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Urbanization and climate change impacts on future urban flood risk in Can Tho city, Vietnam

H. T. L. Huong[1] and A. Pathirana[2]

[1]Vietnam Institute of Meteorology, Hydrology and Environment, Hanoi, Vietnam
[2]UNESCO-IHE, Institute for Water Education, Westvest 7, Delft, The Netherlands

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Correspondence to: A. Pathirana (a.pathirana@unesco-ihe.org)

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Abstract

Urban development increases flood risk in cities due to local changes in hydrological and hydrometeorological conditions that increase flood hazard, and also to urban concentrations that increase the vulnerability. The relationship between the increasing urban runoff and flooding due to increased imperviousness better perceived than that between the cyclic impact of urban growth and the urban rainfall via microclimatic changes. The large-scale, global impacts due to climate variability and change could compound these risks. We present the case of a typical third world city – Can Tho (the biggest city in Mekong River Delta, Vietnam) – faced with multiple future challenges, namely: (i) climate change-driven sea-level rise and tidal effect, (ii) increase river runoff due to climate change, (iii) increased urban runoff driven by imperviousness, and (iv) enhancement of extreme rainfall due to urban growth-driven micro-climatic change (urban heat islands). A set of model simulations were used to assess the future impact of the combination of these influences. Urban growth of the city was projected up to year 2100 based on historical growth patterns, using a land-use simulation model (Dinamica-EGO). A dynamic limited-area atmospheric model (WRF), coupled with a detailed land-surface model with vegetation parameterization (Noah LSM), was employed in controlled numerical experiments to estimate the anticipated changes in extreme rainfall patterns due to urban heat island effect. Finally, a 1-D/2-D coupled urban-drainage/flooding model (SWMM-Brezo) was used to simulate storm-sewer surcharge and surface inundation to establish the increase in the flood risk resulting from the changes. The results show that, if the city develops as predicted, the maximum of inundation depth and area in Can Tho will increase by about 20 %. The impact of climate change on inundation is more serious than that of urbanization. The worse case may occur if the sea level rises 100 cm and the flow from upstream happen in the high-development scenarios. The relative contribution of causes of flooding are significantly different at various locations; therefore, detailed research on adaptation are necessary for the future investments to be effective.

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1 Introduction

In 2008, for the first time in the history of human civilization, more than half of the world's population was living in cities. By 2030, the urban population will reach 5 billion – 60 % of the world's population (UN, 2006). The increase in population in urban areas occurs more in the developing countries than developed countries. Many cities in the developing world are growing rapidly due to real population growth but a much larger extent due to migration from rural areas to the cities and transformation of rural settlements into cities. The result is an uncontrolled urban sprawl with increasing human settlements, industrial growth and infrastructure development (UN, 2006).

Urbanization invariably increases the flood risk as a result of heightened vulnerability to floods due to concentration of population, wealth and infrastructure to smaller areas (Ishigaki et al., 2009). Flood hazard also increases by hydrological and hydroclimatological changes brought about by the land-use and microclimatic changes driven by urbanization (WMO/GWP, 2008). The hydrological changes that result in urban flooding are long understood and quantified. The increase in artificial surfaces due to urbanization cause an increase in flooding frequency due poor infiltration and reduction of flow resistance. The hydrometeorological changes and resulting impacts on extreme rainfall is also being established. A significant amount of research over the last twenty years has shown a strong relationship between urban areas and local micro-climate. The "urban heat island" (UHI) effect is now well established, whereby urban areas have higher temperatures than surrounding regions (Seto and Kaufmann, 2009). In many cases, UHI can increase the rainfall in vicinity of the cities. A number of studies have found an increase in rainfall in regions downwind of urban areas, with increases as high as 25 % in some cases (Shepherd, 2002; Mote, 2007).

In urbanized areas, huge amounts of anthropogenic waste heat is emitted due to human activities, and the increase of energy consumption is causing environmental problems, including the temperature rise in the urban atmosphere (Aikawa et al., 2008). The absence of trees decreases the evapotranspiration and hence the latent heat flux.

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Further, the radiative properties of the urban environment are found to be distinctly different and could absorb more radiation due to the nature of the urban canopy. These changes in surface heat-budget make the atmospheric conditions in urbanized areas to have some unique characteristics compared with those of pristine or rural areas (Shepard, 2002; Pathirana, 2011a). These changes can have significant impacts on the local circulation and meteorological parameters and their association with precipitation (Aikawa et al., 2008).

The climate variability and change have direct consequence on global flood hazard (Milly et al., 2008). The increased frequency of occurrence of flood events in the world is partially attributed to climate change-driven increase of extreme precipitation (IPCC, 2002, 2007). Due to global warming, the global water cycle is likely to be accelerated, resulting in many regions with an increase of flood magnitude as well as flood frequency. Climate change is making weather less predictable, rains more uncertain and heavy storm rainfalls more likely. Heavy thunderstorms appear to have increased in frequency (ActionAid, 2006). The quantitative estimation of the impact of climate change on small-scale, extreme rainfall events is an developing research area and there is a large degree of uncertainty with the current estimates (IPCC, 2007).

Flood incidences in cities that are coastal or on river deltas are influenced by climate change also via the changes in sea-level, tides and large-scale runoff changes (resulting in river level changes). The changes in sea level are fairly well established (IPCC, 2007). A global average sea level rise of 9–88 cm is expected over the next hundred years (UNFCCC, 2005). In Vietnam, sea level rose at the rate of about 3 mm yr^{-1} during the period of 1993–2008 (MONRE, 2009a). Sea-level rise increases the risk of coastal and delta floods, particularly in cases of storm surges.

The effective adaptation measures can be made only when the nature of the impact is well understood. For urban planning and disaster preparedness, the quantitative assessment of the increase of flood hazard is important. From a research point of view, this quantification is relatively easy regarding the impact of a single influencing variable (e.g. flood hazard increase due to increased imperviousness). However, such

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estimations are of little use for adaptation planning, for they do not represent the future reality adequately. On the other hand, the estimation of the combined impact of many of the important parameters is a challenging research problem that invariably results in higher degree of uncertainty and errors. But such attempts are very much required for the adaptation planning to be realistic.

In this paper, we discuss the case of a typical third world city, faced with all these future challenges, namely: (1) climate change driven sea-level rise and tidal effect, (2) increase river run off due to climate change, (3) increased urban runoff driven by imperviousness and (4) enhancement of extreme rainfall due to urban growth driven micro-climatic change (urban heat islands).

Can Tho is a city of around 1.2 million population located on the south bank of the Hau River, the bigger branch of the Mekong River (see Sect. 2 for a detailed description). Its location on the bank of a large river, not more than 84 km upstream of the river mouth in South China Sea and its low elevation (60–80 cm a.m.s.l. – above mean sea level), makes it vulnerable to all four of the above factors impacting flood hazard. The rapid increase of population/densities, poor living conditions, and poor quality of the infrastructure also cause the vulnerability of the city to floods to increase.

In this study, model simulations have been used to estimate the changes in flood hazard in the city driven by future change that is both global (e.g. climate change) and local (urban growth). The climate change drivers have been studied widely and we used available research output to establish the magnitude of these (e.g. river levels increase due to future sea level rise and increase of runoff upstream of Can Tho). On the other hand, the impact of urbanization on local rainfall of Can Tho has previously not been studied. We use an urban growth model to predict the urbanization in the future, and then we employ controlled numerical experiments with an atmospheric-land-surface model to estimate the impact of urbanization on local extreme precipitation by "what-if" type simulations of historical extreme rainfall events. Finally, a 1-D/2-D coupled urban drainage/flooding model (SWMM-Brezo) is used to simulate storm-sewer surcharge and surface inundation to establish the increase in the flood risk resulting

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from the changes of rainfall and climate change drivers. This last analysis is limited to a neighbourhood in the inner-city due to limitations of data.

The results show that both local changes driven by urbanization and large-scale climate impact significantly influence the picture of the future flooding of Can Tho. The climate change-driven sea-level and runoff increase cause the most serious increases to flood hazard in the city. In the worse case (sea level rises up to 1.0 m and the surcharge from upstream caused by high development), the maximum inundation depth of an event similar to year 2009 flood will increase by 79 %.

There are two main causes for inundation that are represented by two classes of inundated areas: along the canals, there are the most serious inundation areas largely caused by high water surcharge from the river. There are other areas in the center of the district that have been affected only by rainfall changing and have not had clear impacts by the water surcharge from the river. These two different types of inundation call for different mitigatory action. We recommend that planning for response should follow careful study of the effectiveness of the different intervention options on each locality of the city.

The following sections describe the study area in detail with an overview of the flooding problem, followed by the research methodology adapted. Then we present the results, discussion and conclusions.

