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Disaster Risk Assessment And Mitigation Strategy For Tropical Cyclone Induced Storm Surge Hazard And Coastal Impacts Of Climate Change In Sri Lanka

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DISASTER RISK ASSESSMENT AND MITIGATION STRATEGY FOR TROPICAL CYCLONE INDUCED STORM SURGE HAZARD AND COASTAL IMPACTS OF CLIMATE CHANGE IN SRI LANKA

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Coastal flooding due to tropical cyclone induced storm surges has caused considerable damage and loss of life in the North Indian Ocean region including in Sri Lanka. Moreover, climate change impacts are likely to exacerbate the impacts of such coastal hazards on existing and future coastal communities and development. Whilst some impacts such as possible sea level rise are gradual and occur over a long time-frame, extreme weather events can occur at any time and can have a significant impact on the coastline. Accordingly, this paper is concerned with an assessment of the risk of the storm surge hazard to the vulnerable communities of Sri Lanka, particularly in view of the coastal impacts of climate change. The storm surge 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 storm surge scenarios with appropriate recurrence intervals representing medium-, and long-term timescales. A numerical model 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 corresponding to each scenario in the city of Chilaw on the west coast of Sri Lanka, as a pilot study. An appropriate mitigation strategy for the storm surge hazard based on the aforementioned risk analysis is also outlined. The risk assessment and mitigation strategy described in the paper will be useful in the formulation of disaster management policies, development of preparedness plans, allocation of resources for disaster risk reduction, and in education and awareness activities in regard to the tropical cyclone induced storm surge hazard in Sri Lanka.

INTRODUCTION

Sri Lanka, an island nation located off the southern tip of India, is vulnerable to tropical cyclones generated mostly in the southern part of Bay of Bengal, and to a lesser extent, to those in the southeast of Arabian Sea (Figure 1). These cyclones generally form during the later part of the post-monsoon season or early part of the winter and pre-monsoon season. However, owing 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 [1]; some of these, the severe cyclonic storms in particular, have resulted in loss of lives of the order of several hundred as well as considerable damage to housing and other infrastructure due to both the surge and the high winds.

Only a few studies involving analysis and assessment of the storm surge hazard are available for the coastline of Sri Lanka. A study on storm surges and tide around Sri Lanka was carried out by Henry and Murty [2]. They used a model with a 9 km spatial resolution to study the behavior of the tide and the storm surge around the island. More recently, Wijetunge [3] employed a grid of 2 km spatial resolution to compute the distribution of expected storm surge heights in the nearshore sea off Sri Lanka corresponding to four different cyclone scenarios. However, unfortunately, no detailed analysis and assessment of the vulnerability and the risk of the storm surge hazard due to coastal inundation has been carried out for the coastline of Sri Lanka. Such analyses should also incorporate the potential coastal impacts of climate change. Clearly, information gathered from such an assessment would provide the basis for disaster risk mitigation policy planning and decision making in regard to the cyclonic storm surge hazard for Sri Lanka. Accordingly, this paper describes a detailed assessment of the risk of tropical cyclone-induced storm surge hazard assessment carried out as a pilot study for the city of Chilaw in the west coast of Sri Lanka.

STUDY AREA

The city of Chilaw is located in the Chilaw Divisional Secretariat of the Northwestern Province of Sri Lanka (Figure 2). The extent of the study area is about 150 km^2 with a population of about 70,000. The city of Chilaw comprises 20 Grama Niladhari (GN) divisions, which is the lowest level administrative unit in Sri Lanka. The coastal belt of the city consists of a large sand spit, a lagoon and its associated waterways. Fishing and agriculture are the main livelihoods in this densely populated city.

