Conference Paper, Published Version

Wu, Meng-Hsuan; Chen, Ching-Nuo; Tsai, Chih-Heng; Tsai, Chang-Tai

Influence of Storm Surge on the Inundated Potential in the Coastland

Influence of Storm Surges on the Inundated Potential in the Coastland

Meng-Hsuan Wu[1], Ching-Nuo Chen[2], Chih-Heng Tsai[3] and Chang-Tai Tsai[4]

[1] Ph.D. student, Department of Hydraulics and Ocean Engineering, National Cheng-Kung University
No.1, University Road, Tainan 70101, Taiwan, e-mail: n8893105@mail.ncku.edu.tw
[2] Post-Doctor, Department of Hydraulics and Ocean Engineering, National Cheng-Kung University
No.1, University Road, Tainan 70101, Taiwan, e-mail: cnchen@mail.hyd.ncku.edu.tw
[3]Assistant Professor, Department of Resources and Environment, Leader University
No.188, Sec. 5, Anjhong Rd., Annan District, Tainan City 709, Taiwan, e-mail: jht@mail.hyd.ncku.edu.tw
[4] Professor, Department of Hydraulics and Ocean Engineering, National Cheng-Kung University
No.1, University Road, Tainan 70101, Taiwan, e-mail: htct@mail.ncku.edu.tw

ABSTRACT

Storm surges do not only affect the capacity of drainage system but also lead to serious inundation damages in the coastland. The basin of the Jiangjyun river is used as an illustrative example in this study. The Physiographic Drainage - Inundation model is applied to evaluate the inundated potential for a historical typhoon event and twelve designed heavy-rains with the conditions for storm surges and astronomical tides as different individual conditions. The influence of the storm surge on the inundated potential in the basin of the Jiangjyun river is investigated by the simulation of above cases for inundated potential. The results obtained for the case of the surge storm for inundated potential simulation are compared with those for the astronomical tide. The simulated results obtained from inundated potential reveals that inundated potential in the coastland in terms of the inundation depth and area for the case of the surge storm are plainly greater than those for the astronomical tide. Therefore, it is crucial to consider the influence of storm surges when planning the scale of drainage systems and dikes in the coastland.

Keywords: storm surge, inundated potential, inundation depth, inundation area, climate changes

1. INTRODUCTION

Due to the development of economy, increasing population, and transportation infrastructure of the coastland, drainage system and land uses have been changed for decades in Taiwan. These changes along with groundwater over-pumping lead to not only the increase of surface runoff but also the acuteness of land subsidence. The retarding effect of roads might alter the basin boundary of the drainage. This effect induces the overbasin flow which can also exceed the capacity of the present drainage system. Therefore, there is a special need to evaluate the current drainage system and the influence of these changes.

In addition to physical changes, we need to pay additional attention on extreme hydrological events due to climate changes. These extreme hydrological events include storms, super typhoons, and astronomical tides. Especially, super typhoons often bring heavy rain as well as rise the sea level because of the barometric depression. Therefore, these extreme hydrological events may further strike the drainage system and increase the damage of inundation. This study applies the Physiographic Drainage - Inundation model to evaluate the inundated potential in the coastland in terms of the inundation depth and area, and to estimate the influence of the storm surge on the inundated potential in the coastland.

The basin of the Jiangjyun river is used as an illustrative example in this study. The

Physiographic Drainage - Inundation model is applied to simulate the inundated scenarios for a historical typhoon event and twelve designed heavy-rains with the conditions for storm surges and astronomical tides as different individual conditions. The influence of the storm surge on the inundated potential in the basin of the Jiangjyun river is investigated by the simulation of above cases for inundated potential.

2. PHYSIOGRAPHIC DRAINAGE - INUNDATION MODEL

The computed cells in accordance with the landscape and drainage network of the watershed are automatically generated in the Physiographic Drainage - Inundation model. The water flow calculation uses the Physiographic Drainage - Inundation model, which is based on the continuity equation and discharge theory in each cell. The continuity equation for water flow is given (Yang, 2000).

$$As_i \frac{dh_i}{dt} = Pe_i + \sum_k Q_{i,k}\left(h_i, h_k\right) \tag{1}$$

where As_i = the area of 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 $Q_{i,k}$ in Eq 1 can be represented by any appropriate discharge formula as described below.

