Towards a secure nation: how safe are we against cyclone-induced sea surges?

J. J. Wijetunge

Department of Civil Engineering, University of Peradeniya, Sri Lanka

janakaw@pdn.ac.lk

Abstract— *Several severe tropical cyclones have hit Sri Lanka in the past century, with those in 1964 and 1978 being the worst, resulting in loss of lives of the order of several hundred as well as considerable damage to housing and other infrastructure due to both the sea surge and the high winds. In comparison, the death toll in Sri Lanka due to the tsunami disaster in December 2004 was of the order of several tens of thousands, however, a tsunami event of such magnitude is extremely rare, expected only once every several centuries. So, tropical cyclone induced storm surges appear to pose a more frequent, albeit comparatively less severe, threat of flooding in most parts of the coastline of Sri Lanka than tsunami. Nevertheless, it must be noted that the severity of the storm surge hazard could be greater even compared to the tsunami for certain parts of the coastline of Sri Lanka. For example, the city of Mannar and the nearby localities are probably more at risk of coastal flooding due to storm surges than tsunami. So, whilst improving our tsunami preparedness in coastal areas, we must also pay due attention to the potential threat of coastal flooding due to cyclone induced sea surges as well. How can the country prepare itself for a severe cyclone event? As far as sea surges are concerned forecasting of storms, early warning and evacuation are necessary to save lives. Furthermore, as in tsunami mitigation, public education and awareness is also an important aspect in storm surge hazard mitigation as well. So, it is prudent to integrate the tsunami hazard with cyclone induced sea surges as part of a multi-hazard risk reduction strategy.*

Keywords— **Hazard Assessment, Coastal Flooding, Storm Surges, High Winds, Vulnerability and Risk.**

I. INTRODUCTION

Sri Lanka is vulnerable to cyclones generated mostly in Bay of Bengal, and to a lesser extent, in Arabian Sea (Figure 1). Some of the cyclones that form at low latitudes in Bay of Bengal move west or west-to-northwest into the Gulf of Mannar across Sri Lanka. On the other hand, a few of the cyclones that form in Southern Arabian Sea could also make landfall in the west coast of Sri Lanka. The months of November and December are the most cyclone-prone months for Sri Lanka.

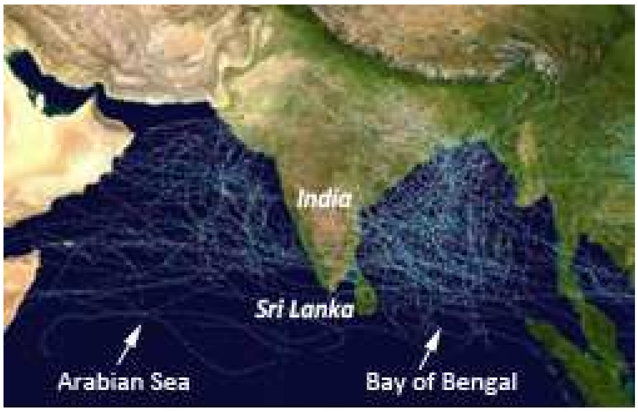
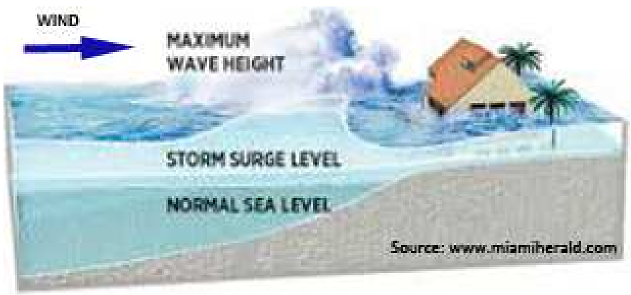


Figure 1. Tracks of cyclones in North Indian Ocean during 1970-2005.

Together with extreme winds, heavy rainfall and sea surge, land-falling cyclones, typhoons and hurricanes often cause immense death and destruction in vulnerable coasts. Usually, much of the death toll and damage to property in coastal areas is as a result of cyclone-induced storm surge



('sea surge') causing flooding of low-lying coastal lands [1] (Figure 2).

