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Urban Flood Modeling in Phnom Penh Using Flo-2D: Consideration of Climate Change Effect

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Abstract: *Phnom Penh, the Capital City of Cambodia, frequently gets flooded when there is heavy precipitation. To this concern, warming temperature and changing precipitation patterns may intensify the situation. This study aimed at (1) assessing the applicability of the urban inundation model of Flo-2D and (2) forecasting inundation characteristics in the downtown area of Phnom Penh under climate change scenario. The selected study area of 12.50 km^2 is an independent catchment frequently affected by precipitation-flood events. Also, baseline (2010) and near future (2030s) extreme precipitation events were taken as a case study. The overall model performance was evaluated based on the JICA survey study and flood photo analysis. The result showed that Flo-2D model is applicable in modeling the complex storm drainage in this particular area. Based on the ECHAM4 model under SRES A2, the inundation area will be expanded, and the inundation depth is also expected to increase between 0.20 m and 0.50 m in the near future. This study will provide fruitful information on inundation conditions in the Phnom Penh city, especially most prone and affected areas under future extreme precipitation to local people, researchers, and policymakers to formulate any structural and non-structural adaptation options to overcome the current and future challenges.*

Keywords: Climate change; Flo-2D; Phnom Penh; urban flood

1. INTRODUCTION

Flooding is a very common environmental hazard because of the widespread distribution of river floodplains and low-lying coasts and the importance they had on human settlement throughout the history of mankind (Vu and Ranzi, 2017). The rise of extreme urban flooding/sewer flooding has been growing rapidly due to rapid urbanization and climate change, especially in low- and middle-income countries (IPCC, 2013). Molyvann (2003) also stated that when the city is being developed with little planning or control, there will be results in flooding problems, informal settlement along with drainage ways, increased landfill, and poor urban infrastructure. Not only flooding affects the normal daily life but also flooding has negative effects on the environment and society as a whole, in terms of tangible and intangible losses and damage.

Several studies indicated that the increase in the life expectancy, economy, and the quality of the environment can be also related to the population and wealth growth in the floodplain areas (Barredo, 2009; Barredo et al., 2012; Bouwer et al., 2010; Doyle, 2012; Geoffrey, 2009; Jongman et al., 2012; Jonkman et al., 2008; Kreft, 2011; Kundzewicz and Takeuchi, 1999; UN and ISDR, 2007; UN and ISDR, 2011). According to Geoffrey (2009), the Greater Mekong is one of the most vulnerable regions in the world to the impact of climate change. Doyle (2012) also reported that Cambodia, particularly Phnom Penh city, will be significantly susceptible to the change in precipitation patterns and warmer temperature. Likewise, a recent mapping assessment identified Cambodia as being particularly vulnerable to climate change because of climate impacts such as droughts, floods, and sea-level rise due to the country's relatively low adaptive capacity (Christensen, 2013). Notably, aspects of Phnom Penh's existing infrastructure much of which are aged and damaged due to the neglect during the war, struggles to keep up with this development, and rapid population growth.

In recent year, heavy sewer flooding and waterlogging hazards have occurred frequently because of the intensive precipitation, low flood flow capability of urban drainage systems, and a large proportion of impervious areas. These have negatively affected the social-economy in the Phnom Penh city. So, it is very important to invest in structural and

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non-structural measures for the flood mitigation which are parts of the investment allocated for the socio-economic development (Kundzewicz and Takeuchi, 1999; UN and ISDR, 2007). Meanwhile, flood modeling can provide a logical representation of urban drainage systems and essential information for the managerial and technical decision making. That is why the quantification of inundation change in the future is crucial for reducing flood losses and damage and to raise awareness and preparedness to people to cope with the current and future flood hazard. Better preparation is also required among the people and the decision-makers. Thus, the objective of this study is to estimate inundation characteristics in the downstream area of Phnom Penh under the climate change scenario using the Flo-2D model.

2. METHODOLOGY

2.3 Model framework

The overall study framework is illustrated in Fig. 1. So, to build the inundation model, a balance should be sought between the grid element size, resolution of the desired Flo-2D result, and the model computer runtime. The grid element size should reflect the topographic data resolution and result in an acceptable number of total grid elements.