2.1 Channel-Linked Discharge Formula

Selection flow conditions for the flow between cells without obvious obstacles can be treated as an idealized channel flow and the discharge can be calculated by the Manning formula (Yang and Tsai, 1997). The discharge can be calculated by Eq.2 and Eq. 3.

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

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

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

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

where α = an weighting-coefficient; Φ = the flow parameter, defined as $\Phi(h) = \frac{\frac{1}{n} A R^{2/3}}{\sqrt{\Delta x}}$.

where Δx = the distance of the canter between the k-th and i-th cells; n =the Manning's roughness coefficient of the cells; 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, $R = R(\bar{h}_{i,k})$.

2.2 Weir-Linked Discharge Formula

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

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

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

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

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

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 $\mu_2 = 2.6\,\mu_1$.

Therefore, the explicit finite-difference representation of Eq. 1 can be written as

$$\Delta h_i = [Pe_i + \sum Q_{i,k}(h \ , h_k)]\Delta t / A_{si} \tag{7}$$

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

3. STUDY AREA

The basin of the Jiangjyun river is used as an illustrative example in this study. The lagoon of the lowland plain and hill along the coast from the south of the Bajhang river to the north of the Zengwun river was selected as the study area for investigating the inundation phenomena of the basin of the Jiangjyun river. In addition to the Jiangjyun river, the study area also contains the Jishuei and Cigu rivers. The area of the Jiangjyun river basin is about 158.4 square kilometer and the length of the main stream is about 28 kilometer. The basin of the Jiangjyun river in the study area is shown in Figure 1.

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 are also included in the GIS database. The entire basin was divided into 6,626 irregular grids (as shown in Figure 2) by automatic modeling-cell-delimitation method that used 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 Physiographic Drainage - Inundation model.