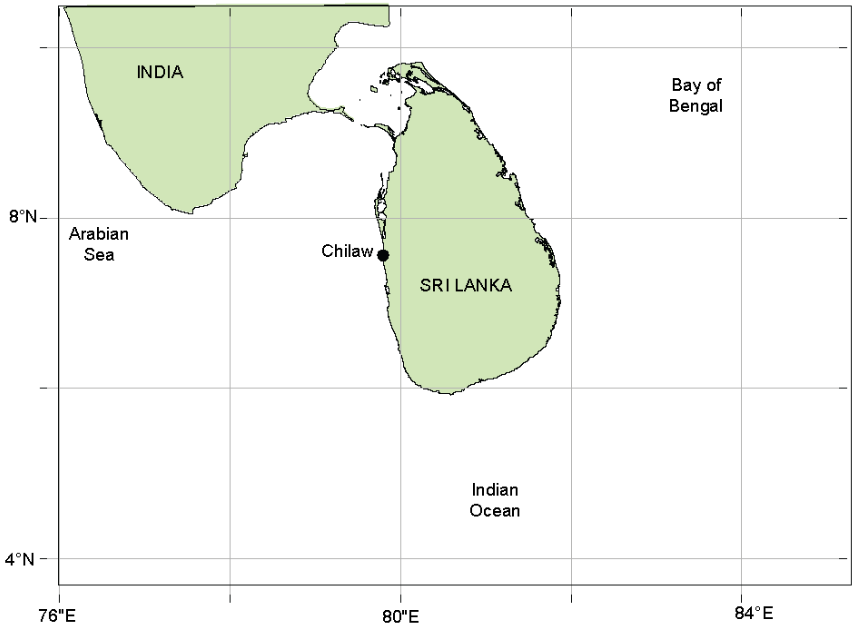

Figure 1. Sri Lanka is vulnerable to cyclones generated in Bay of Bengal and Arabian Sea

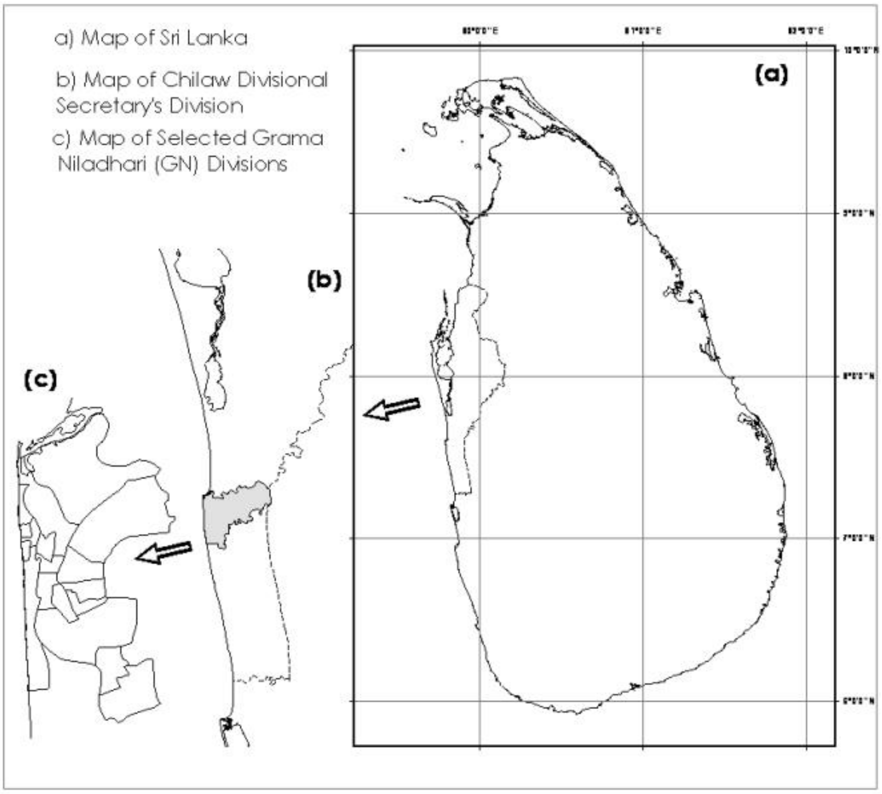

Figure 2. Location map of the study area: (a) Map of Sri Lanka, (b) Chilaw Divisional Secretariat, and (c) Chilaw City with GN Division boundaries

METHODOLOGY

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 [3] 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 [4] method, following Rupp and Lander [5] 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. Figure 3 shows the resulting plot of wind speed against the reduced variate: the intercept and the slope of the linear regression line give the mode (*u* = 32.26) and slope (*a* = 11.68) of the fitted Type-I extreme value distribution.

The recurrence interval for different wind speeds could thus be deduced, and accordingly, the following scenarios were selected for the storm surge hazard assessment: a maximum sustained wind speed of 270 km/h with an estimated recurrence interval of 300 years (Scenario-1); a wind speed of 215 km/h with an estimated recurrence interval of 90 years (Scenario-2); and a wind speed of 160 km/h with an estimated recurrence interval of 30 years (Scenario-3). Scenario-1 may be termed the worst-case scenario whilst scenario-2 a long-term event, and scenario-3 a medium-term event.