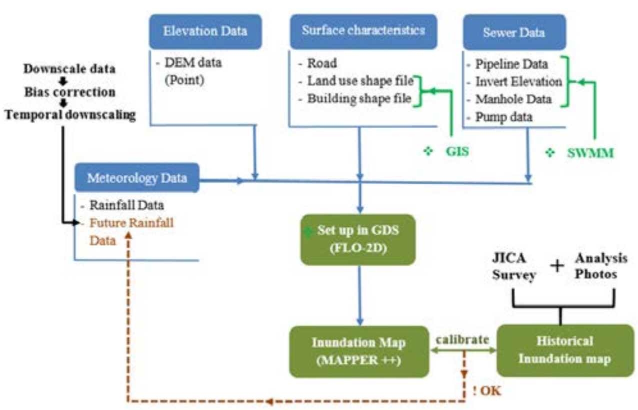


Fig. 1. Methodological framework of the study area

In this selected area, the grid system was created with the cell size of 10 m (square grid), and a satellite image (resolution 2 m × 2 m) was used to visualize the computational domain. The grid elevation was obtained from the interpolation of surveyed DTM data points, which used only along the road. Different types of land use within the study area were classified using ArcGIS based on a satellite image from MRC and observed building data in Phnom Penh. The baseline hydrograph was selected from the annual maximum (AM) precipitation within the period of 2009-2016 from Institute of Technology of Cambodia (ITC) station. Flo-2D model was calibrated with the observed inundation information carried out by the JICA team of the survey and the flood photo analysis (Heng et al., 2016). Once the model performance was successfully calibrated and validated with acceptable results, the future inundation condition in the Phnom Penh city can be estimated from the future bias-corrected climate data. The future precipitation hydrograph was established from the future AM precipitation downscaled by PRECISE GCM of ECGAM4 under SRES A2. This GCM was also employed in previous studies (Heng et al., 2017; Sreymom et al., 2015) and available and ready for use at the time of conducting this research.

2.2 Study area

Phnom Penh is the capital city of Cambodia and the center of economic, tourism, cultural heritage, and diplomacy with a population of about 2.2 million. The coverage area is 678 km^2 (Fig. 2).

Fig. 2. Location map of the study area

Also, it is remarkably noticeable that there has been rapid urbanization in the capital city. In the Mekong region, Phnom Penh is located at the confluence of the Mekong Rivers, Tonle Sap, and Bassac. This intersection has been known as the “Four Faces”. These rivers provide potential freshwater and river ecosystems as vital resources for sustainable environmental conditions, nature's beauty, and prosperous culture for Cambodians since the past. The city center is at an elevation of around 10 m above the mean sea level. Urban drainage systems in the Phnom Penh capital city are combined sewer systems which have functions of draining stormwater and domestic wastewater.

In Phnom Penh, the average precipitation is approximately 1,500 mm. However, the range of annual precipitation is wide (E.g., 1,912 mm in 2008 and 1,171 mm in 2004). Besides, the annual average of the maximum and minimum monthly temperature is 32°C and 22°C, respectively. In this study, only 12.5 km^2 regularly inundation downstream area of the Phnom Penh city covering was selected. Based on the storm drainage master plan of Phnom Penh Capital Hall, the flow direction is from the north to south (Beoung Trabeck station, P1). The study area is an independent catchment consisting of opened channels, closed conduits, and groundwater storages. There are four pumping stations at outfall (Fig. 2). The study area is surrounded by the Tonle Sap River on the east, other busy roads, and several municipal administrations, namely Royal Palace, Olympic Stadium, and embassies. The land use was classified into impermeable type including building and asphalt road surface, in which the surface runoff will be fast and generate a large volume.

2.1 Flow-2D model

Flo-2D is a two-dimensional grid-based physical process flood routing model, which is an effective tool for delineating flood hazards, regulating floodplain zone or designing flood mitigation over unconfined flow surfaces or in the channel using the continuity equation (Eq. 1) and momentum equation (Eq. 2).

$$\frac{\partial h}{\partial t} + \frac{\partial hv}{\partial x} = i \quad \text{(Eq. 1)}$$

$$S_f = S_0 - \frac{\partial h}{\partial x} - \frac{v}{g} - \frac{\partial v}{\partial x} - \frac{1}{g}\frac{\partial v}{\partial t} \quad \text{(Eq. 2)}$$

where h is the flow depth, V is the depth-average velocity and i is the excess precipitation intensity. S_f and S_0 represent the bottom friction and bed slope, respectively.

