RADAR RAINFALL MAPPING AND HYDROLOGIC MODELING FOR FLOOD INUNDATION IN LINBAIN RIVER BASIN, TAIWAN

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ABSTRACT

Recently, radar rainfall data have emerged as an alternative to in situ observations due to their availability over vast ungauged regions. The focus of this study is to integrate the available radar products within a distributed hydrologic model to characterize the spatial extent of flooding. We present a methodology based entirely on radar rainfall data to set up and calibrate a hydrologic model, simulate the spatial extent of flooding.

This study used a two-dimensional hydrologic model for the simulation of extreme flood events that occurred in the Linbain River watershed during Typhoon Morakt, 2009. The analysis showed the value of integrating radar precipitation data along with space-based flood inundation extents as inputs to the distributed hydrologic model. Results show that the quantification of flooding spatial extent with radar data can help to calibrate and evaluate hydrologic models and, hence, potentially improve flood inundation prediction and flood management strategies in the catchments.

1. INTRODUCTION

Flood damage in the world has dramatically increased since intensity and frequency of local heavy rainfall as well as scale and magnitude of typhoon tend to increase. Floods are the frequently occurring natural disasters in Taiwan. On average, three to four typhoons attack the island each year. In Taiwan, serious disasters such as flooding, landslide or debris flow brought by typhoon rainfall often cause life loss and major economic impacts. To mitigate disasters due to typhoons, various kinds of disaster warning systems are developed. During typhoons, rainfall forecasting plays the most essential role in disaster warning systems. Subsequently, more accurate and reliable forecasts of rainfall are required as an important reference for runoff forecasting to mitigate flood damages.

Accurate prediction of the flood inundation area and dissemination of information on the inundation areas to emergency managers and urban planners is necessary to accomplish this prevention or reduction of losses (Merwade et al., 2008). Typhoon Morakot struck Taiwan during 7–9 August 2009 and caused record−breaking rainfall in Southern Taiwan. The extreme amount of rainfall triggered severe flooding throughout southern Taiwan. Consequently, Typhoon Morakot led to the worst flooding in the last 50 years in Taiwan. We present a methodology based entirely on radar rainfall data to set up and calibrate a hydrologic model, simulate the spatial extent of flooding.

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2. STUDY AREA & TYPHOON MORAKOT

The Linbain River watershed located in Pingtung County of the southwestern Taiwan is 336.30 km^2, and the length of the main stream is 42km. To highlight the spatial resolution of radar QPE (quantitative precipitation estimation), the south flood plain of the Linbain River is selected as the study area in Fig. 1. Due to two levee breaks during Typhoon Morakot, the study area suffered the most serious flood in past 50 years, and the recovery procedure took over years. Finally, Typhoon Morakot is also selected as the study case to evaluate the qualities of various radar QPEs for inundation model due to the record-breaking rainfall, 2,884 mm in 100 hours as shown in Fig. 1, causing the most serious landslide that buried the entire town of Xiaolin.