2 Study area

Can Tho city is the largest city of the Vietnamese Mekong River Delta and considered as the capital of the region. In 2009, the city was recognized as the first level city in Vietnam and hence in future, Can Tho is envisaged to develop considerably (NIURP, 2010). Over the next 20 years, Can Tho is projected to be a dynamic city serving the Mekong River Delta Region, the southern part of Viet Nam, and the adjacent international regions.

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The area of the city is 1390 km^2 with the population of 1.2 million (in April 2009). The city's population is projected to grow at a moderate rate; however, the inward migration towards the urban areas and industrial zones could possibly increase the total population to 1.8 million by 2020 (National Institute for Urban and Rural Planning, 2010).

2.1 Flooding problem in Can Tho

Just like other cities in Vietnam, Can Tho faces many typical problems of urbanization (e.g. pollution, social issues), but one of the most serious problems is flooding. Recently, flooding in the city has happened more often and more seriously. It has been reported that in the past, the flooding area generally accounted for about 30 % of the total city area, but recently that number increases up to 50 % (Tran Van Tu, 2010). Inundation happens even when the rainfall is not too heavy. There are several historical flooding events recorded in the city, some of which are discussed below.

In 2000, a flood happened earlier than usual in the rainy season and caused serious flooding in the lower Mekong River Delta (National Hydro-meteorological Service, 2010a). This event was regarded as one of the biggest floods that ever happened in the Mekong river Delta. The observed flooding at Tan Chau and Chau Doc were the highest recorded in last 76 years. At Can Tho, flood levels were just 1–3 cm below the 40 year record level. The observed river level at Can Tho hydrological station was 1.9 m. It was the highest value in the last 40 years (National Hydro-meteorological Service, 2010b). According to Can Tho Water Supply Company, in 2008, in the centre of the city out of 81 main roads, 21 were inundated with more than 30 cm water level largely due to high tide and 10 due to heavy rainfall (MONRE, 2009b). On 5 October 2009, heavy rains lasted over one hour and again caused serious inundation to the city. Several roads such as Mau Than, Tran Hung Dao, Xo Viet NgheTinh, HoaBinh, and Ly TuTrong were inundated under one-meter-height of water. The local people said

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that this was the largest flooding event over several decades. Many houses and streets in the city were inundated. (Fig. 2)

2.2 Reasons for flooding today

One reason for flooding in Can Tho is the low topography of the city, with the average height above mean sea-level ranging from 1 to 1.5 m. In fact, many places have topography below 1m sea-level and the ability to drain into the river remains limited. The average rainfall in the city is not significantly large (1640 mm year^{-1}) compared to Vietnamese norms, but is prone to be concentrated in extreme events. Rainfall ranging from 50 to 100 mm day^{-1}, combined with high tide, typically cause flooding in Can Tho. Meanwhile, the city's drainage system is incomplete, and where it exists, is under-capacity. The awareness of the people remains limited, which is also an indirect reason for more serious flooding: Often people throw garbage into canals and drainage pipes and construct buildings encroaching canals. The inner city has grown significantly over the last several decades and hence more houses, businesses and factories are built.

A storm-sewer network has been developed only for the central Ninh Kieu district (Fig. 1), and its capacity is inadequate during heavy rainfall. Urban flood protection is a matter under the control of Can Tho's municipal authorities. According to a survey by a construction consultant company (under the Ministry of Construction), the current drainage system of Can Tho has a total length of over 23 500 m with the diameter of about D300–D1.200 mm, and the built ditches have a total length over 7.000m from 0.2 to 0.5 m in width and hundreds of meters of natural drainage ditches. However, much of this drainage system is malfunctioning or has limited drainage capacity. At many places such as Mau Than Road, 30-4 Road, and 3-2 Road, the drainage system is encroached by illegal construction or filled by solid waste. While in many other roads, the drainage system fails to meet the technical requirements, leading to limited capacity to collect wastewater or rainwater. The uncollected rainwater and gray water from sewer surcharges run over streets. When the surcharges coincide with high tide in Hau River, the city is seriously flooded.

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Canals criss-crossing the city play an important role, acting as outlets for drainage network. Private houses are routinely constructed obstructing these drainage canals, worsening the drainage capacity of the system. Funds for periodic dredging the canal bed is limited, so sedimentation also is a serious issue. In case of heavy rainfall combined with high tide, the water level in the canals often rise higher than that in the drainage pipes, causing surcharge and back-flow. This is the prime reason for inundation in quarters close to the river or canals.

2.3 Anticipated situation in the future

The drainage system in Can Tho city is far from optimal and the flooding is already a problem. However, future changes will further aggravate this situation.

– *Climate change*:
  it is likely that climate change (CC) has already caused event increases in catastrophic natural disaster, especially typhoons, floods and droughts (MONRE, 2009a). By the end of the 21st century, the temperature in Vietnam will increase by 2.3 °C relative to the average of 1980–1999, the annual and rainy season's rainfall will increase about 5 % compared to that of the period 1980–1999, and the mean sea level is expected to increase about 30 cm by mid 21st century and 100 cm by the end of 21st century (MONRE, 2009a) (Table 1).

– *Urbanization effect*:
  urbanization may likely cause increase in precipitation, and therefore will cause more serious flooding for the city. Furthermore, the hydrological changes of urbanization will increase the flood peaks and decrease the concentration times.

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- *Land Subsidence*:
  Land subsidence would also contribute to the increasing flooding situation in Can Tho city (Vietbao, 2006). However, there are no studies on the land subsidence rate in Can Tho.

It is anticipated that Can Tho city will witness an exponential growth during the next several decades, largely due to its strategic location. The dramatic change in land use within and surrounding the city will impose both direct (hydrological) and indirect (UHI) impacts on the urban water cycle, resulting in more frequent and higher magnitude floods. The climate change-driven increase in tidal peaks and the runoff in Mekong River could aggravate the problem.

Urgent adaptation actions are necessary to prevent damage caused by climate change in Can Tho. In order to develop sound adaptive measures, it is necessary to quantitatively estimate the impacts of the future changes on flooding with models for simulating the possible microclimatic changes, taken together with other signals of climate change (e.g. rainfall increase due to global warming, and sea-level rise).

3 Methodology

We used three different simulation models to achieve the objectives of this study. The overall modelling framework is given in Fig. 3.

The main emphasis of the research will be on the impacts of global and local climate change on urban flooding. Whenever suitable external resources for impacts are available, they were directly adopted (e.g. global climate change impacts on the extreme rainfall) with necessary caveats (e.g. scale issues).

However, for local changes (e.g. UHI), external resources are hardly available. The availability of good urban growth scenarios was fundamental to the success of the study. In order to predict the future urban growth scenarios, the cellular-automata based land-use simulation model, Dinamica-EGO (Mas et al., 2010), was used.

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The detailed procedure of modelling urban growth and its impacts are described by Denekew et al. (2011). Output from Dinamica-EGO was used as input in a specially modified mesoscale atmospheric model (Pathirana, 2011a) to ascertain the changes that it will induce in the urban microclimate for the city of Can Tho resulting in changes in the precipitation patterns. To achieve this, a meso-scale atmospheric model (WRF), coupled with a land-use model with vegetation parameterization (Noah LSM), was applied. The necessary modeling framework was already developed for this purpose (Pathirana, 2011a; Denekew, 2011; Verbeek, 2011), so this framework was applied for Can Tho city with the realistic urban growth scenarios. For urban flood modelling, an integrated model (SWMM-Brezo) developed during the period 2007–2010 was used (Delelegn et al., 2011).

3.1 The models

3.1.1 The urban growth model

Dinamica-EGO is a spatially explicit cellular automata based simulation model of landscape dynamics (Mas et al., 2010). EGO stands for Environment for Geo-processing Objects. In the current application, the basic task of the Dinamica-EGO is to: (1) analyse historical urbanization patterns of Can Tho city and (2) use the historical transition patterns together with any other rules (e.g. area that are protected from urbanization) to simulate the future land-use change (Veerbek et al., 2011).

3.1.2 The atmospheric model

The Weather Research and Forecasting (WRF) is a Non-Hydrostatic, limited-area atmospheric model that can simulate the full set of atmospheric processes including wind, moisture-state-transformation including cloud formation and precipitation and destiny of atmospheric pollutants. It can be used to simulate situations ranging from simple-idealized numerical experiments to sophisticated real-time weather forecasting

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applications. The model requires the specification of initial conditions for the entire modelling domain and the lateral boundary conditions for the whole period of the model integration. Surface representation based on topography and land use could be a simple thermal diffusion model or a detailed land surface model with extensive surface and vegetation hydrology (Tewari et al., 2008). In the current application we used WRF coupled with Noah land surface model (Noah LSM) (Mitchell, 2005).