Flo-2D has several components to simulate street flow, buildings and obstruction, sediment transport, spatial variable and infiltration, floodways, and many other flooding details. The Flo-2D also includes a Grid Developer System (GDS), a MAPPER++ program, and two other processor programs, namely PROFILE and MAXPLOT. Significantly, the Flo-2D flood routing model integrates with the Storm Water Management Model (SWMM), which is developed by the Environmental Protection Agency (EPA). At runtime, Flo-2D is linked to the EPA-SWMM model, so there can be an exchange between overland flow and storm drain conveyance. The Green-Ampt method was applied to simulate the infiltration in this study over the Soil Conservation Service curve number because of the soil suitability and data availability.

2.4 Bias correction method

Because either General Circulation Models (GCMs) or Regional Climate Models (RCMs) exist with their own bias, so these models are not ready to be used in any decision support tool. They are not perfect and different from the observed climatic data (Sharma et al., 2007). So, the historical and future climate models are required to perform bias correction to reduce some degree of uncertainties, so the result of any assessment study can be reliable enough. However, Teutschbein and Seibert (2012) conferred that the quality of adjusted RCM temperature and precipitation strongly depend on the choice of the correction algorithm, both for current and future climate conditions. In this study, a linear correction method proposed by Leander and Buishand (2007) was used. In this method, precipitation amounts, P, are transformed into P^* such that $P^* = aP$, using a scaling factor, $a = O/P$, where O and P are the monthly mean observed and RCM precipitation, respectively. Here, the monthly scaling factor is applied to each uncorrected daily observation of that month, generating the corrected daily time series.

2.5 Temporal downscaling method

The sub-daily precipitation (5 min, 1 h, or 2 h) are needed to input in the simulation. Since Southeast Asia START Regional Center provides future climate data at the daily interval, it is necessary to temporally downscale the precipitation data. There are different types of downscaling techniques such as linear regression, stochastic method and artificial neural networks which have been developed over the years and used so far. These methods are used to develop the artificial hydrograph for designing storm drain, etc. For this study, the extreme AM precipitation pattern in the past was selected to construct the extreme AM precipitation for the future. This method is described in Eq. 3:

$$i_f = i_{cf}\frac{i_p}{i_{cp}} \quad \text{(Eq. 3)}$$

where i_f and i_p rainfall intensity for a specific day in past and future (mm/s) and i_{cf} and i_{cp} are accumulative rainfall intensity in a specific day of past and future (mm/day). The extreme precipitation among the AM daily precipitation with the period of 2009-2016 recorded by ITC station near to the study area was chosen to generate precipitation hydrograph for the analysis.

2.6 Observed inundation data

Since there is no historical record of inundation conditions in the study area, the Flo-2D model was calibrated with observed inundation map extracted from the JICA survey database and flood photo analysis which is very crucial when lacking the observed data (Luo et al., 2018; Sea et al., 2018). According to JICA (2017), the inundation map was established using data from the interview with citizens after the completion of some development projects as shown in Fig. 3. Some 108 respondents corresponding to 83% of the total number of interviewees replied that they had experienced flooding in front of their houses. The experienced flooding depth ranged from ankle to waist-deep. Around 80% of interviewees have experienced flooding mentioned that the depth was up to the shin (about 20 cm) or higher. Besides, some flood information was obtained from photos posted on Facebook, YouTube, etc. 11 photos were collected from Facebook including one photo each of flood event in 2012 and 2017 and the rest are 2015 flood events. The location of flooding was found on their status based on the spot in photos like hotels, restaurants, schools, or their living locations. Similarly, the specific time of flooding might be on the information they shared. The inundation depth could be recorded by estimating flood depth in comparison with any inundated objective such as the human body and vehicle (Table 1 and Table 2). The observed inundation depth in various locations from these sources is depicted in Fig. 3.

