Please cite as: Chen AS, Hsu MH, Teng WH, Huang CJ, Yeh SH, Lien WY. (2006) Establishing the database of inundation potential in Taiwan, Natural Hazards, 37 (1-2), 107-132, DOI:10.1007/s11069-005-4659-7.

Establishing the database of inundation potential in Taiwan

ALBERT SHIUAN-HUNG CHEN[1,*], MING-HSI HSU[2], WEI-HSIEN TENG[3], CHEN-JIA HUANG[1], SEN-HAE YEH[1], and WAN-YU LIEN[1]

[1] Flood and Drought Disaster Reduction Division, National Science & Technology Center for Disaster Reduction

[2] Dept. of Bioenvironmental Systems Engineering, National Taiwan University

[3] Dept. of Architecture, National United University

Abstract. The structural measure was the major solution for flood defense in Taiwan. However, the measure is always limited to the design standard and can not prevent the damages when floods exceed certain scale. Therefore, non-structural measures for flood mitigation are the indispensable complements to structural solutions. The study introduces the establishment of inundation potential database that provides required information for the non-structural measures in Taiwan. The database was built by numerical simulations, based on different rainfall scenarios, and has been applied in the local governments of Taiwan for land use managements, flood warning systems, emergency responses, and flood insurance programs to reduce the flood damages and impacts.

Keywords: inundation potential, flood mitigation, overland flow model, non-structural measures, flood defense strategies

1. Introduction

For sustainable development and environmental protection, non-structural measures have become popular solutions for flood hazard mitigation in the world (Changnon, 1998; Harman

---

* Author for correspondence: 3F, No. 106, Sec. 2, Hoping E. Rd., Taipei, Taiwan, ROC. 106;

Tel: +886-2-66300646; Fax: +886-2-66300600; E-mail: albertchen@ncdr.nat.gov.tw

et al., 2002; Klijn et al., 2004). Japan and U.K., both are island countries with similar geographic conditions to Taiwan, have used the flood maps to set up the non-structural strategies. In Japan, the flood maps are important basis of the Basic Disaster Management Plan (Cabinet Office, 2003) The sequence of disaster countermeasures such as preparedness, emergency response, recovery and reconstruction is described in the plan. The duties assigned to the Government, public corporations and the local governments are also clarified in the plan. Based on the plan, the governments develop comprehensive flood control measures to mitigate the disaster impacts. In the U.K., the Environment Agency (EA) provides the flood mapping information to arise awareness that the areas could be flooded in certain conditions. EA also sets out the Strategy for Flood Risk Management, including flood warning, floodplain managements and flood insurance, according to the flood maps, to minimize the risk from flooding to life, property and the environment (Murphy, 2003).

The most complete flood risk mapping in actual practice is the National Flood Insurance Program (NFIP) in the U.S., which was initiated by the Congress in 1968 (Burby, 2001). The flood risk was distributed to both government and individuals by requiring the homeowner in a floodplain to buy insurance that would replace government grants and loans. The administrator of the NFIP, the Federal Insurance Administration (FIA), which is a branch of the Federal Emergency Management Agency (FEMA), produces maps of participating NFIP communities that indicate areas in the communities with high flood risk. The successful program helps the governments and civilians to enhance the prevention and reduce the flood risks. The FEMA is embarking on applying the experience to modernize the flood maps and develop multi-hazard maps (Lowe, 2003).

Besides flood maps, many non-structural measures were also adopted for flood hazard mitigations. For examples, the basin rainfall monitoring system (Subramaniam and Kerpedjiev, 1998) and real time flow forecasting (Bae et al., 1995) were adopted to assist the emergency managers in evaluating flood situations. The virtual database and decision support system were applied to the Red River basin in Canada (Simonovic, 2002) for providing a more transparent and efficient process in flood management to reduce the economic, environmental and social damages. The flood risk managements for land use were implemented in Rhine basin in Europe (Bohm et al., 2004; Hooijer et al., 2004; Middelkoop et al., 2004), Camel catchment (Sullivan et al., 2004) and New South Wales (Yeo, 2003) in the U.K. The combinations of flood risk information and geographical information system (GIS) provide powerful tools for flood managements (Al-Sabhan et al., 2003; Gunes and Kovel, 2000; Zerger and Wealands, 2004).

Most non-structural measures require risk analyses, which are carried out by physical or numerical models, as the rational basis for flood-alleviation planning. In many applications, different approaches were adopted for flood risk assessments via hydrological, hydraulic or ecological models (Abbott, 1998; Djordjevic et al., 1999; Hooper and Duggin, 1996; National Science Foundation, 1980). The degrees of flood risk for flood-prone areas were identified by using these models. Accordingly, based on the flood risk information, the governments developed the policies for land use management, set the flood insurance premium rates and established the criteria for construction in alluvial plains.

In Taiwan, the island-wide inundation potential database was built in 2001 by using a series of numerical models. The models were combined to reflect the hydrologic and hydraulic characteristics within a watershed, including the surface runoffs in upstream catchments, channel flows in rivers, overland flows on alluvial plains and sewer flows in drainage systems. The processes of building the inundation potential database in Taiwan and practical applications are reviewed in the study.

2. Description of the study area

The annual precipitation in Taiwan is about 2,500 mm and more than 78% of the precipitation concentrates in monsoon and typhoon seasons during May to October (Water Resources Agency, 2003). The tremendous amount of rainfall accompanying with typhoons often results in serious inundation. According to the official statistics, 152 typhoons that hit Taiwan occurred between 1958 and 2001 which resulted in 16,305 causalities (Lin, 2002). On an average, the number of floods that hit Taiwan was increased from 3.0 times per year in 1970s to 5.6 times per year in late 1990s (Table I). Although the authorities had increased investments in flood structural works, but the flood-damage losses did not slow down in trend (Wu, 1995). Table II shows severe damages incurred by typhoons in Taiwan in recent years. In 2001, the intensive typhoons, named Trami, Toraji and Nari, resulted in 323 death and missing tolls within three months.

The major factor exacerbating the flood damages is the over-development of urban areas. For example, Lee et al. compared the satellite images of 1988 (Figure 1) and 1998 (Figure 2) of the Sijhih City in north Taiwan and found that 16% of the city area was altered from cultivate and wood lands to buildings and roads in the decade (Lee et al., 1999), whereas the population increased 74% quickly, from 85,001 to 147,507, at the same period (Sijhih City Household Registration Office, 2004). Most of the urbanized areas concentrated along the Keelung River and situated in the floodplains. As a result, the watershed is worse for floodwaters due to increasing the impervious pavements, shortening the time of concentration and raising the peak discharges of floods. Undoubtedly, the Sijhih City has become as one of the most frequently flooded areas in Taiwan.

On the other hand, the structural solutions usually provide an incorrect impression to civilians, even including the officers, that their lives and properties are free from being flooded. The following unbridled developments often lower the protection of structural measures, which forced the government to spend more budgets in structural works for re-strengthening the safeties. The vicious circle can not solve the problems, contrarily, the environments and ecosystems are frequently damaged. Nowadays, like many developed countries, the Taiwan government and publics realize that structural solutions are limited in preventing the threat of floods. More non-structural measures such as alluvial plain managements, flood forecasting and warning systems, flood insurance programs and public awareness are introduced to mitigate flood risks in recent years.

In Taiwan, the National Science and Technology Program for Hazards Mitigation (NAPHM) launched the project to build the inundation potential database in 1998. The main goal of the project was to analyze the flood risk for improvement in the flood management around the island. The database was finished in 2001 and released to public for practical flood hazard prevention and mitigation.

3. Methodology

The inundation potentials were simulated by using a series of numerical models. The work was proceeded by watershed divisions individually. Geographically, Taiwan was split up into 53 watersheds for numerical simulations. Within a watershed, several numerical models were composed for hydrological and hydraulic routings with different design rainfalls. Consequently, each watershed was divided into upstream mountain catchments, river channels, and downstream alluvial plains, with the assistance of GIS, for numerical model simulations.

3.1 Surface runoffs of mountain catchments

Upstream catchments of watersheds in Taiwan are mountainous with steep land slopes, the surface runoffs concentrate rapidly to channel flowing into downstream alluvial plain once the storm rainfall starts. The HEC-1 model (U.S. Army Corps of Engineers Hydrologic Engineering Center, 1992) was applied for hydrologic analysis. The excess rainfall hyetographs based on Horton's infiltration equation were used to compute the surface runoffs of the mountain catchments, whereas the runoff hydrographs at outlets of catchments were treated as boundary inputs for the numerical routing in river channels or downstream alluvial plains.

3.2 Channel flow of rivers

The flood flows in rivers can be described by the 1-D unsteady gradually varied flow equations (i.e. the St. Venant equation). A dynamic flood routing based on the 1-D continuity and momentum equations in open channels was developed by using the four-point Preissmann scheme (Cunge et al., 1980). The model had been applied to several studies in Taiwan (Chang et al., 2000; Hsu et al., 2003). The model was performed herein to calculate the channel floods.

3.3 Overland flow of alluvial plains

Assuming that the acceleration term of water flow on the land surface is small, compared to gravitation and friction terms, the inertial term in the motion equations is neglected. Then, the shallow water flows on land surface can be described by 2-D depth-averaged non-inertial wave equations. In the study, the non-inertial model was adopted for solving the equations by the alternating direction explicit scheme (ADE), which allows calculations with zero water depth and velocity (Hsu et al., 1990). The authors had conducted a series of studies in Taiwan and found that the model could accurately simulate the overland flow characteristics of alluvial plains (Hsu, 1992; Hsu, 1998; Hsu et al., 1998).

3.4 Sewer flows in urban areas

For the urban regions with detailed sewer drainage systems, the Storm Water Management Model (Huber, 1975; Huber and Dickinson, 1988) was applied for sewer flow routing. The model is used to solve the storm sewer flow component and provide surcharged flows for overland flows. The bidirectional interactions between sewer networks and ground surfaces were considered for linking the SWMM model and 2-D overland flow models (Hsu et al., 2002).