Figure 2. Cyclone-induced sea surge causing onshore flooding.

Storm surge is a rise of sea level caused mainly by pushing and consequent piling up of water against a coast under the action of high winds like those due to cyclones. The low pressure accompanying a cyclone also helps raise the sea water level further. The worst impacts occur when the storm surge arrives on top of a high tide. Waves generated by the powerful winds also contribute to a higher sea level. [2]

The height of the storm surge depends on cyclone characteristics such as the wind speed, the pressure drop, the angle with which the cyclone crosses the coast as well as on the shape of the sea floor and the coastline. The surge of water so generated by the cyclone induced wind then rushes inland causing flooding. The severity and the extent of flooding depend primarily upon the surge height and the prevailing tide as well as the elevation, the slope and the roughness of the terrain. [1]

Since the tsunami disaster in 2004 [3-7] there has been a greater awareness of the tsunami hazard and its potential for flooding onshore coastal lands. Moreover, tsunami disaster preparedness and evacuation plans have also been developed and put in place. The question, however, is as a country are we sufficiently aware of the threat of coastal flooding caused by cyclone-induced storm surges; are there any areas along the coastline that are particularly prone to such flooding due to storm surges?

Accordingly, this paper first presents a brief review of some of the notable past cyclones that made landfall in Sri Lanka and then describes an assessment of the cyclone-induced storm surge hazard carried out for the coastline of Sri Lanka.

II. LITERATURE REVIEW

A. Notable Past Cyclones Across Sri Lanka

According to the classification of revolving tropical systems adopted in Sri Lanka, maximum sustained wind speeds of 62 to 88 km/h and 89 to 118 km/h are categorized as cyclonic storms and severe cyclonic storms, respectively. Sixteen cyclones, of which five are severe cyclonic storms, are known to have crossed Sri Lanka during the past 130 years [8] (see Table 1). Table 1 also gives the general area of formation of these cyclones as well as the coastal region of Sri Lanka where each cyclone made landfall. We see that, of the 16 cyclones that crossed Sri Lanka during the past 130 years, only two have been formed in Arabian Sea and made landfall in either western or northwestern coastlines of the country; the rest have all been formed in Bay of Bengal and made landfall on the north and east coasts.

Of the five severe cyclonic storms, the systems that developed in December 1964 and November 1978 appear to have caused the most notable death and destruction. Only little information is available on the impact in terms of number of casualties and damage to property due to the severe cyclonic storms that crossed Sri Lanka in 1907, 1922 and 1931.

Table 1. Past cyclones that made landfall in Sri Lanka during 1881-2011 [8].

Year/ Month	Classification	Formed in	Landfall
1906 Jan	Cyclonic Storm	Bay of Bengal	North
1907 Mar	Severe Cyclonic Storm	Bay of Bengal	East
1908 Dec	Cyclonic Storm	Bay of Bengal	North
1912 Dec	Cyclonic Storm	Bay of Bengal	South
1913 Dec	Cyclonic Storm	Bay of Bengal	South East
1919 Dec	Cyclonic Storm	Bay of Bengal	North
1922 Nov	Severe Cyclonic Storm	Bay of Bengal	East
1925 Mar	Cyclonic Storm	Arabian Sea	North West
1931 Dec	Severe Cyclonic Storm	Bay of Bengal	North
1964 Dec	Severe Cyclonic Storm	Bay of Bengal	East
1966 Nov	Cyclonic Storm	Bay of Bengal	East
1967 Dec	Cyclonic Storm	Arabian Sea	West
1978 Nov	Severe Cyclonic Storm	Bay of Bengal	East
1980 Dec	Cyclonic Storm	Bay of Bengal	East
1992 Dec	Severe Cyclonic Storm	Bay of Bengal	South East
2000 Dec	Severe Cyclonic Storm	Bay of Bengal	East

B. Trincomalee Cyclone of December 1964

The severe cyclonic storm that made landfall near Trincomalee on 23rd December, 1964 with reported maximum wind speeds of about 215 to 240 km/h resulted in a death toll of about 650 with 400 missing in the northern province according to *Dinamina* newspaper of 25th December, 1964. The 1964 cyclone also induced a massive storm surge of height up to about 4.5 metres (15 feet) in the city of Mannar inundating and destroying low-lying coastal settlements and also contributing to the death toll. A detailed account of the impact of the storm surge is given in *Ceylon Daily Mirror* newspaper issued on the 29th

