Tech. J. River Res. Inst. 13(1): 87-101, 2016 (October), ISSN: 1606-9277

ESTIMATING URBAN FLOOD HAZARD ZONES USING SWMM IN CHITTAGONG CITY

Aysha Akter[1] and Ahad Hasan Tanim[2]

Abstract

Identifying urban flood-prone areas with their relative hazard scale is the fundamental work of urban flood management. This may introduce using a probabilistic methodology by flood hazard zoning of potential urban flood hazard area. Based on statistical analysis of US EPA Storm Water Management Model (SWMM) with a threshold value of maximum depth of each node of link network number of overflow events in a specified time period can be obtained. Further using Kernel hazard density the spatial analysis in ArcGIS can be used to obtain a GIS compatible maps for the hazard zoning of the potentially flood prone areas. In this study Chittagong city, the second largest city of Bangladesh has been taken as a case study and the wettest year 2014 was selected for model simulation. The validated model outcome reasonably identified the flood prone vulnerable zones which is comparable to the outcome of recent field studies. Thus, it is expected that the acquired flood hazard mapping will play major role once this is observed using details field data. Finally, this would provide flood risk information to the decision makers and flood protection works to prioritize the relatively more flood hazard zone for management purpose.

Introduction

Chittagong city area has experienced the highest number of flood incidence in last decades. Social environment, local economy and ecology have been hampered and degraded due to prolonged urban flooding. During the flood about 7 million city dwellers face severe disruption in their daily life (CWASA 2015). The overflow in the drainage system frequently occurred due to combined effect of heavy rainfall as well as tidal effects. Attempts have been made by frequent dredging of the drainage systems without any comprehensive study of flood. As a result overall flood protection works fail to offer the expected supports. More than 2.73 Billion Bangladeshi Taka has already been employed by the Chittagong Development Authority (CDA) during last decades but the overall flood protection work faces difficulties to provide permanent protection to the adjacent city dwellers. Including Chittagong Water Supply and Sewerage Authority (CWASA) project based study, there were few research studies identified the key issues, i.e., heavy rainfall, tidal effect of adjacent Karnafuli River, intervention in sewerage system due to solid waste blockage as well as climate change (CWASA2015; Table 1). Thus, while analyzing the flood risk hazard those factors must be considered in addition the idiosyncratic topography of the area.

---

[1]Chairman, Center for River, Harbor & Landslide Research (CRHLSR) and Professor, Department of Civil Engineering, Chittagong University of Engineering & Technology (CUET) Chittagong 4349, Bangladesh, Email: aysha_akter@cuet.ac.bd; aysha_akter@yahoo.com
[2]Research Assistant, CRHLSR, Chittagong 4349, Bangladesh

Table 1. Research study summary on urban flooding in Chittagong City area

References	Causes	Identification method	Limitations
Mohit and Akter (2013)	Climate change, solid waste blockage	Field survey	Proper identification of water logged hotspot, extent and depth
Mohit et al. (2014)	Heavy rainfall	Hydrological modeling	Water logging extent and surcharged location in drainage system
Ahmed et al. (2014)	Heavy rainfall, tidal effect, urbanization	Field survey	Tidal effect and Hydraulic data scarcity of modeling study
Tanim and Akter (2015)	Heavy rainfall	Numerical modeling	Tidal effect
Tanim et al. (2015)	Heavy rainfall	Hydrological modeling	HEC-HMS inability to simulate tidal effect
Akter and Tanim (2015)	Tidal effect	Numerical modeling	Hotspot of urban flooding

With the advent of computer based numerical modeling, flood hazard mapping can be achieved with reasonable accuracy. So far a number of factors have to be considered while studying flood hazard based on topography. Elkhrachy (2015) considered some causative factors while generated flood hazard mapping those are runoff, soil type, surface slope, surface roughness, drainage density, distance to main channel and land use. Mastin (2009) proposed a watershed model for flood management that can simulate several factors such as influence of frozen ground on peak discharge, evaporation and groundwater flow, channel losses. Špitalar et al. (2014) carried out a probabilistic analysis based on the human impacts on the flash flood that relies on the computation of probability distributions by occurrence (PDF) and the PDF of occurrences weighted by the number of injuries and fatalities for different spatial, temporal, and hydrologic parameters. Bhatt et al.(2010) applied satellite based observations for alluvial plains of North Bihar (India) that are most vulnerable to flood hazards. Recently, GIS and other modern spatial techniques such as HEC-GeoRAS offer capabilities to extract drainage networks and basins that have potential to influence accumulation of runoff. To identify the nodes that are most vulnerable can be integrated using GIS (Youssef and Pradhan 2011).