3.5 Model linkages

Figure 3 displays the simulation processes among models. The HEC-1 model was first routed to simulate runoff discharges of the upstream catchments. The discharges were considered as the upstream boundary conditions for routing in alluvial plains where the 2-D non-inertial model was used for overland flow simulations, 1-D channel dynamic model for river flows and SWMM for storm sewer system.

The flow interactions are set as internal boundary conditions between 1-D and 2-D, 2-D and SWMM models with the considerations of their relative water stages. The 1-D and 2-D models were linked by weir discharge formula for physical lateral weir connections (Chang et al., 2000). For some areas with high flood levees, the pumping stations were set to drain the inland water into channels during floods. Hence, the pumping discharges were also considered for such connections.

In township or urban areas with storm drainage systems, the surface drainage through inlets to sewer systems or overflows from surcharged manholes to ground surface were used for model linkages between the overland flow model and sewer routing model. The former is treated as the sink and the later as the source in the 2-D model. The source codes of SWMM were rewritten by the authors for dynamic coupling with the 2-D model. The detailed descriptions of the models can be found in authors' earlier study (Hsu et al., 2002).

3.6 Model inputs

The flood risk analysis had never been executed in the national scale in the past due to the great amount of input data required for numerical models. Fortunately, with the rapid advance in technology, the tedious work of data collection was simplified by using GIS, digital terrain model (DTM) and digital elevation model (DEM). Since the irregular nature of surface land area, it was usually easier to sample a rectilinear grid of a fixed size than to fit unstructured grid to the underlying topography (Bishop and Catalano, 2001). Meanwhile, the structured nature of a finite-difference grid costs less time and efforts for building detailed topography and roughness maps. Furthermore, the computing grids are more readily sampled for topography data and easier for fitting into raster-based GIS. To complete the large-scale project in three years, a grid size of 200 m x 200 m was chosen as the compromise between accuracy and efficiency. The ground elevation and roughness of grids were extracted from DEM and DTM, respectively. The river channels, levees, storm sewer systems were mapped onto overland surface with help of GIS for model linkages.

4. Model Calibrations and Verifications

In early years, the flood extents, depths and related information in Taiwan were seldom recorded during floods. The field surveys were only proceeded after major flood events, which resulted in severe damages such as life losses or big area of inundations. Meanwhile, most of the field records are quite simple and contain limited information for detailed analysis. Fortunately, the governments of all levels are increasing the attentions on field investigations and building databases of disaster information in recent years. More available information can be obtained for further applications in the future.

The accuracy of model calibration and verification is highly dependent to the available records. The historic typhoon events were used to calibrate the parameters of numerical models, including the roughness of catchments, channels and floodplains. The other typhoon or flood events were applied for model verifications. For a watershed without enough event records, the flood-prone areas, where frequently suffered serious inundation in the past, were described according to the experiences of flood managers in local governments and adopted for model verification. The procedures were conducted by watershed divisions individually. The experience of the Sijhih City is illustrated as following example.

4.1 Model Calibrations

The Sijhih City in northern Taiwan, which is mentioned earlier, is a densely developed town in Keelung River basin. The area suffers from flood disasters frequently in last decade because of the excessive development. In 1998, typhoon Zeb and Babs continuously invaded the Sijhih City in 10 days and caused serious damage. The precipitation records of rain gauges in surrounding areas were input for numerical simulations. The flood extents and water depth ranges, surveyed by the water management authority, were used for calibrations.

Typhoon Zeb flooded 291 hectares of the Sijhih City with water depths varied from 0.5 to 4.0 m. Typhoon Babs resulted in a smaller damage by 286 hectares of flooded areas with depths varied from 0.5 to 3.8 m. The flood extents of field surveys and numerical simulations of two events are shown in Figure 4. The calibrated Manning's roughness for various types of land use is listed in Table III. In common, cultivate and wood lands have the highest roughness due to the dense vegetations. On the contrast, river channel and transportation facility have the lowest ones because there are less barriers insides for water flows.

The flooded areas and maximum inundation depths are compared in Table IV. The simulation results tend to over-estimate the flooded area and depths, due to the detailed information of drainage systems in the area was not available to be considered in the models. The physical phenomena of the overland flow that drains into sewers can not be properly reflected. The water was trapped in local depressions in the simulation results, which caused over-estimated flooded areas and depths.

4.2 Model Verifications

With the calibrated parameters, another typhoon event, the typhoon Xangsane on Oct. 31th 2000, was adopted for model verification. Typhoon Xangsane brought torrential rainfall and inundated 356 hectares in the area. The rainfall records of the nearby rain gauges during the event were input for numerical routings. The investigated and simulated flood extents are shown in Figure 5. The flooded area and depth range are also compared in Table IV, which demonstrates that the numerical result has high consistency with the survey records.

Similar calibration and verification processes were carried out by watershed divisions. For watersheds with more information, such as flood depths at specific time and locations, the parameters can be further tuned and verified. For instance, the typhoon Nari event in 2001 induced the most severe flood disaster of Taipei City in recent years. A number of pumping stations failed to operate and many underground infrastructures were submerged due to the unexpected flood. The failing time of pumping stations and flood volumes in underground basements were recorded and compared to the results of numerical simulations as a verification in downtown Taipei (Chen et al., 2004; Hsu et al., 2002).

For watersheds without complete historical inundation records of storm events, the flood-prone areas were used for model verifications. Figure 6(a) shows an example of the flood-prone areas delineated by the local government of Tainan County. Consequently, the numerical simulation result with rainfall of 5-year occurrence interval was compared to the flood-prone areas. The result shown in Figure 6(b) reveals that the inundation areas agreement with the investigated flood-prone areas.

5. Construction of the Database

The torrential rainfall is the major factor that leads to flood disasters in Taiwan. The flash floods that result in serious damages usually occur in 24-hour duration, thus, the design rainfall pattern of 24-hour duration was applied for numerical simulations. The alternating block method (Chow, 1988) was employed to estimate the temporal distribution of the design rainfall for each watershed. Meanwhile, the real time simulation during floods by using 2-D overland flow models is difficult to achieve because the models are time-consuming. Hence, the inundation potential database was planned to be applied in emergency managements.

Table V shows the rainfalls in 24 hours with different occurrence intervals for each county in Taiwan. The rainfalls with the same occurrence interval in individual counties are quite different. In addition, the rainfall-frequency analysis results fluctuated due to the increasing extreme rainfall events in recent years. For uniform quantity of inundation potential database and better understanding of rainfall conditions to the emergency managers, the specific amounts of rainfall were adopted for simulations instead of using the rainfalls with different occurrence intervals. Four hyetographs with equal intervals, namely, 150 mm, 300 mm, 450 mm and 600 mm of total rainfall, were selected as the design rainfalls. During floods, the emergency managers can easily compare the current rainfall conditions with the design rainfalls in order to estimate the flood extents and depths from by using the inundation potential database. The equivalent occurrence intervals and exceedence probabilities of design rainfalls for each county are listed in Table VI. Accordingly, the managers can also understand the flood risks of different rainfall scenarios by referencing the table.

The spatial variation of rainfall is assumed uniform distributed within the same watershed for simplifying the scenarios. The cases with different spatial distributions can be considered in the future plans to expand the database. The flood defense structures such as levees, pumping stations, and flood proof gates were assumed working normally without failure in the simulations.

The results were in digital format and coordinated into a database, which can be queried by setting user-defined criteria for analyses, and transformed into different forms for further applications with different purposes. The county government is the local administrative division and the basic authoritative unit for emergency response in Taiwan. Therefore, the database was approved by the Executive Yuan, ROC, and published as inundation potential maps of counties for flood managements in local governments. Figure 7 is the island-wide inundation potential map for 600 mm of rainfall in 24 hours and Table VII shows the statistics of inundation potential areas of four design rainfalls for each county. The southwest counties, Tainan and Yunlin, have larger flooded areas than other counties under the same total rainfall conditions. More than 1,000 km^2 of area in the counties could be inundated when total rainfall in 24 hours reaches 600 mm. It helps the central government to set up the land use policy in national scale to reduce flood risks of the area. The local governments and water management authority may as well allocate more resources on the area for hazard mitigation.

Moreover, the digital database makes the map easily exported in different scales for distinct applications. Figure 8 shows the inundation potential maps, overlapped with the township division layers, of the Tainan County on southwest part of the island. The information helps the county government realizing flood potential within its administration. The east regions of the county are upstream mountainous areas with lower flood risks. On the contrast, the Sinshih Township, where the Southern Taiwan Science Park (STSP) is located in, and the southwest costal regions are identified as the area with the highest flood risks. From Table VI and Table VII, we can find that there is 117.8 km^2 of areas in the county could be inundated more than once in a year and 578.6 km^2 has a exceedence probability 0.008 of being flooded per year.

The STSP is Taiwan's second science-based industrial park, specializing in microelectronics, semiconductors, and agricultural biotechnology industries. The park was scheduled as two stages for development. The first stage with 638 hectares evolution area was started at 1997 and will be completed by the end of 2005. The second stage with another 400 hectares developing area was planned to be finished in 2010. The base site of STSP was selected before the approving of inundation potential database. Lacking of the flood-related information and historical records, the flood risk was not well-considered until a serious flood event happened in 1998 when the park was under construction. Figure 9 displays the detailed inundation potential around the base area of STSP. The high flood risk could affect the normal operations of investors.

The government spent tremendous efforts and budgets on the flood-proofing measures for the first development stage, including raising the ground surface elevation of the base area, building storm drainage systems and detention ponds. The ground surface of the base area of the first development stage was elevated to prevent the flood with 200-year occurrence interval. Four storm sewer systems, designed by rainfall with 25-year occurrence interval, were constructed to collect the surface runoffs within the park. Four detention ponds with total areas of 45 hectares were built, at outlets of each sewer system, for reducing the peak outflow discharges which may impact the downstream regions. Figure 10 demonstrates that the flood-proofing measures, which cost 53 million U.S. dollars, for the first development stage successfully reduced the flood risk. The flooded area of the scenario with 600 mm daily total rainfall was reduced from 484 to 168 hectares, where the flooded locations after the flood-proofing measures are the detention ponds and drainage improvement.