3.1.3 The urban flood model

In the case of design problems that involve prevention of flooding at a given design standard (rainfall event), often 1-D urban drainage models are adequate tools. However, the current application requires the simulation of surcharged conditions of storm sewers and estimation of inundation depth. Due to the highly dynamic and swift nature of urban floods, such estimations are best made by dynamic inundation models. In this study, a coupled 1-D/2-D model – a product of coupling EPA-SWMM 5 (EPA,2010) with Brezo – a 2-D inudation model (Begnudelli and Sanders, 2006) – was used for the purpose. The details of the coupled model are explained by Pathirana et al. (2011b). The model is capable of dealing with various flow conditions that may occur in actual floodplains and the simulation results show a reduction in flood extent due to the consideration of bidirectional interaction.

3.2 Applying methodology in Can Tho

3.2.1 Future land use

Dinamica-EGO needs several historical land-use maps in order to calculate the land-use transition patterns. Land-cover maps derived from the Landsat ETM and ETM+ images data were used to calibrate the Dinamica-EGO growth model. Two landcover maps at 30-m spatial resolution for two different years were processed. The maps are obtained from the website of USGS Earth Explorer, which are Landsat ETM and ETM+

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images created using remote sensing techniques. The various land cover classes are then derived from these remotely sensed satellite images by maximum likelihood classification (Supervised). Different categories of Land cover classes are adopted from USGS classification scheme. For Can Tho, landcover maps of the years 1989 and 2005 are used as the initial and final landcover maps and the following categories are identified from the training of RS images: Open Water (11); Developed areas: low-intensity (22), medium-intensity (23) and hign-intensity(24); infrastructure (25); shrub (52) and grassland (71). The two maps were used to derive historical growth patterns with Dinamica-EGO. Landuse simulation was done from 1989 to 2100 at time steps of 5 years.

The resulting urban extent and land-cover distribution predictions of the Can Tho city are used as input for the atmospheric model for further analysis of increases in precipitation and increment imperviousness to investigate the associated flood risk. The process is explained in sections below.

3.2.2 Rainfall changes due to urbanization

The domain configuration was set up to cover study area with a resolution of 1 km (Fig. 4). We set three two-way nesting domains in order to achieve 1 km resolution over Can Tho with computational economy. The time for integration step is 15 s. The results of historical rainfall event of October 2009 simulation are shown in Fig. 5.

The standard input of Geographical data for WRF-Noah model is the USGS data sources. First we confirmed the proper operation of the model with standard data. Then the configured model was used to estimate the change of rainfall due to urbanization in the future by replacing the land use of the model with urban growth model-based values. This process is explained in the Results section.

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3.2.3 SWMM – BreZo

Study area focus on Ninh Kieu district (Can Tho city). Ninh Kieu is the central district of Can Tho city, northern is Hau Giang River, eastern is Can Tho river. The total areas of the district is 2900 ha. However, the sewer system only covers one part of the district, 660 ha to which we applied the urban model.

The data for 1-D dimension were collected from three sources: (1) hydro-meteorological data were collected from National Hydro-meteorological Service; (2) drainage system were collected from Can Tho Water Supply Company; (3) DEM was developed by Vietnam Institute of Meteorology, Hydrology and Environment.

In 2000 and 2009, the heavy rainfall caused inundation to the city. The largest rainfall events of these years at Can Tho meteorological station are chosen to be used in EPA-SWMM model, from 18:00 LT, 18 October 2000 to 04:00 LT, 19 October 2000 (Fig. 6), and from 14:00 LT on 5 October 2009 to 01:00 LT on 6 October 2009 (Fig. 7). The river water level recorded at Can Tho hydrological station was applied for all locations of outfalls. In the 2000 event, the water level fluctuated (due to tidal effect) between +1.6 and +0.92; and in the 2009 event, between +1.69 and +0.28 (Fig. 8).

Due to the flat nature of the land and the fact that the city is criss-crossed with canals, the drainage system has evolved into a fairly complex one. The 1-D SWMM urban model we built consists of 303 sub-catchments, 524 conduits, 465 junctions, 51 outfalls and 8 pumps (Fig. 9). The 2-D Brezo model covered only the acutely flooded area (northwestern part of the 1-D network) of the city (Fig. 10). The 2-D model has 1.7 million triangular cells each of area 112.5 m^2. The 1-D/2-D systems were bi-directionally coupled using internal boundary conditions at each junction of the 1-D model (see Pathirana 2011b, for details on this process).

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3.2.4 Climate change scenarios

At present, many regions and countries have developed climate change scenarios at regional, national, or smaller scales. Most climate change scenarios are constructed for the timeframe of decades of the 21st century.

In Vietnam, there are a number of climate change scenarios developed and applied for different purposes of climate change-related activities. In order to have more comprehensively scientific and practical based scenarios for the implementation of National Target Program to Respond to Climate change (NTP), the Government has assigned Ministry of Natural Resources and Environment (MONRE) to be a coordinating agency for developing climate change scenarios, especially sea level rise for Vietnam.

The scenarios of climate change-related sea level rise for Vietnam presented in this paper were developed based on the available national and international studies, as well as the comments and ideas of experts and managers of relevant ministries and sectors (IMHEN, 2010).

In order to predict the impact of sea level rise and river flow changes by climate change scenarios, the study referred to the results of the water level of Hau River (one branch of Mekong River) from the project of "Impacts of Climate change on Water Resources and Adaptation measures" implemented by the Institute of Meteorology Hydrology and Environment, Ministry of Natural Resources and Environment, Vietnam, funded by DANIDA (Danish International Development Agency) (IMHEN, 2010). The results show that, in case of sea level increase up to 1 m and water flow from upstream in scenarios of high emission scenario (A1F1), the river level at Can Tho will be increased up to 1.1 m in an event similar to year 2009.

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4 The application

4.1 Future urbanization

After a satisfactory result is obtained from the simulation and validation of the model setup, the same model was used to project future land cover maps in five-year intervals up to the year 2100. The configuration and internal parameters of the 1989–2005 simulation model have been used along with other input parameters like restricted areas. Projections of land cover maps for the years 2035, 2050 and 2100 are shown together with observed landcover in 2005 in Fig. 11.

Figure 11 shows the observed landscape map for the year 2005 and projected maps of land cover for the years 2035, 2050 and 2100, respectively. Comparison of the maps confirms that there will be a consistent infill and expansion of the current urban core in all the corners. Owing to the flat nature of the terrain, most of the land covered by grass and shrubs at the outskirts of the city will be filled by scattered and low to medium intensity urbanization up to mid 21st century. These will slowly change to a high-density metropolitan area by 2100. There is also a considerable densification of the existing urban core at the heart of the city. A unique feature of urban growth of Can Tho is the high growth and densification along water bodies.

The total built-up area will increase by 27.6 km^2 by the year 2035; an approximate 41 % increase in 30 years time. By 2050, the total increment in built-up area with respect to the year 2005 will be38 km^2 (55 %). Grasslands and shrubs are subjected to a combined decrease of about 12 % by 2035 and 17 % by 2050.

4.2 Impacts of urbanization on local precipitation

The land-use distribution from the urban growth model were used as inputs for the atmospheric model runs to establish the impacts of urbanization on local precipitation. Two different maps of land use in the year of 2005 and 2050 were used to perform

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controlled numerical experiments to establish the possible changes of extreme rainfall if the city develops per the projected scenario.

The process of obtaining these results is as follows: Several historical storms over Can Tho city were selected. The WRF/Noah model has been developed by using NCEP-FNL global data as initial/boundary conditions and land-use data from Dinamica EGO models (2005 as "Past" and 2050 as "Future"). The models were validated to closely reproduce the historical results with the "Past" scenario. Then the same model parameters were used with "Future" land-use scenario in order to estimate the impact of urbanization on local precipitation. Figure 12 shows the differences between past and future simulated rainfall, in terms of total simulated rainfall amounts for an extreme event recorded in October 2009. Figure 13 shows the distribution of rainfall intensity quintiles at 15 min resolution for different historical events.

There is a clear impact of urban growth to increase the extreme rainfall quantities. In most of the case studies, the results show that, with the projected land-use map of 2050, the rainfall may increase respectively, especially for the heavy rainfall of 30–40 mm in 15 min. In the case of the historical rainfall event of 5 October 2009, the results show that, when precipitation more than 40 mm, the rainfall in the "Future" case is greater than in the "Past" case by about 10 %. These values will be used for the urban flood simulation below.