Table 1. Average inundation depth at parts of the human body

Parts of body	Ankle	Shin	Knee	Thigh	Waist
Average depth (cm)	10	20	40	60	80

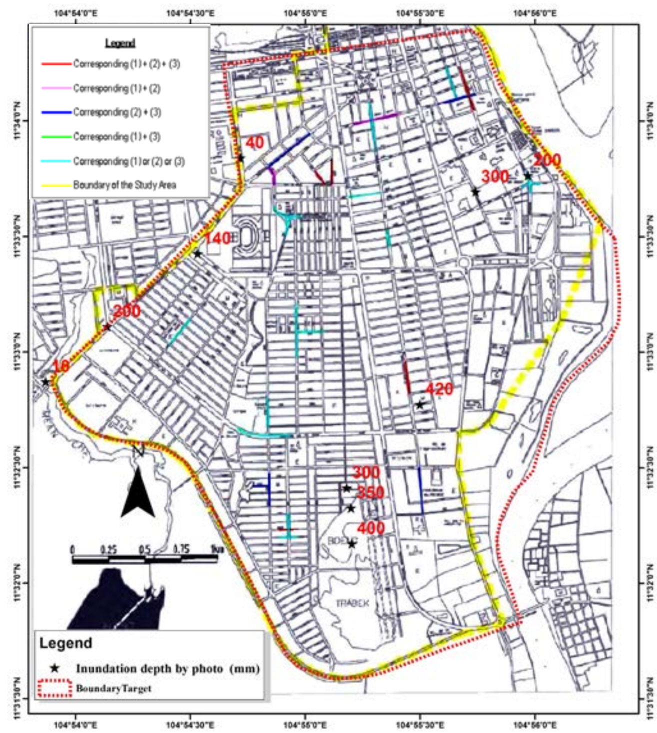
Table 2. Average inundation depth at parts of the car

Part of car	Ground clearance	Type
Average height (cm)	16	40

3. RESULTS AND DISCUSSION

3.1 Future precipitation scenario

The bias-corrected precipitation data from the ECHAM4 model under SRES A2 in comparison with the observed precipitation data recorded at Pochentong station, near the Phnom Penh International Airport, is illustrated in Fig. 4. The cumulative density function (CDF) of daily precipitation from the ECHAM4 model under SRES A2 does not agree well with the CDF of daily precipitation from the gauge observation. So, a linear correction method was used to correct the bias in this study. The precipitation data from GCM given by ECHAM4 under SRES A2 simulation and observed precipitation data from Pochentong station (1985-2012) was used to define a scaling factor. As a result, the bias-corrected precipitation data from ECHAM4 under SRES A2 pretty improved closeness to the observed data (Fig. 4). This scaling factor was used to adjust the future precipitation from ECHAM4 under SRES A2 for the 2030s (2020-2038). Fig. 5 shows the adjustment result of the downscaled precipitation data using the defined scaling factor.



No.	Conditions
(1)	All of the interviewees replied that flood inundation frequency is more than 4 times a year.
(2)	Half or more interviewees replied that inundation depth is higher than the shin.
(3)	Half or more interviewees replied that inundation duration is longer than 2 or 3 hours.

Fig. 3. Observed inundation by JICA survey in 2017 and flood photo analysis

3.2 Temporal downscaling of future precipitation

Based on ECHAM4 under SRES A2, the annual maximum precipitation is expected to have a decreasing direction in the near future (Fig. 6). This can be subjected to the employed climate model and emission scenario, local climate conditions, especially the bias correction method. The precipitation intensity will likely vary between 50 mm/year and 1,600 mm/year in the 2030s. However, the extreme precipitation in the 2030s was selected to temporally downscale daily to sub-daily precipitation to quantify the future change in the inundation depth of the downstream area in the Phnom Penh city. Also, the extreme event on 11 October 2010 was used to construct the precipitation pattern of the extreme precipitation in 2010

(Fig. 7). The precipitation data from the temporal downscaling to a time interval of 5 min has the peak precipitation intensity of 70 mm/hr. From JICA data (JICA, 2017), the peak precipitation intensity for 2-year and 5-year recurrence interval is 44.8 mm/hr and 63.2 mm/hr respectively. Precipitation with an intensity of 70 mm/hr could probably happen even in one year.