Cherqui et al. (2015) first analyzed the combined sewerage system at a strategic scale (based on the intervention in combined sewerage system) of the whole territory, then analyzed specific areas which potential flooding is identified using Kernel density function. Understanding of past long-term hydrologic variability required to anticipate the effects of potential climate change impact (natural or anthropogenic) on hydrology. Such probabilistic estimation is a critical need for extreme floods for better understanding of flood processes, flood-hazard mitigation and flood risk assessments. This paleohydrologic information provides valuable information based on which flood hazard analysis can be performed. Probabilistic estimation of flood frequency can be obtained from the statistical analysis of overflow events. On the other hand US EPA Storm Water Management Model (SWMM) is Federal Emergency Management Agency (FEMA) approved computer program that computes dynamic rainfall-runoff for flood analysis single event and long-term (continuous or period-of-record) runoff quantity and quality from developed urban and undeveloped or rural areas. FEMA specified following steps must be followed while modeling with SWMM (e.g. this procedure assumes that the floodplain areas beyond the encroachment stations will be completely filled).

- SWMM can consider the loss of floodplain storage and the loss of conveyance, while steady flow models can consider only the loss of conveyance in computing floodways. However, unsteady flow programs do not have an option to determine floodways automatically to account for the loss of floodplain storage and conveyance. Therefore, the encroachment stations for the floodway must be determined first from a steady flow model, such as HEC-2, using the equal conveyance reduction method;

- The HEC-2 format is recommended when specifying data for the natural cross sections in the SWMM model; and

- The maximum computed flow at the cross sections (conduits) and the corresponding time of occurrence is obtained from the Conduit Summary Statistics table for the 1% annual chance flood.

For this reported study following the above mentioned issues, the statistical analysis of SWMM on a particular node was carried out and supposed to provide such sorts of information which can be incorporated with Kernel flood hazard density to identify potential flooding zone.

Methodology

Study area

The study area (Figure 1) was considered to be representative of urban flood prone area, which is located adjacent to the bank of Karnafuli River. These small catchments (44.19 km^2) originate in Chittagong district in the southern range of country having tertiary maritime deposit and reach the sea forming a coastal river estuary transition zone. This means that the alluvial fan of flood plains have combination of free flash flooding and coastal flooding of adjacent river. Historically human occupation of the city area has changed the land use pattern that reveals increased urbanization is one of the impact factors of flood occurrence. The physical properties of study area are shown in Table 2. The soil formation in the study area varies from sandy to silty type. The studied basin lied in tropical climate with mean annual rainfall 3000mm. There are 3 major primary drains viz. Mohesh Khal, Khal no 18 and a major parts of Chaktai Khal (CDA 1995) those are connected to a numbers of secondary drainage systems. Finally, there are 8 outfalls those are disposing in the Karnafuli River. These outfalls are located in the estuary.

Table 2. Physical properties of sub-catchments

Sub-catchment ID	Area(Hectors)	Width(m)	% slope	Imperviousness (%)
S1	363.09	1780	4.14	62.99
S2	176.51	1154	11.59	59.64
S3	409.9	1602	5.52	4.52
S4	153.47	775	7.12	84.39
S5	331.24	1409	4.14	64.21
S6	320.05	3170	7.25	83.4
S7	363.24	1628	3.39	32.05
S8	158.94	1431	8.17	41.02
S9	233.49	2501	13.55	17.97
S10	177.69	1112	16.44	0.46
S11	355.25	1822	3.69	48.93
S12	146.24	995	3.44	60.34
S13	191.8	1222	6.45	48.91
S14	158.14	1839	2.56	38.32
S15	314.63	1701	3.98	13.05
S16	274.63	1789	8.82	71.71
S17	190.16	1584	4.61	63.26
S18	100.1	475	5.1	74.93

Data preparation

The topography information was acquired from the Shuttle Radar Topography Mission (SRTM) of 30 m Digital Elevation Model (DEM). The link network (drainage network) was developed using Chittagong Development Authority (CDA) vector data. The SCS-CN method was used to determine the infiltration amount for the given precipitation data. Meteorological data, i.e. precipitation, evapotranspiration, wind speed, radiation and temperature, for the catchment area were obtained from Bangladesh Meteorological Department (BMD) for the year 2014. Thus, the obtained meteorological data were further processed to obtain evapotranspiration. The land slopes of the sub-catchments were obtained using spatial analysis of Arc-GISv9.3 (Figure 2).