4.3 Impacts of urbanization and climate change on flooding

In order to estimate the impacts of urbanization on the flooding situation for Can Tho city, results of the rainfall even of October 2009 (in past and future land-use maps) were used as input for all considered scenarios. For this event, "Future" rainfall series were constructed under the assumption that if the October 2009 event would happen in 2050, its magnitude would increase by the indicated magnitudes of the respective statistical quintiles. An analysis similar to the one shown in Fig. 13 was done at an hourly level with all analysed rainfall events combined (in order get a more statistically

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robust estimate). This analysis gives a 1:1 relationship between the quintiles of future and past rainfall:

$$R_\mathrm{F}(Q) = f\left[R_\mathrm{P}(Q)\right]$$

where $R_\mathrm{F}(Q)$ and $R_\mathrm{P}(Q)$ are hourly rainfall intensities of the quintile Q in the future and past, respectively. Then the "Future" event $r_\mathrm{F}(t)$ of a recorded extreme rainfall event $r_\mathrm{P}(t)$ was estimated as:

$$r_\mathrm{F}(t) = r_\mathrm{P}(t)\,\frac{f\left[R_\mathrm{P}(Q)\right]}{R_\mathrm{P}(Q)}.$$

Results of eight different combinations of scenarios are discussed in this paper for four climate scenarios: (i) current situation, (ii) sea-level rise of 50 cm, (iii) sea-level rise of 100 cm, and (iv) sea-level rise of 100 cm combined with increase of river runoff for high emission scenario (A1F1). Each of these climate scenarios was combined with two local scenarios (a) current land use and (b) future land use (2050), resulting in eight combined scenarios.

Figure 14 shows sample inundation results for four of the scenarios. The results of all eight are summarized in Fig. 15.

5 Discussion and conclusions

We conducted a detailed modelling study on the urban water system of Can Tho city in order to understand the impacts of future change on the already serious urban flooding situation of the city. Where possible, we used external resources to establish the future change, for example due to global climate change (sea-level rise and changes in Mekong river flow). However, for local changes that are also important, there were no reliable external sources so we resorted to model simulations. First we employed an urban growth model to simulate future changes in land use driven by urbanization, and then a specially set-up limited-area atmospheric/land-surface model to estimate the changes in the local extreme rainfall due to land-use change. Finally, we applied a dynamic 1-D/2-D coupled urban flood model on a selected neighbourhood to simulate the combined effects of sea level rise, upstream flow of Mekong, the local changes of rainfall, and hydrological changes due to urbanization on the already serious problem of urban flooding in Can Tho.

5.1 Results

The results show that (Fig. 15), in case the city develops as predicted, the maximum inundation depth in the analysed area for a rainfall event like October 2009 will increase by 21 % (about 18 cm) by 2050, solely due to the land-use change driven hydrological and hydrometeorological effects (i-b). The inundated area will increase by 18 %. The impact of climate change, in its worst combination (A1F1 flow with SLR 100 cm – scenario iv-a) on inundation depth is much more serious than that of urbanization-driven land-use change. The maximum inundation depth in Can Tho may increase by more than 50 cm (around 60 %) in (iv-a). However, the inundated area is more sensitive to urbanization-driven hydrological and meteorological changes (scenario i-b against ii-a, iii-a and iv-a).

In (iv-b), the scenario that combines climate impact with urban growth, the maximum inundation depth will increase to 1.51 m – an 80 % increase. The most seriously inundated area is the area surrounding the intersection of Nguyen Van Cu and Mau Than Streets, close to Can Tho Medical College (Fig. 16a), all of which are located near the Ngong Channel – the main collecting water channel of the district. When heavy rain occurs, the water from other roads, channels and sewers will concentrate in this channel. As the drainage capacity of the channel is not sufficient for this large amount of water, the low surrounding areas are routinely inundated. The possibility of the increase of inundation depth in this area up to 1.51 m is alarming indeed, as this level may pose a danger to human life.

Beside the above critical areas, the maximum inundation depth of the rest of the areas do not change significantly. When these critical areas are neglected, this value is

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only 0.73 m in the scenario of A1F1 + SLR 100 cm compared to 0.66 m in the baseline scenario, which is located near Nguyen Thi Minh Khai, Phan Dinh Phung street. Detailed analysis showed that these areas' inundation depth is more sensitive to land-use driven changes than to the impacts of the river water level.

Both in the present and the future, the area with high inundation depths (>0.5 m) is not excessively large. The maximum area of inundation depth >0.5 m increased to only 26 ha (accounting for 12 % of the total inundated area). The area increased by 20 % due to urbanization driven change (i-b) and 34 % due to climate change (iv-a). The combination of these two facts increase it by 50 %. It is interesting to note that while the total inundated area was more sensitive to land-use driven change, the "significantly" inundated area is much more affected by climate change driven parameters.

5.2 Sensitivity of drivers

Investigation of the flooded areas show two distinct categories of flooding, namely: (i) the areas dominated largely by local rainfall-driven flooding (Nguyen Thi Minh Khai, Phan Dinh Phung streets) and (ii) those influence mainly by river water level. The area with highest flood levels (Fig. 16a) is close to a major branch canal and hence directly influenced by the river level much more significantly. This is the reason for its high sensitivity for the climate drivers (for which we used river level as proxy). However, the relative insensitivity of the river level to the total inundated area shows that the influence of the river at the levels we have considered is not felt by the entire modelled area. The influence is very much localized to the neighbourhood of canals.

The area with second largest flood depth (Fig. 16b) is much more influenced by urbanization impact (our proxies for this were rainfall change and the change in hydrologic properties), though there is a significant impact of the climate change as well.

In our model, the influence of river level remains a local phenomenon largely affecting the waterfront while the urbanization effects are felt over the entire model area. Another interesting feature of the impact of the river level is that it seems to have a certain tipping-point value – an increase of 50 cm alone (iii-a) does not have any influence on the inundation depth as compared to 100 cm. On the other hand, a 50 cm increase combined with urbanization effect (iii-b) has non-negligible increase of maximum flood height compared to urbanization only. These complex interactions deserve future investigations.

5.3 Limitations

The goal of the present study was ambitious. The results we obtained should be interpreted with the necessary attention to the limitations of the methodology and uncertainty inherent to complex modelling tasks.

First of all, by no means have we considered nearly all of the major influences of a changing environment. Climate change does not only influence the river levels, though for the case of Can Tho, this remains a major connection. It will influence the nature and magnitude of extreme rainfall events. How this influence will interact with the urbanization-lead rainfall remains to be studied.

The drainage model we have constructed was quite accurate in terms of locations, structure and dimensions as this was based on the construction plans obtained from the city authorities. However, there are a host of parameters that had to be estimated largely based on judgement. Examples are various catchment parameters, roughness values of pipes and exact operation of pumping stations. However, all of these parameters were kept constant between different scenario, and therefore have not influenced the comparative results. Nevertheless, there are factors that could definitely change with time. For example, there are locations of the drains that are severely blocked due to sedimentation and solid waste at the moment. This situation could improve or become aggravated in the future, depending on the policies of the city and the behaviour of its populace. These dynamics were ignored.

Perhaps the significant assumption we made was that the growth of the city follows the historical growth patterns. In reality, it could deviate from that significantly. On the one hand, enlightened city authorities may control the urban densities and might intervene in ways that could alleviate micro-climatic impacts (e.g. introducing green

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areas), On the other hand, various new factors (e.g. new, faster means of transport from Ho Chi Minh city) could even accelerate the growth rate in the future.

We limited our analysis at the level of maximum flood depth and flooded area. However, for the policymaker the flood damage is much more tangible parameter for comparison. We made a deliberate decision to not to include this additional step in analysis due to large uncertainties involved in applying the process to Can Tho.

5.4 Conclusions

The present study is an attempt to integrate the impacts of several drivers of future change and therefore involves a complex chain of analysis. As stated at the beginning and explained above, such analyses invariably generate significant degree of uncertainty in the final outcome. We urge the reader to exercise caution when interpreting the results presented here in a quantitative sense. Each stage of simulations has its own sources of significant uncertainties: urbanization modelling was largely based on rules derived from past behaviour of the city. While this would capture the essential behaviour of the urbanization as conditioned by geographical, cultural and societal factors – there are a host of other parameters that will not remain unchanged in the future. For example a major trunk road is being constructed between Can Tho and the Ho Chi Minh city which would make travel between the two cities much faster. This will definitely have a hitherto unseen influence on growth. On the other hand, the government of Vietnam is very active in planning for the future, taking climate change and other future changes into account. Future regulatory action can restrict urban growth.

In the case of UHI driven rainfall simulation, we have considered only a several past rainfall events due to practical limitations of computational expense. This definitely leads to a large degree of uncertainties in the results. Finally, the urban flood model was calibrated only using reported flood depths. There was no way to do a systematic calibration of the 1-D and 2-D components of the model and their integration due to complete lack of observed data. While this is a common situation in urban flood studies, nevertheless it should be taken into account when interpreting the presented results.