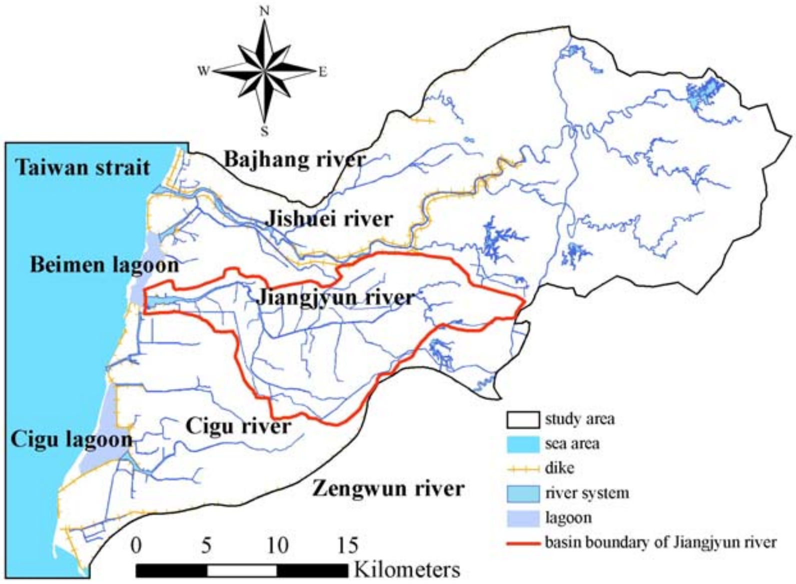


Figure 1 The basin of the Jiangjyun river in the study area

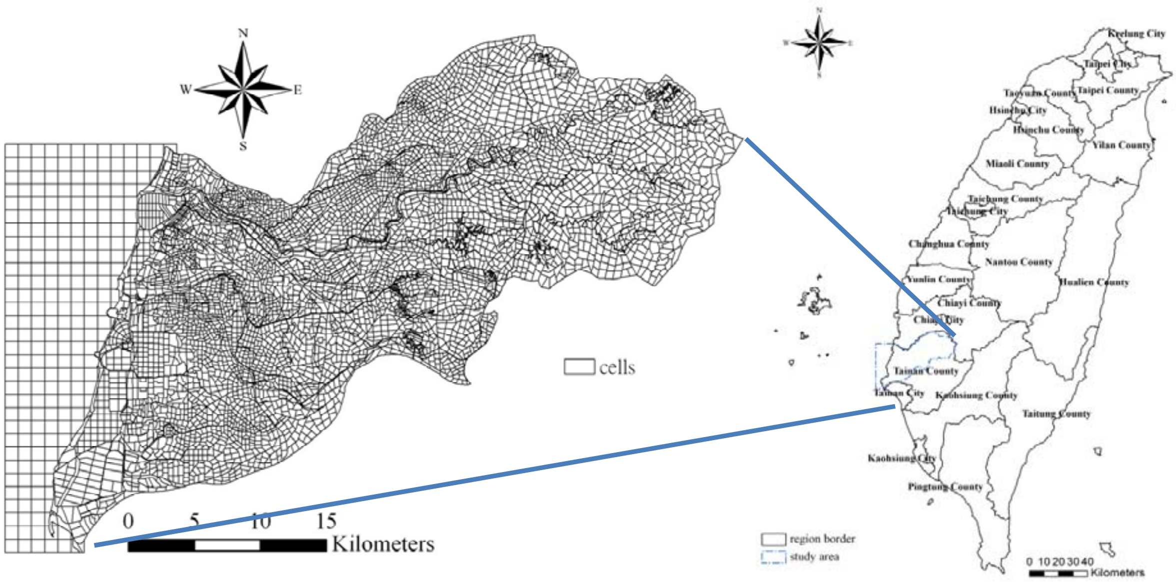


Figure 2 Construction of cells in the study area

4. RESULTS AND DISCUSSIONS

The basin of the Jiangjyun river is used as an illustrative example in this study. Based on the physiographic properties of the Jiangjyun river basin, GIS system is applied to construct the cells of the study area automatically. The hydrologic parameters and the physiographic parameters of each cell are obtained from above analyses. The Physiographic Drainage - Inundation model is applied to simulate the inundated scenarios for twelve designed heavy-rains with the tidal conditions for storm surges and astronomical tides as different individual conditions. Thus, the influence of the storm surge on the inundated potential in the basin of the Jiangjyun river is investigated by the simulation of the above cases for inundated potential.

4.1 Hydrologic Data

In order to test and verify the physiographic Drainage - Inundation model, the results of simulation of the historical typhoon event are compared with observation and investigation in the field. Floods are caused by twelve designed heavy-rains with different durations and return periods obtained from frequency analysis and storm pattern analysis. Influence of storm surges on the inundated potential in the coastland was investigated by simulating floods caused by twelve designed heavy-rains.

The study area was divided into several control areas of the rain gage stations by utilizing the Thiessen polygons method. In this study, the rainfall data of each rain gage station for each cell were utilized to simulate the phenomena of the historical typhoon.

Distribution and control areas of the rain gage stations possessed by the Central Weather Bureau were shown in Figure 3. The rainfall data of the rain gage stations in study area and the adjacent area were utilized to proceed frequency analysis and storm pattern analysis. Floods are caused by twelve designed heavy-rains with different durations and return periods obtained from the results of frequency analysis and storm pattern analysis.

The tide levels in the coastland of the historical typhoon were obtained from the historical data of the Jiangjyun tidal gauge station. The tide levels in the coastland of the twelve were obtained from the results of the analyses of astronomical tide and surge deviation. The results of the tidal analysis were shown in Figure 4.