December, 1964: "A fantastic tidal wave, rising fifteen feet over the land, whipped over the island of Mannar at the very height of the awesome cyclone. Today, six days after the event, only a sheet of water, subsiding ever so slowly, marks the place where once a city stood." The powerful storm surge due to this cyclone also overturned a passenger train running between Pamban and Dhanushkody, 30 km west of Talaimannar, killing all 150 passengers on-board. [1, 2, 9]

C. Batticaloa Cyclone of November 1978

The severe cyclonic storm that made landfall near Batticaloa on 24th November, 1978 with estimated maximum wind speeds of 222 km/h caused loss of lives as well as extensive damage to housing and buildings and generated a storm surge of height 1 to 2 metres near Batticaloa with inland penetration of inundation reaching 1.5 km in Kalkudah [8]. The death toll attributed to this cyclone varies from 323 [10] to 915 [8].

The death toll due to the severe cyclonic storm that made landfall on 12th November, 1992 was only 4, with over 29,000 housing units damaged. The severe cyclonic storm that crossed Sri Lanka on 26th December, 2000 also resulted in 8 deaths and considerable property damage. In May 2003, a cyclone that did not cross Sri Lanka but moved further east, however, induced extremely heavy rainfall in some parts of Sri Lanka, resulting in about 250 to 300 deaths due to inland floods and landslides [8].

It must be added that the casualty and damage figures given above are usually due to the combined influence of one or more of the following cyclone related effects: storm surge, high winds, and heavy rainfall. [1,2]

III. ASSESSMENT OF STORM SURGE HAZARD FOR SRI LANKA

A. Distribution of the Height of Storm Surge

Unfortunately, no detailed analysis and assessment of the cyclone induced storm surge hazard has been carried out for the coastline of Sri Lanka prior to that reported in [1]. 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, Figure 3 shows the distribution of the storm surge heights around the coastline of Sri Lanka corresponding to a tropical cyclone of maximum sustained wind speed 220 km/h with an estimated recurrence interval of about 100 year. This map is based on computer simulations of a large number of different cyclone paths across the country so as to obtain the maximum surge height for each location [2,11]. The cyclone wind and pressure fields were simulated using Holland's model [12] whilst the hydrodynamics of the storm surge utilizing depth-averaged equations of mass and momentum conservation.

Clearly, the northwestern and northern coastal areas of Sri Lanka are likely to experience more severe flooding caused by storm surges than the south and the west. The shallow bathymetry and the wider continental shelf fronting the north and northwest are primarily responsible for the higher level of surge heights. On the other hand, the southwestern coastal areas are exposed to a lower level of storm surge hazard. Note that, although there is a higher probability of cyclones making landfall on the eastern and northeastern coasts than the west, cyclones induce sea surges not only during approach (landfall) but whilst leaving a coastline as well.

