A Deterministic Hazard Assessment for Storm Surge Induced Flooding: A Case Study

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***Abstract*—Coastal flooding due to tropical cyclone generated storm surges has caused considerable damage and loss of life in the North Indian Ocean region including in Sri Lanka. This paper is concerned with a deterministic analysis of the storm surge hazard for the city of Chilaw on the west coast of Sri Lanka, as a case study. The present hazard assessment utilizes a database of historical events of tropical cyclones in the North Indian Ocean region. A statistical analysis of the past events has been carried out to identify an appropriate storm surge scenario. Numerical models comprising a parametric cyclone model and a hydrodynamic model based on shallow water equations have been employed to simulate cyclone wind velocity and pressure fields as well as coastal inundation due to the storm surges. The spatial distribution of the depth of inundation as well as maps of the hazard to population and residential buildings in the study area are presented and discussed.**

Keywords—tropical cyclones; hazard assessment; numerical modeling; surge height; depth of inundation.

I. Introduction

Sri Lanka is vulnerable to cyclones generated mostly in the southern part of Bay of Bengal, and to a lesser extent, to those in the southeast of Arabian Sea. The cyclones which form over the southernmost part of Bay of Bengal at low latitudes mainly move west or west to northwestwards into the Gulf of Mannar across the coast of Sri Lanka. These cyclones generally form during the later part of the post-monsoon season or early part of the pre-monsoon season. On the other hand, cyclones that form over Arabian Sea mostly move north or north-easterly while a few travel west or northwestwards [1].

However, due to atmospheric dynamics associated with cyclones and the relative proximity of Sri Lanka to the equator, a large proportion of cyclones generated in Bay of Bengal and Arabian Sea, fortunately, do not make landfall in Sri Lanka. Yet, sixteen cyclonic or severe cyclonic storms have made landfall in Sri Lanka during the last century according to the Department of Meteorology, Sri Lanka [2]. The loss of lives and damage and destruction to property and the environment caused by land-falling tropical cyclones could be due to some or all of the following phenomena associated with such intense weather systems, namely, extreme winds, storm surge, heavy rainfall, and also sometimes as a secondary hazard, excessive rainfall leading to landslides.

It must be added that, usually, much of the death toll and damage to property in coastal areas is as a result of cyclone-induced storm surge causing inundation of low-lying onshore lands [3, 4]. A storm surge is a rise above the normal water level along a shore resulting from strong onshore winds and/or reduced atmospheric pressure. The worst impact occurs when the storm surge arrives on top of a high tide. The height of the storm surge depends on cyclone dynamics such as the wind speed, the translation speed, the angle of attack at landfall, the pressure drop and also on coastal and shelf morphological factors such as the bathymetry and the shape of the coastline [5]. Further, the severity and the extent of onshore inundation depend primarily upon the surge height and the prevailing tide as well as the elevation, the slope and the surface roughness of the terrain [6].

However, unfortunately, no detailed assessment of the hazard of flooding caused by storm surges has been carried out for the coastline of Sri Lanka. Accordingly, the present research employs numerical modeling tools to carry out a hazard assessment for potential coastal flooding due to tropical cyclone generated storm surges in the city of Chilaw on the west coast of Sri Lanka, as a case study.

II. Methodology

A. Study Area

The city of Chilaw is located in the Chilaw Divisional Secretariat of the Northwestern Province of Sri Lanka (Fig. 1). The study area comprises 18 Grama Niladhari (GN) divisions with a population of about 33,850. The coastal belt of the study area consists of 30 m wide sand spit, lagoon and its associated waterways. Fishing and agriculture are the main livelihoods in this area.