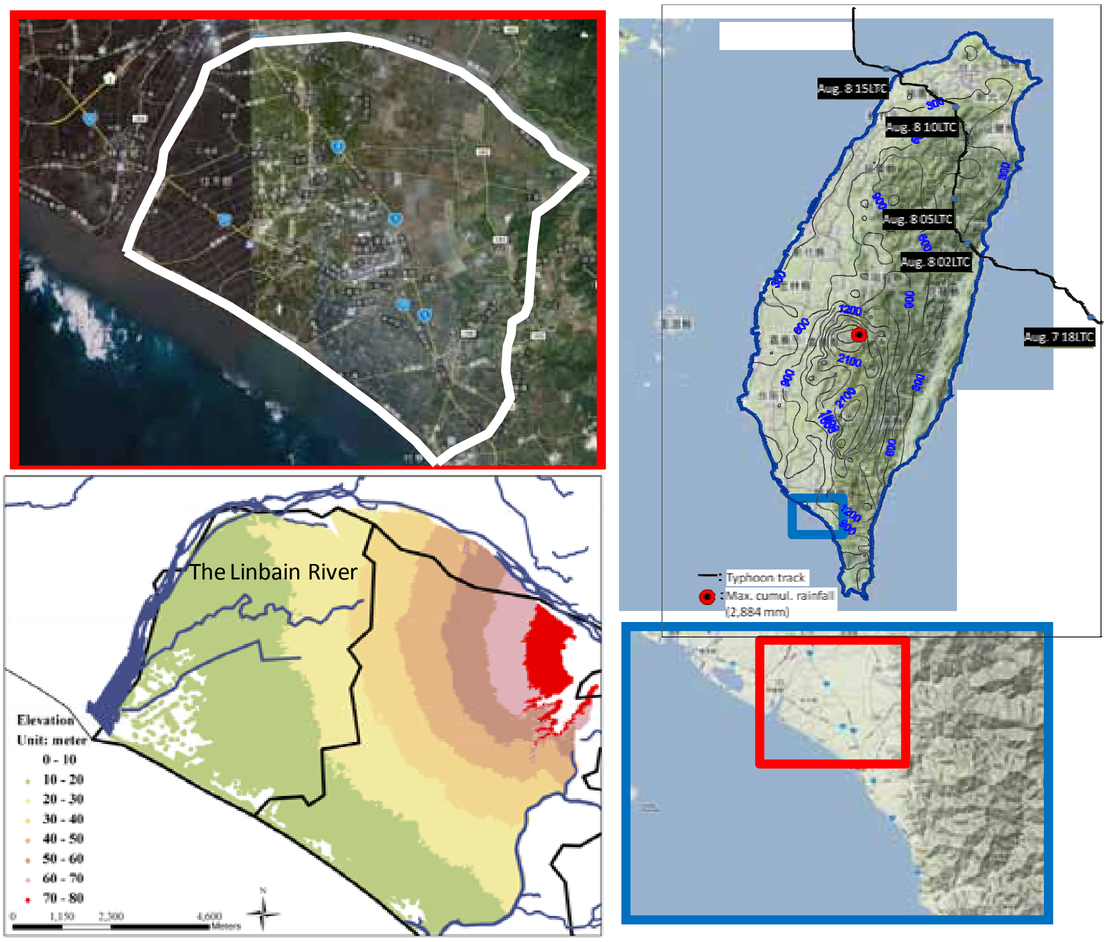


Fig. 1 The study area of the Linbain River Watershed, and the track and the cumulative rainfall of Typhoon Morakot from August 5 to 10 in 2009.

3. METHOD

The methodology consists of three major steps as shown in the study flowchart of Fig. 2. First, the data of DEM and land use information were collected for setting up the 2D overland-flow model of study area. The flood survey data were used for calibration and validation of the inundation model based on the observed radar QPE. After model calibration and validation, the grid-based distributed inundation model was implemented to generate the inundation potential map based on the observed rainfall of Typhoon Morakot in the study area. Finally, the time to maximum depth and maximum depth were determined within the watershed for flood management.

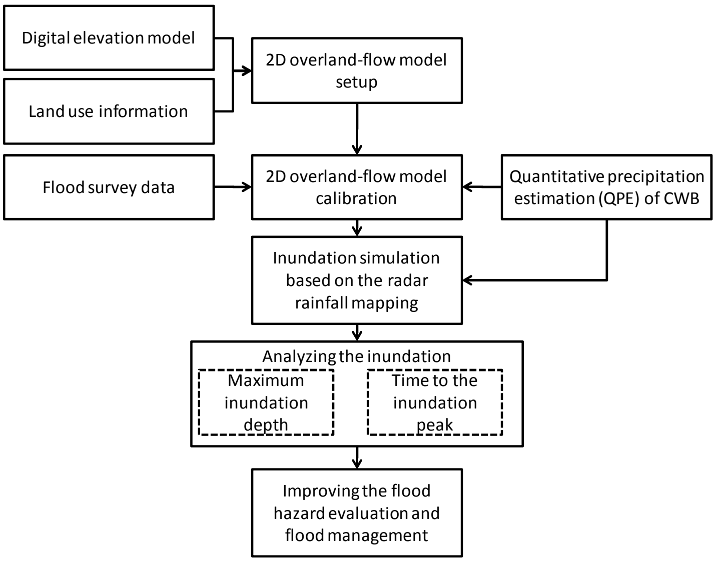


Fig. 2 Flowchart of the study.

3.1 Radar QPE

The CWB has collaborated with the US National Oceanic and Atmospheric Agency's National Severe Storms Laboratory to deploy the QPE system (Chang et al., 2008). The radar system contains four radars that cover Taiwan and its surrounding area completely. The system provides the spatial distribution of rainfall by integrating with the software named Quantitative Precipitation Estimation and Segregation Using Multiple Sensors (QPESUMS). The QPESUMS uses the Mosaic Hybrid Scan Reflectivity (Zhang et al. 2005), and the reflectivity–rainfall (Z–R) relationship equation (Xin et al. 1997, Chen et al., 2011) to estimate the precipitation. It records base reflectivity with a spatial resolution of 0·0125° (~1·25 km) in both longitude and latitude and a temporal resolution of 10 minutes. The CWB provided radar base reflectivity data for 7–9 August 2009, corresponding to the event of Typhoon Morakot, for the study area (Fig. 1).