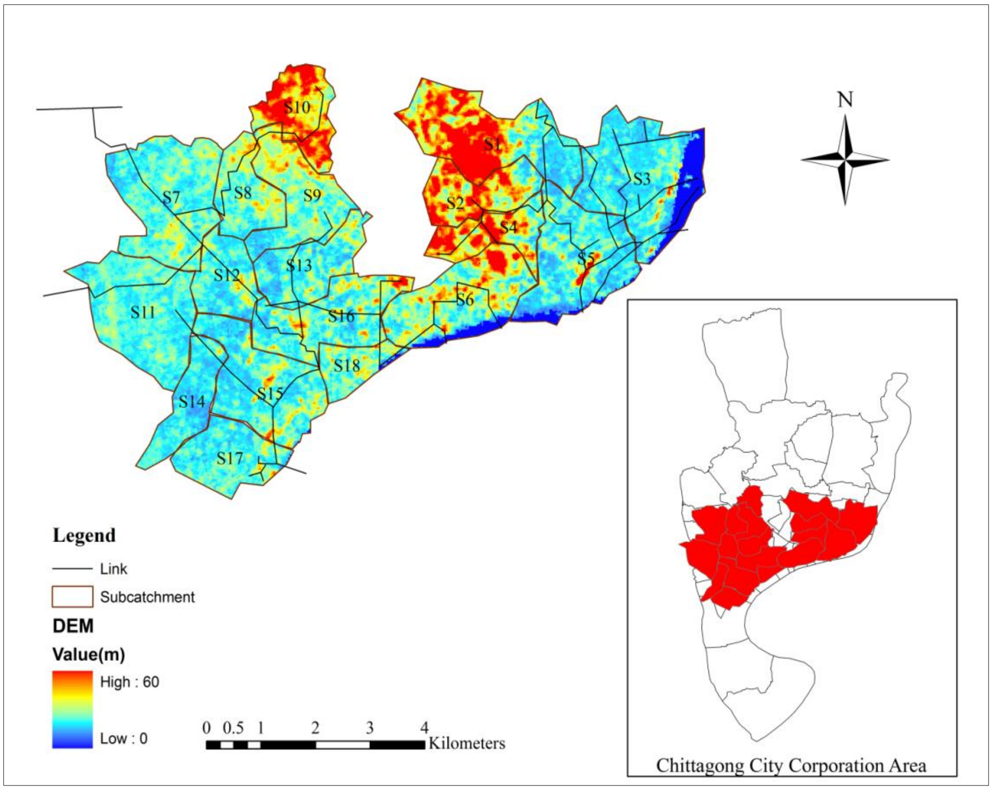

Figure 1. Study area

As the basis of hydrologic impact evaluation, urban land use study was carried out using the images acquired from U.S geological survey Landsat_8 (http://earthexplorer.usgs.gov) for 1st December 2013 considering cloud cover of1. 11.

This image was further processed using ERDAS IMAGINE. The satellite images were generated by applying coefficients for radiometric calibration, geometric rectification and projected to the Universal Transverse Mercator (UTM) ground coordinates with a spatial re-sampling of 30 m. Land use study was carried considering 4 criteria viz. vegetation, bare soil, water body and built-up area. The built-up area was accounted as impervious area (Table 2).

The overall accuracy ranges are from 0 to 1, and kappa value exists between -1 and 1. If the test samples were in perfect agreement (all the same between classification results and predicted results), values for the overall accuracy and Kappais equal to 1. The overall classification accuracy of each image was over 85.25% with kappa values over 0.816, meeting the accuracy requirements.

Delineation of sub catchment

Initially raw data from Shuttle Radar Topography Mission (SRTM) with 30m resolution Digital Elevation Model (DEM) was analyzed with Arc-GISv9.3 and HEC-GeoHMSv5.0 terrain processing tool with input stream network. The output 18 sub-catchments were obtained with the input stream network which is existing link network of study area. The delineation was followed several steps such as DEM reconditioning, filling sink in DEM, assigning flow direction and flow accumulation. Obtaining stream segmentation finally sub-catchment grid cell was processed which was used with terrain processing of HEC-GeoRASv4.3 preprocessing with stream network. The area of each sub catchment can be calculated in SWMM interface which imported as metadata from ArcView.