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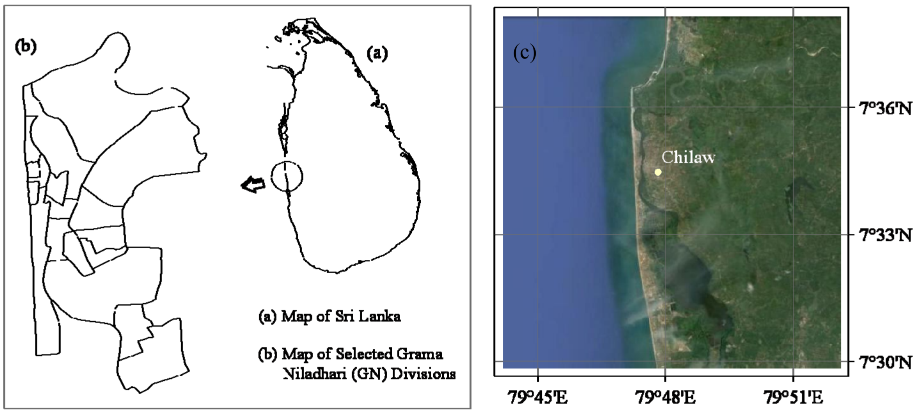

Fig. 1. Study area of Chilaw: (a) Map of Sri Lanka, (b) Map of Grama Niladhari (GN) Divisions in the study area, and (c) Google Earth Image of the study area.

B. Statistical Analysis

A database of historical tropical cyclone events was compiled for the North Indian Ocean (NIO) region for the period 1900-todate using 'best-track' data from several sources including Joint Typhoon Warning Centre (JTWC) of the US Navy and SAARC Meteorological Research Center (SMRC). An observation window or a 'scan-box' bounded by 4–11^{o}N and 78–93^{o}E covering probable cyclone generation and feeder regions in southern portions of both Bay of Bengal and Arabian Sea was demarcated and all cyclones that had either formed or crossed the scan box during the above period were considered to have the potential to make landfall in or in the vicinity of Sri Lanka provided that necessary atmospheric forcing satisfied the requirements for the same. Of the subset of 201 independent cyclone events found to be falling within the scan-box mentioned above, the portion of the data prior to satellite observations (i.e., 1945), as well as those events for which it was not possible to assign reliable maximum wind speeds were excluded. Accordingly, the peak annual wind speeds corresponding to the remaining 59 independent cyclonic events were then statistically analysed using Gumbel's method [7], following [8] for tropical cyclones in Guam, and several others. The fact that, of the 201 cyclonic events in the database since 1900, only about 8% have made landfall in Sri Lanka, was also incorporated into the probabilistic analysis by employing the multiplication rule. Fig. 2 shows the resulting plot of wind speed against the return period based on the Type-I extreme value distribution. The recurrence interval for different wind speeds could thus be deduced, and accordingly, a maximum sustained wind speed of 270 km/h with an estimated recurrence interval of 300 years was selected for the present hazard assessment.

C. Numerical Model Set-Up

The computational domain for the present study was selected based on consideration of past studies of storm surges in the NIO region covering Sri Lanka, for example, those of [9] and [10]. Accordingly, a rectangular region extending from 77^{o}E – 85^{o}E and 4^{o}N – 12^{o}N was selected as the 2430 m spatial resolution outermost grid of the 5-level nested grid set-up (Fig. 3). The resolutions of the inner grids are 810 m, 270 m, 90 m and 30 m.

The bathymetry for the computational grid of 2430 m spatial resolution was at first interpolated from 30 arc-sec GEBCO data and was then updated with data from navigation charts. These navigation charts typically covered depths down to about 3000–4000 m at scales 1:150,000 or 1:300,000. The depths in navigation charts were reduced from Chart Datum (i.e., Lowest Astronomical Tide) to Mean Sea Level (MSL). The topography of the grids was constructed using Light Detection and Ranging (LIDAR) data of horizontal resolution 1 m and vertical resolution not less than 0.3 m.

A hydrodynamic model, Delft3D, based on the quadratic wind friction formulation and depth-averaged, non-linear equations of conservation of mass and momentum was employed to compute the water surface elevation due to cyclone induced forcing of space- and time-varying wind and pressure fields. The wind and pressure distributions due to the cyclone were computed using an axisymmetric parametric formulation, similar to that of Holland's model [11].