It must be added that the surge heights shown in

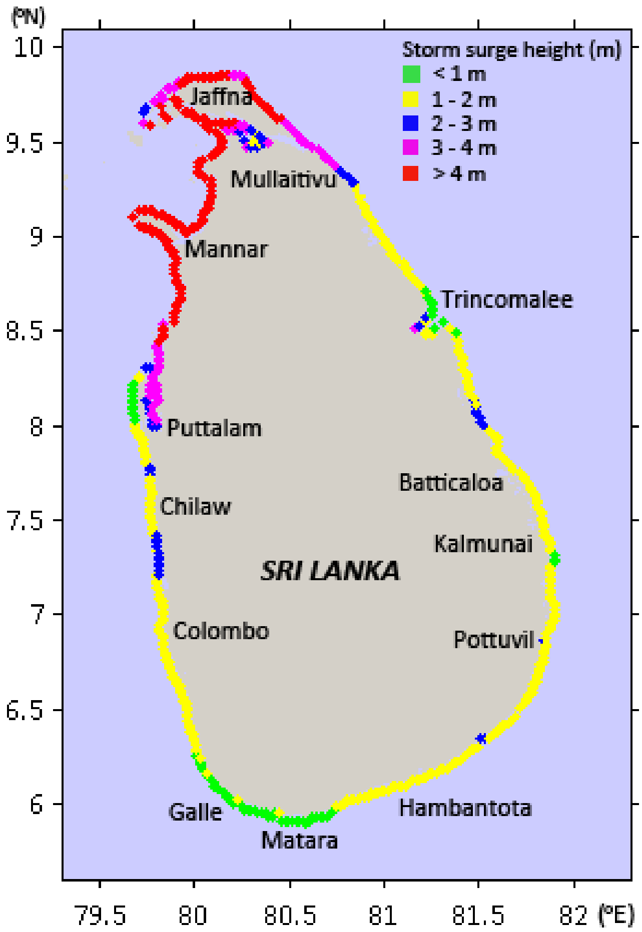


Figure-3 do not include possible effects of the astronomical tide or the wave set-up.

Figure 3. Computed spatial distribution of the storm surge hazard around the coastline of Sri Lanka corresponding to a tropical cyclone of maximum sustained wind speed 220 km/h.

B. Height of Storm Surge due to Cyclone-01B in 2014

A low pressure weather system that formed over the Bay of Bengal about 350 km east of Batticaloa, Sri Lanka on 4th January 2014 developed into a deep depression and marginally reached cyclonic wind speeds before making landfall near Mullaittivu on 6th January 2014 (Figure 4). Numerical simulations of the above system as it was predicted to approach Sri Lanka was performed in order to estimate its potential sea surge as depicted in Figure 5. We see that the computed surge heights are mostly on the order of 0.2-0.3 m except at Mannar where it could be up to about 0.8 m due to shallow bathymetry. We see that these computed surge elevations due to the above very weak system are of the order of astronomical tide prevailing in these areas.

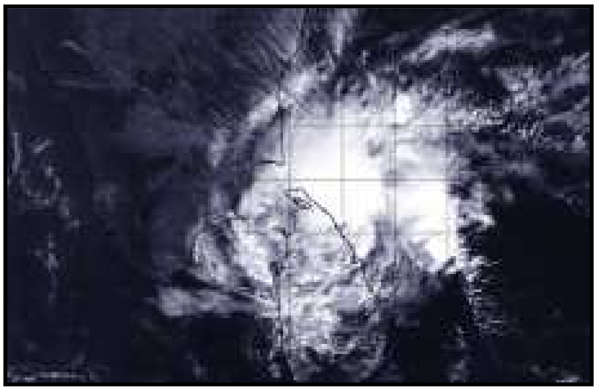


Figure 4. Tropical Cyclone-01B as it was over northern Sri Lanka on 6th January 2014 (Image credit: NRL/NASA).

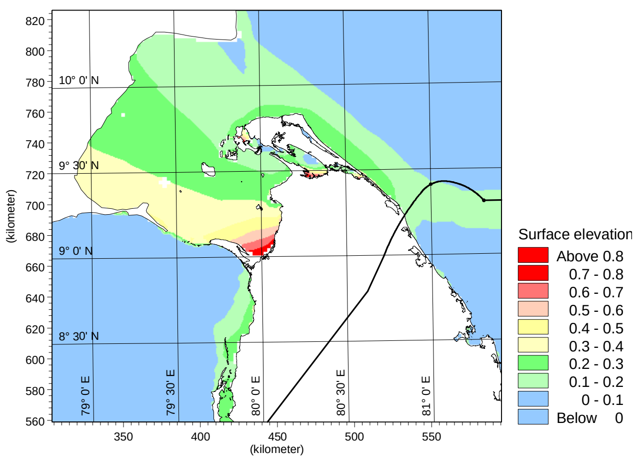


Figure 5. Computed water levels of the minor surge due to the deep depression/tropical cyclone-01B in January 2014.

C. Vulnerability and Risk Assessments

Detailed storm surge hazard assessments have also been carried out for several selected cities by performing onshore inundation simulations of the sea surge. As an example, Figure 6 shows the distribution of the storm surge hazard for Trincomalee due to a tropical cyclone of maximum sustained wind speed 220 km/h, and classified as low, moderate, high and very high, based on computed inundation depths.