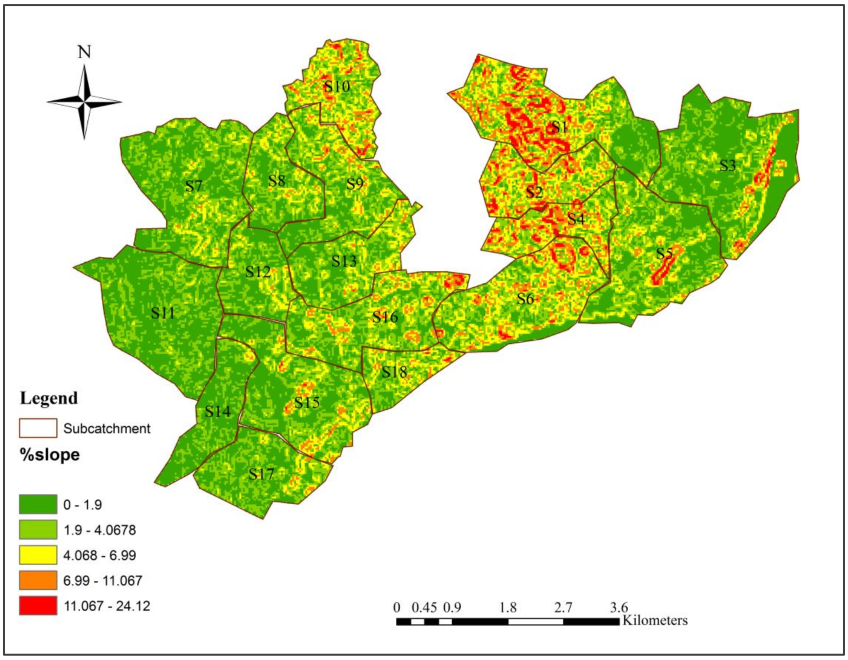

Figure 2. Slope analysis of study area

Importing stream-network in SWMM from HEC-GeoRAS

HEC-GeoRAS v4.3 preprocessing was conducted using the raw SRTM 30 m as grid layer. Then channel topography like stream centerline, flow path, bank line and cross section with floodplain are processed from exporting HEC-GeoRAS. Total 152 conduit links as transects (irregular channel cross section) and 144 junction nodes are imported in SWMM. Total 8 numbers of outfalls are located in adjacent Karnafuli River. Each conduit is subjected to an upstream boundary condition of runoff hydrograph and downstream boundary condition of tide curve at outfall.

Tidal harmonics of Karnafuli River

Observing water level records in coastal waterways in Karnafuli river has two tides a day each tidal cycle lasting about 12 hours 24 min. Both of the tidal range and the main water level vary seasonally and from place to place along the river (Akter and Tanim 2015). The variation in a month shows a neap tide and a spring tide. The tidal fluctuations can be classified as a diurnal fluctuation because tide usually describes in this case one high and one low water occur in the period of the rise, and also of the fall, of tide is approximately 12 hours (NOAA, 2006). Figure 3 shows the pattern of tidal fluctuations during June 2014 in Khal 10.

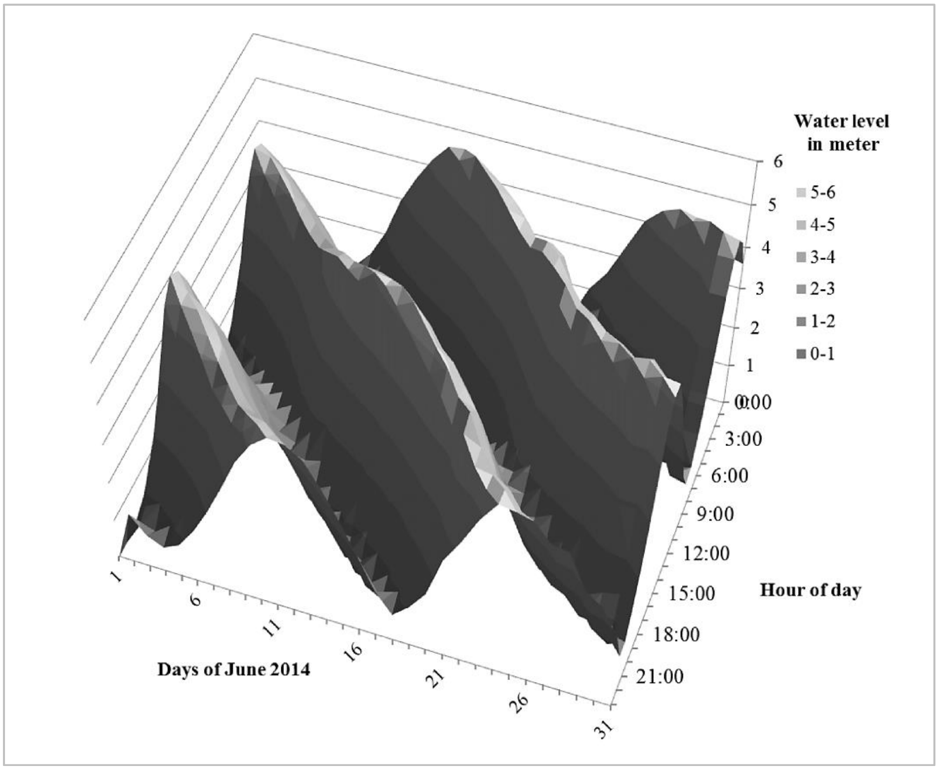

Figure 3. Tidal pattern of Karnafuli River at the Mohesh Khal outfall

Routing method and time steps

Dynamic wave routing method, based on 1D Saint-Venant flow equations, was used for simulating this study. In this method, flood occurs when the water depth at a node exceeds the maximum available depth as described by Rossman (2008). Thus, to simulate backwater effect the dynamic wave routing method with a time steps less than 60 s can be accounted. A time series of June 2014 with time steps of 30s was selected for the model simulation.