Currently, the government continues planning the follow-up flood-proofing measures by using the inundation potential database to mitigate the flood hazard for the base area of the second development stage.

6. Applications

6.1 Land use management

The site selection of STSP was a painful experience. To avoid recommitting again in the future, the inundation potential database has taken an important role in the floodplain managements. Nowadays, the government indicates the inundation potential, by applying the database, for urban planning to keep from inappropriate land use. The areas with high flood risk are announced by the authorities as evolution-forbidden. Further, the emergency response strategies, such as rescuing resources allocating, evacuating routes and shelters planning, are also established by using the database. The database is also used for setting the proper flood prevention strategies for hazard mitigation, both structural and non-structural measures.

6.2 Flood warning and emergency response

For emergency responses for flooding, a decision support system (DSS) is developed to help the commanders identifying the inundation potential. The island-wide real time precipitation records are collected and updated with a 10 minute frequency by the system. The real time rainfall conditions are analyzed and compared to the design rainfall patterns that used for building the inundation potential database. The inundation potential information which was generated by the closest pattern to the real time rainfall condition is automatically picked up from the database by watershed divisions individually in the system. The information is displayed as a map that overlapped with other spatial information layers, such as streets, rivers, buildings and districts. Once the inundation potential risks are identified, there are usually 2 or 3 hours before floods occurring. Emergency managers can issue the flood warning to residents in high flood risk areas and evacuate them to safe shelters through appropriate routes.

Figure 11 shows the inundation potential map of the south Pingtung County, the most southern county of Taiwan, that was automatically selected by the DSS during typhoon Melor event in 2003. The emergency managers issued warnings and evacuated residents in the high inundation potential areas by using the DSS. Figure 12 displays the reported flood area of the same region. It reveals that the application of inundation potential map successfully helped the commanders to reduce the damage of flood.

6.3 Flood proof measures

In 2001, the Academia Sinica, a famous research institute in Taiwan, suffered a tremendous loss caused by the flood brought by typhoon Nari. Dozens of building were submerged and many valuable books, equipments and research records were damaged. After the event, the administrator of the Academia Sinica decided to enhance the flood proof measures of buildings and the rainfall with 200-year occurrence interval was set as protection standard. The surface elevations in the academy area and heights of building entrances were surveyed. Hence, the inundation potential in the area was updated by using higher grid resolution 20 m x 20 m and rainfalls with different occurrence intervals. By overlapping the inundation potential with the entrance elevations, the building entrances lower than the flood level were clearly identified in Figure 13. The information helped the administrator determining flood proof measures of the Academia Sinica.

6.4 Flood risk zoning

Figure 14 demonstrates the inundation potential map of the Mujha area, a district in southern Taipei, with 600 mm total rainfall in 24 hours. The area is too densely developed to build any flood control structures. Hence, the non-structural measures must be conducted. Accordingly, the area is categorized into 3 classes of zoning based on the inundation potential maps. The Zoning 1 has the highest risk during floods and first priority to evacuate the citizen lives in to the nearest shelters, where are selected public buildings with lowest risk of flood. Then, the Zoning 2 would be the next for rescuing and resources allocating.

6.5 Damage estimating and flood insurance

After the flood events, in addition to the investigation of flood extents and depths in the affected areas, the post flood questionnaire surveys might also be proceeded among the individuals and communities to estimate the economic damages caused by flood (Dutta et al., 2001). The investigations build the database of stage-damage functions. Incorporating with the database of inundation maps, the potential losses accompanying with the flood scenarios could be evaluated. The information helps decision makers for setting proper flood mitigation measures to reduce the damage losses. Besides, it could also be used for the flood insurance programs to determine the insurance premium rates.

7. Conclusions

The inundation potential database of Taiwan was conducted by numerical simulations of models. It provides important information for flood hazards mitigation and helps the public to realize the potential flood risk of the environment. The flood defense authorities and the governments of different levels have adopted the information for implementing the flood mitigation measures and flood defense strategies.

References

Abbott, M. B.: 1998, *Computational Hydraulics*, Ashgate Publishing Company, Vermont, 59-62.

Al-Sabhan, W., Mulligan, M., and Blackburn, G. A.: 2003, A real-time hydrological model for flood prediction using GIS and the WWW, *Computers, Environmental and Urban Systems*, **27**, 9-32.

Bae, D. H., Georgakakos, K. P., and Nanda, S. K.: 1995, Operational forecasting with real-time databases, *Journal of Hydraulic Engineering-Asce*, **121**(1), 49-60.

Bishop, W. A., and Catalano, C. L.: Year, Benefits of two-dimensional modelling for urban flood projects, In: *6th Conference on Hydraulics in Civil Engineering*, Hobart, Australia.

Bohm, H. R., Haupter, B., Heiland, P., and Dapp, K.: 2004, Implementation of flood risk management measures into spatial plans and policies, *River Research and Applications*, **20**(3), 255-267.

Burby, R. J.: 2001, Flood Insurance and Floodplain Management: the US Experience, *Environmental Hazards*, **3**, 111-122.

Cabinet Office, G. o. J.: 2003, *White paper on disaster management*, Cabinet Office, Government of Japan.

Chang, T. J., Hsu, M. H., Teng, W. H., and Huang, C. J.: 2000, A GIS-assisted distributed watershed model for simulating flooding and inundation, *Journal of the American Water Resources Association*, **36**(5), 975-988.

Changnon, S. A.: 1998, The historical struggle with floods on the Mississippi River basin - Impacts of recent floods and lessons for future flood management and policy, *Water International*, **23**(4), 263-271.

Chen, S. H., Hsu, M. H., and Chen, T. S.: Year, The integrated inundation model for urban drainage basins, In: *5th international conference on sustainable techniques and strategies in urban water management*, Lyon, France.

Chow, V. T.: 1988, *Applied hydrology*, McGraw-Hill Book Company, New York, 465-470.

Cunge, J. A., Holly, F. M., and Verwey, A.: 1980, *Practical aspects of computational river hydraulics*, Pitman Publishing Ltd., London, U.K.

Djordjevic, S., Prodanovic, D., and Maksimovic, C.: 1999, An approach to simulation of dual drainage, *Water Science Technology*, **39**(9), 95-103.

Dutta, D., Herath, S., and Musiake, K.: Year, Direct flood damage modeling wowards urban flood risk management, In: *Joint Workshop on Urban Safety Engineering 2001*, Thailand, Asian Intitute of Technology.

Gunes, A. E., and Kovel, J. P.: 2000, Using GIS in emergency management operations, *Journal of Urban Planning and Development-Asce*, **126**(3), 136-149.

Harman, J., Bramley, M. E., and Funnell, M.: 2002, Sustainable flood defence in England and Wales, *Proceedings of the Institution of Civil Engineers-Civil Engineering*, **150**, 3-9.

Hooijer, A., Klijn, F., Pedroli, G. B. M., and Van Os, A. G.: 2004, Towards sustainable flood risk management in the Rhine and Meuse river basins: Synopsis of the findings of IRMA-SPONGE, *River Research and Applications*, **20**(3), 343-357.

Hooper, B. P., and Duggin, J. A.: 1996, Ecological Riverine Floodplain Zoning, *Land use Policy*, **13**(2), 87-99.

Hsu, M. H.: Year, Simulation of inundation with overflow on levee along Keelung River, In: *The CCNAA-AIT Joint Seminar on Prediction and Damage Mitigation of Meteorologically Induced Natural Disasters*, Taipei, Taiwan.

Hsu, M. H.: 1998, *Inundation study for stations and depots of Taiwan High Speed Rail*, Hydraulic Research Laboratory, National Taiwan University.

Hsu, M. H., Chen, S. H., and Chang, T. J.: 2002, Dynamic inundation simulation of storm water interaction between sewer system and overland Flows, *Journal of the Chinese Institute of Engineers*, **25**(2), 171-177.

Hsu, M. H., Fu, J. C., and Liu, W. C.: 2003, Flood routing with real-time stage correction method for flash flood forecasting in the Tanshui River, Taiwan, *JOURNAL OF HYDROLOGY*, **283**(1-4), 267-280.

Hsu, M. H., Lai, J. S., and Yen, C. L.: Year, Two-dimensional inundation model for Taipei City, In: *Proceedings of the Fifth International Conference on Urban Storm Drainage*, Osaka, Japan.

Hsu, M. H., Teng, W. H., and Wu, F. C.: 1998, Inundation models for the Pa-chang creek basin in Taiwan, *Proc. National Science Council ROC*, **22**(2), 279-289.

Huber, W. C.: 1975, *Model for Storm Water Strategies*, APWA Reporter.

Huber, W. C., and Dickinson, R. E.: 1988, *Storm Water Management Model. User's Manual Ver. IV*, U. S. Environmental Protection Agency.

Klijn, F., van Buuren, M., and van Rooij, S. A. M.: 2004, Flood-risk management strategies for an uncertain future: Living with Rhine river floods in the Netherlands? *Ambio*, **33**(3), 141-147.

Lee, K. T., Yu, W. S., Yang, M. S., and Shih, H. M.: 1999, *The ananlysis of flood disaster in Shiji area during typhoon Zeb and Babs events*, Department of River and Harbor Engineering, National Taiwan Ocean University.

Lin, L.: 2002, *The statistical analysis on natural disasters Taiwan-Fuchien area*, MOI Statistical information service.

Lowe, A. S.: 2003, The federal emergency management agency's multi-hazard flood map modernization and The national map, *Photogrammetric Engineering and Remote Sensing*, **69**(10), 1133-1135.

Middelkoop, H., Van Asselt, M. B. A., Van't Klooster, S. A., Van Deursen, W. P. A., Kwadijk, J. C. J., and Buiteveld, H.: 2004, Perspectives on flood management in the Rhine and Meuse rivers, *River Research and Applications*, **20**(3), 327-342.

Murphy, D.: 2003, *Strategy for flood risk management (2003 - 2008)*, Environment Agency, U.K.

National Science Foundation: 1980, *A report on flood hazard mitigation*, National Science Foundation.

