The Impact of Climate Change on Inundation Potential

Ching-Nuo Chen and Chih-Heng Tsai

Abstract—**This study is aimed at using the physiographic inundation model to simulate inundation potential of 24-hour and 48-hour design rainfalls for baseline and climate change scenarios for several return periods and then discuss the impact of climate change on inundation potential. The Typhoon Haitang in 2005 and Typhoon Morakot in 2009 were used to verify the physiographic inundation model by comparing with field investigations. Furthermore, the inundated potential was simulated with the hydrologic conditions for the duration of 24-hour and 48-hour design rainfalls for baseline and climate change scenarios for 25- year, 50- year, 100-year and 200-year return periods. The comparisons reveal that the inundated areas and volumes increase significantly under climate change scenario. Hence, climate change results in more serious flood damages.**

Index Terms—**Climate change, physiographic inundation model, inundation potential, Geographic Information System.**

I. Introduction

Flooding is an inevitable disaster in Taiwan since it lies within the most active zone of tropical-cyclone formation in the Western Pacific. With an average of three to four typhoons per year hitting Taiwan, summer seasons in Taiwan are always marked by high-intensity rainfalls associated with severe damages. To prevent severe storms inducing damages to agriculture and property in the downstream alluvial plains and urban areas, many structural flood-mitigation measures such as dikes and channel improvements had been well implemented over the past decades in Taiwan. However, rapidly economic growth associated with population increase leads to expansion of residential, commercial, and industrial districts. Additionally, extreme rainfall conditions are further deteriorated by the effects of climate change. Raised inundation potential for such changes needs to reevaluate the design criterion of existing flood-mitigation measures for those areas. Thus, a quantitative assessment of inundation potential is not only an essential component in water resources management, but also a primary concern in land development.

The purpose of this study is to develop the physiographic inundation model that is used in conjunction with Geographic Information System (GIS) to evaluate the impact of climate change on inundation potential. The proposed model is applied to simulate the inundation potential for the Tainan City watershed located in southern Taiwan for baseline (1980-1999) and climate change scenarios (A1B, 2020-2039). Four various recurrence intervals including 25-, 50-, 100-, and 200-year of 24-hour and 48-hour design rainfall for baseline and climate change scenarios are used to assess the impact of climate change on inundation potential of the study area.

Manuscript received March 5, 2013; revised May 4, 2013.

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II. Physiographic Inundation Model

The computational cells in accordance with the landscape and drainage network of the watershed are automatically generated in the Physiographic Inundation model. The water flow calculation is based on the continuity equation and discharge theory in each cell. The continuity equation for water flow is given [1].

$$A_{si}\frac{dh_i}{dt} = Pe_i(t) + \Sigma Q_{i,k}(h_i, h_k) \tag{1}$$

where A_{si} = the area in the i -th cell; h_i = water depth in the i -th cell; t = time; $Q_{i,k}$ = the discharge from the k -th cell, which is the adjacent cell of the i -th cell, into the i -th cell; Pe_i = the effective rainfall intensity multiplied by the area of the i -th cell. The discharge $Q_{i,k}$ in (1) is represented by any suitable discharge formula as described below.

A. Channel-Linked Discharge Formula

Flow between cells without obvious obstacles can be treated as an idealized channel flow and the discharge can be calculated using the Manning formula [2]. The discharge can be calculated by following (2) and (3)

$$Q_{i,k} = \frac{h_k - h_i}{|h_k - h_i|}\cdot\Phi(\bar{h}_{i,k})\cdot\sqrt{|h_k - h_i|} \qquad (\text{if } \frac{\partial Q_{i,k}}{\partial h_i} < 0) \tag{2}$$

$$Q_{i,k} = \Phi(\bar{h}_{i,k})\cdot\sqrt{|h_k - h_i|} \qquad (\text{if } \frac{\partial Q_{i,k}}{\partial h_i} > 0) \tag{3}$$

where $\bar{h}_{i,k}$ = the water stage from the k -th to i -th cells, given as:

$$\bar{h}_{i,k} = \alpha h_k + (1-\alpha)h_i \tag{4}$$

where α = a weighting coefficient; Φ = the flow parameter, defined as $\Phi(h) = (1/n)AR^{2/3}/\sqrt{\Delta x}$, Δx = the distance of the center between the k -th and i -th cells; n =the Manning's roughness coefficient of the cell; A = the cross-sectional flow area between the k -th and i -th cells, $A = A(\bar{h}_{i,k})$; R = the hydraulic radius between the k -th and i -th cells, $R = R(\bar{h}_{i,k})$.