Model outcomes

The statistical analysis of flood in SWMM

The statistical analysis in SWMM can be performed for any hydrologic events. This analysis includes any event variable such as flood, runoff, precipitation, lateral inflow, discharge volume etc. The mean statistical analysis was conducted on each node with assigning a depth as variable. The maximum depth as threshold limit of each node was selected so that the number of over flow event and frequency during June 2014 can be determined (Figure 4). The water logging duration in June 2014 can also be obtained from simulation results (Figure 5).

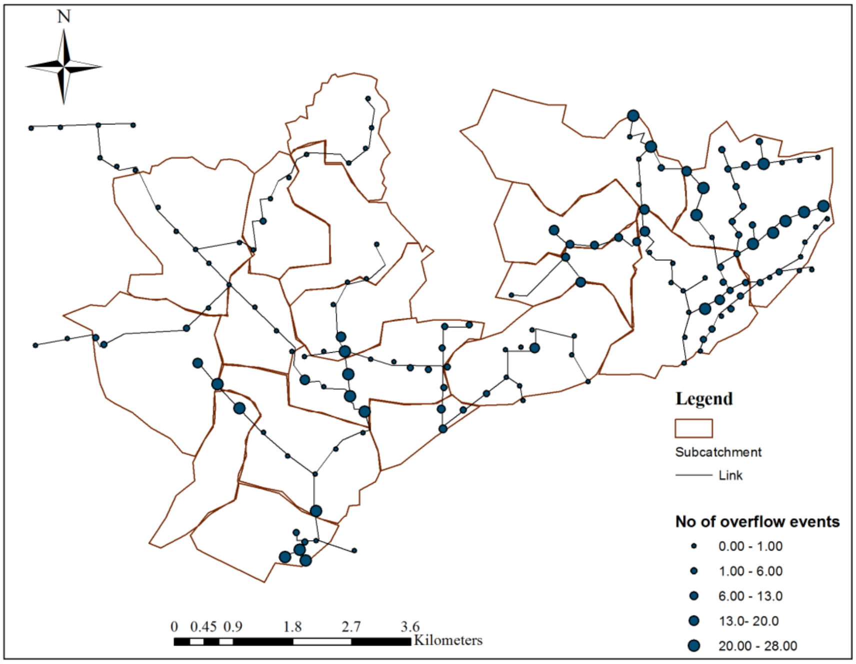

Figure 4. SWMM statistical analysis (numbers of overflow events during June 2014)

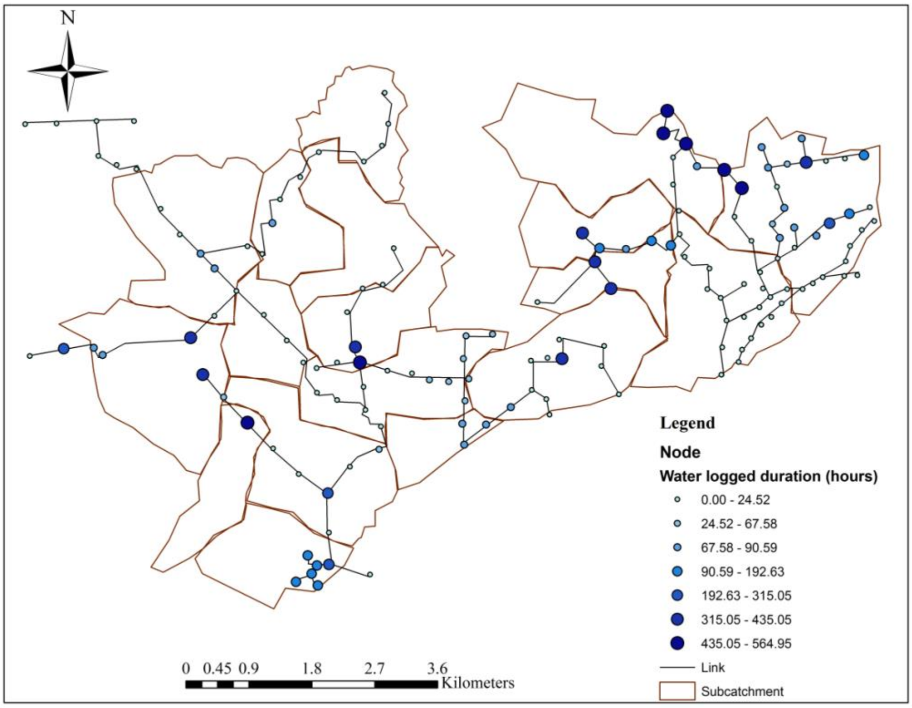

Figure 5. Water logging durations at different nodes during June 2014

Flood hazard analysis method

There are multiple approaches of flood hazard mapping, among them three main methodologies are available, those are: paleohydrological methods, hydrogeomorphological methods, and hydrological–hydraulic methods (Baker 1988; Benito et al. 2004). In addition to these the recent appearance of dendrogeo-morphological methods also engaged in this regard (Díez-Herreroet al. 2008). However, in most hazard analysis they are complementary of each other. Paleohydrological methods are suitable for statistical analysis regarding overflow events and can provide expected information while hydrological–hydraulic methods require large amounts of hydrological data those are integrated with SWMM.