Sijhih City Household Registration Office: 2004, The household and total population statistic information of Sijhih City. Sijhih City Household Registration Office, Taipei County Government, Taipei County.

Simonovic, S. P.: 2002, Two new non-structural measures for sustainable management of floods, *Water International*, **27**(1), 38-46.

Subramaniam, C., and Kerpedjiev, S.: 1998, Dissemination of weather information to emergency managers: A decision support tool, *Ieee Transactions on Engineering Management*, **45**(2), 106-114.

Sullivan, A., Ternan, J. L., and Williams, A. G.: 2004, Land use change and hydrological response in the Camel catchment, Cornwall, *Applied Geography*, **24**(2), 119-137.

U.S. Army Corps of Engineers Hydrologic Engineering Center: 1992, *HEC-1 hydrograph package*, Water Resources Support Center.

Water Resources Agency: 2003, *Hydrological year book of Taiwan Republic of China 2002, Part I - Rainfall*, Water Resources Agency, Ministry of Economic Affairs, ISSN 0257.5442.

Wu, C. M.: Year, The regulation of river and flood defense, In: *When will the flood disasters end? - Proceeding of flood disaster and defenses conference*, Taipei, Chinatimes cultural and educational fundation.

Yeo, S.: 2003, Flood risk management for caravan parks in New South Wales, *Australian Geographer*, **34**(2), 195-209.

Zerger, A., and Wealands, S.: 2004, Beyond modelling: Linking models with GIS for flood risk management, *Natural Hazards*, **33**(2), 191-208.

Appendix A: Abbreviations

DEM	:	Digital Elevation Model
DTM	:	Digital Terrain Model
EA	:	Environment Agency of U.K.
EOI	:	Equivalent Occurrence Interval
FEMA	:	Federal Emergency Management Agency of U.S.
FIA	:	Federal Insurance Administration of U.S.
GIS	:	Geographical Information System
NAPHM	:	National Science and Technology Program for Hazards Mitigation
NFIP	:	National Flood Insurance Program
SWMM	:	Storm Water Management Model
STSP	:	Southern Taiwan Science Park

Table I. The flood disasters occurrence, induced by typhoons and severe storms, between 1972 and 2001 in Taiwan and the average no. of each consecutive 5 years

year	disasters in 5 years (times)			average disasters in a year (times)		
	typhoon	Severe storm	sum	typhoon	severe storm	sum
1972 - 1976	11	4	15	2.2	0.8	3.0
1977 - 1981	13	5	18	2.6	1.0	3.6
1982 - 1986	16	3	19	3.2	0.6	3.8
1987 - 1991	21	7	28	4.2	1.4	5.6
1992 - 1996	21	6	27	4.2	1.2	5.4
1997 - 2001	23	5	28	4.6	1.0	5.6

Table II. Typhoon events caused heavy casualties in recent years

year	typhoon event	death/ missing	injured
1996	Herb	73	463
1997	Winnie	28	46
1998	Zeb, Babs	17	8
2000	Xangsane	89	65
2001	Trami, Toraji	219	192
2001	Nari	104	265
2004	Mindulle	41	16

Table III. The calibrated Manning's roughness for various types of land use for the Sijhih City

land use	Manning's roughness
cultivate and wood land	0.200
highway, road	0.030
industrial area	0.075
park	0.150
residential area	0.100
waterway	0.020
others	0.050

Table IV. The field survey records and simulation results of flooded area and maximum inundation depth in the Sijhih City during typhoon Zeb, Babs and Xangsane events

typhoon event	recorded flood		simulated flood	
	area (hectare)	max. inundation depth (m)	area (hectare)	max. inundation depth (m)
Zeb	291	4.0	293.2	4.15
Babs	286	3.8	287.5	3.93
Xangsane	356	7.5	364.8	8.00

Please cite as: Chen AS, Hsu MH, Teng WH, Huang CJ, Yeh SH, Lien WY. (2006) Establishing the database of inundation potential in Taiwan, Natural Hazards, 37 (1-2), 107-132, DOI:10.1007/s11069-005-4659-7.

Table V. The total rainfalls in 24 hours of different occurrence intervals for each county in Taiwan

County	rainfalls with different occurrence intervals (mm)					
	5 year	10 year	25 year	50 year	100 year	200 year
Changhua	250	303	373	426	480	536
Chiayi	335	399	474	526	575	621
Hsinchu	269	315	369	407	442	475
Hualien	443	530	600	706	773	842
Kaohsiung	352	413	484	533	580	624
Keelung	264	312	381	437	498	564
Miaoli	281	345	406	482	540	595
Nantou	354	420	497	550	600	648
Pingtung	342	411	472	553	613	673
Taichung	354	420	497	550	600	648
Tainan	330	410	480	530	580	625
Taipei	330	374	426	463	505	550
Taitung	379	445	498	580	634	685
Tauyuan	335	399	474	526	575	621
Yilan	458	549	654	728	797	863
Yunlin	236	276	322	354	385	413

Table VI. The equivalent occurrence interval (EOI) and exceeding probability (EP) of different total rainfalls in 24 hours for each county in Taiwan

County	150 mm		300 mm		450 mm		600 mm	
	EOI (year)	EP	EOI (year)	EP	EOI (year)	EP	EOI (year)	EP
Changhua	1.4	0.698	9.8	0.102	67	0.015	457	0.002
Chiayi	< 1	> 1	2.9	0.345	20	0.050	140	0.007
Hsinchu	< 1	> 1	8.0	0.125	115	0.009	> 500	< 0.002
Hualien	< 1	> 1	1.3	0.769	5.0	0.200	20	0.050
Kaohsiung	< 1	> 1	2.2	0.455	17	0.059	132	0.008
Keelung	< 1	> 1	8.0	0.125	55	0.018	360	0.003
Miaoli	1.0	1.00	6.0	0.167	35	0.029	205	0.005
Nantou	< 1	> 1	2.3	0.435	15	0.067	100	0.010
Pingtung	< 1	> 1	3.2	0.313	17	0.059	90	0.011
Taichung	< 1	> 1	3.2	0.313	22	0.046	150	0.007
Tainan	< 1	> 1	2.8	0.357	19	0.053	130	0.008
Taipei	< 1	> 1	4.8	0.208	40	0.025	330	0.003
Taitung	< 1	> 1	1.8	0.556	11	0.091	68	0.015
Tauyuan	< 1	> 1	2.9	0.345	20	0.050	140	0.007
Yilan	< 1	> 1	1.1	0.909	4.0	0.250	17	0.059
Yunlin	< 1	> 1	17	0.059	400	0.0025	> 500	< 0.002

Table VII. The inundation potential areas with different total rainfalls in 24 hours of each county in Taiwan

County	areas with different total rainfalls in 24 hours (km^2)			
	150 mm	300 mm	450 mm	600 mm
Keelung	2.3	4.6	5.8	6.4
Taipei	23.1	40.6	57.8	77.7
Tauyuan	11.0	30.8	53.9	149.8
Hsinchu	14.1	29.6	41.8	59.8
Miaoli	28.2	45.7	60.7	73.4
Taichung	16.8	44.2	77.0	108.2
Changhua	25.2	96.2	194.1	288.6
Nantou	9.5	20.8	32.6	47.8
Yunlin	68.7	221.2	360.2	463.6
Chiayi	48.8	143.0	227.9	300.9
Tainan	117.8	306.6	456.2	578.6
Kaohsiung	35.8	97.8	153.7	199.3
Pingtung	90.5	160.4	218.8	235.0
Taitung	14.4	27.9	37.1	44.6
Hualien	22.0	34.9	47.4	57.6
Yilan	5.2	42.1	74.6	99.3

Figure 1. The satellite image of the Sijhih City in 1988
(source: Center for Space and Remote Sensing Research, National Central University, Taiwan)

Figure 2. The satellite image of the Sijhih City in 1998
(source: Center for Space and Remote Sensing Research, National Central University, Taiwan)

