Chapter 2
Coastal Flooding in India: An Overview

P. S. Swathy Krishna, L. Sheela Nair, and M. Ramesh

Abstract The continuously changing coastal zones have been under the threat of natural disasters such as tsunamis, cyclones, flooding, erosion, along with human interventions. Flooding is one of the major coastal disasters while changing climate and sea-level rise intensify its impact. Increasing trend in flooding events adversely affects inland in the following ways as salt water intrusion damages vegetation and soil fertility and disturbs the coastal livelihood and its socioeconomic impacts can be very relevant in India with densely populated coastal zones. However, India has a long history of coastal flooding; only few are studied while many went unnoticed, with most of the studies restricted to storm surges and wind waves. Hence, a proper analysis of wind, wave, tide, and coastal morphology along Indian coast is needful as India comes under the influence of seasonally reversing monsoons and increased frequency of tropical cyclones along with risk of rising sea level. This chapter provides details on the coastal flooding scenario along Indian coast so far, considering the contributing factors as a critical input in the further development of an early flood warning system and thereby appropriate adaptation measures can be taken.

Keywords Coastal flooding · Storm surge · Swells · Kallakkadal · Sea-level rise

2.1 Introduction

Shorelines and coastal process are continuously changing under the influence of rising sea levels, freak waves, tides, along with many more anthropogenic factors and are becoming risky (Narayana et al. 2012). Coastal flooding has become a serious issue in many parts of the world, which adversely affects the foreshore defense

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mechanism and posing threat to hazard management in coastal and estuarine zones (Nicholls et al. 2007). Several factors contribute in coastal flooding, which comes from oceanographic, geophysical, atmospheric, or even astronomic sources (Pugh 1987; Gornitz 1995; Cazenave and Llovel 2010) and the influence is quantified based on their amplitude (Middleton and Thomson 1986). Higher annual variation in sea levels could contribute to nuisance flooding in low-lying coasts, which occurs with the combined effect of spring tides and high mean sea level, under the clear sky (Moftakhari et al. 2015). The long period swells along the English Channel coast and posed serious threat of coastal flooding in Atlantic basin, even though the severity was rarely found (Sibley et al. 2015). Such swell-dominated flooding event was explained by tracking the long distant extra tropical storms and was later concluded for the cause of "nuisance flooding."

The extremity in rainfall and its uneven spread, intensity of storm surges, and hazardous coastal floods are growing in numbers with alarming trends in global warming and the fluctuating sea level (Burton and Kates 1964). Apart from that, increased strength of atmospheric process tends to amplify the frequency of high magnitude floods and storms (Berz 1993). The interaction of high winds with spring tides elevates the mean and fluctuating sea levels, floods the coastal plain, thus abolishing the coastal structures and affecting the coastal community (Hunt 2005). Climate change-induced subsidence has significant influence on increasing the risk due to coastal floods and the impact of inundations on coastal community can be of much relevance in ocean front countries, especially for a subcontinent like India. This chapter provides a review of various types of coastal flooding events, its impacts, and the status of flood risk in India along with some recently identified flooding events along the southwest (SW) coast of India.

2.2 Coastal Flood Risk Along Indian Coast: Monsoon, Climate, and Cyclones

India has a coastline of 7517 km comprising the Andaman and Nicobar Islands and the Lakshadweep Islands (IYB 2007). The wave climate of the IO depicts the multimodel spectrum as waves evolve from varying geographic areas with distinct atmospheric driving forces, especially, of the monsoon driven waves in the Arabian Sea (AS). However, over Bay of Bengal (BoB), the increased number of cyclones determines most of the wave climate in this basin. The coastal cyclones during 2006–2020 were analyzed and disclosed the influence of SW monsoon in creating 29 cyclonic disturbances near to the cost and 27 cyclonic turbulences associated to North East monsoon and 5 during the non-monsoon period (Mahadevan and Latha 2001). The Indian Ocean Tsunami during December 2004 was the most devastating Tsunami in modern times, flooding the entire coast, caused deaths of nearly 8835 people along with widespread destruction along Indian mainland (Georges 2011). It had significant impact on the southern peninsular region of India that severely affected the coastal states of union territories of Pondicherry and Kerala. Coastal flood hazard in India is classified as high (Fig. 2.1) with the extremity in mean sea level expected to increase in the coming years.