Flood hazard analysis requires information regarding hotspot areas i.e., the place experiences overflow frequently. The basis of identification might be either field survey or numerical modeling. The database for statistical analysis must contain location of overflow nodes and number of overflow events in the nodes. A numerical modeling study i.e, SWMM integrated with GIS is more convenient to represent and gather such information. The statistical analysis in SWMM is detailed below.

Kernel density estimation for flood hazard

A flood is usually caused by a channel that has over flowing banks during high runoff period which can be predicted using annual stream flow study. Thus, for flood hazard analysis it is essential to determine the number of overflow events and this can be determined using statistical analysis in SWMM. Most common probability distribution used in hydrologic extremes modeling is Gumbel Probability Distribution. But, this probability distribution underestimates largest rainfall amounts. Kernel Density Estimation (KDE) plays an important role in the probabilistic characterization of phenomena through reducing identification difficulties of a well-defined probability density function (PDF) in the parametric sense (Tehranyet al. 2014)

Spatial analysis of flood hazard

To identify potential flood hazard zone it is difficult to rely on a well-defined probability distribution function. In such cases researchers suggested for Kernel Density function to determine spatial distribution of flood hazards (Cherqui et al. 2015; Baah et al. 2015; Camarasa et al. 2011; Kaźmierczak and Cavan 2011, Caradot et al. 2011). The hazard density (D) was calculated at each pixel in the territory (Cherqui et al. 2015):

$$D = \frac{\sum_{i=1}^{n} H_i . c_i}{S} \qquad \text{eq. (1)}$$

H_i corresponds to value of the hazard score for sewer flooding i, that is to say the number of events observed for each pixel of the map; c_i is a decreasing smoothing coefficient Eq. (2) and S is the area of a circle with radius R containing n sewer flooding events.

$$c_i = \left(1 - \left(\frac{r_i}{R}\right)^2\right) \text{If } r_i < R$$
$$c_i = 0 \quad \text{If } r_i > R \qquad \text{eq. (2)}$$

The Kernel density approach has been successfully utilized in many fields such as road accidents, health disease. Visual surveillance of photogrammetry, remote sensing based flood assessment etc. (Branko 2008). Usually a grid based representation provides a better representation of flood hazard than point based database. However if the point based flood hazard density able to estimate than it is convenient to interpolate the hazard density to the surrounding pixel. Thus at first, KDE was obtained at each node considering the SRTM 30m as unit pixel depth. Further, KDE with surrounding pixel are interpolated with overflow node KDE using the inverse distance weighted (IDW) surface interpolation method. IDW surface interpolation method takes the concept of spatial auto correction laterally. As statistical analysis carried out over 144 nodes in the study area it is expected that after interpolation KDE in the link network will represent reasonable value as distance among nodes varies from 100m to 500m. Thus obtained flood hazard map is shown in Figure 5

Flood hazard analysis scale

Depending on the needs of the water utility manager, the hazard density can be represented into two different scales:

- A strategic scale (i.e., Kernel density radius of 5 km) which represent a strategic overview of the main flood areas at city scale (Caradot et al. 2011); and

- An operational scale (i.e., Kernel density radius of 500 m) which is a complementary representation shows the disparities within each main flood area. This operational overview makes it possible to identify the network components responsible. This strategic scale is used for hazard mapping in the study area.

Identification of urban flooding hotspot

Based on Kernel hazard density, the location of study area can be classified in three categories i.e., most vulnerable, moderate vulnerable and less vulnerable (Figure 6). The details on urban flooding prediction note down in Table 3.