B. Weir-Linked Discharge Formula

On the other hand, for the adjacent cells divided by roads or hydraulic structures, the flow over them can be treated as the weir flow. The discharge can be calculated according to (5) and (6).

a. For a free over weir, $(h_i - Z_w) < \frac{2}{3}(h_k - Z_w)$

$$Q_{i,k} = \Phi_f (h_k - Z_w)^{3/2} \quad ; \quad \Phi_f = \mu_1 b\sqrt{2g} \tag{5}$$

b. For a submerged weir, $(h_i - Z_w) \geq \frac{2}{3}(h_k - Z_w)$

$$Q_{i,k} = \Phi_d (h_i - Z_w)(h_k - h_i)^{1/2} \quad ; \quad \Phi_d = \mu_2 b\sqrt{2g} \tag{6}$$

where Z_w = the elevation of the weir crest; b = the effective width of the weir; μ_1 and μ_2 = the weir discharge coefficients (μ_1 = 0.37-0.57 and μ_2 = 2.6 μ_1) [3]. Therefore, the explicit finite-difference representation of (1) can be written as

$$\Delta h_i = \frac{(Pe_i^j + \sum_k Q_{i,k}^j) \cdot \Delta t}{A_{si}^j} \tag{7}$$

where A_{si}^j, Pe_i^j, and $Q_{i,k}^j$ are the area and rainfall intensity of the i-th cell, and the discharge from the k-th cell into the i-th cell at t^j, respectively; Δt is the time step of t^j to t^{j+1}; Δh_i is the i-th cell increment of water stage in a time step.

III. Study Area

Tainan city is used as an illustrative example in this study. There are four major rivers basins in the study area: the Yanshui, Zengwen, Chiangchun, and Jishui river basins. The lengths of the main stream of four major rivers are about 41.3, 138.5, 27.6 and 65 kilometer, respectively; the areas of the river basins are about 343, 1117, 158 and 379 square kilometer, respectively. The study area is about 1997 square kilometer. The study area is shown in Fig. 1.

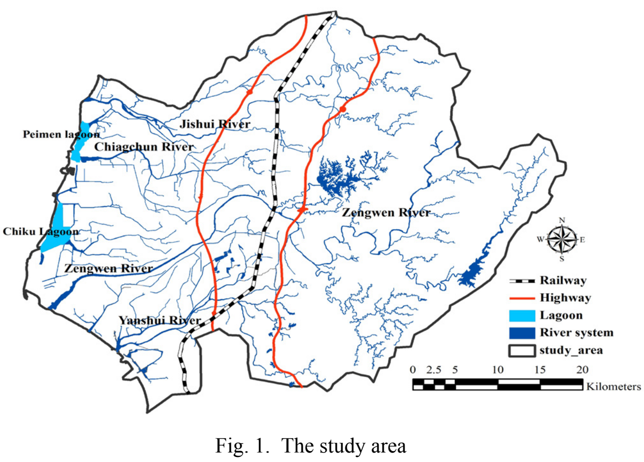


Fig. 1. The study area

ArcGIS™ software - ArcView® and ArcInfo® - are adopted in this study to analyze DEM, slope, and pool of the study site. Information of roads, drainage ditches, and land use is also included in the GIS database [4]. The entire basin was divided into 15410 irregular grids as illustrated in Fig. 2 using automatic modeling-cell-delimitation method by the spatial analyst, hydrologic model, and Object-oriented Programming of ArcView. All attributes of data fields were also calculated to build the necessary database for the Physiographic Inundation model.

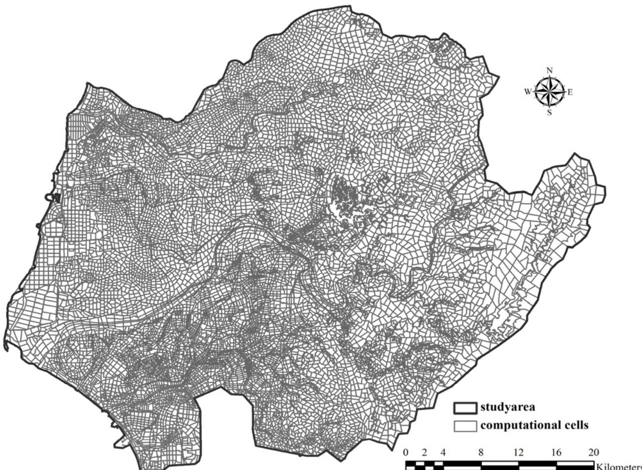


Fig. 2. Construction of cells in the study area

IV. Results and Discussions

The Tainan city was selected as the study area. By using GIS, the computation cells for the Yanshui, Zengwen, Chiangchun and Jishui river basins were generated according to their physiographic characteristics. The hydrological and physiographic parameters were simultaneously obtained by combining the information of soil distribution and that of land use. Then, the physiographic inundation model was applied to simulate the inundation potential caused by 24-hour and 48-hour design rainfalls of different return periods for baseline and climate change scenarios.