3.2 Two-dimensional overland-flow model

The numerical simulation of free surface flows that alternately flood and dry out over complex topography is a difficult task. In order to describe this kind of phenomenon, the model equation set generally is the two-dimensional (2D) shallow water equations. It is used for the analysis of distributed surface with adverse slopes and irregular geometry in floodplain. For flows caused by a dam-break, since the local accelerations are large while a majority of dams are built on sloping slides usually followed by valleys with a complex topography. A simplified form usually neglecting the inertial terms but considers the backwater effect, is physically applicable to simulate regional overland flow in rural areas. It is determined by the topography, land cover and soil type generally can be appropriately described by the two-dimensional (2D) diffusive overland-flow model based on non-inertia surface flow dynamics in rural areas (Wasantha Lal 1998; Hsu *et al.* 2000). The non-inertia wave (diffusion wave) model was first proposed by Cunge *et al.* (1980), and similar approaches have been developed and applied by many researchers (Vongvisessomjai *et al.* 1985; Bates *et al.* 2003). The flood inundation situations are strongly related to the basic data of ground elevation changes and the flood propagation is also impeded by the obstruction existing on the land surface such as the buildings, vegetations, soil types, etc (Hsu *et al.* 2002; Yu and Lane 2006). Hsu *et al.* (1990) and Wasantha Lal (1998) compared the performance of various numerical schemes on the 2D non-inertia wave equations. In the present study, a 2D diffusive-wave model, namely the 2D overland-flow model, with the alternating direction explicit (ADE) scheme is adopted for flood inundation simulation.

3.2.1 Basic equations

As the floods overflow the rural areas of wide plain, the acceleration term of water flow on the ground surface is small compared to gravitational and frictional terms, so the inertial terms in the motion equations are neglected. It is found that the non-inertia flow is suitable for modeling of slowly evolving flow conditions. The depth-averaged shallow water equations on ground surface can be written as:

$$\frac{\partial d}{\partial t}+\frac{\partial(ud)}{\partial x}+\frac{\partial(vd)}{\partial y}=q \tag{1}$$

$$-\frac{\partial(d+z)}{\partial x}=u\left[\frac{n^2|u|}{d^{4/3}}+\frac{q}{d\cdot g}\right] \tag{2}$$

$$-\frac{\partial(d+z)}{\partial y}=v\left[\frac{n^2|v|}{d^{4/3}}+\frac{q}{d\cdot g}\right] \tag{3}$$

where d is the depth of flow (m), u is the velocity component in x-direction (m s^{-1}), v is the velocity component in y-direction (m s^{-1}), t is the time (second), q is the rainfall intensity or pumping capacity per unit area (m^3 s^{-1} m^{-1}), z is the ground elevation (m), n is Manning's roughness, and g is the gravitational acceleration (m s^{-2}), $S_{fx}=\frac{n^2u|u|}{d^{4/3}}$ is friction slope in x direction, $S_{fy}=\frac{n^2v|v|}{d^{4/3}}$ is friction slope in y direction.

3.2.2 Boundary conditions

In the simulation domain, boundary conditions consist of the radar QPE of Typhoon Morakot event in each mesh node. Along the levees and the ground elevation contour lines of 50 m are defined as the close boundaries. This assumes that the simulation domain is protected by a levee that is designed to protect 100-year flood and high enough to prevent river water flowing over the top of the levee. On the boundaries along the levee, the lateral inflow normal to the close boundary is set to be zero. Due to the lack of levees along these small river channels, the small river channels are included in the model domain for flood simulation.