Such storm surge hazard assessments have been extended to risk assessments by incorporating vulnerability of the population as shown in the corresponding storm surge risk map in Figure 7. Given the paucity of additional indicators at the desired spatial resolution, the vulnerability assessment is based primarily on the density, the gender and the age of the population.

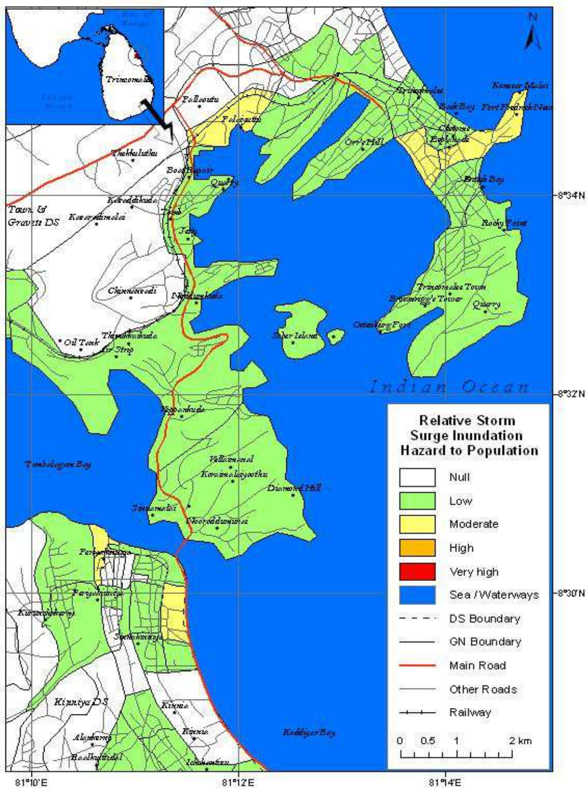


Figure 6. Distribution of storm surge hazard for Trincomalee.

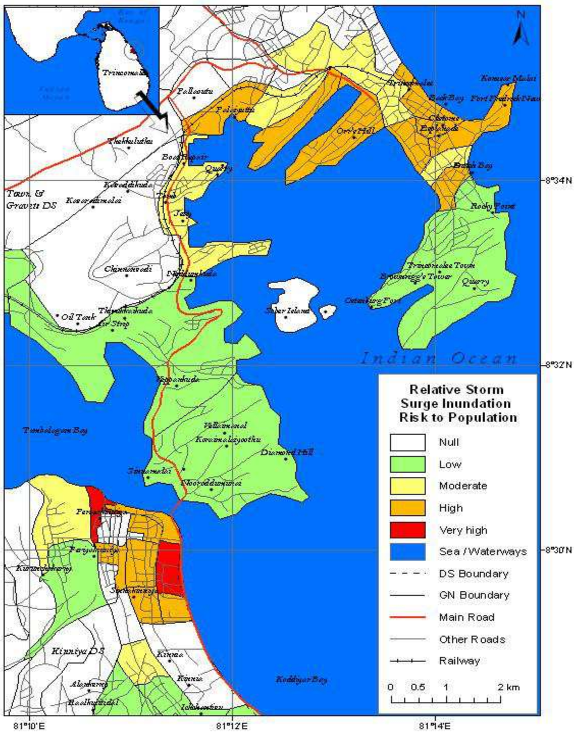


Figure 7. Distribution of risk to populations due to storm surge hazard for Trincomalee.

IV. CONCLUDING REMARKS

We must remind ourselves that several severe cyclones have hit Sri Lanka in the past century, with those in 1964 and 1978 being the worst, resulting 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. In comparison, the death toll in Sri Lanka due to the tsunami disaster in December 2004 was of the order of several tens of thousands, however, a tsunami event of such magnitude is extremely rare, expected only once every several centuries [13]. So, tropical cyclone induced storm surges appear to pose a more frequent, albeit comparatively less severe, threat of flooding in most parts of the coastline of Sri Lanka than tsunami. Nevertheless, it must be noted that the severity of the storm surge hazard could be greater even compared to the tsunami for certain parts of the coastline of Sri Lanka. For example, the city of Mannar and the nearby localities are probably more at risk of coastal flooding due to storm surges than tsunami [1, 11, 14]. So, whilst improving our tsunami preparedness in coastal areas, we must also pay due attention to the potential threat of coastal flooding due to cyclone induced storm surges as well.