A. Simulation for a Historical Typhoon Event

The physiographic inundation model was first applied to simulate the inundation phenomenon of the Tainan city induced by Typhoon Haitang in 2005 and Typhoon Morakot in 2009. The simulated maximum potential inundation depth, area and flooding disasters were compared to field investigations in the Tainan city [5]. The results are shown in Fig. 3 and Fig. 4.

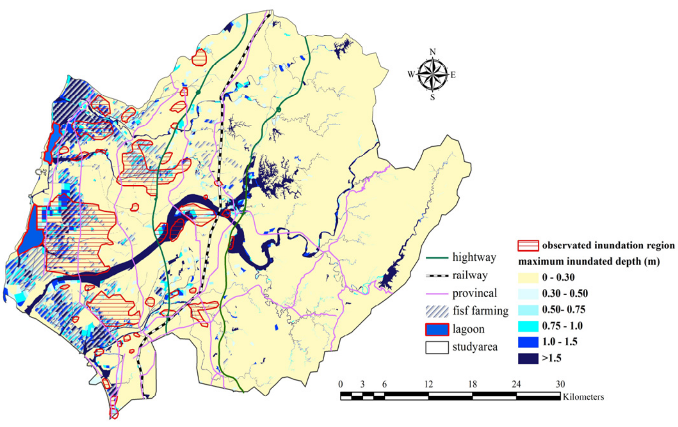


Fig. 3. Comparison of the simulated maximum inundated depth and those in field observation in the study area during Typhoon Haitang.

From the comparison of Fig. 3 and Fig. 4, the simulated maximum inundated depth and area are consistent with those in field investigations, implying that, it is reasonable and applicable to use the physiographic inundation model to study the inundation phenomena.

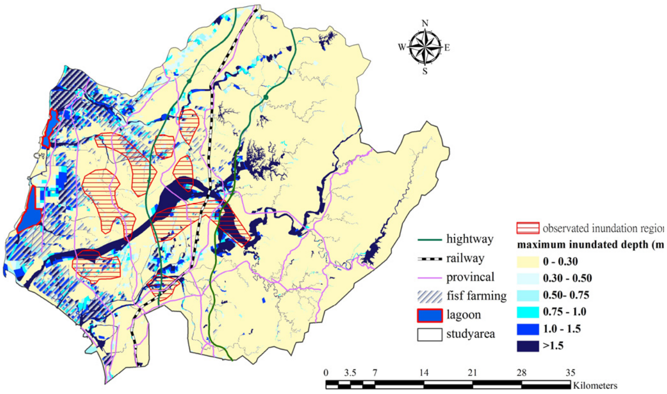
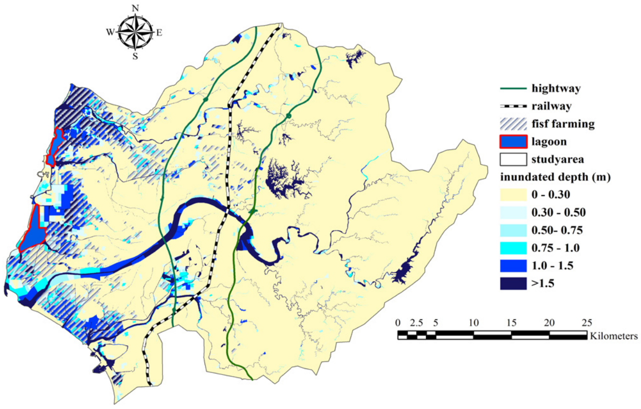


Fig. 4. Comparison of the simulated maximum inundated depth and those in field observation in the study area during Typhoon Morakot.

