Flood Scenario Simulation and Disaster Estimation of Ba-Ma Creek Watershed in Nantou County, Taiwan

S H Peng¹ and Y K Hsu¹

¹ Department of Spatial Design, Chienkuo Technology University, Changhua City, Taiwan, R.O.C.
E-mail: librakyo@cc.ctu.edu.tw

Abstract. The present study proposed several scenario simulations of flood disaster according to the historical flood event and planning requirement in Ba-Ma Creek Watershed located in Nantou County, Taiwan. The simulations were made using the FLO-2D model, a numerical model which can compute the velocity and depth of flood on a two-dimensional terrain. Meanwhile, the calculated data were utilized to estimate the possible damage incurred by the flood disaster. The results thus obtained can serve as references for disaster prevention. Moreover, the simulated results could be employed for flood disaster estimation using the method suggested by the Water Resources Agency of Taiwan. Finally, the conclusions and perspectives are presented.

1. Introduction

In recent years, increasing and frequent hazards caused by typhoons and heavy rainfalls in Taiwan have resulted in huge damages and financial loss. Local drainage in urban and rural regions plays an important role in flood control [1]. For this reason, the project known as “Outline of Flood Control in Potential Flood Districts” has been implemented in Taiwan. The aim of the project is to decrease the inundation disasters caused by typhoons and torrential rainfalls in regions located in proximity to minor streams or local drainage. After the Chi-Chi earthquake in 1999, the large amount of loose debris has resulted in floods or landslides under heavy rainfall in Nantou County, Taiwan. In 2001, the heavy downpour brought by Typhoon Toraji triggered the overflow of embankment in Ba-Ma Creek, causing the serious disasters in many villages. According to the local residents, Typhoons Herb, Toraji and Mindulle had flooded a total area of about 36 hectares. Hence, estimation of flooding range or damage using numerical models of flood inundation has become very important. The models of flood inundation have different theoretical background and assumptions. One-dimensional steady flow [1] or unsteady flow [2] model is relatively simple, less initial conditions and calculation time. Two-dimensional model [3, 4] can simulate the movement of flood inundation zone, but the calculation requires more information to construct the computed domain, and longer computer algorithm time to analyze simulation in flooded terrain. Besides, many previous studies [5-7] also provided very valuable reference. This study simulated several scenarios of flood inundation using the FLO-2D model [8]. With the simulated results, flood damages of various return periods were estimated, which could serve as references for planning flood control strategy.
2. Materials and methods

2.1. Site description

The main region of Ba-Ma Creek Watershed, with an area of 709.1 ha, is located in Shui-Li Township, Nantou County, Taiwan. The main stream and two branches are 6.475 km, 1.11 km and 1.878 km long, respectively. Manning’s roughness coefficient for scenario simulation was obtained by investigation of riverbed particle size [9]. A 10-year or 25-year flood frequency was adopted as the criterion for peak flow calculation in order to plan or design the capacity of channels. The current design standard is a 10-year return period including an extra height of 0.5 m over the bank, and the water level should not overflow the levees for a 25-year return period flood at the same time.

Many typhoon and storm events occurred during 1957 to 2015 were used in the hydrological analysis. The peak flow discharges for various return periods at different hydrological stations were also calculated based on the design storm for 1-day using the rational method, triangle unit hydrograph method and instantaneous unit hydrograph, respectively [10]. Finally, the peak flow discharges estimated by the triangle unit hydrograph method for 2-, 5-, 10-, 25- and 50-yr return periods are suggested to be the discharges for simulations.

2.2. Numerical model

Hydraulic computations involving 1D and 2D modeling were also carried out. In 1D simulation, the Hydraulic Engineering Center: River Analysis System (HEC-RAS) model was employed to compute the flood level. The results thus obtained can assist in planning the locations and heights of levees and checking the stream cross-sectional area of existing structures such as bridges and culverts. 2D simulations were also calculated using the FLO-2D model, a two-dimensional flood routing model used by engineers and floodplain managers to predict flood hazards, and flood damages can be evaluated from the simulation results [11]. The general constitutive fluid equations including the continuity equation and the equation of motion (dynamic wave momentum equation) [3] are

\[ \frac{\partial h}{\partial t} + \left( \frac{\partial (hu)}{\partial x} + \frac{\partial (hv)}{\partial y} \right) = i \]  

(1)

\[ S_{fx} = S_{ux} - \frac{\partial h}{\partial x} - \frac{\partial u}{g \partial t} - u \frac{\partial u}{g \partial x} - v \frac{\partial u}{g \partial y} \]  

(2)

\[ S_{fy} = S_{uy} - \frac{\partial h}{\partial y} - \frac{\partial v}{g \partial t} - u \frac{\partial v}{g \partial x} - v \frac{\partial v}{g \partial y} \]  

(3)

where \( h \) is the flow depth (m); \( u, v \) are the depth-averaged velocities in the \( x \)- and \( y \)-axis directions (m/s); \( i \) is the excess rainfall intensity (mm/hr); \( S_{fx}, S_{fy} \) are the friction slope components according to Manning’s equation of the \( x \)- and \( y \)-axis directions; \( S_{bx}, S_{by} \) are the bed slopes of the \( x \)- and \( y \)-axis directions; and \( g \) is acceleration of gravity (m/s\(^2\)).

3. Results

3.1. Scenario simulation

To compare the simulated and real flood inundations, rainfall data of Typhoon Toraji in 2001 were employed to compute the flood depths using the FLO-2D model. Meanwhile, site visits were made to understand the flood range caused by Typhoon Toraji and to survey the flood mark for describing the inundated regions, which covered approximately 39.2 ha. The maximum depth was around 3 m along the bank of the main stream near the National Shui-Li Vocational High School of Industry and Commerce. In this scenario simulation, the numerical result indicated that the main flood area was about 19.2 ha and the maximum depth along the main stream bank near the school was approximately 4 m (see figure 1 and table 1).
Figure 1. Comparison of simulated and investigated flood regions.