Table 3. Model predicted hotspot of urban flooding

Vulnerability class	Locations	Kernel hazard density at strategic scale 500 m radius
Most Vulnerable	Bakalia (West and South), some part of Chawkbazar (adjacent to Bakalia) Chittagong port, Probortak, Uttar Moddaya Halishahar	0.25-0.47
Moderate Vulnerable	South Agrabad, Sadarghat	0.17-0.24
Less Vulnerable	Rest of the parts of Study area	0-0.16

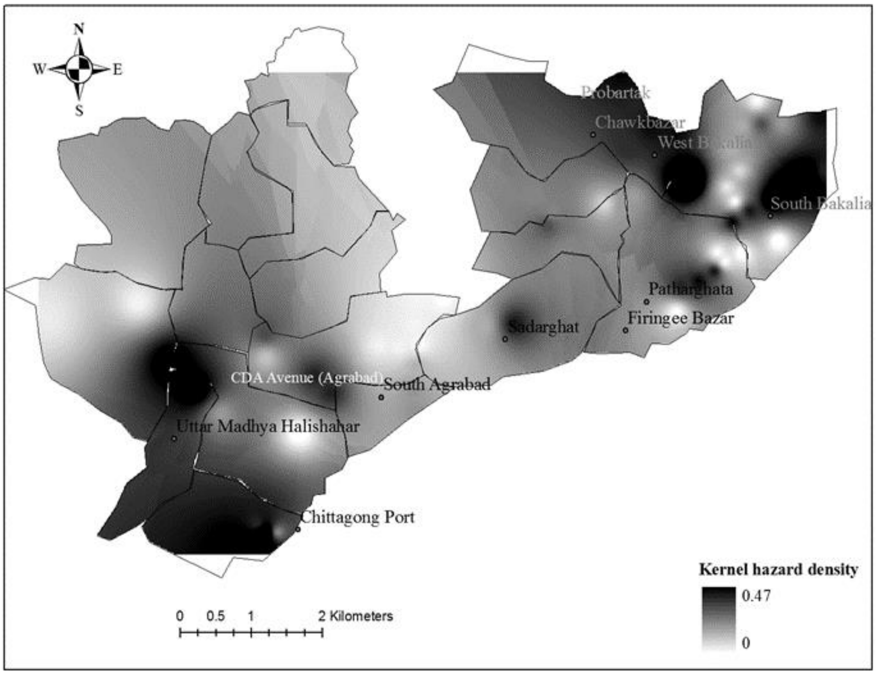

Figure 6 . Strategic representation of potential flooding based on kernel density function (radius 0.5 km) at nodes

Validations of model outcome

The predicted hotspots are verified with an intensive study of CWASA (2015) and Mohit et al. (2014). The vulnerable locations identified from those studies are Bakalia, Halishahar, Agrabad and Sadarghat in the study area. Several validations need to be justified from the study:

- Given the marginal sensitivity of topography and Manning's n value the model outcome might be influenced. The terrain elevation collected based on 30 m SRTM DEM might be fail to mimic the channel topography thus there might be influence on flow direction in link network;
- Manning's 'n' was taken in a range of 0.03-.04, a value in the theoretical range of roughness specification. Whilst a uniform roughness value of 0.03 simplifies the representation, given the scenario-based nature of this study, it is regarded as an adequate assumption;
- Inadequacies of rain gauge make the rainfall amount uniform over the study area. This might be overcome using Tropical Rainfall Measuring Mission (TRMM) precipitation or Next Generation Weather Radar (NEXRAD)

following Wen et al. (2013) but those were not available during study period; and

- Determination of soil hydraulic conductivity from the SCS-CN method may not accurate representation for overall catchment area. But model assumptions required one constant value throughout the sub catchment.

Concluding remarks

The reported study is a part of existing study. Observing serious urban flooding in June 2014, this study was focused on Chittagong city based on available rainfall data from Patenga rain gauge. The GIS based SWMM could reasonably identify the flood hazard locations compare to the earlier field studies. In addition to the identification based on the Kernel hazard density, the validated model could estimate the intensity of flood hazards and thus the most vulnerable spots are spreads over Bakalia (West and South), some part of Chawkbazar (adjacent to Bakalia) Chittagong port, Probortak and Uttar Moddaya Halishahar. The validated model supposed to provide guidance once the model estimation could be verified by the available field survey.

Acknowledgement

The authors gratefully acknowledge the financial supports provided by the Center for River, Harbor & Landslide Research (CRHLSR), Chittagong University of Engineering and Technology (CUET), Bangladesh. Logistic supports from CDA, CWASA and CPA are highly appreciated. The authors gratefully acknowledge the technical supports provided to develop land use study by remote sensing provided by GIS Expert Md. Kamrul Islam.

References

Ahmed S., Mohit S.A. and Akter A. 2014.A study on water logging reduction in Chittagong city. In proceedings of the 2nd International Conference on Civil Engineering for Sustainable Development (ICCESD-2014), 14~16 February 2014, KUET, Khulna, Bangladesh, ISBN: 978-984-33-6373-2. pp. 400-406.

Akter A. and Tanim A.H. 2015. Predicting Urban Floods through Tidal Flow Simulation, 1st National Conference of Earthquake and Disaster (NCEED-2015), 17th December, 2015. Paper ID 40

Baah K., Dubey B., Harvey R and McBean E. 2015. A risk-based approach to sanitary sewer pipe asset management. Sci. Total Environ. 505, 1011–1017.