4. RESULTS

Fig. 3 shows the cumulative rainfall of typhoon Morakot. The cumulative downpour during Typhoon Morakot was very close to the World Record for 1, 12, 24, 48, and 72 hrs cumulative rainfall amounts. The typhoon track in Fig. 1 shows that the southwestern Taiwan suffered the southwestern rain band of the typhoon after the typhoon center past the Central Mountain Range. Furthermore, a strong southwestern monsoon was induced by Typhoon Morakot. Therefore, the cumulative rainfall was very close to the World Record in Fig. 3. Fig 4 shows the spatial cumulative rainfall maps (6 hr, 12hr, 24hr and 48hr accumulated) from 08/ 07: 08AM. The maps show that the cumulative rainfalls in the upstream of Linbain River watershed are larger than that in the downstream. Record rainfall caused Linbain River to flood. Fig 5 shows the maximum inundation map associated with rainfall aggregation map at a resolution of 1 km. The serious inundation across the watershed is above three meters at the southern of study area near the seashore where is the lowland area with high potential inundation. Furthermore, through comparing the image of study area in Fig. 1 and the maximum inundation map of Fig. 5, some inundations were induced by the foundation of highway. Generally speaking, the spatial characteristics of inundation in study area are consistent to the terrain as shown in Fig 1. The elevation of study area decreases from northeastern to southwestern. The trend of elevation causes the lowest area near the seashore suffering the most serious flood. Fig 6 shows the event time with the maximum inundation depth. During the heavy rainfalls, the maximum inundation happens at 30~40 hours after 08/ 07: 08AM. Furthermore, the lowland area drains water hardly without any pumping station. The inundation depth increased until the end of event. Therefore, the time to the maximum inundation depth is often detected at 30~40 hours.

In this study, the model provides a quantitative insight into the spatial distributions of inundation depth and time that will be useful for refining rescue plans and developing hazard management scenarios.

5. CONCLUSION

The QPESUMS (Quantitative Precipitation Estimation and Segregation Using Multiple Sensors) was acquired to retrieve spatial rainfall data during the rainfall period from August 7 to 9 in 2009 when Typhoon Morakot struck Taiwan. The retrieved data were used for setting up the flood inundation model. The rainfall monitoring algorithm based on QPESUMS provides more detailed information than the limited number of ground-based rainfall stations for interpreting the spatial distributions of rainfall events, and therefore is more suitable for hydrologic modelling.

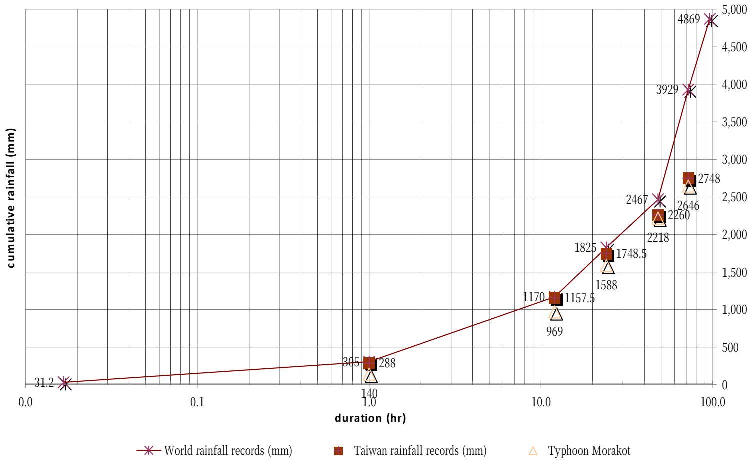
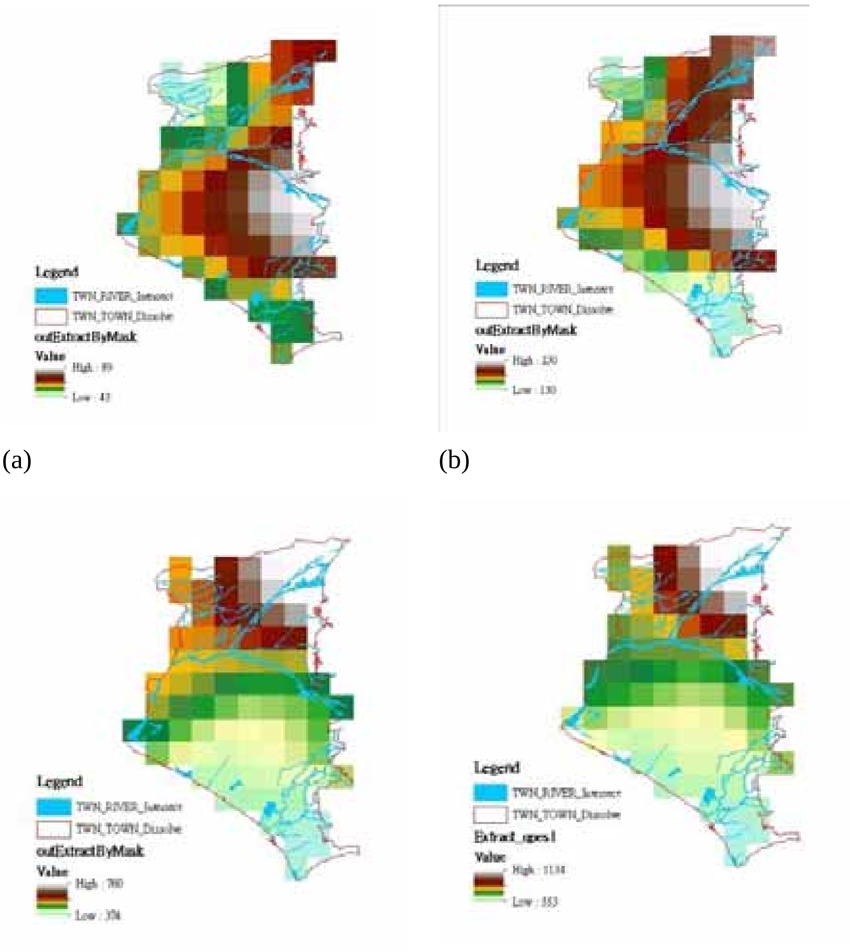