Fig. 2.1 Coastal flood risk map. (Source: https://data.amerigeoss.org/dataset/ss-global-muis-2)

2.3 Classification of Coastal Flooding in India

Coastal erosion and storm surges were the serious coastal hazards studied so far, whereas only a few cases of coastal flooding were studied in India, when compared to other parts of the world. Kurian et al. (2009) were the first to classify the coastal flooding phenomena in Indian context, based on the causative factors as:

(a) Synoptic scale flooding—due to storm surge where the forcing is from large-scale weather systems.
(b) Mesoscale flooding—known as “Rissaga,” which is a high amplitude sea-level oscillation and occurs quite frequently.
(c) Remote forcing—“kallakkadal,” distinguished with its frequency and local impact.

2.3.1 Flooding Due to Storm Surges

The occurrence of high amplitude waves in the Indian Ocean is often due to stronger storm events, with 7% of the global TC occurring in the NIO (Gray 1985). Coastal flooding owing to TC-generated storm surge in NIO often occurs with severity during post and pre-monsoon seasons. In fact, the disastrous flooding happens when the peak storm surge combines with high spring tide, which caused considerable damage and property loss (Bertin et al. 2014; Shaji et al. 2014; Marasinghe and Wijetunge 2015). During the landfall of cyclone, the sea water inundates the low-lying coastal regions, thereby floods the entire region leaving behind an eroded beach and most often damaging the vegetation and reducing soil fertility. The vulnerability of Indian coastline to coastal flooding was categorized into four zones in view of surge potential, of which coastal zones of BoB along with its off-shore islands are found more prone to storm-surge (~10–13 m). However, a major part of Orissa coast is under the Very High-Risk Zone (VHRZ) (~5–7 m) (ESSO-INCOIS-Indian National Centre for Ocean Information Services). The flooding due to surge is more noticeable in the East coast as BoB is considered one of the cyclogenesis areas of the world oceans. In areas with a wide continental shelf, a traveling external surge can have significant interaction with locally generated waves and tide (Mahadevan and Latha 2001; Wolf 2009). There a decline in frequency of the cyclonic disturbances from about six to seven per hundred years was reported, whereas the frequency of cyclonic storms from about one to two per hundred years over BoB and AS in the monsoon season, respectively (Singh 2001). Seasonal wise, the frequency of TC was found to be high in the post-monsoon and greater intensities during the pre-monsoon period (Li et al. 2013). Occurrences of TC are comparatively less in AS basin to Bob and exhibit a frequency ratio of 4:1 (Dube et al. 1997). On an average, 4.7 cyclonic storm days per year evolved over the AS from 1979 to 2008, with more than 15 cyclonic storm days during 1998 and 2004 (Evan and Camargo 2011).

Fig. 2.2 (**a**) Cyclone Hudhud at Uppada beach, Andhra Pradesh. (**b**) Cyclone Tauktae damages the beach roads in Alappuzha, Kerala

Vulnerability of Andhra Pradesh coast to TC and storm surges is reported by newspaper (https://timesofindia.indiatimes.com/city/visakhapatnam/three-million-at-risk-from-storms-along-aps-cyclone-prone-coast/articleshow/86818958.cms) and a file photo of cyclone impact is shown in Fig. 2.2a. Similarly, on the west coast, Cyclone Tauktae, the fifth strongest storm since 1998, in the AS, persisted for over 4 days along the West coast from May 14 to 17, 2021 (https://india.mongabay.com/2021/05/cyclone-tauktae-exposes-vulnerabilities-along-indias-west-coast/), is shown in Fig. 2.2b.