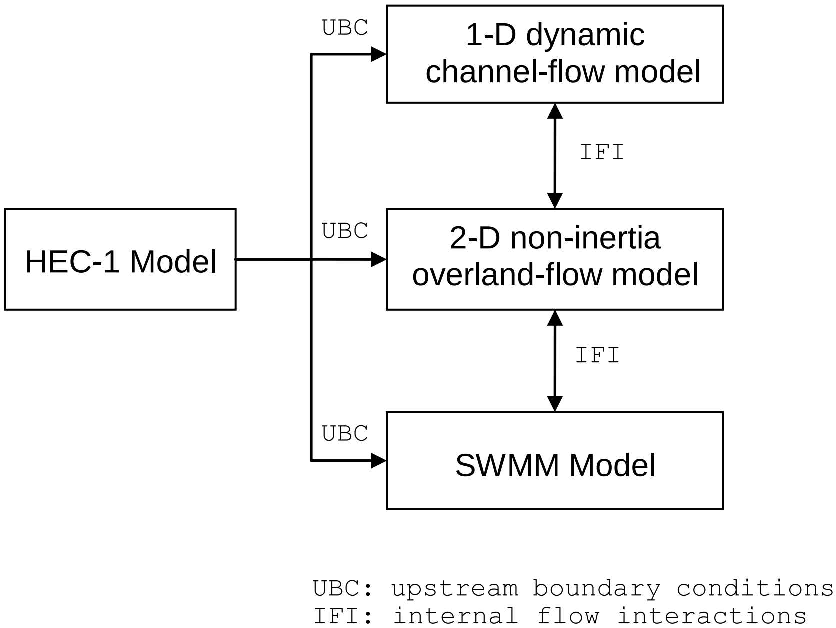
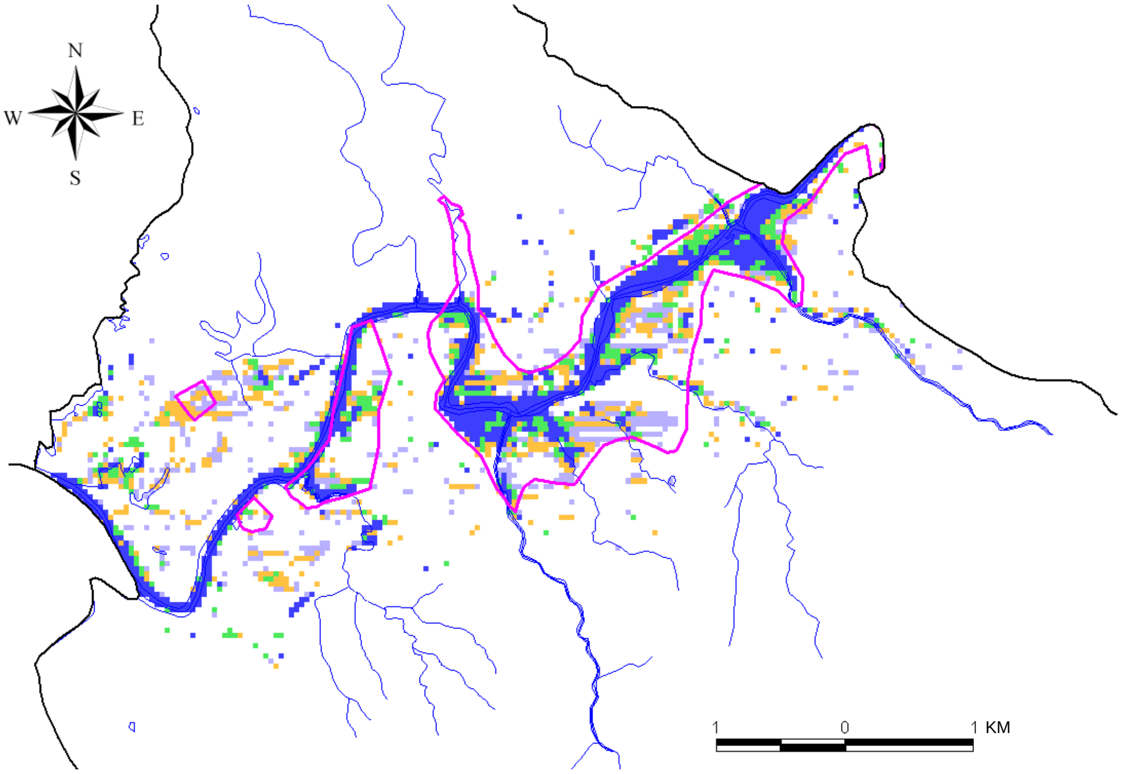
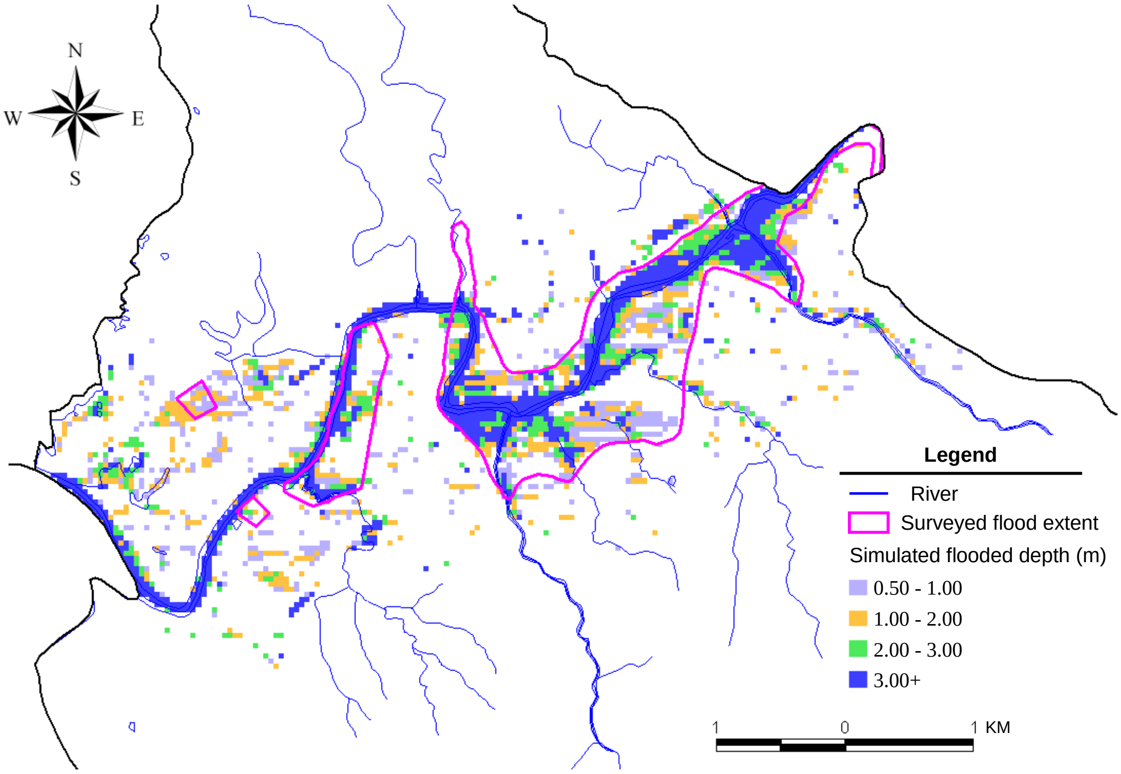


Figure 3. Relationships between numerical components for inundation potential simulations



(a) typhoon Zeb event



(b) typhoon Babs event

Figure 4. Model calibrations of the Sijhih City

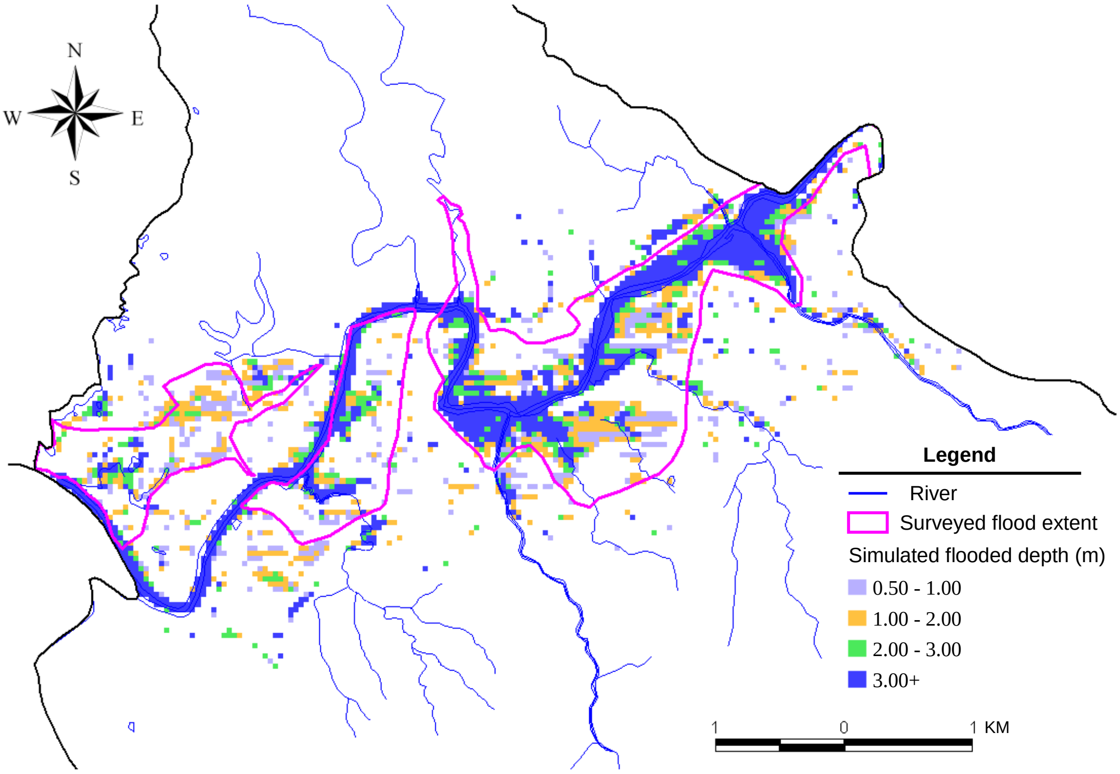
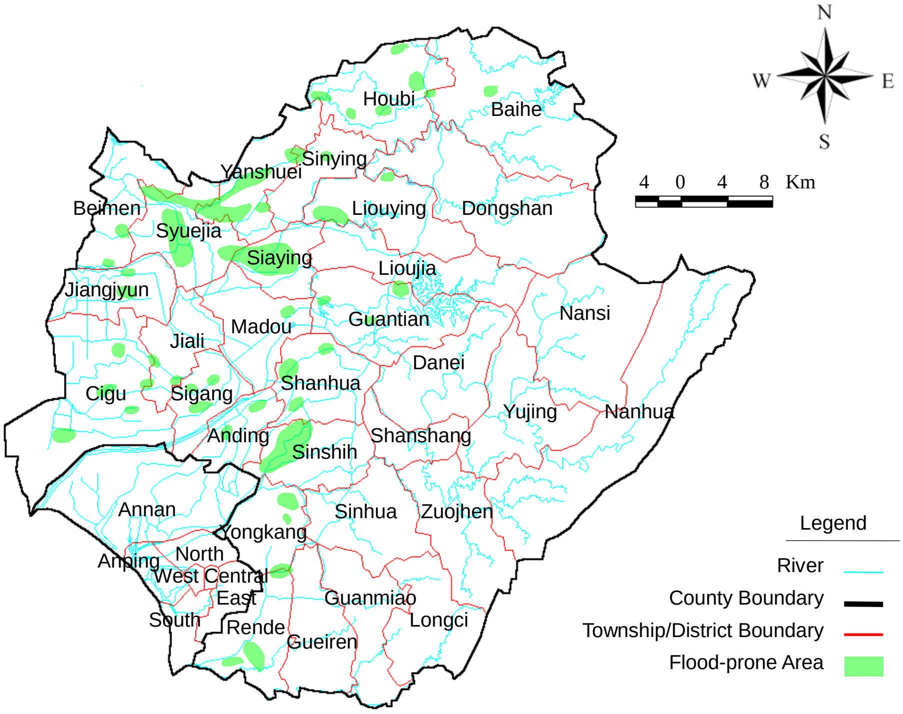
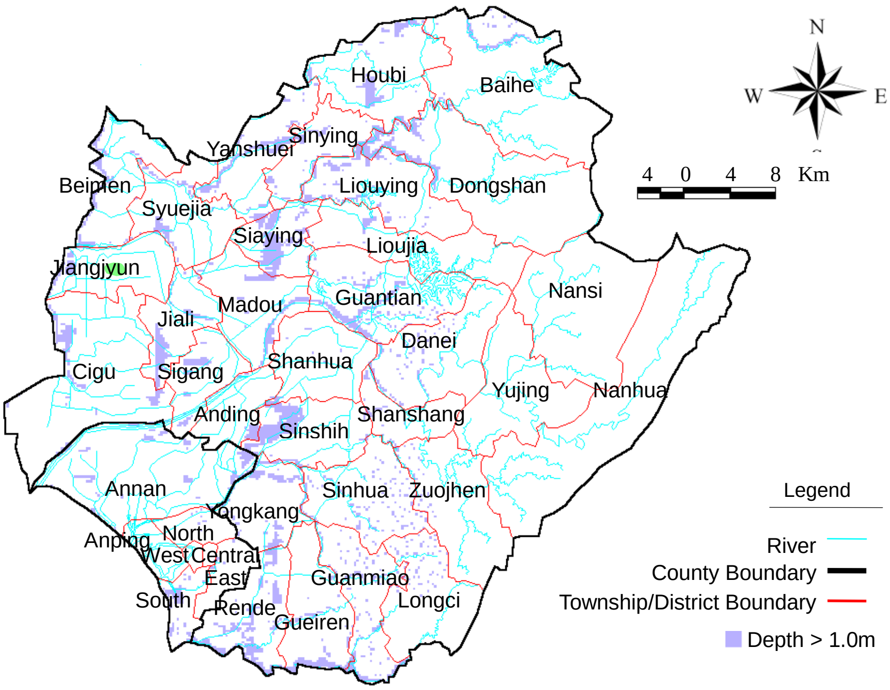