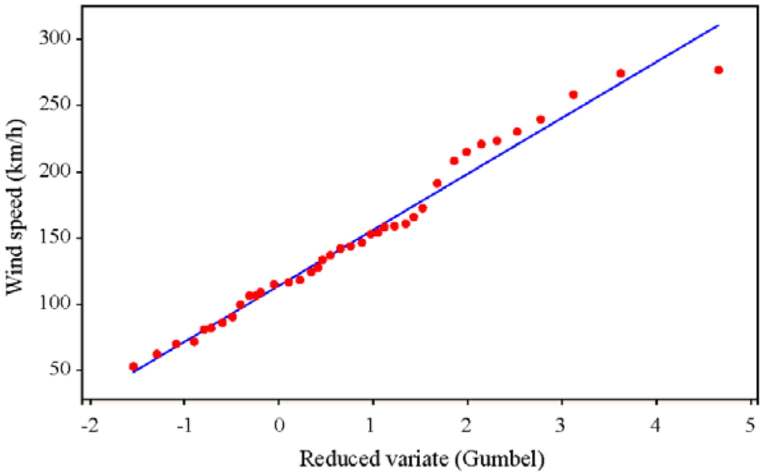

Figure 3. Analysis of annual maxima of cyclonic wind speeds using the Gumbel method

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 Henry and Murty [2] and Chittibabu et al. [6]. Accordingly, a rectangular region extending from 77°E – 85°E and 4°N - 12°N was selected as the 2430 m spatial resolution outermost grid of the 5-level nested grid set-up. 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 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 model, i.e., Holland's [7] model.

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.

Numerical simulation of hazard scenarios

For each hazard scenario, the landfall location of the cyclone at the coastline was varied at 0.045^o (~5 km) intervals along the latitude covering the study area and an array of separate model simulations was carried out for each hypothetical track. The models for cyclone scenarios-1 and -2 were integrated with a maximum pressure drop of 80 hPa and a radius of maximum wind of 40 km. The model for cyclone scenario-3 was integrated with a maximum pressure drop of 70 hPa and a radius of maximum wind of 35 km.

The anticipated sea level rise was estimated based on the predictions of the Intergovernmental Panel on Climate Change (IPCC) as given in its Fourth Assessment Report [8]. Accordingly, the sea level rise due to anticipated climate change for 100-year and 50-year time horizons was estimated to be 0.59 m and 0.29 m, respectively. The inundation due to each hazard scenario was numerically modeled by incorporating the sea level rise with respect to both time frames.

Risk analysis and assessment

Risk is a function of the hazard frequency and the severity, the exposed element or elements at risk, and the vulnerability of that element, and may be expressed as follows:

$$\text{Risk} = \text{Hazard} \times \text{Exposure} \times \text{Vulnerability} \qquad (1)$$

The hazard due to flooding depends on several factors, such as the depth of inundation, the flow velocity and the duration of flooding. Following Wijetunge [9] in the case of tsunami flooding, we utilize the mean depth of inundation as the primary parameter to quantify the hazard to the population and residential buildings. The vulnerability of the coastal community was estimated based on data available from the Department of Census and Statistics of the Government of Sri Lanka as well as utilizing data collected through field studies. The indicators of vulnerability employed in this study are primarily gender, age and income level with regard to population and the type of wall material with regard to dwellings.

RESULTS AND DISCUSSION

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.

Table 4 Comparison of simulated and observed maximum surge heights.

Cyclone event	Location	Observed storm tide level	Simulated maximum storm surge level
1964-Cyclone	Rameswaram and Madanpan	3.0 – 4.2 m [10]	3.0 – 4.0 m
	Pamban and Nagapattinam	3.0 – 5.0 m [10]	3.0 – 3.7 m
	Tondi	3.0 – 6.0 m [11]	3.2 – 5.8 m
	Dhanushkodi	3.0 – 6.0 [12]	2.8 – 3.4 m
	Mannar	4.8 - 5.2 m [13]	4.6 m
1978-Cyclone	Batticaloa	1.0 – 2.0 m[7]	0.8 – 1.6 m
	Tondi and Devipattinam	3.0 – 5.0 m [10]	2.4 – 3.3 m

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 be noted that the simulated surge levels do not include the effects of the tide whereas the observed surge levels include the storm surge and the effects of the tide at the time.