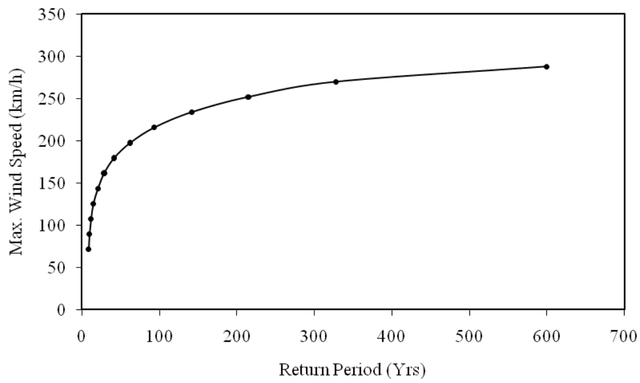

Fig. 2. Estimated maximum sustained wind speed and corresponding recurrence interval for cyclones that make landfall in Sri Lanka.

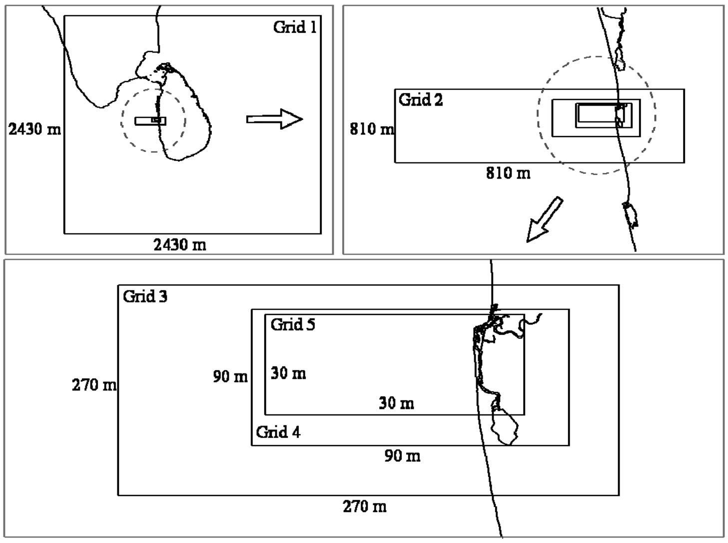

Fig. 3. The nested grid set-up for inundation simulations in Chilaw.

D. Model Calibration and Verification

Two past cyclone events that resulted in storm surges in some parts of the coastline of Sri Lanka have been utilized to calibrate and verify the numerical model, namely, the severe cyclonic storms of 1978 and 1964, respectively.

The model verification run with 1964 cyclone as the forcing was carried out with the same values of model parameters such as wind friction factor and Manning's coefficient as in the simulation for 1978 cyclone. The computed maximum surge heights were then compared with available records of observed surge heights due to the cyclones of 1978 and 1964.

E. Numerical Simulation of Selected Hazard Scenario

For the selected hazard scenario, the landfall location of the cyclone at the coastline was varied and an array of separate model simulations was carried out for each hypothetical track shown in Fig.4.

The models corresponding to these cyclone scenarios were integrated with a maximum pressure drop of 80 hPa and a radius of maximum wind of 40 km based on historical cyclone events in the region.

The track that is likely to cause the highest impact was identified based on the computed peak surge heights immediately offshore of the study area. The detailed inundation simulations were then carried out for the identified track mentioned above.

The numerical output of the model simulations gives the space- and time-varying water surface elevation from which the distribution of flow depth as well as the extent of inundation could be found.