Figure 5. Model verification of the Sijhih City by using typhoon Xangsane event



(a) The flood-prone areas delineated by the local government



(b) Simulated flood extents of rainfall event with 5-year occurrence interval

Figure 6. The model verification in Tainan County

Please cite as: Chen AS, Hsu MH, Teng WH, Huang CJ, Yeh SH, Lien WY. (2006) Establishing the database of inundation potential in Taiwan, Natural Hazards, 37 (1-2), 107-132, DOI:10.1007/s11069-005-4659-7.

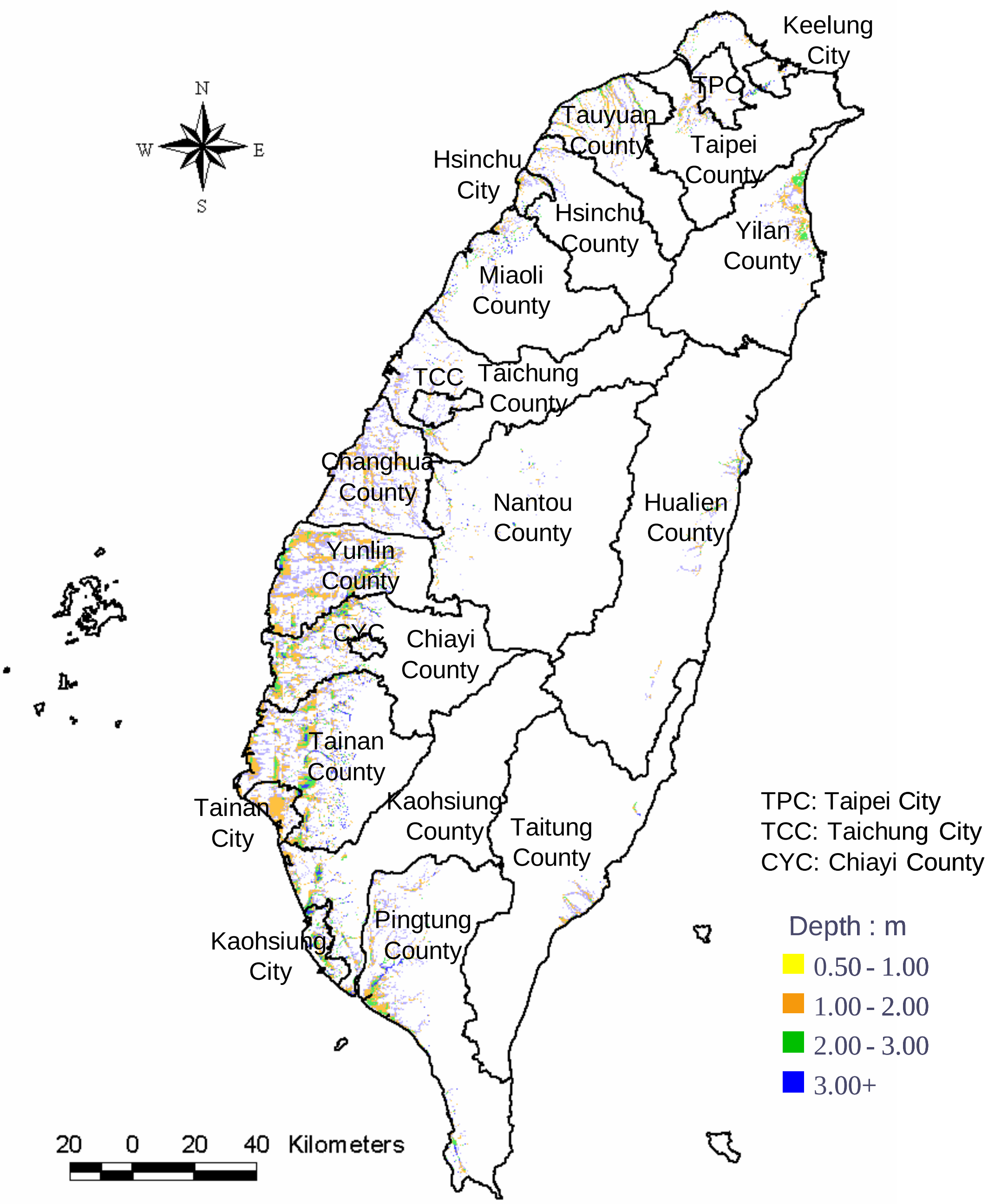
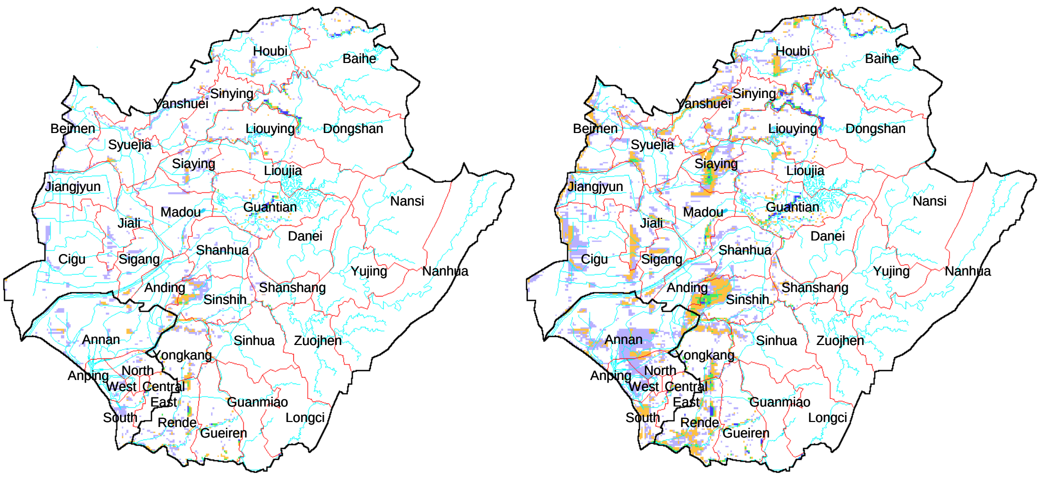
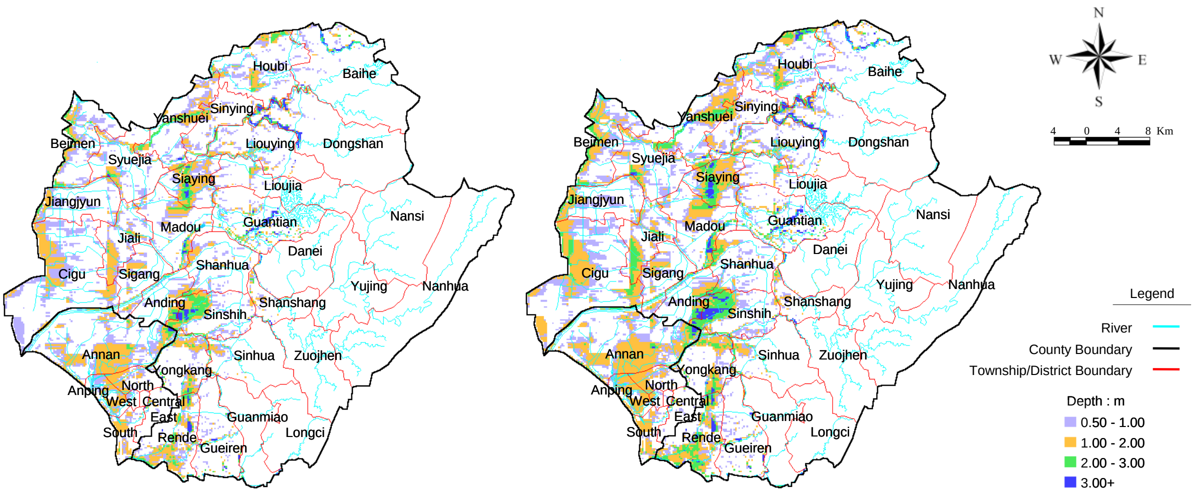


Figure 7. The inundation potential map of Taiwan
(with 600 mm rainfall in 24 hours)

Please cite as: Chen AS, Hsu MH, Teng WH, Huang CJ, Yeh SH, Lien WY. (2006) Establishing the database of inundation potential in Taiwan, Natural Hazards, 37 (1-2), 107-132, DOI:10.1007/s11069-005-4659-7.