Assessment of risk of coastal inundation

The spatial distribution of inundation due to tropical cyclone induced storm surge hazard corresponding to a maximum sustained wind speed of 270 km/h (scenario 1) is shown in Figure 4. Note that, the inundation depths shown in Figure 4 correspond to the high-tide and a sea level rise of 0.29 m (i.e., 50-year scenario). A three-level classification of inundation, i.e., 0-1.5 m, 1.5-2.5 m, and >2.5 m has been utilized in Figure 4 whilst the waterways are shown in blue. We see that the northern and southern localities of the city of Chilaw are likely to be inundated most with flood depths exceeding 2.5 m. The model simulations also indicate that the waterways and low points in elevation along the coastline are the primary conduits of storm surge flooding into areas further inland.

Figure 5 depicts the spatial distribution of the computed relative risk to (a) population, and (b) dwellings in connection with potential inundation

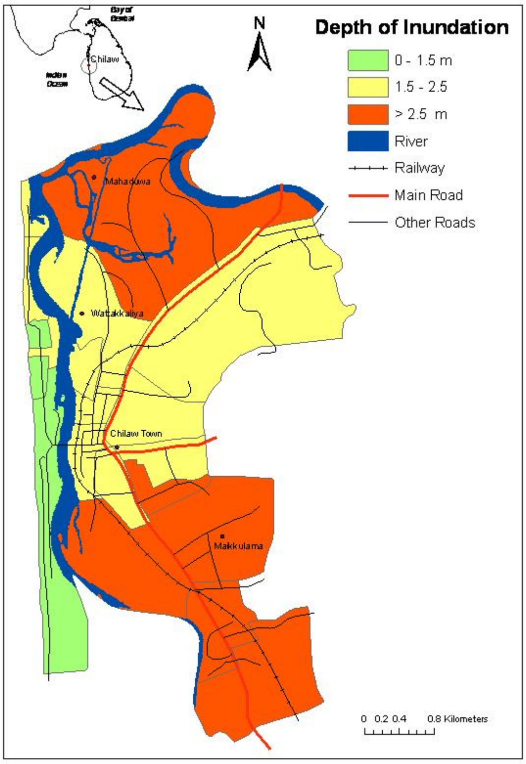

Figure 4. Spatial distribution of inundation in Chilaw, Sri Lanka due to the storm surge caused by a tropical cyclone of wind speed 270 km/h

caused by a storm surge due to the above cyclone event together with anticipated sea level rise over a time horizon of 50-years and at high tide. The risk in both cases, computed using eqn. (1), has been classified into four levels as low, medium, high and very high.