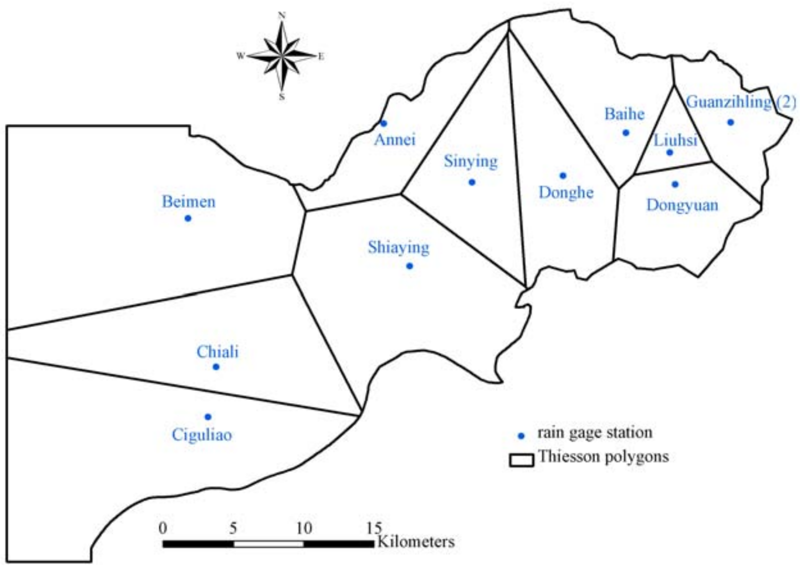
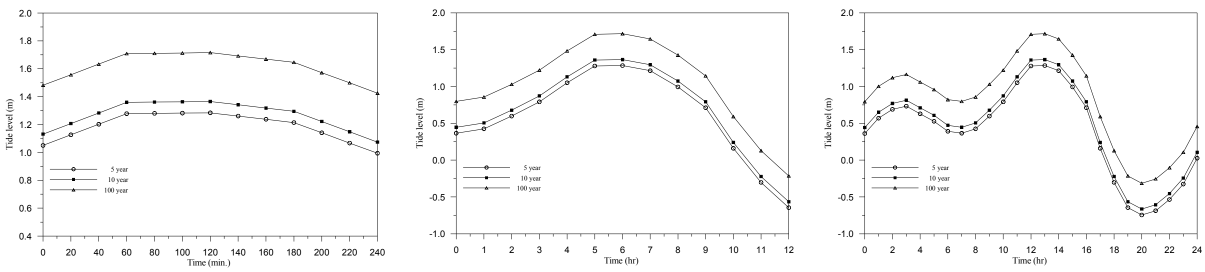


Figure 3 Thiesson polygons in the study area



4 hour duration of rainfall　　12 hour duration of rainfall　　24 hour duration of rainfall

Figure 4 Tidal boundary condition for the case of designed heavy-rains (in meter)

4.2 Simulation for a Historical Typhoon Event

Typhoon Haitang, which occurred in 2005 to cause serious inundated damages in the basin of the Jiangjyun river, was utilized as an illustrative example. The maximum inundated depth based on the simulations was shown in Figure 5. Further, the result of simulation of Typhoon Haitang is compared with observation and investigation in the field (Water Hazard Mitigation Center, Water Resources Agency, MOEA, 2007) in order to test and verify the physiographic Drainage - Inundation model. The simulated results contain the inundation depth, area, and so on. The results of observation and investigating in the field were shown in Figure 6.

Based on the comparison of simulated results with the observed data shown in Figures 5 and 6 individually, the simulated results obtained from inundating potential reveals that inundated potential in the coastland in terms of the inundation depth and area are coincident with the results of observation and investigation in the field.

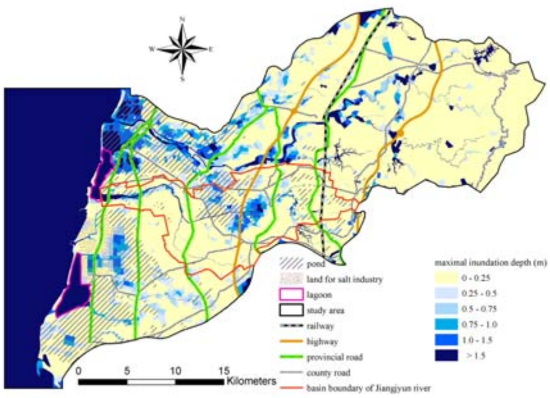
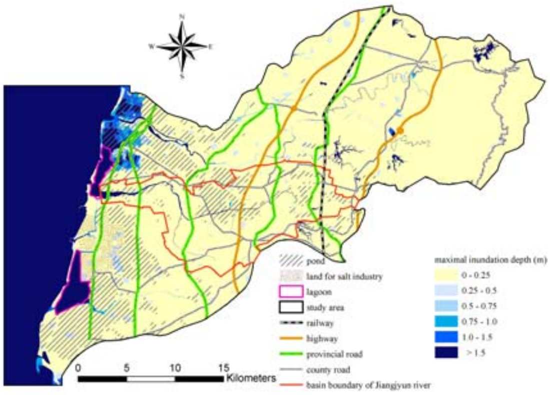