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The indications are that the combined influence of climate change and urban growth on the urban flooding situation is significant indeed. However, the starting point of the solution is not only related to the distant future, but has very much to do with the present situation: The city does not have a suitable urban drainage system and adequate flood protection. All remedial action should probably start at this point. However, the fact that majority of the area of the city not having a drainage system provides a wonderful opportunity for planning for future. When the new systems are designed, it is extremely important to consider the anticipated changes in the future: Not only due to climate change, but also due to the impacts (hydrologic and hydro-meteorological) of urban growth. These demand innovative designs that combine both traditional solutions (implementing and upgrading the drainage system and flood defences and non-standard (e.g. sustainable urban drainage, resilient buildings) approaches. This is an extremely important area for future research.

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Table 1. Sea Level Rise (cm) relative to period of 1980–1999.

Scenarios	Decades in the 21 Century								
	2020	2030	2040	2050	2060	2070	2080	2090	2100
Low emission scenario(B1)	11	17	23	28	35	42	50	57	65
Medium emission scenario (B2)	12	17	23	30	37	46	54	64	75
High emission scenario (A1FI)	12	17	24	33	44	57	71	86	100

Source: Ministry of Natural Resources and Environment, Vietnam (MONRE, 2009b).

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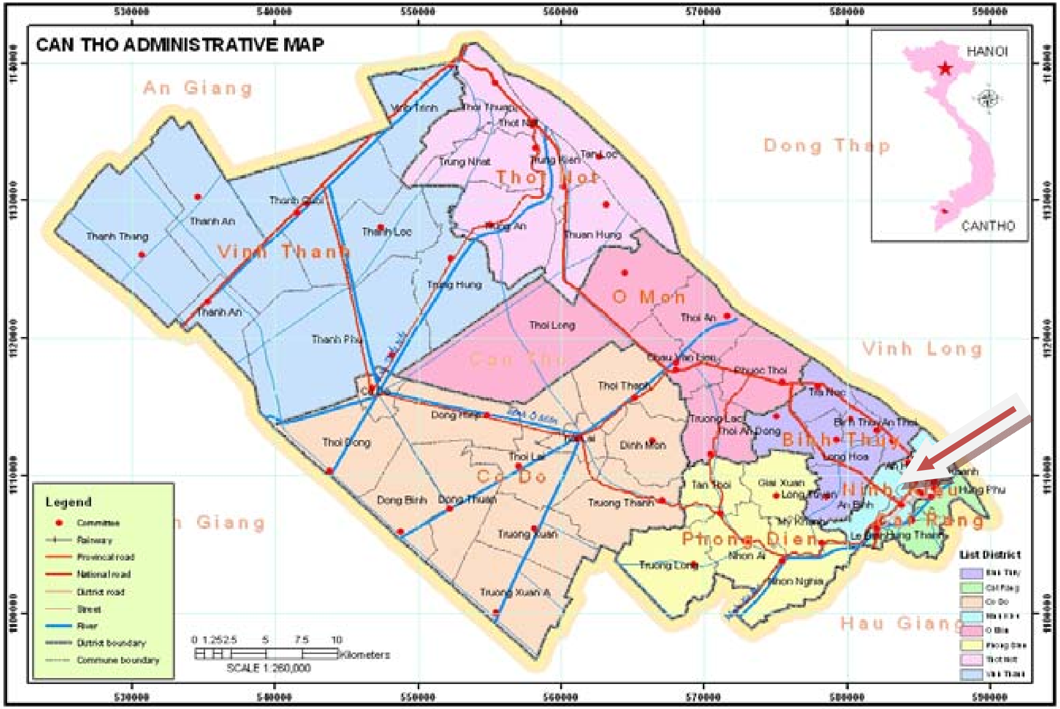

Fig. 1. A map of Can Tho city administrative area (includes the surrounding agricultural land). Ninh Kieu district used for 1-D/2-D urban flood model is marked by the arrow.

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Fig. 2. Flooding in Can Tho City on 5 October 2009. Left panel: HoaBinh Avenue. Right panel: Whole Ly TuTrong Streen in inner city was transformed into a river (Source: Youth online, 2009).

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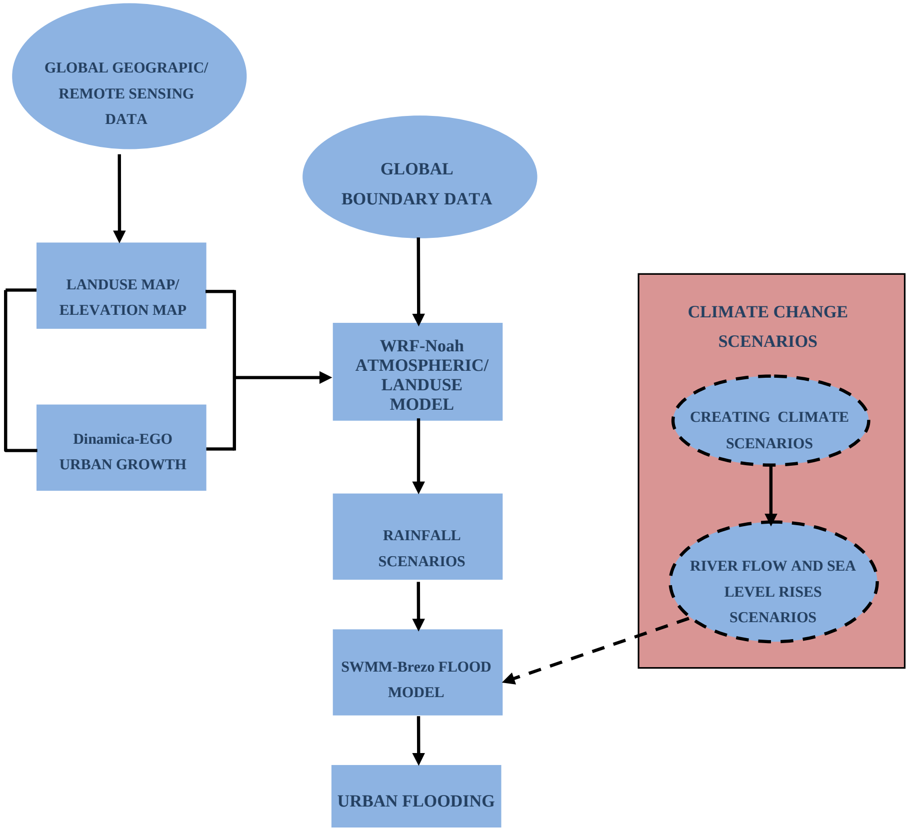

Fig. 3. The modelling framework used to quantify future changes in flooding. The climate change scenarios were adapted from outside sources.

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Fig. 4. The Can Tho WRF-Noah simulation setup. Three telescopic domains were used to achieve high-resolution simulations over Can Tho area.

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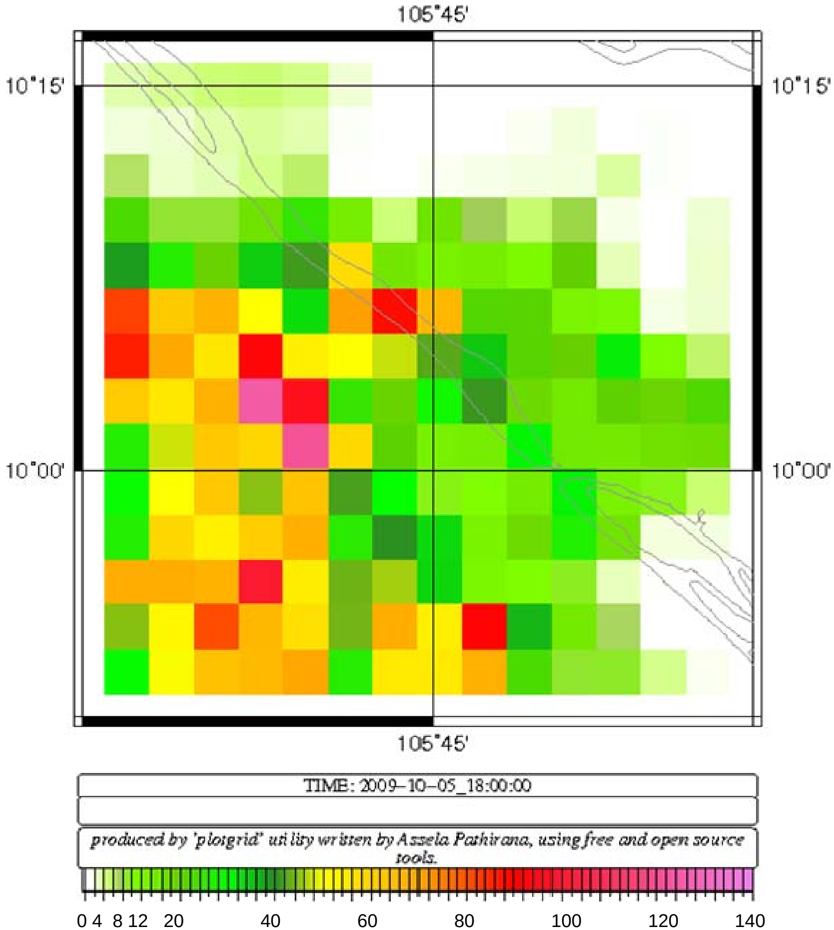

Fig. 5. WRF results (total accumulated rainfall) of 2009 October rainfall event.