Fig 3. Cumulative rainfall (mm) during Typhoon Morakot compared to world record (Lin et al., 2011).



(a) (b)

(c) (d)

Fig 4. Spatial cumulative (a) 6hr, (b) 12hr, (c) 24hr and (d) 48hr radar-based rainfalls.

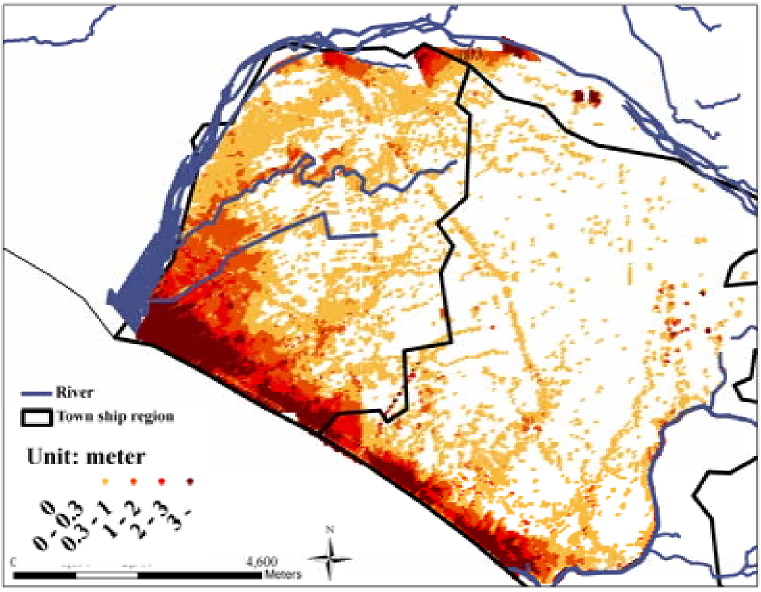


Fig 5. Maximum inundation depth (m)

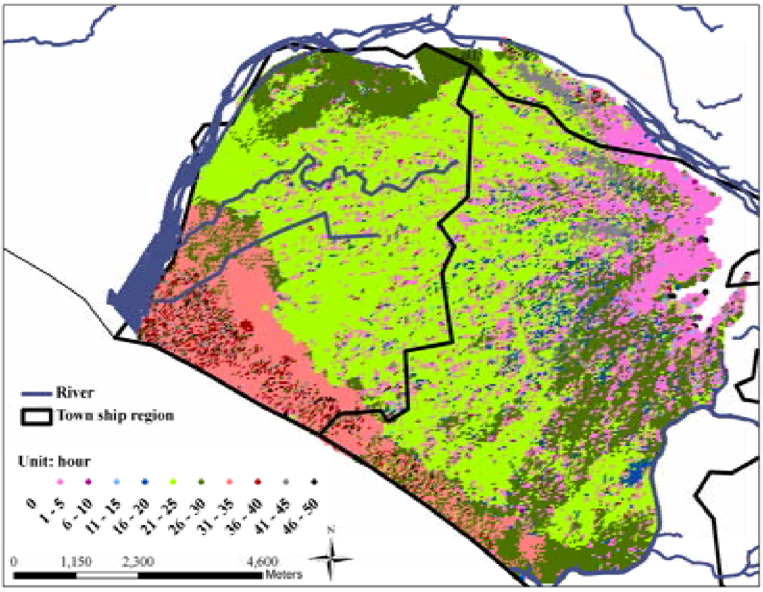


Fig 6. Event time to the maximum inundation depth (hr)

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