Figure 5 The simulated maximum inundated depth of Typhoon Haitang in 2005

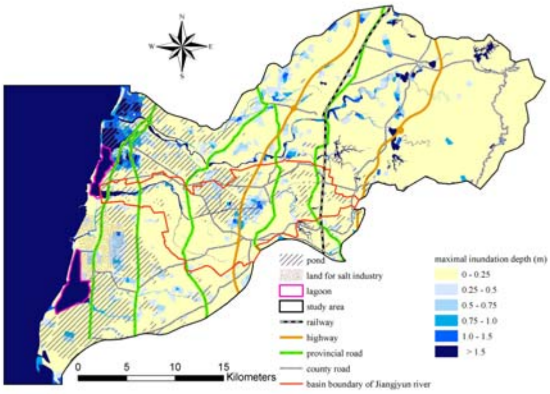
Figure 6 The inundated depth of Typhoon Haitang in Tainan county in 2005

4.3 Simulation for designed heavy-rains

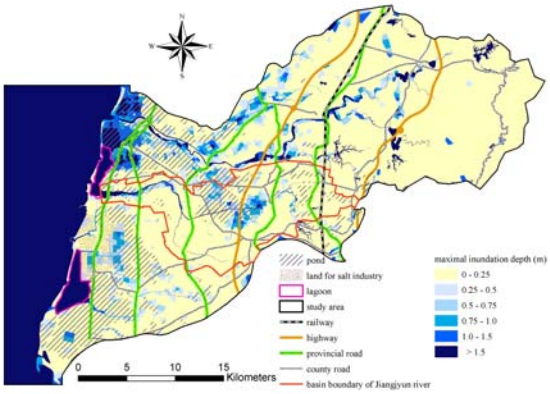
In order to investigate the influence of storm surges on the inundated potential in the coastland, the Physiographic Inundation model is applied to simulate the inundated potential of the study area with the hydrologic conditions for the duration of 2-hour, 4-hour, 12-hour, and 24-hour floods for 5- year, 10- year and 100-year return periods. The storm surge and the astronomical tide were used as tidal conditions. 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 4-hour, 12-hour, and 24-hour floods for 5- year and 100-year return periods were utilized as an illustrative example as shown in Figures 7 and 8.



4-hour duration

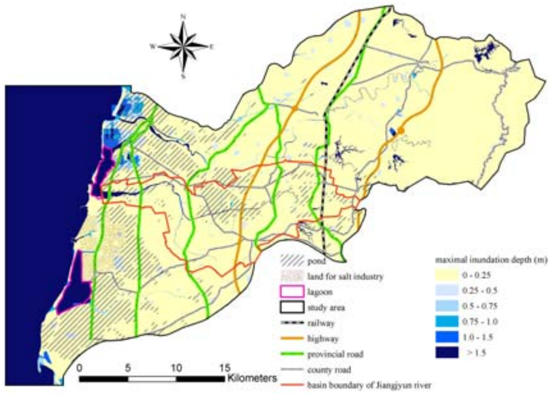


12-hour duration

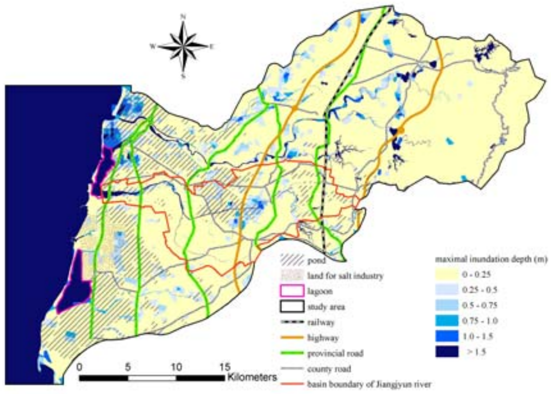


24-hour duration

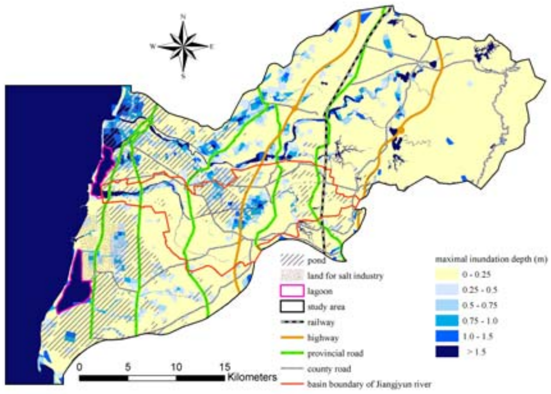
Figure 7(a) Comparison of the simulated maximum inundated depth of 5-year return period (storm surge)