How can the country prepare itself for a severe cyclone event? As far as storm surges are concerned forecasting of storms, early warning and evacuation are necessary to save lives. Furthermore, as in tsunami mitigation, public education and awareness is also an important aspect in storm surge hazard mitigation as well. So, it is prudent to integrate the tsunami hazard with cyclone induced storm surges as part of a multi-hazard risk reduction strategy.

REFERENCES

[1] J. J. Wijetunge, 'A multi-scenario analysis of the storm surge hazard for Sri Lanka', in *Proc. 35th IAHR World Congress*, Chengdu, China, 2013.

[2] J. J. Wijetunge, 'Cyclones: Sri Lanka's underrated hazard', *The Sunday Times*, 29 December 2013, Vol. 48, No. 31, Wijeya Newspapers Ltd, Colombo, 2013.

[3] J. J. Wijetunge, 'Field measurements and numerical simulations of the 2004 tsunami impact on the south coast of Sri Lanka' *Ocean Engineering* 36 (12), 960-973, 2009.

[4] J. J. Wijetunge, 'Field measurements and numerical simulations of the 2004 tsunami impact on the east coast of Sri Lanka', *Pure and Applied Geophysics* 166 (4), 593-622, 2009.

[5] D. P. L. Ranasinghe, Goto K., Takahashi T., Takahashi J., Wijetunge J. J., Nishihata T., and Imamura F., "Numerical assessment of bathymetric changes caused by the 2004 Indian Ocean tsunami at Kirinda Fishery Harbor, Sri Lanka", *Coastal Engineering*, 81, 67–81, 2013.

[6] J. J. Wijetunge, "Numerical simulation and field survey of inundation due to 2004 Indian Ocean tsunami in Trincomalee, Sri Lanka", *Natural Hazards*, 54(1), 177– 192, 2010.

[7] J. J. Wijetunge, "A deterministic analysis of tsunami hazard and risk for the southwest coast of Sri Lanka", *Continental Shelf Research,* Vol. 79, pp 23-35, 2014.

[8] DMSL, Department of Meteorology Sri Lanka, Tropical cyclones; Cyclone events 1900-2000, Government of Sri Lanka: Department of Meteorology, 2010. http://www.meteo.gov.lk/, Visited, 15th January 2013.

[9] CDM, Ceylon Daily Mirror Newspaper of 29 December, Times of Ceylon, Colombo, 1964.

[10] T.S. Murty, The storm surge problem in the Bay of Bengal. *Prog. Oceanog.*, 1986.

[11] J. J. Wijetunge, *An Introduction to Coastal Engineering: Processes, Theory, Hazards and Design Practice*, S. Godage Publishers, Colombo, 2013.

[12] G. J. Holland, 'An analytic model of the wind and pressure profiles in hurricanes,' *Monthly Weather Review*, 108, 1212–1218, 1980.

[13] J. J. Wijetunge, 'Assessment of potential tsunamigenic seismic hazard to Sri Lanka,' *International Journal of Disaster Resilience in the Built Environment* 1 (2), 207-220, 2010.

[14] J. J. Wijetunge, 'Nearshore tsunami amplitudes off Sri Lanka due to probable worst-case seismic scenarios in the Indian Ocean, *Coastal Engineering* 64, 47-56, 2011.

Prof. J. J. Wijetunge graduated from University of Moratuwa and received his Ph.D. in Coastal Engineering from Cambridge University in 1997. He is a Professor in Civil Engineering in the Faculty of Engineering, University of Peradeniya. He has also been a Visiting Professor at University of Southern California, Cornell University and University of Oxford during his sabbatical leave. His research areas include wave-structure interaction, tsunami and storm surge hydrodynamics, coastal hazard assessments and wave-current boundary layers.