(a) 150 mm rainfall in 24 hours (b) 300 mm rainfall in 24 hours



(c) 450 mm rainfall in 24 hours (d) 600 mm rainfall in 24 hours

Figure 8. The inundation potential maps of Tainan County

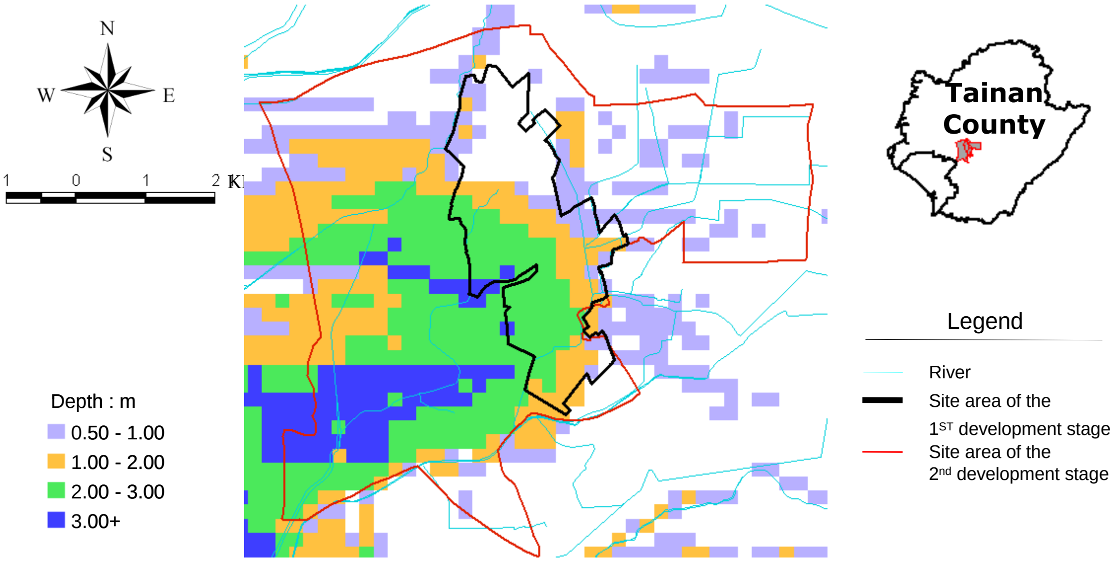


Figure 9. The inundation potential map of STSP without flood-proofing measures (600 mm rainfall)

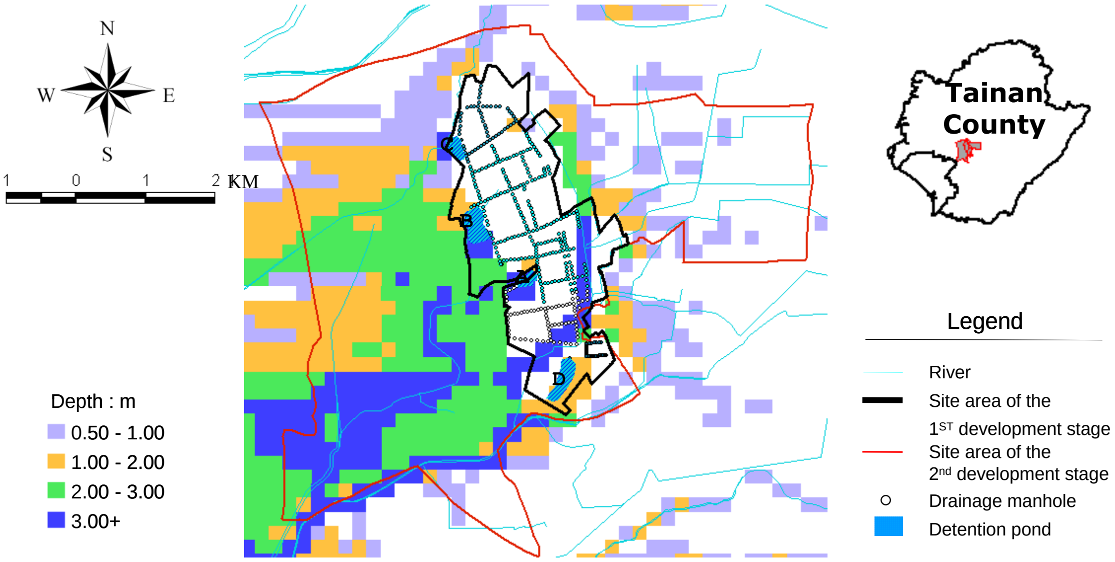


Figure 10. The inundation potential map of STSP with flood-proofing measures for the first development stage (600 mm rainfall)

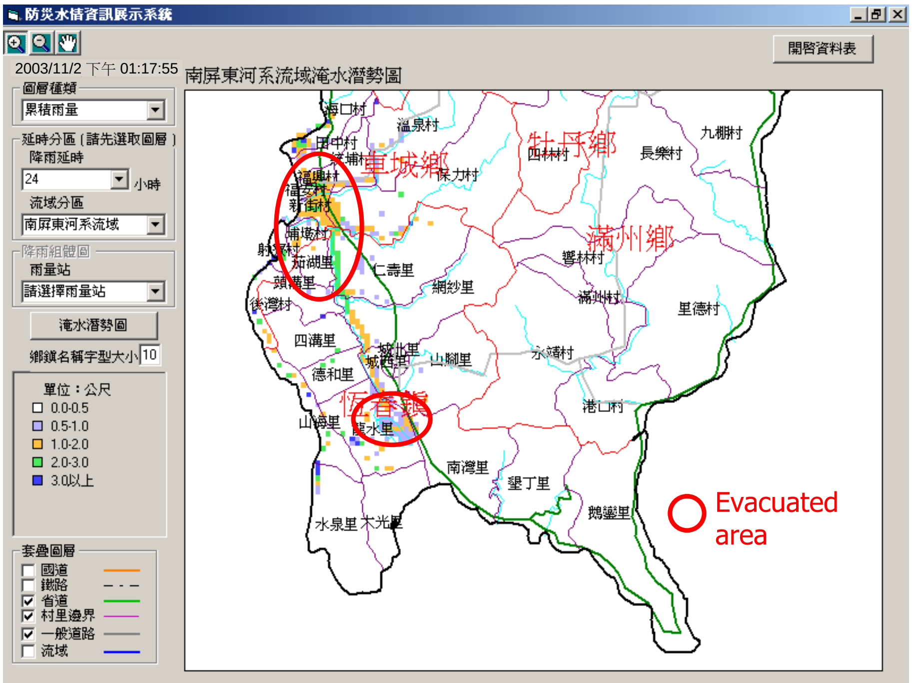


Figure 11. The inundation potential map selected by the decision support system and the evacuated area of the south Pingtung County during typhoon Melor event

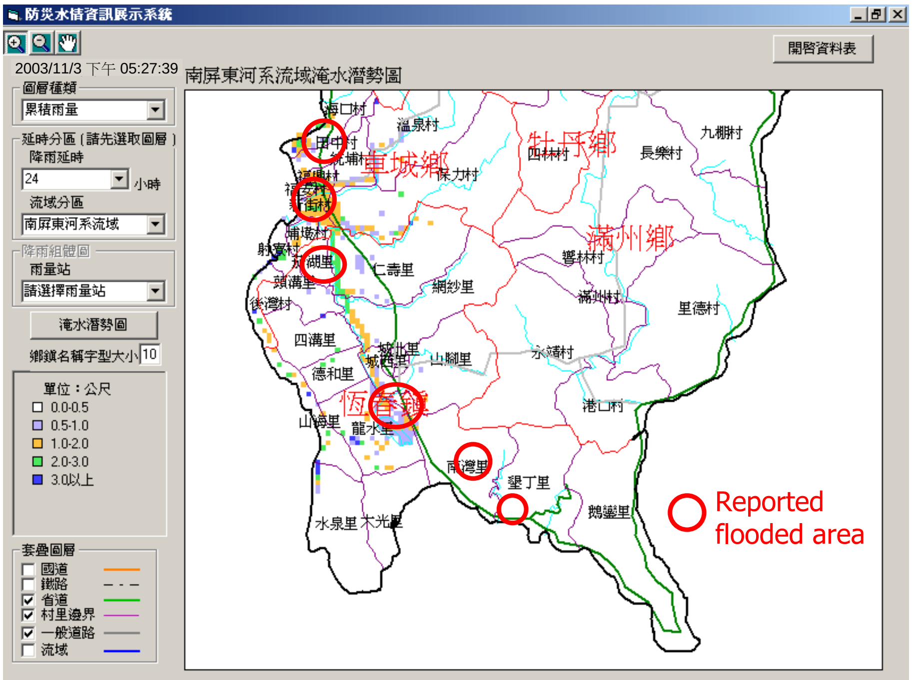


Figure 12. The inundation potential map selected by the decision support system and the reported flood area of the south Pingtung County during typhoon Melor event