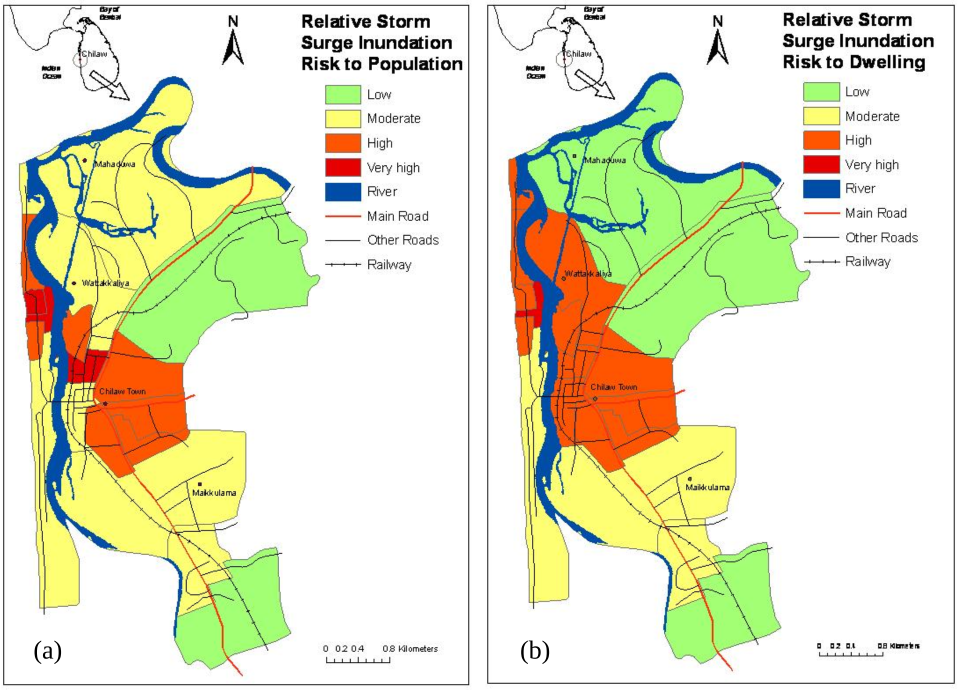

Figure 5. Spatial distribution of the relative risk to (a) population, and (b) dwellings in connection with inundation caused by a storm surge due to a tropical cyclone of maximum sustained wind speed 270 km/h

A field survey of the study area revealed that most 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 1.5-2.5 m deep inundation zone.

It is proposed that the storm surge risk mitigation strategy for the pilot study area ought to 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. Accordingly, as a first step, an operational storm surge forecasting model was developed and training was provided to engineers and scientists from the Department of Coast Conservation and the Disaster Management Center in order to build higher level capacity in numerical simulation of storm surges, and further work is in progress.

Limitations

One limitation is that the resolution of the modeling is no greater or more accurate than the bathymetric 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. It must also be added that depth-averaged models assume a uniform velocity profile across the flow depth and neglect vertical accelerations. 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.

CONCLUSIONS

Numerical simulations have been performed to compute the spatial distribution of inundation due to tropical cyclone induced storm surges in Chilaw, Sri Lanka as a pilot study. The effects of the tide as well as the anticipated sea level rise have also been incorporated in inundation computations. The simulated flood depths as well as the available vulnerability indicators have been used to delineate the distribution of relative risk to population and housing. A risk mitigation strategy consisting primarily of non-structural measures has also been proposed.

Acknowledgment

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REFERENCES

[1] DMSL, Department of Meteorology, Sri Lanka, “Tropical cyclones; Cyclone events 1900-2000”, Department of Meteorology, Government of Sri Lanka, (2012), http://www.meteo.gov.lk/, accessed on 15-7-2013.

[2] Henry R.F. and T.S. Murty, “Storm surges and tides around Sri Lanka”, *Recent advance in Marine science and technology*, 92, (1992), pp. 205-218.

[3] Wijetunge J. J., “A multi-scenario analysis of the storm surge hazard for Sri Lanka,” *Proc. 35th IAHR Congress*, Tsinghua University Press, Beijing, (2013).

[4] Gumbel, E.J., *Statistics of Extremes.* Columbia University Press, New York, (1958).

[5] Rupp, J. A. and Lander, M. A., “A technique for estimating recurrence interval of tropical cyclone-related high winds in the tropics: Results from Guam”. *J. Ame. Met. Soc*., (1996), pp. 627-637.

[6] Chittibabu, P. , Dube, S. K. , Sinha, P. C. , Rao, A. D. and Murty, T. S., “Numerical Simulation of Extreme Sea Levels for the Tamil Nadu (India) and Sri Lankan Coasts”, *Marine Geodesy*, 25(3), (2002), pp. 235-244.

[7] Holland, G. J., “An analytic model of the wind and pressure profiles in hurricanes”, *Monthly Weather Review*, 108, (1980), pp. 1212–1218.

[8] IPCC, *Climate Change 2007: Synthesis Report.* Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC), Geneva, Switzerland, (2007), 104 pp.

[9] Wijetunge J. J., “A deterministic analysis of tsunami hazard and risk for the southwest coast of Sri Lanka”, *Continental Shelf Research,* (2013), 10.1016/j.csr.2013.09.009.

[10] Ramesh, R., “Sethusamudram Canal Project and the unconsidered high risk factors: Can it withstand them?”, Doctors for Safer Environment, Coimbatore, Tamil Nadu. (2004).

[11] Murty, T.S., Flather, R.A., and Henry, R.F., “The storm surge problem in the Bay of Bengal”, *Prog. Oceanog*., 16, (2004), pp. 195-233.

[12] SMRC, “The impact of tropical cyclones on the coastal regions of SAARC countries and their influence in the region”, SAARC Meteo. Res. Centre, Bangladesh, (2004).

[13] CDM, Ceylon Daily Mirror, Ceylon Daily Mirror Newspaper of 29 December 1964, Times of Ceylon, (1964), Colombo.