4-hour duration

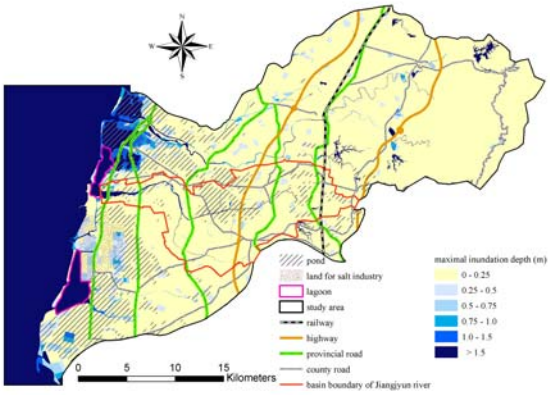


12-hour duration

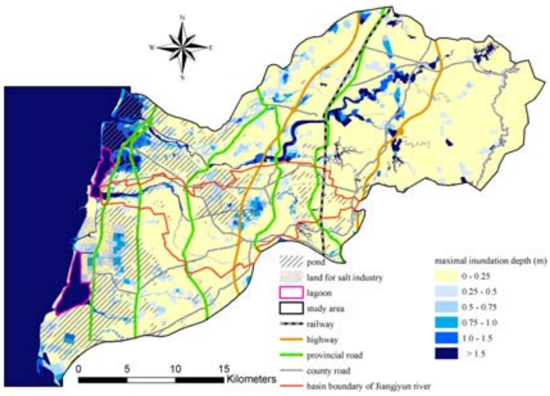


24-hour duration

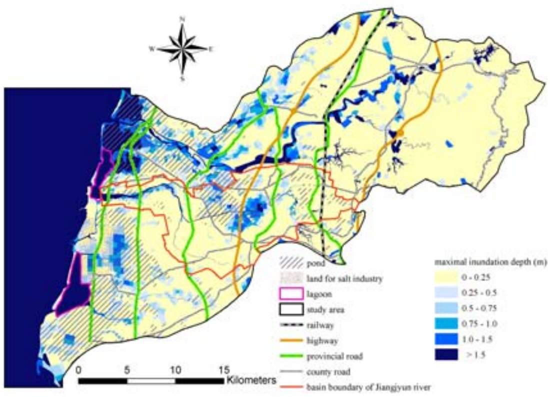
Figure 7(b) Comparison of the simulated maximum inundated depth of 5-year return period (astronomical tide)



4-hour duration

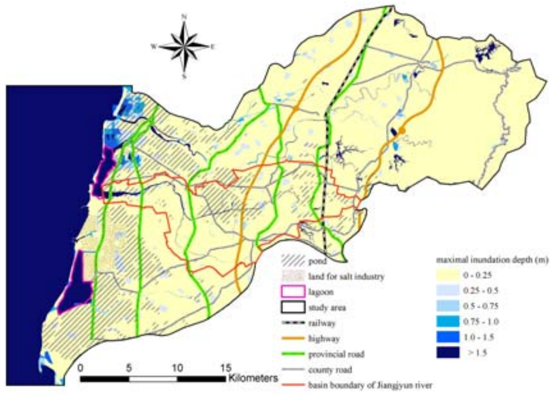


12-hour duration

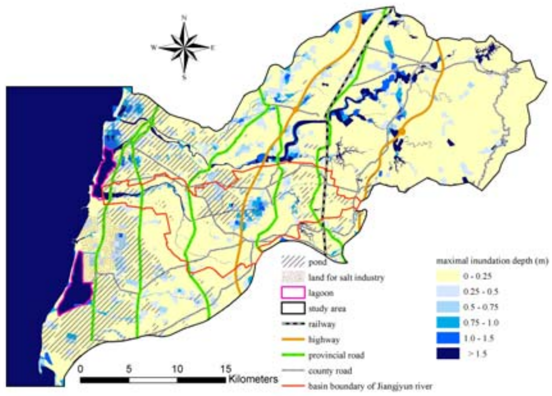


24-hour duration

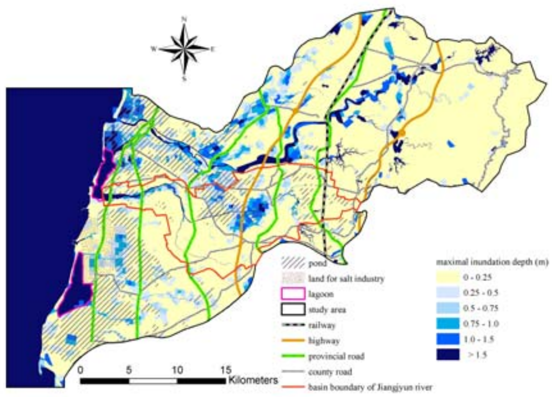
Figure 8(a) Comparison of the simulated maximum inundated depth of 100-year return period (storm surge)