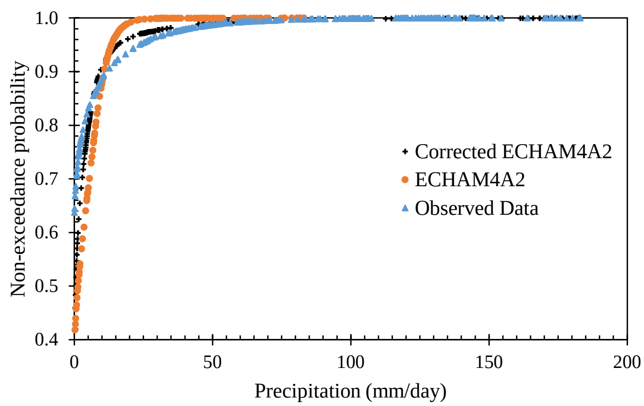


Fig. 4. Simulated and corrected CDF of daily precipitation in the baseline (1985-2012)

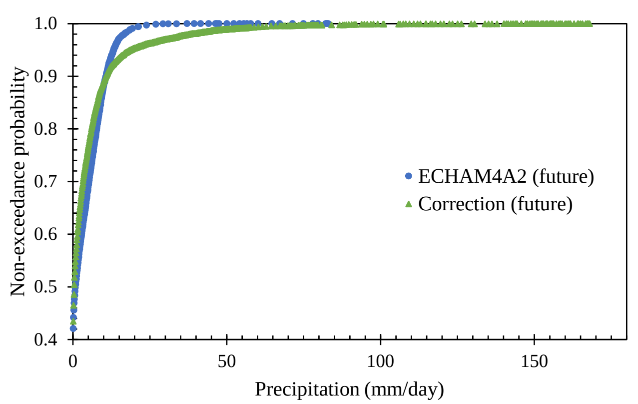


Fig. 5. Simulated and corrected CDF of daily precipitation in the near future (2030s)

3.3 Baseline and future inundation conditions

In the calibration stage, the validity of the model was confirmed by comparing the simulation result under the observed precipitation time series on 11 October 2010 and the observed inundation. Fig. 8 shows the result of flood depth from Mapper++ (Flo-2D). The established model for the study area was well-calibrated because the spatial distributions of the inundation map were pretty matched with the observed inundation. The result showed that the inundated area around the Royal Palace is the most serious and vulnerable. The maximum inundation depth can reach 0.57 m (A-B). Also, the inundation at Beoung Trabeck market area can be expected between 0.10 m and 0.47 m (C-D). However, light inundation is observed at the east, north and west part of the study area, the area around Olympic National Stadium, and the area along the opened drainage channel.

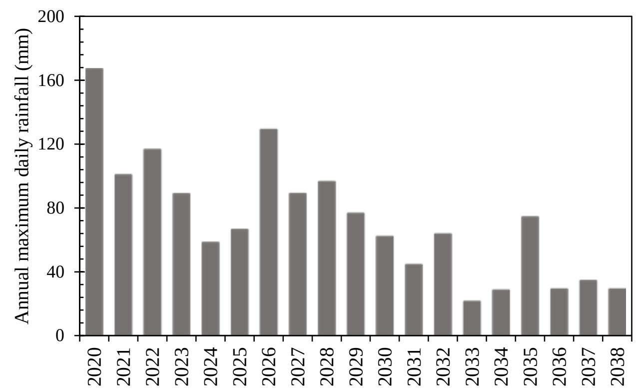


Fig. 6. Annual maximum daily precipitation from 2020 to 2038

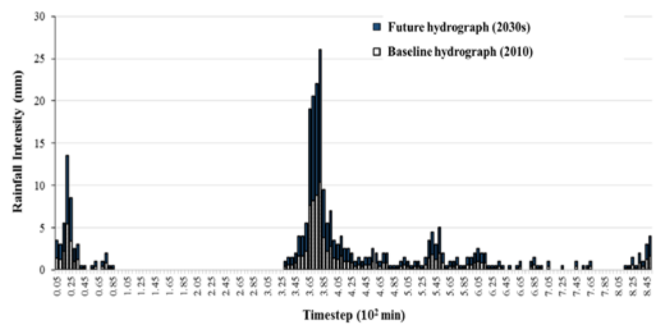


Fig. 7. Extreme precipitation events in 2010 and 2030s

Under the assumption of no change in infrastructure and pump capacity, the inundation depth in the downstream area of the Phnom Penh city under climate change scenario can refer to Fig. 9. The future precipitation with the same pattern as the extreme event on 11 October 2010 was applied in this study to find the inundation changes. The infrastructure and the pump capacity were not changed in the simulation. Fig. 9 illustrates the future inundation depth. The area around the Royal Palace and Beoung Trabeck market still showed the extreme inundation with the water depth over 0.8 m in some area. The edge of open channel b3-b4 (Fig. 2) has extremely changed inundation condition with the maximum water depth of 0.75 m. All areas along the open drainages affected by inundation likely influenced by backwater effects from the overflow of the open channel. Appendix A shows the graph of the volume of overbank outflow of both baseline and near future. The volume of overbank flow will increase by 1.15 of the baseline volumes. Appendix B illustrates the flow depth profile from point A to B and C to D for both baseline and near future. Overall, the simulation result showed differences in the extension of submerged areas with the peak flood depth typically range between 0.03 m to 1.00 m for the near future precipitation. Also, the inundation depth will be increased from 0.20 m to 0.50 m in the submerged area and spread over the study area.