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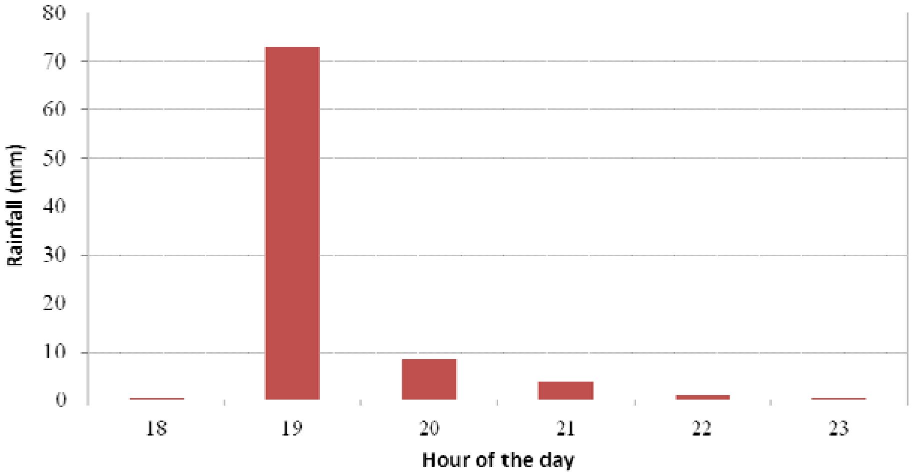

Fig. 6. Rainfall at Can Tho meteorological station (18 October 2000).

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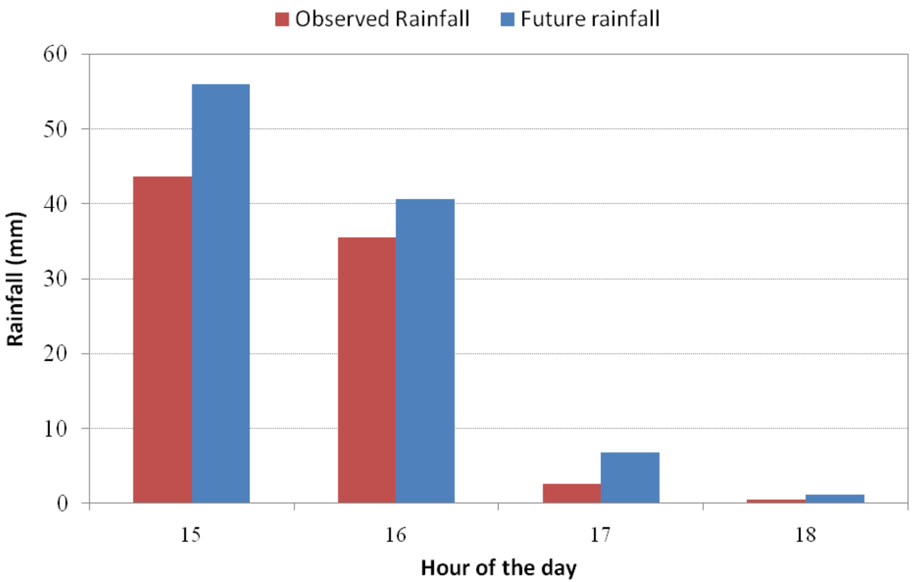

Fig. 7. Hourly Rainfall at Can Tho meteorological station (5 October 2009). The anticipated hourly rainfall amounts if the same event happened in 2050 are also shown.

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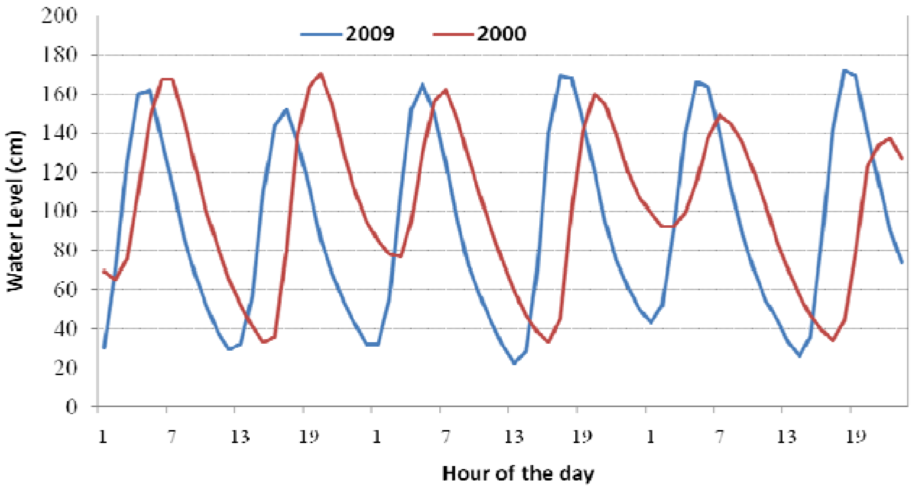

Fig. 8. Water level at Can Tho hydrological station (18 October 2000 and 5 October 2009).

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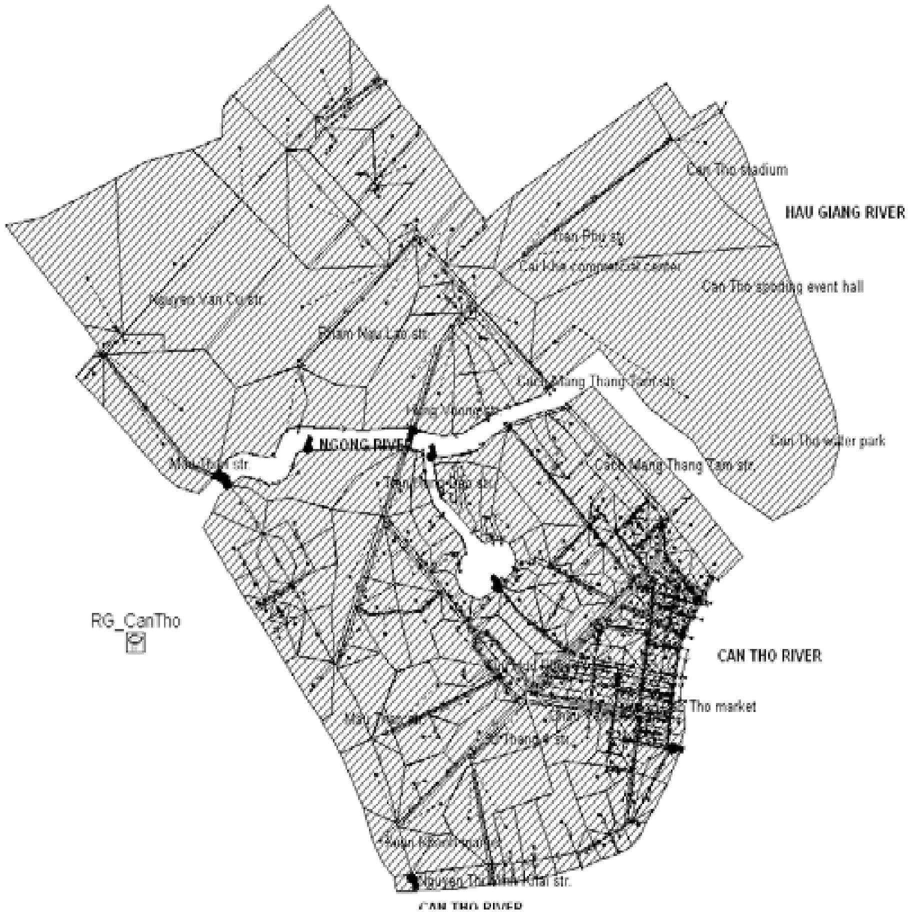

Fig. 9. 1-D SWMM model developed for Ninh Kieu District.