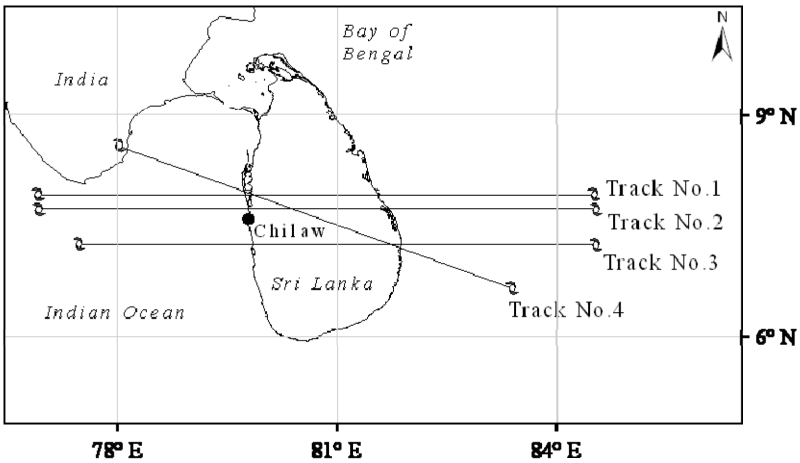

Fig. 4. Hypothetical tracks of cyclones for trial simulations.

Since tidal dynamics is not incorporated in the model, following [12] in the case of tsunami inundation and also in keeping with the present objective of hazard mapping based on the worst-case scenario, Mean High Water (MHW), which is on average 0.3 m above MSL for the study area, was used as the baseline vertical datum in developing digital elevation models for the simulations. The depths in navigation charts were also reduced from Chart Datum (i.e., Lowest Astronomical Tide) to the same vertical datum representing MHW.

F. Hazard Assessment and Classification

Following [13] in the case of tsunami inundation, we utilized statistics relating to the computed flow depths in the inundation zone as the primary parameter to quantify the hazard to the population and residential buildings. Accordingly, the model results were processed and analysed using a combination of Matlab Version 7.7, Arc GIS Version 10.2 and Global Mapper Version 8.0 software to determine the spatial distribution of maxima of flow depths in the inundation zone in each GN division. The mean flow depth for each GN division was then classified into four classes as very high, high, moderate and low. This classification was done separately for the population and residential buildings based on respective fragility curves (e.g., [14] and [15]).

III. RESULTS AND DISCUSSION

A. Model Verification

Table 1 compares the maximum values of the simulated surge levels and the corresponding observed maximum storm tide levels at several locations in Sri Lanka and in South India. The locations of observed storm tides have been identified only by the general area of the city or village, so in the absence of exact coordinates of these locations of observed surge levels, we give a range of simulated maximum surge heights in the vicinity of the general area of each location; the source of information regarding observed maximum storm tide levels is also given.

We see in Table 1 that the ranges of computed storm surge levels are, on the whole, in reasonable agreement with the observed storm tide levels. It must, however, be noted that the simulated surge levels do not include the effects of the tide and waves whereas the observed surge levels include the storm surge and the effects of the tide at the time as well as the wave set-up.

B. Assessment of Hazard of Coastal Flooding

The spatial distribution of onshore flooding in the city of Chilaw due to tropical cyclone induced storm surge hazard corresponding to a maximum sustained wind speed of 270 km/h is shown in Fig. 5. Note that, the inundation depths shown in Fig. 5 correspond to the high-tide and the classification of inundation utilized is also shown alongside together with the waterways and water bodies shown in blue. We see that the low lying parts of Chilaw could experience high flood depths of about 2-3 m with a few localities possibly subjected to flow depths exceeding 3 m. It must also be added that, examination of compiled video animations of onshore flooding due to storm surge, i.e., the time variation of the spatially distributed inundation, indicated that rivers and other waterways present provide a low resistant path for the flood water to travel further interior. The video playbacks also revealed that, in an area south of the city centre, flood water approaching from two directions merging in relatively low elevated terrain resulting in large volumes of flood.