Baker V.R., Kochel R.C. and Patton P.C. 1988. Flood geomorphology.Toronto: Wiley Interscience.

Beniston M. and Stephenson D.B. 2004. Extreme climatic events and their evolution under changing climatic conditions. Global and Planetary Change, 44, 1–9.

Benito G., Lang M., Barriendos M., Llasat C., Francés F. and Ouarda T., et al. 2004. Use of systematic, paleoflood and historical data for the improvement of flood risk estimation. Review of Scientific Methods. Natural Hazards, 31, 623–643.

Bhatt C.M., RaoG.S., Manjushree P. and Bhanumurthy V. 2010. Space based disaster management of 2008 Kosi floods, North Bihar, India. J. Indian Soc. Rem. Sens. 38 (1), 99–108.

Branko M. 2008. Kernel density estimation of reliability with applications to extreme value distribution, a Ph.D. dissertation, 1-96.

Camarasa A.M., López-García M.J. and Soriano-García J. 2011. Mapping temporally variable exposure to flooding in small Mediterranean basins using land-use indicators. Appl. Geogr. 31 (1), 136–145.

Caradot N., Granger D., Chapgier J., Cherqui F. and Chocat B. 2011. Urban flood risk assessment using sewer flooding databases. Water Sci. Technol. 64 (4), 832–840

CWASA 2015. Preparation of a simulation and drainage improvement strategy and Master plan for the city of Chittagong, Chittagong Water Supply and Sewerage Authority, 42-67

Díez-Herrero A., Ballesteros J. A., Llorente M., Bodoque J.M., Stoffel M., Eguíbar, M. A., et al. 2008. Towards a classification of dendro geomorphological evidences and their utility in flood hazard analysis. Geophysical Research Abstract, 10, 07837.

Cherqui F., BelmezitiA., Granger D., Sourdril A. and Gauffre P.L. 2015. Assessing urban potential flooding risk and identifying effective risk-reduction measures. Science of the Total Environment, 514, 418–425.

Elkhrachy I. 2015. Flash Flood Hazard Mapping Using Satellite Images and GIS Tools: A case study of Najranity, Kingdom of Saudi Arabia (KSA), The Egyptian Journal of Remote Sensing and Space Sciences, 18, 261–278.

Kaźmierczak A. and Cavan G. 2011. Surface water flooding risk to urban communities: anal ysisof vulnerability, hazard and exposure. Landsc. Urban Plan., 103 (2), 185–197.

Mastin M. 2009. Watershed models for decision support for inflows to potholes reservoir, Washington

ŠpitalarM., GourleyJ. J.,Lutoff C., KirstetterP.E., and Carr N. 2014. Analysis of flash flood parameters and human impacts in the US from 2006 to 2012, Journal of Hydrology. 519 (2014) 863–870.

Mohit S.A. and Akter A. 2013. Climate Change Effect on Muradpur Water Logging in Chittagong. In proceedings of the International Conference on Climate Change Impact and Adaptation (I3CIA), 14-16 November 2013, DUET-Gazipur, Bangladesh, pp.952-957

Mohit S.A., Huq M. A. and Akter A. 2014. Prediction of water logging in Chittagong city using hydrological model. In proceedings of the 2nd International Conference on Advances in Civil Engineering 2014 (ICACE 2014), WRE061, 26 – 28 December 2014, CUET, Chittagong, Bangladesh, pp. 1151-1156.

Rossman L.A. 2008. SWMM5 Manual Storm Water Management Model, 80-252.

Tanim A.H. and Akter A. 2015. Modeling of storm induced water logging in the selected parts of Chittagong. International Conference on Recent Innovation in Civil Engineering for Sustainable

Development (IICSD-2015).Department of Civil Engineering, DUET, Gazipur, Bangladesh. Paper ID: WRE-017.

Tanim A.H.,MohitS.A. and Akter A. 2015. A Comparative Study on Hydrological Modelling Study on Urban Water Logging Problem, 1st National Conference of Earthquake and Disaster (NCEED-2015), 17th December, 2015. Paper ID 40.

Wen Y., Cao Q., Kirstetter P. E., Hong Y., Gourley J. J., Zhang J. and Yong B., et al. 2013. Incorporating NASA spaceborne radar data into NOAA National Mosaic QPE system for improved precipitation measurement: A physically based VPR identification and enhancement method. Journal of Hydrometeorology, 14 (4), 1293–1307.

Youssef A.M., Pradhan B. 2011. Flash flood risk estimation along the St. Katherine road, Southern Sinai, Egypt using GIS based morphometric and satellite imagery. Environ. Earth Sci. 62 (3), 611–623.