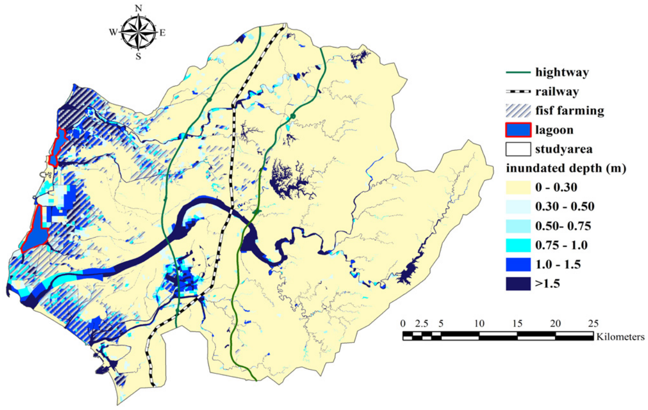
B. Simulation Inundated Potential for Baseline and Climate Change Scenario

In order to investigate the influence of climate change on the inundated potential in Tainan city, the Physiographic Inundation model is applied to simulate the inundated potential of the study area with the hydrologic conditions for the duration of 24-hour and 48-hour design rainfalls for baseline and climate change scenarios for 25- year, 50- year, 100-year and 200-year return periods [6]. The results for simulating the inundated potential of the study area were illustrated in the figure of the inundated depth. The inundated potential of the study area with the hydrologic conditions for the duration of 48-hour design rainfall for baseline and climate change scenarios for 25- year and 100-year return periods were utilized as an illustrative example as shown in Fig. 5 and 6.

As shown in Fig. 5 and 6, the inundated area and maximum inundated depth increase significantly under climate change scenario based on the same rainfall duration and return period. Thus, the inundated area and maximum inundated depth increase significantly with return periods of climate change scenario. The areas of inundation potential with the duration of 24-hour and 48-hour design rainfalls for baseline and climate change scenarios were different, mainly due to variations in rainfall changes under climate change scenario. We analyze changes in rainfall at the gage stations in study area with the duration of 24-hour and 48-hour design rainfalls for baseline and climate change scenarios under various return periods. The rainfall of various rain gage stations in study area were different for baseline and climate change scenarios, the results of which are shown in Tables I and II.

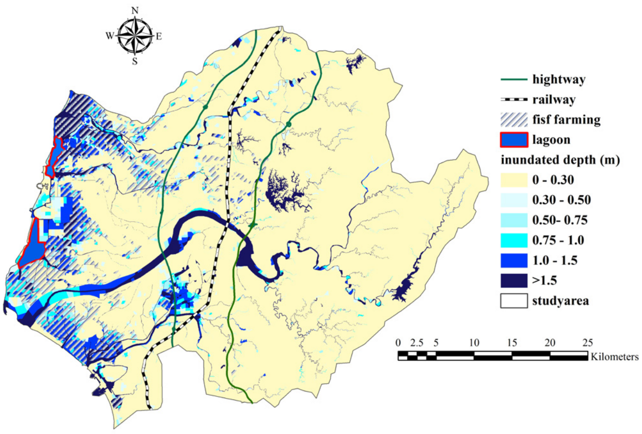


(a) Baseline (1980-1999)

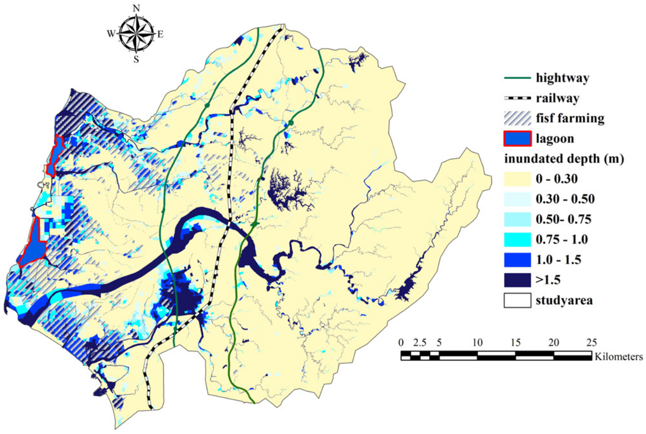


(b) climate change scenario (A1B, 2020-2039)

Fig. 5. Comparison of the simulated maximum inundated depth of 25-year return period



(a) Baseline (1980-1999)



(b) climate change scenario (A1B, 2020-2039)

Fig. 6. Comparison of the simulated maximum inundated depth of 100-year return period

In order to investigate the difference in inundated potential under baseline and climate change scenarios in the study area. Further, the inundated potential was analyzed with the hydrologic conditions for the duration of 24-hour and 48-hour design rainfalls for baseline and climate change scenarios under four various return periods and the increases in inundated depths areas and volumes were summarized in Tables III and IV. In Tables III and IV, positive value indicates the increase in inundated areas and volumes under climate change scenario as compared to baseline; a negative value indicates the decrease in inundated areas and volumes under climate change scenario as compared to baseline.