Now, Figs. 6 (a) and (b) depict the spatial distribution of the computed relative hazard to population and dwellings, respectively, classified into four classes as very high, high, moderate and low in connection with potential inundation caused by a storm surge due to the above cyclone event at high tide as outlined in Section II(F). Fig. 6 suggests that many GN divisions in the study area fall into high and very high hazard categories as far as a 'worst-case' cyclone scenario with an estimated recurrence interval of about 300 years is concerned.

TABLE I. COMPARISON OF SIMULATED AND OBSERVED MAXIMUM SURGE HEIGHTS

Cyclone Event	Location in Sri Lanka and South India	Observed Storm Tide Level	Simulated Maximum Storm Surge Level
1964-Cyclone	Rameswaram and Madanpan	3.0 – 4.2 m [16]	3.0 – 4.0 m
	Pamban and Nagapattinam	3.0 – 5.0 m[16]	3.0 – 3.7 m
	Tondi	3.0 – 6.0 m [17]	3.2 – 5.8 m
	Dhanushkodi	3.0 – 6.0 m [18]	2.8 – 3.4 m
	Mannar	4.8 - 5.2 m [19]	4.6 m
1978-Cyclone	Batticaloa	1.0 – 2.0 m [2]	0.8 – 1.6 m
	Tondi and Devipattinam	3.0 – 5.0 m [16]	2.4 – 3.3 m

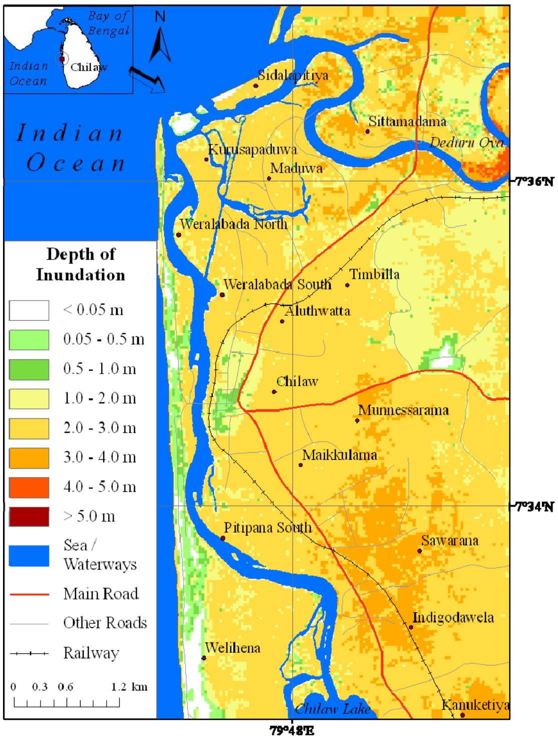

Fig. 5. Spatial distribution of inundation in Chilaw due to the storm surge caused by a tropical cyclone of wind speed 270 km/h.

A field survey of the study area revealed that part of the inundation zone is heavily populated with many residential buildings and commercial establishments; moreover, vital infrastructure such as hospitals, fire stations, electricity sub-stations, schools, etc are also located in the inundation zone.

It is proposed that the storm surge risk mitigation strategy for the case study area should comprise cyclone and storm surge forecasting, provision of early warning to vulnerable communities to enable their evacuation as well as education and awareness programs at the community level.

Finally, there are certain limitations inherent in a study of this nature. One limitation is that the resolution of the modeling is no greater or more accurate than the bathymetric and topographic data used. Moreover, the tide has been linearly superimposed on the computed storm surge levels on a conservative basis although the tide-surge interaction is non-linear. It must also be added that the set-up due to wave breaking has not been incorporated in the present model simulations. Moreover, the mathematical formulation employed in the present model does not explicitly account for all means of energy dissipation. For instance, although energy dissipation due to bottom friction is included in the present model, dissipation due to turbulence is not explicitly formulated.

