhoon rainfall value model ensemble forecasting experiments starting from July 2010. The forecasting experimental results were provided in real-time to the Central Weather Bureau, the Water Resources Agency, and the National Science and Technology Center for Disaster Reduction to analyze disaster warnings.

Because the rainfall output coordinates of the platform are latitude and longitude coordinates and cannot directly overlay the second sub-bands of the city and township layers, the coordinates of the rainfall grid of the quantitative rainfall outputs are transformed before overlaying the city and township layers, as shown in Figure 5(a). To determine the average rainfall of each

city and township, this study uses the Thiessen method to calculate the weighting ratio of point rainfall in each city and township (Figure 5(b)) and derive the rainfall output weighting table of each city and township. Thereafter, the system can calculate the average rainfall of each city and township directly from the weighting table without going through the overlay.

6. Establishment of an Integrated System

To complete the spatial display of hydrometeor data, the county-city boundaries of the entire island of Taiwan are extracted for transformation into KML format. Furthermore, the time series data of the quantitative precipitation forecast is estimated for rainfall flooding in metropolitan areas and transformed into a three-dimensional KML format.

Data is integrated with dynamic processing. When users employ the inquiry system dynamic integration is combined with a database using webpage application programs to write time series information in KML; this

data is saved in the users' personal files on the server. In summary, establishing the integrated system involves the following three steps: data input to provide hydrological data (as shown in Figure 6, which is a schematic diagram showing the transformation of rainfall and flooding data in metropolitan areas into KML with time series), transform GIS boundaries, and display data using webpage application programs.

Additionally, this study uses three-tier architecture (Figure 7). Each function is logically dissected into the presentation tier, the business tier, and the integration tier. Each tier is assigned with specific tasks and cooperates with each other in diverse manners; therefore, if a novel technology or better method becomes available, the existing elements can be replaced without affecting the functions and architecture. Struts technology under a Java EE Web framework is used within the Model-View Controller (MVC) concept. The data content used by each tier is shown in Figure 8.

Figure 6. Transformation of rainfall and flooding data in metropolitan areas into KML with time series.

Figure 7. Image of the three-tier architecture.

Figure 8. Image of Struts architecture.

Figure 9. The displayed frame arrangement of the rapid flood estimation system.

7. Release of Flooding Estimations

This study forecasts 4 times per day and each forecast estimates the flooding probability of the next 1 to 6 h. The greatest flooding probability and the time within the next 1 to 6 h when this flooding is initially estimated to occur is selected and displayed as the estimation outcome. The estimation (the maximum flooding probability and the timing of this flooding) is displayed as the final result and used as a reference for subsequent flooding studies.

Figure 9 shows the outcome of the system display. The left side of the figure shows the search condition input block, which is divided into the entire island of Taiwan, the Northern region, the Northeast region, the Central region, and the Southern region. The right side of the figure shows the WEB GIS interface; its main function is to display the outcome of flooding estimation. The flooding estimation of each metropolitan area is expressed using color mapping.

Figure 10. A rapid flood estimation for Typhoon Kalmaegi.

Results and Discussion

This study combines the quantitative precipitation forecast results to conduct real-time flood estimation. To verify the accuracy of this system, we conducted flood estimations and analysis using data of Typhoon Kalmaegi. According to the "on-site survey of the disaster conditions caused by Typhoon Kalmaegi and Typhoon Phoenix" [9] conducted by the National Science and Technology Center for Disaster Reduction in September 2008, the torrential rain brought by Typhoon Kalmaegi caused severe flooding in metropolitan areas in Taichung. The flooding occurred because the actual rainfall significantly exceeded the designed capacity standard of the storm water sewers in Taichung City. The recorded rainfall at the Dakeng precipitation station for 1-h duration was 146.5 mm. However, the storm water sewer system of Taichung City adopted the 5 to 120 min maximum rainfall data from between 1944 and 1965; the data was calculated using the Talbot formula and set the 5-y frequency of torrential rains as the standard for torrential rain drainage. The rainfall of 1-h rainfall duration with a 5-y recurrence interval was 73.03 mm, which is significant less than the actual rainfall; thus, severe flooding resulted.

Figure 10 shows a rainfall hyetograph of Typhoon Kalmaegi at the Dakeng precipitation station in the Beitun District of Taichung City. The designed standard of the storm water sewers in Taichung City is 73.03 mm/hr. We multiplied this designed standard by 55 %, 85 %, and 115 %, and displayed the results in Figure 10 for a comparison with the actual rainfall amount. The results

indicate that the actual rainfall at 5 p.m. on July 18, 2008, was between 55 % and 85 %, thus, the system estimated the probability of flooding was low. The actual rainfall was far greater than 115 % at the fourteenth measurement, thus, the system estimated that the probability of flooding was high.

Conclusion

This study combined quantitative precipitation forecasting to establish a rapid, stable, and real-time automatic metropolitan area flood estimation system to provide references for flood warnings and decisions, thereby reducing the losses caused by flooding. This system considers the 314 Taiwan metropolitan areas that have storm water sewers and implements rapid flood estimations of four flood risks (high, medium, and low flood probability, and no flood) through the established database, data processing, and interface display. Finally, we verified the flood timing and the maximum flood probability estimated by the flood estimation system developed in this study using data of Typhoon Kalmaegi, and determined that the results were consistent with the survey data.

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