TABLE I: INCREASE IN INUNDATED AREAS UNDER CLIMATE CHANGE SCENARIO (24-HOUR) (UNIT：MM)

Station Name \ Return-period (years)	25	50	100	200
Yan-Shui	43	78	124	184
Shi-Shih	90	140	198	266
Shin-Shih	64	110	169	240
Lu-Tsao	80	112	146	182
Shih-An	59	100	153	218
Ho-Tang	3	6	7	4
Wu-Shan-Tou	26	42	59	83
An-Shih	26	45	70	105
Chun-Shih	18	32	47	65
Pai-Ho	35	67	108	159
Tung-Ho	26	63	114	179
Shi-Kou	68	99	134	173
Pai-Ho- ShuiKu	-26	-16	-2	15
Tung-Kou	7	28	56	90

(positive value indicates the increase in rainfall for climate change scenario；negative value indicates the decrease in rainfall for climate change scenario)

TABLE II: INCREASE IN INUNDATED AREAS UNDER CLIMATE CHANGE SCENARIO (24-HOUR) (UNIT：MM)

Station Name \ Return-period (years)	25	50	100	200
Yan-Shui	105	162	235	322
Shi-Shih	125	196	287	397
Shin-Shih	81	143	224	327
Lu-Tsao	77	123	176	238
Shih-An	98	151	213	287
Ho-Tang	153	216	296	394
Wu-Shan-Tou	55	97	152	224
An-Shih	62	109	170	246
Chun-Shih	81	117	161	214
Pai-Ho	66	102	149	207
Tung-Ho	57	73	90	111
Shi-Kou	128	187	258	343
Pai-Ho- ShuiKu	17	37	64	97
Tung-Kou	113	161	215	276

(positive value indicates the increase in rainfall for climate change scenario；negative value indicates the decrease in rainfall for climate change scenario)

TABLE III: INCREASE IN INUNDATED AREA UNDER CLIMATE CHANGE SCENARIO (UNIT: 10^4 M^2)

Return-period (years) \ inundated depth (m)		0.30-0.50	0.50-1.00	1.00-1.50	>1.50
25	24-hour	352	-132	220	702
	48-hour	202	231	618	604
50	24-hour	53	383	521	937
	48-hour	-35	776	376	1256
100	24-hour	755	517	103	1990
	48-hour	267	1094	185	2183
200	24-hour	711	920	-152	2746
	48-hour	478	1408	-29	2876

TABLE IV: INCREASE IN INUNDATED VOLUME UNDER CLIMATE CHANGE SCENARIO (UNIT: 10^4 M^3)

Return-period (years) \ inundated depth (m)		0.30-0.50	0.50-1.00	1.00-1.50	>1.50
25	24-hour	146	-108	173	1364
	48-hour	70	134	808	1557
50	24-hour	-14	225	684	2180
	48-hour	-27	554	595	3145
100	24-hour	299	330	141	4546
	48-hour	80	759	285	5482
200	24-hour	302	728	-278	6765
	48-hour	192	1101	-17	7736

Results in Tables III and IV indicate that the inundated depths, areas, and volumes may increase or decrease under the various storm events of different return periods after climate change, but on average they are significantly increased, especially for long return-period rainfall. The greater inundated depth of the region, the more inundated depths areas and volumes.

The inundated areas and volumes increase under climate change scenario with the various storm events of different return period of 24-hour and 48-hour. According to the results, the inundation phenomenon under climate change scenario is more serious than that under the baseline.

V. CONCLUSIONS

The physiographic inundation model was applied to discuss the impact of climate change on inundation potential. The Typhoon Haitang in 2005 and Typhoon Morakot in 2009 were used as two simulation cases to verify the ability and application of the physiographic inundation model. Our result shows that the simulated maximum potential inundation depth and area by the physiographic inundation model are consistent with those in field investigations. Furthermore, the inundated potential in the study area was simulated with the hydrologic conditions under the duration of 24-hour and 48-hour design rainfalls for baseline and climate change scenarios for 25- year, 50- year, 100-year and 200-year return periods. The comparison of the simulated results reveals that the inundated areas and volumes increase significantly under climate change scenario with different return periods of 24-hour and 48-hour, especially for long return-period rainfall. The greater inundated depth of the region, the more inundated depths areas and volumes. Thus, climate change causes more severe flooding disasters. The government should take steps to develop mitigation strategies to cope with the impact of climate change on flood potential.

ACKNOWLEDGMENT

This study was supported by a grant from the National Science Council of Taiwan (NSC-100-2221-E-020-029). The authors gratefully acknowledge the support.

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