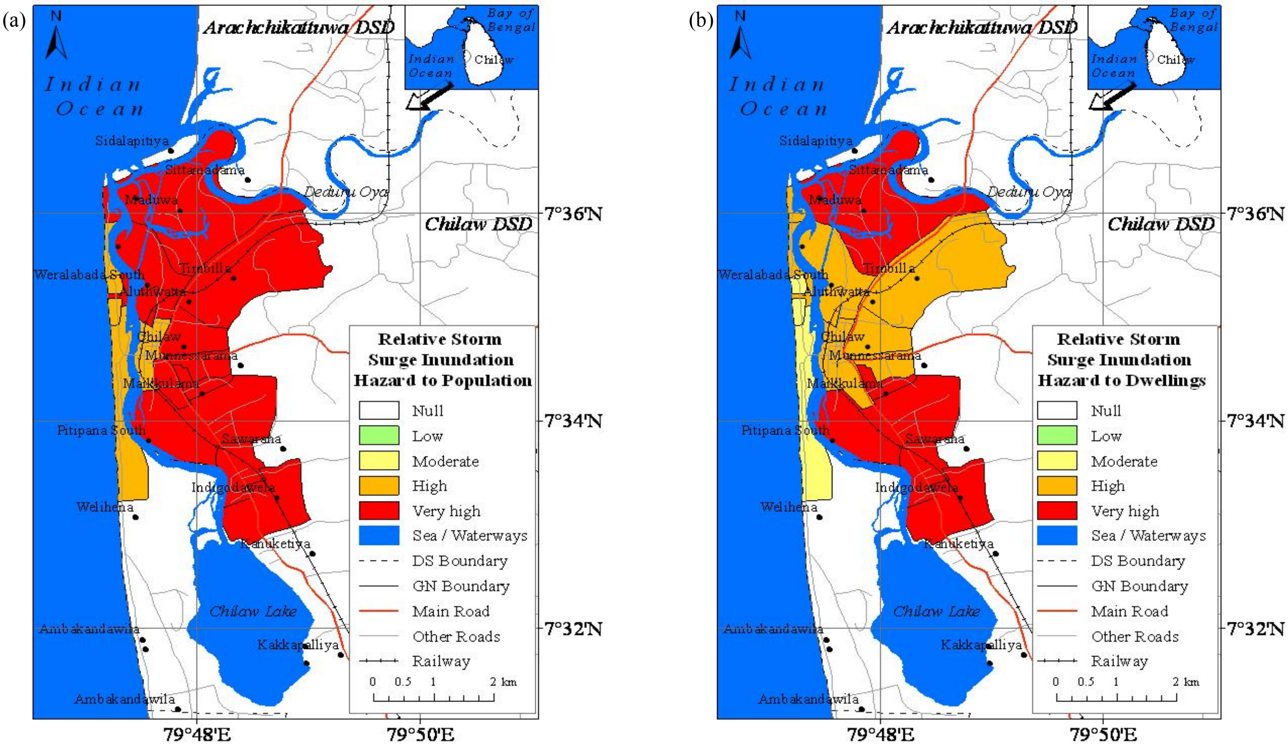

Fig. 6. Relative storm surge hazard in Chilaw due to flooding caused by a storm surge generated by a tropical cyclone of maximum sustained wind speed 270 km/h to (a) population, and (b) residential buildings.

IV. Conclusions

Numerical simulations have been performed to compute the spatial distribution of onshore flooding due to tropical cyclone induced storm surges in Chilaw on the west coast of Sri Lanka as a case study. The selected cyclone scenario corresponds to a maximum sustained wind speed of 270 km/h and a maximum pressure drop of 80 hPa. The effect of the tide has also been incorporated in inundation computations. The results indicate that the low lying parts of Chilaw could experience high inundation depths of about 2-3 m with a few localities possibly subjected to flow depths exceeding even 3 m. The simulated flood depths have been used to delineate the distribution of relative hazard to population and residential buildings in the city of Chilaw and in the neighbouring areas. The effects of the terrain as well as the presence of waterways and water bodies can be seen in the flood distribution in the study area.

Acknowledgment

The authors acknowledge the support received from the National Science Foundation Grant No. RG/2011/ESA/01.

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