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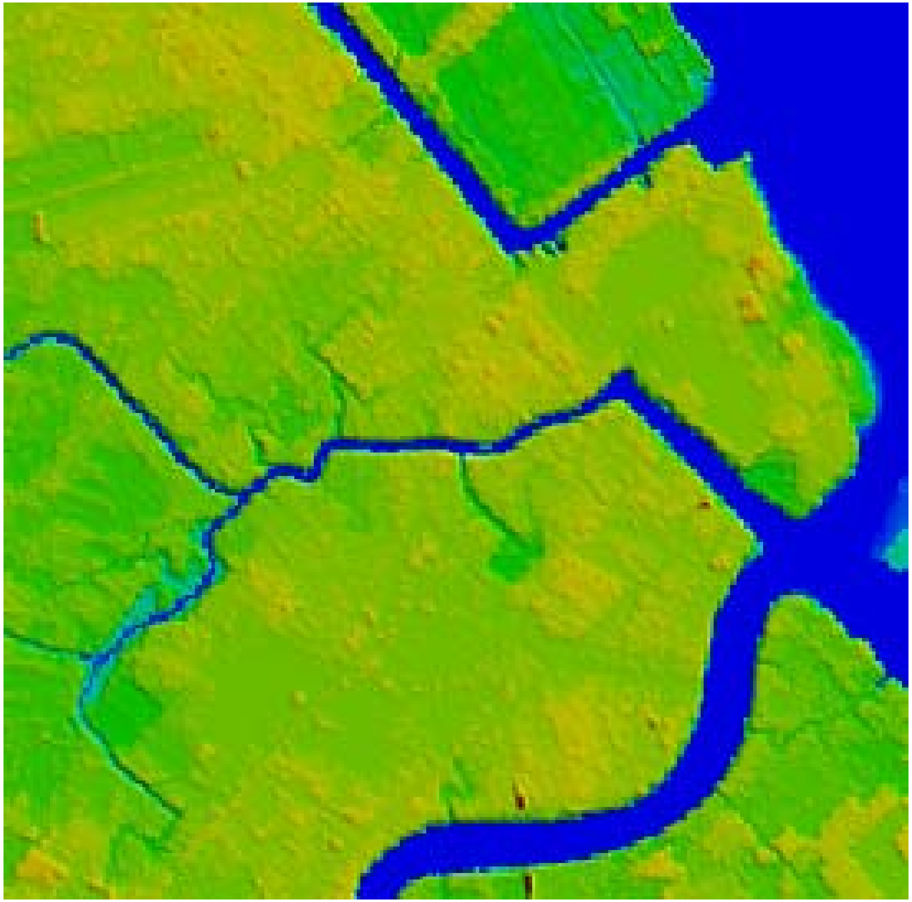

Fig. 10. The elevation map of the area covered in 2-D (Brezo) flood simulation (Source: Verbeek et al., 2011).

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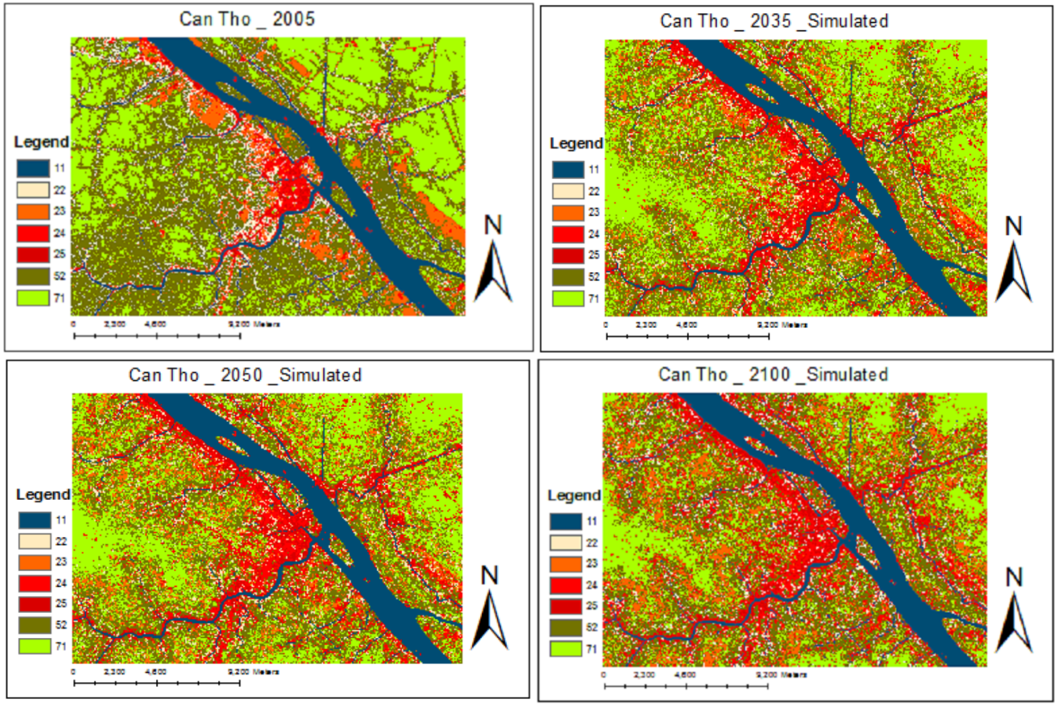

Fig. 11. Future land use change in Can Tho predicted by Dinamica-EGO model.

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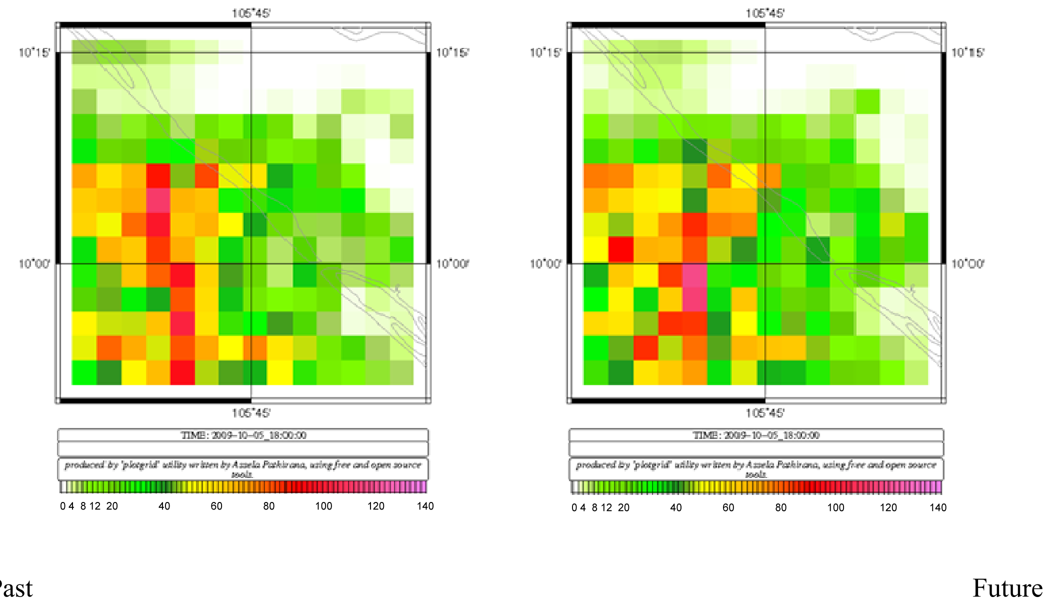

Fig. 12. Total rainfall simulated during the 5 to 6 October 2009 rainfall event for "Past" and "Future" urban growth scenarios.