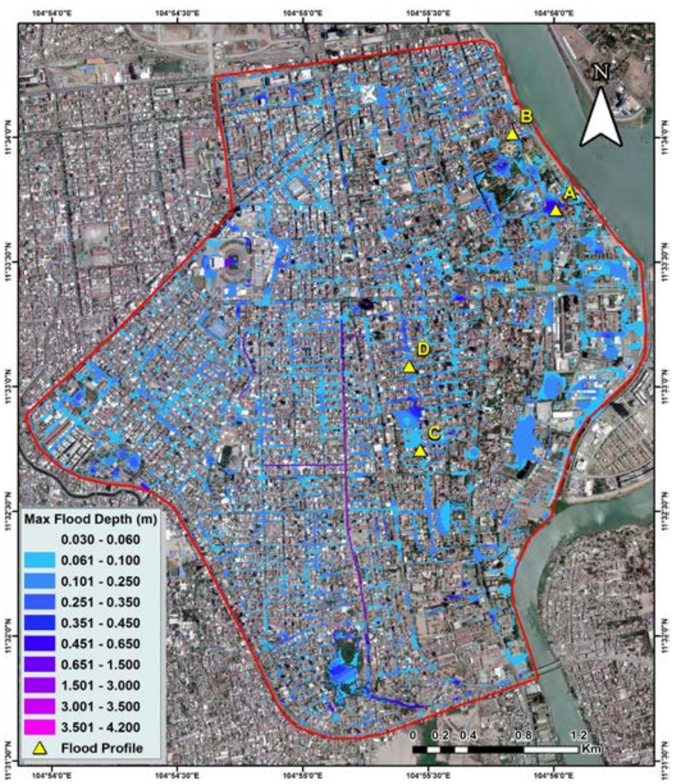


Fig. 8. Inundation condition within the study area in the 2030s

4. CONCLUSIONS

Flo-2D model is applicable to simulate the complex storm drainage in Phnom Penh City since the overall performance of the simulation result was well-calibrated with the observed inundation obtained from the survey and flood photo analysis. However, some uncertainties still existed from the model result. According to the ECHAM4 under SRES A2, there will be probably an increase in volume and area of inundation within the study area in the near future if there is nothing change to the existing drainage system. The inundation depth is predicted to increase between 0.2 m and 0.5 m.

This modeling result could provide useful information to urban planners to work on the renewal and maintenance of drainage systems in some affected and vulnerable areas. Also, increasing the pump capacity at each outlet is required to cope with extreme precipitation in the near future and should parallelly pay attention to develop more detention basin or ground storage along the open drainage channel to minimize the risk of overflow.

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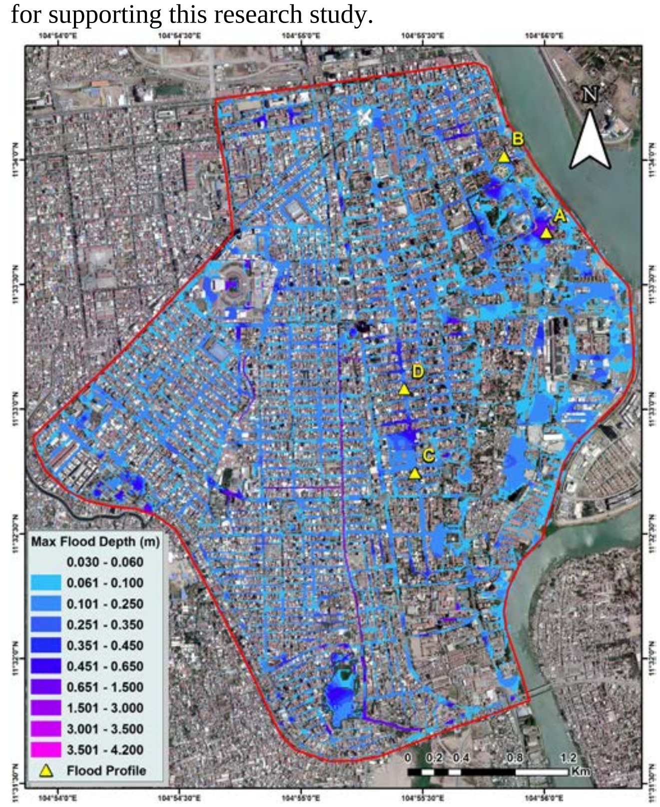