4-hour duration



12-hour duration



24-hour duration

Figure 8(b) Comparison of the simulated maximum inundated depth of 100-year return period (astronomical tide)

As shown in Figures 7 and 8, the inundated area and maximum inundated depth increase significantly with rainfall duration on the condition of the same return period. The inundated area and maximum inundated depth increase significantly with return periods. Thus, the inundated area and maximum inundated depth increase significantly with return periods on the same rainfall duration. Further, in order to investigate the influence of storm surges on the inundated potential in the coastland, the inundated depths and volumes of 24-hour duration for 5- year 10-year, and 100-year return periods with storm surge or astronomical tide conditions were summed up individually. The increases in inundated depths and volumes were summarized in Table 1.

In Table 1, a negative value indicates the decrease in inundated volumes. The influence of storm surges on the inundated potential in the coastland is illustrated at Table 1. As shown at Table 1, the increases in inundated depths and volumes increase significantly when the storm surge occurs. As shown in Figures 7, 8 and, Table 1, the most difference in inundated volumes of different return periods and durations occurr in the coastland. The inundated volumes with the inundated depths of 5-year and 10-year return periods that were greater than 75 cm increase significantly when storm surge occurs. The inundated volumes with the inundated depths of 5-year and 10-year return periods that were less than 75 cm might increase. The inundated volumes with the inundated depths of 100-year return period that were greater than 25 cm increase significantly. The inundated volumes with the inundated depths of 100-year return period that were less than 25 cm might even decrease.

Table 1 Decrease in inundated volume (in 10^3 m^3) of the cases in 2-hour duration floods for 2-, 10- and 100-year return-periods with storm surge or astronomical tide condition

Return-period (years)	Inundation depth (m)						Sum
	0-0.25	0.25-0.50	0.50-0.75	0.75-1.0	1.0-1.50	>1.50	
5	-373.92	1266.40	-3152.80	2371.84	5529.59	121736.50	127377.62
10	171.60	459.26	-1504.54	339.76	7030.66	147986.50	154483.24
100	-453.68	1770.05	3049.44	357.28	8238.54	264175.00	277136.62

5. CONCLUSIONS

In the same designed heavy-rains, regardless of storm surges occur or not, there are obvious influences on the inundation depth and area in the coastland. Inundating potential reveals that inundated potential in the coastland in terms of inundation depth and area in the case of storm surges is plainly greater than that in the astronomical tide. When planning the scale of drainage systems and dikes in the coastland, proceeding typhoon and heavy-rain events and storm surges simulation of the inundating potential which caused by typhoons are necessary. In addition, it is crucial to compare and review the inundation phenomena of flood-prone areas and then to provide improvement.

ACKNOWLEDGMENTS

This study was supported fanacially by a grant from the Water Hazard Mitigation Center, Water Resources Agency, Ministry of Economic Affairs.

REFERENCES

Chen, C.N., Tsai, C.H. and Tsai, C.T. (2007), Reduction of discharge hydrograph and flood stage resulted from upstream detention ponds, *Hydrological Processes*, 21, pp. 3492–3506.

Lee, H.Y. (1999), A Study on Automated District Cells of the Watershed, *Master Thesis, Department of Hydraulics and Ocean Engineering, National Cheng-Kung University*, *Tainan, Taiwan*.

Water Hazard Mitigation Center, Water Resources Agency, Ministry of Economic Affairs (2007), A study on the surge and cross-watershed runoff for the drainage system of the coastland (1/2), *Technical Report, MOEA, Taipei, Taiwan*.

Yang , C. J. (2000), Study on Construction of a Physiographic Inundation Forecasting System, *Doctoral Thesis, Department of Hydraulics and Ocean Engineering, National Cheng-Kung University, Tainan, Taiwan*.

Yang, C. R., and Tsai, C. T. (1997), Development of the GIS-Base Flood Information System for Floodplain Modelling and Damage Calculation, *Journal of the American Water Resources Association*, 36(3), pp. 567-577.