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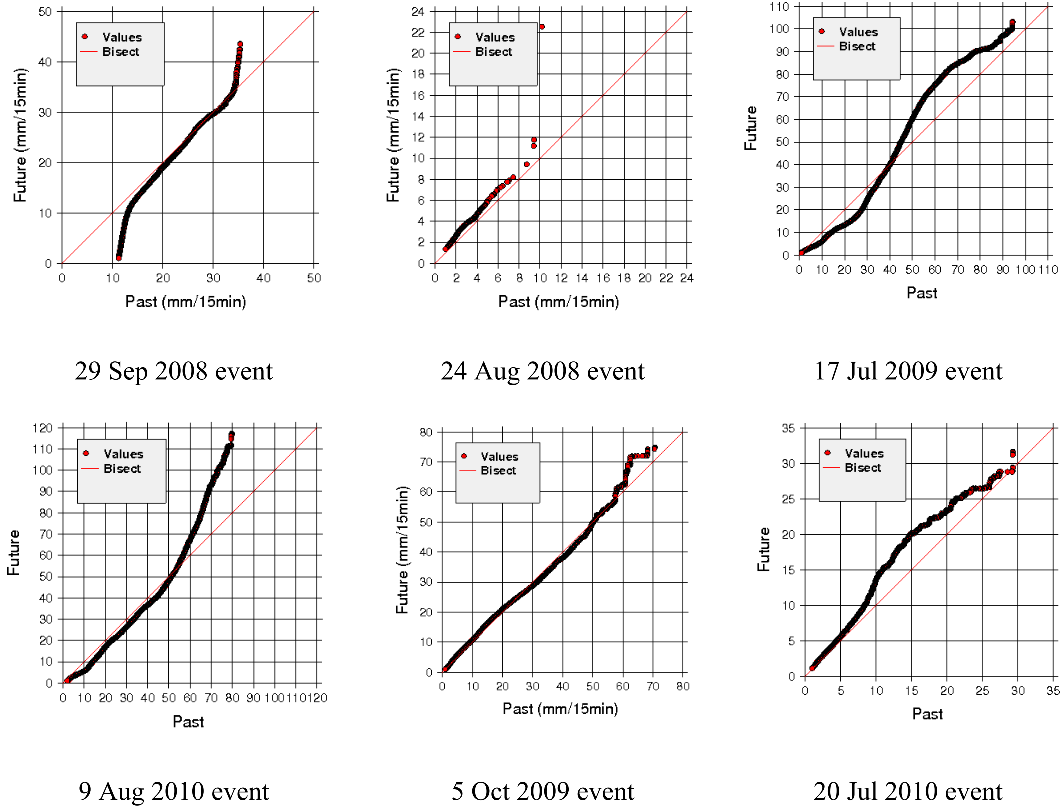

Fig. 13. Comparison of 15 min rainfall intensities for "Past" and "Future" scenarios for various historical events.

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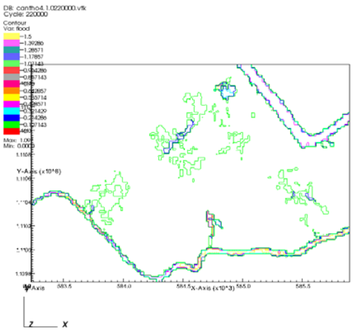
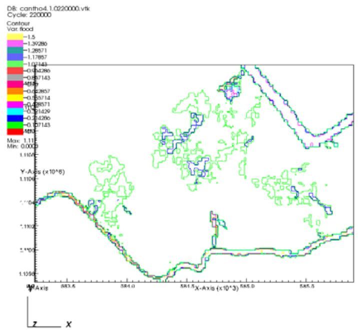
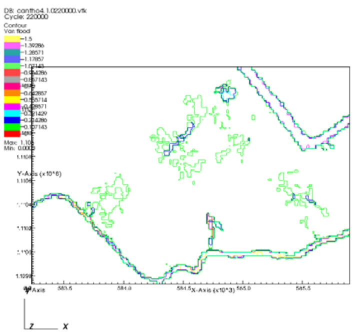


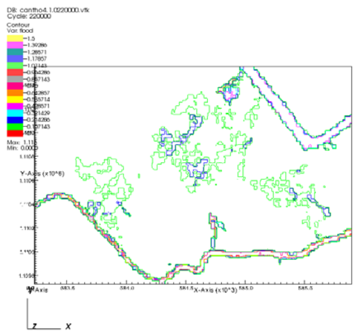
No-change (i-a)



Only rainfall change by urbanization (i-b)



SLR 50 with no urbanization (ii-a)



A1F1 + SLR 100 with urbanization (iv-b)

Fig. 14. Simulated inundation maps of some scenarios (For October 2009 event. At 15:30 UTC, 5 October 2009).

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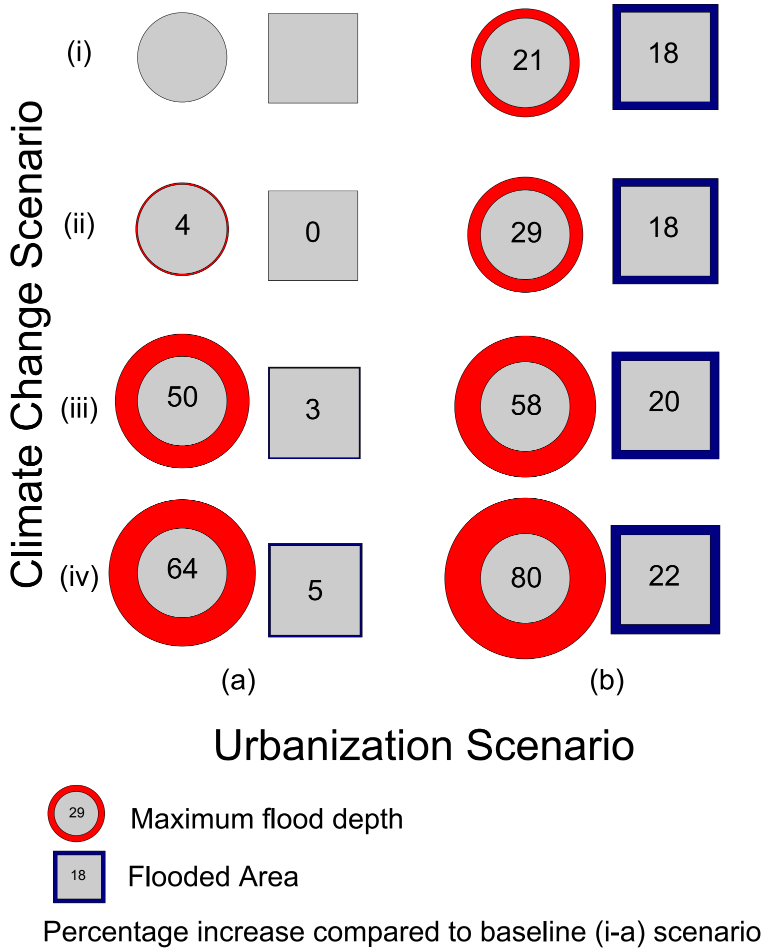

Fig. 15. The maximum inundation height and area of inundation for the eight scenarios. The inundation depth and area for the baseline case was 0.84 m and 177 ha respectively.

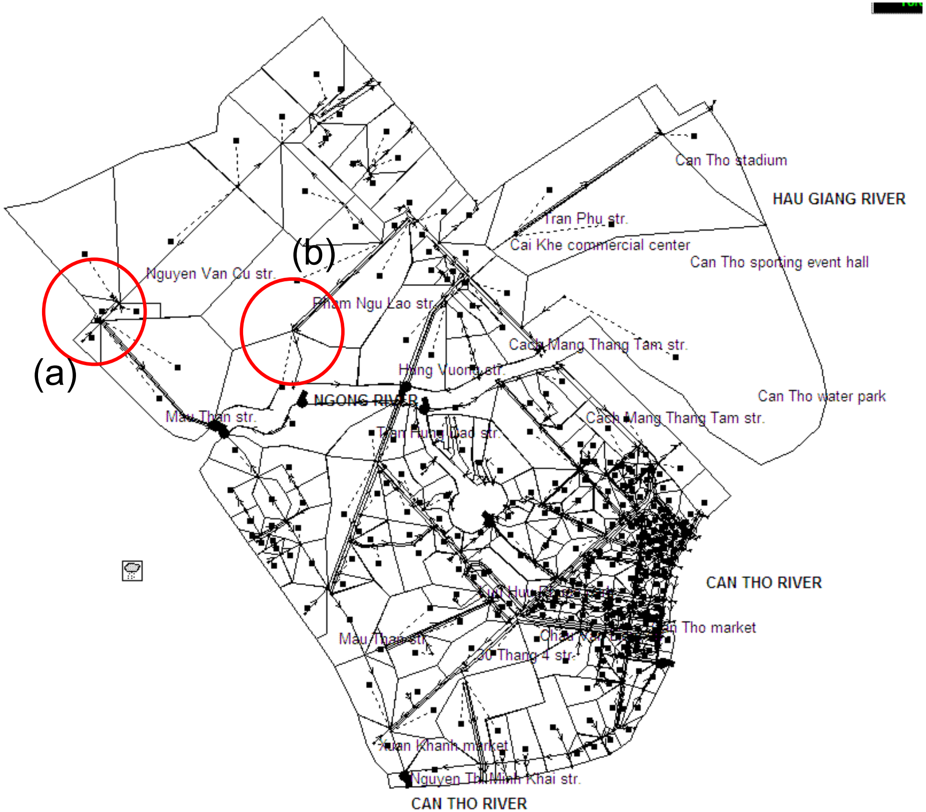

Fig. 16. Highly inundated areas. **(a)** Intersection of Nguyen Van Cu and Mau Than Streets. **(b)** Intersection of Nguyen Thi Minh Khai and Phan Dinh Phung streets.