Fig. 9. Inundation condition within the study area in 2030s

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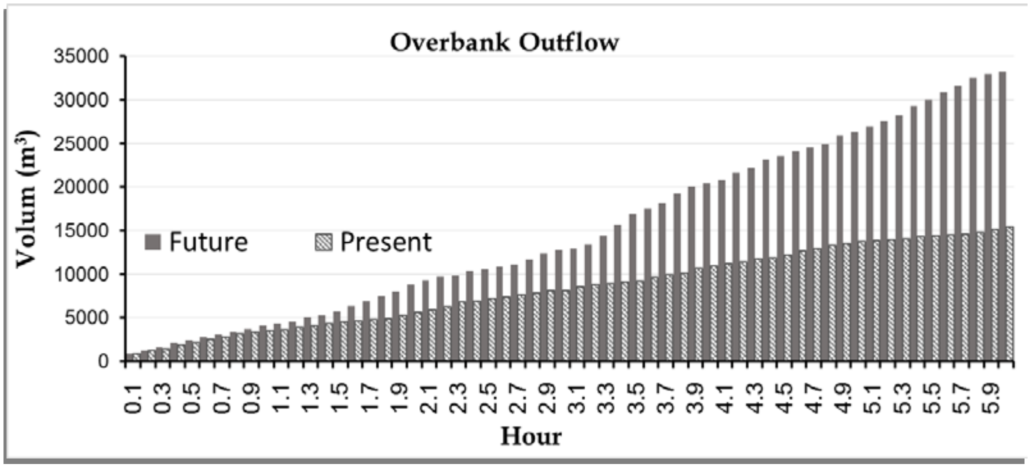
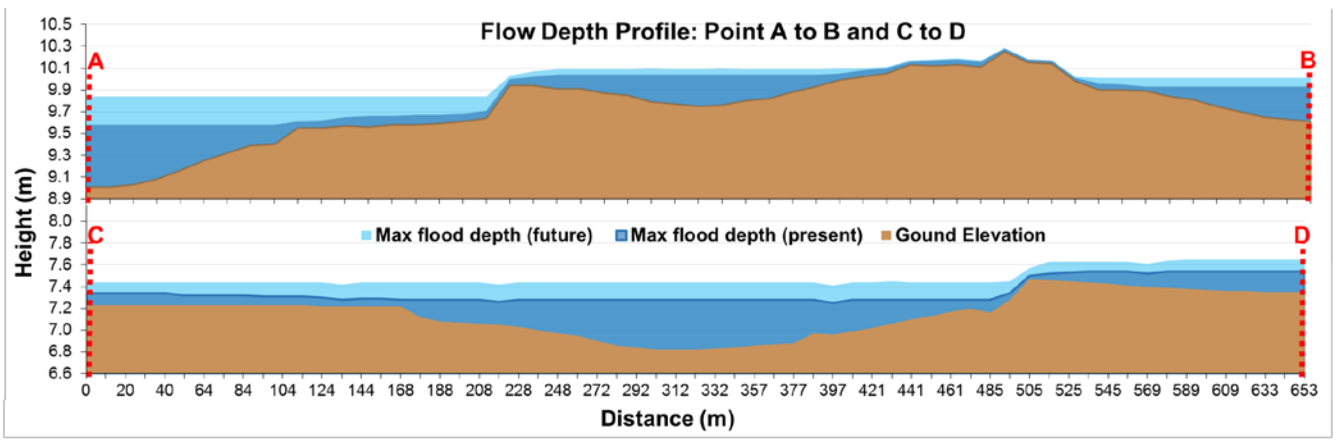
APPENDICES



Appendix A. Overbank outflow volume



Appendix B. Baseline and near future flow depth profile, locations (A, B, C, and D) can refer to Fig. 8 and Fig. 9.