Table 1. Areas and depths of scenario simulation of Typhoon Toraji

| Average depth (m) | Maximum depth (m) | Flood area (ha) |
|-------------------|-------------------|-----------------|
|                   |                   | Total flood area (ha) |
|                   |                   | 0.25-1 m | 1-2 m | 2-3 m | >3 m | 0.25-1 m | 1-2 m | 2-3 m | >3 m |
| 1.092             | 4.19              | 31.04     | 8.8   | 6.72  | 0.96  | 47.52           |

3.2. Numerical model
In addition to the scenario simulation of Typhoon Toraji, simulations of 2-, 5-, 10-, 25- and 50-yr return periods were also completed, respectively. With these simulated flood areas and depths, the flood damage could be estimated. First, the flood areas and depths for various land use types were extracted from the simulated results using the GIS software ArcGIS. Then the damage for farms, buildings and other land uses at various depths were estimated using the method suggested by the Water Resources Agency of Taiwan [12]. Due to the lack of statistical data of flood disaster in Ba-Ma Creek Watershed, therefore, this study estimated the flood damage based on the scenario simulation results and economic situations. The annual average flood losses could be considered from agricultural losses, building losses, public facilities and other losses. The direct agricultural losses were estimated by the statistical analysis of farmland flooding depth and crop yield reduction curve. Building losses were estimated in three parts, namely housing, household goods and business units (commercial, factory), and then calculated the total value of flood losses according to the affected area. Public facilities and other losses were presumed to be based on estimates of past flood damage statistics or the rates of loss of public facilities floods and general assets floods. From this analysis (Table 2), the damages of 2-, 5-, 10-, 25- and 50-yr return periods can be realized. The engineers can decide how much should be invested in the engineering works of flood control or environmental construction plans.
4. Conclusions
In this study, flood inundations for various return periods were simulated and damages were estimated using the method suggested by the Water Resources Agency of Taiwan. There is a little difference between the scenario simulation and real situation in the application of numerical model because the assumptions and simulation parameters are moderately simplified. However, these results of the simulation still offer a considerable benefit for the qualitative trend, and more detailed information such as water depth and range. Although these data are for reference only and do not totally represent the actual situations, at least they may provide the quantifiable data to reflect the relative extent of the different conditions to each other. According to the damage analysis, the total preliminary estimated cost for the construction and repair of the hydraulic structures is around NT$ 107,480,000. The implementation of this planning will be helpful for channel stabilization and prevention of flood disaster. Furthermore, the flood control project is also useful for the river restoration or planning of environmental construction if the engineering works are finished.

Table 2. Flood damage estimations for 2-, 5-, 10-, 25- and 50-yr return periods

| Return period (yr) | Depth (m) | Farm land | Building land | Other land | Total damage (NT$ 1,000) |
|--------------------|-----------|-----------|---------------|------------|-------------------------|
|                    |           | Flood area (ha) | Damage (NT$ 1,000) | Flood area (ha) | Damage (NT$ 1,000) | Flood area (ha) | Damage (NT$ 1,000) |            |
| 2                  | 0.25-1    | 8.09 | 469.2 | 1.35 | 3,375.0 | 4.89 | 283.6 |
|                    | 1-2       | 5.73 | 630.3 | 0.67 | 3,350.0 | 0.34 | 54.4 |
|                    | 2-3       | 0.51 | 76.6 | 0.00 | 0.00 | 0.17 | 81.6 |
|                    | >3        | 0.17 | 34.0 | 0.00 | 0.00 | 0.17 | 244.8 |
| 5                  | 0.25-1    | 9.77 | 566.7 | 1.69 | 4,225.0 | 6.07 | 352.1 |
|                    | 1-2       | 7.92 | 871.2 | 0.67 | 3,350.0 | 0.51 | 81.6 |
|                    | 2-3       | 1.35 | 202.5 | 0.00 | 0.00 | 0.17 | 81.6 |
|                    | >3        | 0.67 | 134.0 | 0.00 | 0.00 | 0.17 | 244.8 |
| 10                 | 0.25-1    | 11.63 | 674.5 | 1.52 | 3,800.0 | 6.57 | 381.1 |
|                    | 1-2       | 6.40 | 704.0 | 0.84 | 4,200.0 | 0.84 | 134.4 |
|                    | 2-3       | 4.21 | 631.5 | 0.00 | 0.00 | 0.17 | 81.6 |
|                    | >3        | 0.67 | 134.0 | 0.00 | 0.00 | 0.17 | 244.8 |
| 25                 | 0.25-1    | 13.65 | 791.7 | 1.69 | 4,225.0 | 7.58 | 439.6 |
|                    | 1-2       | 5.22 | 574.2 | 0.84 | 4,200.0 | 0.84 | 134.4 |
|                    | 2-3       | 6.74 | 1,011.0 | 0.00 | 0.00 | 0.00 | 0.0 |
|                    | >3        | 0.67 | 134.0 | 0.00 | 0.00 | 0.34 | 489.6 |
| 50                 | 0.25-1    | 14.49 | 840.4 | 1.69 | 4,225.0 | 7.58 | 439.6 |
|                    | 1-2       | 5.39 | 592.9 | 0.84 | 4,200.0 | 1.35 | 216.0 |
|                    | 2-3       | 7.08 | 1,062.0 | 0.00 | 0.00 | 0.00 | 0.0 |
|                    | >3        | 0.84 | 168.0 | 0.00 | 0.00 | 0.34 | 489.6 |

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