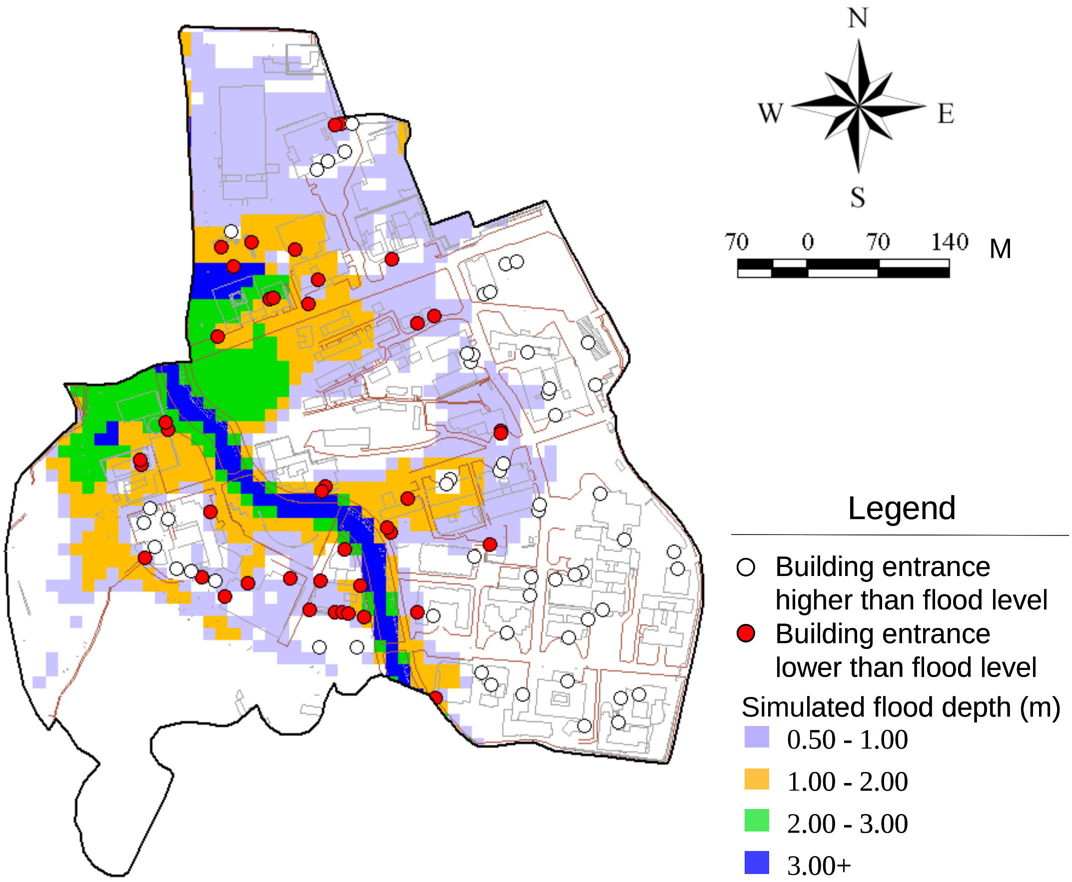


Figure 13. The application of inundation potential to the Academia Sinica

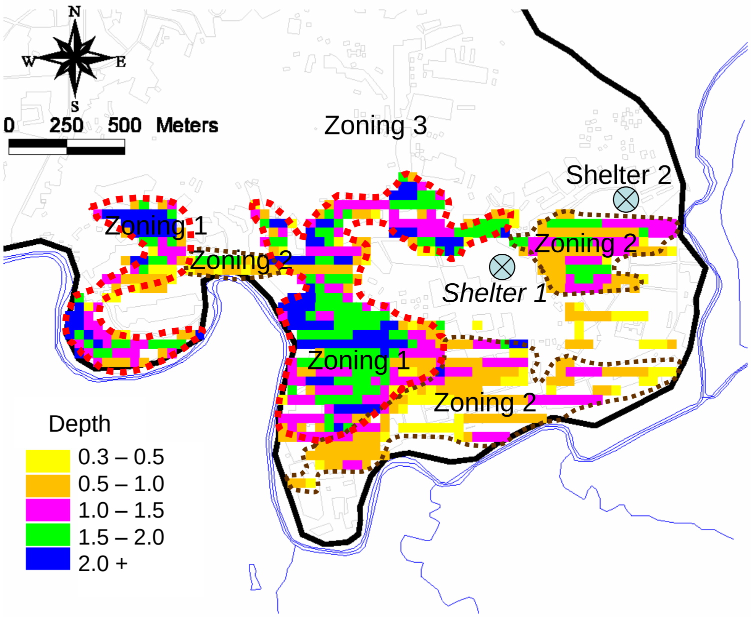


Figure 14. The flood risk zonings and emergency shelters in the Mujha area

Reviewer A's Comments:

Manuscript presents the development of flood risk maps (in digital form) for Taiwan. Inundation potential has been estimated by simulation (integrated use of hydrologic rainfall-runoff and hydraulic flood routing models). Paper is very poorly written. English language is not at the level required for the publication in the scientific Journal. There are many assumptions used in the process that author did not discuss. Calibrations and verification results are not properly presented. I am recommending rejection of the paper in the current form. Authors should be encouraged to revise and resubmit the manuscript. Re-review will be required. If the authors decide to revise the following questions should be addressed in their revision.

Response:
The authors appreciate for the valuable comments. The paper has been rewritten into detail about calibration and verification.

Detailed Comments:
Page2, 3 - Introduction. The authors are quoting only Japan, UK, USA and Taiwan experience in planning flood control measures. Why are only these four examples selected? What is common between Japan, UK, USA and Taiwan? How is the experience in Japan, USA and UK used in Taiwan? What about other examples? What about examples in countries with similar climate? What about examples in countries at the similar level of development?

Response:
Japan and UK are both island countries that have similar geographic environments to Taiwan. Especially, Japan suffers many typhoon attacks and the urban areas are densely developed. The situations are close to the ones that Taiwan faces. Meanwhile, the NFIP of USA is a comprehensive application of flood hazard maps. The experiences in above countries inspired Taiwan to establish its own inundation potential database. Actually, there are also many applications of non-structural flood defense measures in other countries or regions. Some of those (Bae et al., 1995; Bohm et al., 2004; Hooijer et al., 2004; Middelkoop et al., 2004; Simonovic, 2002; Subramaniam and Kerpedjiev, 1998) are reviewed in the revised version.

Page4, 5, 6, 7 – Methodology. Presented methodology is based on the use of HEC-1, SWMM, and two flood routing models (1-D and 2-D). Original elements are quite old (from 1970s). Today there are some standard packages being used all over the world like MIKE 11, MIKE 21, HEC-RAS end other. It will be important that in this section authors clearly justify their choice of models.

Response:
The HEC-1 is widely adopted by many researches in the world and used as the kernel engine of the well-known WMS commercial package. Meanwhile, there were many studies using HEC-1 in Taiwan. Adopting the HEC-1 model saved much time and effort to rebuild the input data. SWMM is the most popular storm management model and also used as kernel engine of many packages like MIKE, XP-SWMM, etc. Above all, the source codes is public available and modified by the authors for tight combination with 2-D overland flow model (Hsu et al., 2002), which reflects the interactions between overland and sewer flows better than other models.

Page8, 9 – Calibration and verification. This is one of the weakest sections of the paper. There are a number of questions to be elaborated here. What calibration data is used in this study? What was the vertical resolution used in the grid (of great importance for overland flooding in flat areas)? How is the spatial variation in precipitation taken into account? Visual comparison of results (for example figure 3 and 4; figures 5 and 6) is not at the level of scientific paper. Are there any calculated values (statistical measures) to support the verification results?

Response:
In Taiwan, the flood-related information is seldom recorded during floods, neither after the disasters. The field surveys are only proceeded after major flood events, and most of the records are quite simple and contain limited information for detailed analysis. For watersheds with proper records of events, the precipitation data of rain gauges in neighborhoods were input in the models for calibrations and verifications. The simulated results were compared to the investigation records of flood extents, statistical area, depths, etc. Therefore, the model calibration and verification is highly dependent to the available records.
As building the inundation potential database, the spatial distribution of rainfall was assumed uniform within the same watershed for simplification. More scenarios for different spatial and temporal distributions of precipitation will be considered in the future to expanding the database. More statistical information is provided in the revised version to explain the model calibration and verification processes.

Page9, 10, 11 – Construction of the database. Why are the inundation risk maps called the database? I would like much more serious discussion of the choice of 24-hour design rainfall?????? Results are presented at different scales? However, there is no indication how is the accuracy changing with the change of scale? Again separate illustrations in figures 10 and 11 do not allow clear identification of the difference.

Response:
The simulation results are in digital format. It is necessary to coordinate the information in order to be queried by setting user-defined criteria for analyses, and transformed into different forms for different purposes. By using a database, the information can be easily integrated and used for further applications. The flood risk map is just one of the output forms of the database. The accuracy of the inundation potential depends on the input data for numerical simulations, which is not subjected to the output scale. The statistical flooded areas are compared in the revised paper to show the difference before and after the flood-defense measures of the science park.

In conclusion, the paper is a mix of different material intended to illustrate quite an important study. I would recommend that the authors change the emphasis of the paper and devote much more attention to the presentation of one issue. Since the methodology is not offering anything new I would recommend refocusing the paper on the application.

Response:
The article has been rearranged and the detailed descriptions of methodology are omitted in order to focus on the establishing and applications of the inundation potential database.

Reviewer B's Comments:

The authors applied a series of numerical models to determine the inundation potential in Taiwan. This information should be useful to decision-makers for the planning of flood hazard mitigation strategies with non-structural measures. The paper is generally well written. However, prior to the publication, the authors should consider the following suggestions:

1. **The proposed alternating direction explicit (ADE) scheme is conditionally stable.**

   Please provide stability criteria for this scheme.

Response:
The paper has be rewritten and the detailed descriptions of the models can be found in authors' earlier study (Hsu et al., 2002).

2. **The model calibration and verification section is weak (Section 3). In terms of model parameter calibration, please show the calibration criterion used. Is it the standard least-squares error minimization? Show the objective function and constraints as well as some typical calibration results, i. e., the calibrated parameter values and the rate of convergence in calibration. Is the calibration done by trial-and-error or by an algorithm?**

Response:
The model calibration and verification are highly relevant with the available event records. The more information were collected and used for simulation, the more accuracy that parameters can be tuned and verified. The section is rewritten to explain the processes.

3. **The following papers listed under References do not appear to be cited in the text: Hsu et al. (2002); Computational Hydraulic Int.(2002); DHI Software (2002); and XP Software Inc. (2002).**

Response:
The citing and typing errors have been corrected in the revised version.