2.3.2 Sea-Level Rise (SLR) and Associated Chances of Coastal Flooding

Coastal areas are characterized as “at-risk” regions due to climate change through SLR (Deborah et al. 2019) and the water level variability at the coast was critical for coastal flooding assessment. The general mean sea level (GMSL) rose to 100 m below the present GMSL in 15,000 years (Clark et al. 2016) and would continue to increase and expected to exceed 1 m by 2100 (Church et al. 2013). The flood magnitude and frequency were affected by SLR and enduring changes in the wave climate (Fig. 2.3), thus the areas lying under MSL will experience higher frequency of floods due to under SLR (Vitousek et al. 2017). Sea-level changes in the Indian Ocean were not considerably noted for the flooding studies. However, a positive trend of mean sea level in the NIO was noticed, with an average growth of about 4 mm $year^{-1}$ for 1993 to 2001 (Chowdary and Behra 2015) and the contribution of sea-level rise on the flooding phenomenon along Indian coast must also be taken into account.

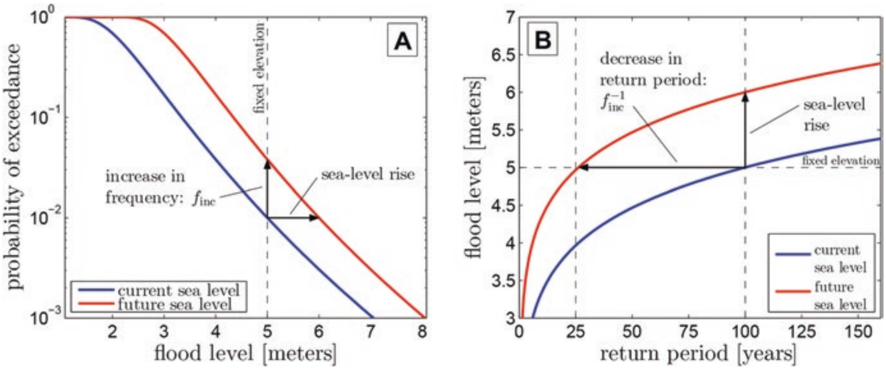

Fig. 2.3 A 1 m increase in SL increases the frequency (**a**) lowers the return period (**b**) of the 5 m flood level (Vitousek et al. 2017)

2.3.3 Remote Forcing: Swell-Induced Coastal Flooding

Swells hold the particular characteristics of the nature and intensity of wind at the generation zone which are pioneer to distant storms, tropical cyclones, or monsoon (Bhowmick et al. 2011). Apart from the storms and seasonal reversing monsoon winds, the SIO swells also determine the wave regime over NIO and along Indian coast (Chowdary et al. 2019). The eastward propagating swells from the South Atlantic spread energy all over the entire IO, with three swell generation zones, namely, tropical NIO, tropical SIO, and extra tropical SIO (Alves 2005). Such swells generated from the Southern Ocean belt took only 4 days to reach the South Indian coast (Fig. 2.4) and with least dissipation (Nayak et al. 2013).

The presence of Southern Ocean swells in the NIO could be found during the fair season and thus NIO is swell dominated (Glejin et al. 2013; Sandhya et al. 2015), where the amplitude of wind seas is quite lower in comparison with swells (Anoop et al. 2015). During monsoon, the swell average time period is found comparatively less in the eastern AS (Sanil Kumar et al. 2010), as they are generated within NIO domain due to a higher southwest wind condition (11–12 m/s). Such long period waves would reach to the Indian coast without much dissipation and most of the times resulted in flooding along the coast especially along the SW coast of India.

2.3.3.1 Kallakkadal

Kallakkadal is an intense wave activity, occurring along the SW coast of India that continues for several days without any change in local weather as in a flash flooding nature and causes panic and severe destruction to coastal communities. One of most noticed and studied Kallakkadal was 2005-May event (Murty and Kurian 2006; Kurian et al. 2009; Remya et al. 2016). According to fisherman, it occurs almost every year, where the coastal inundation due to Kallakkadal invites the attention of

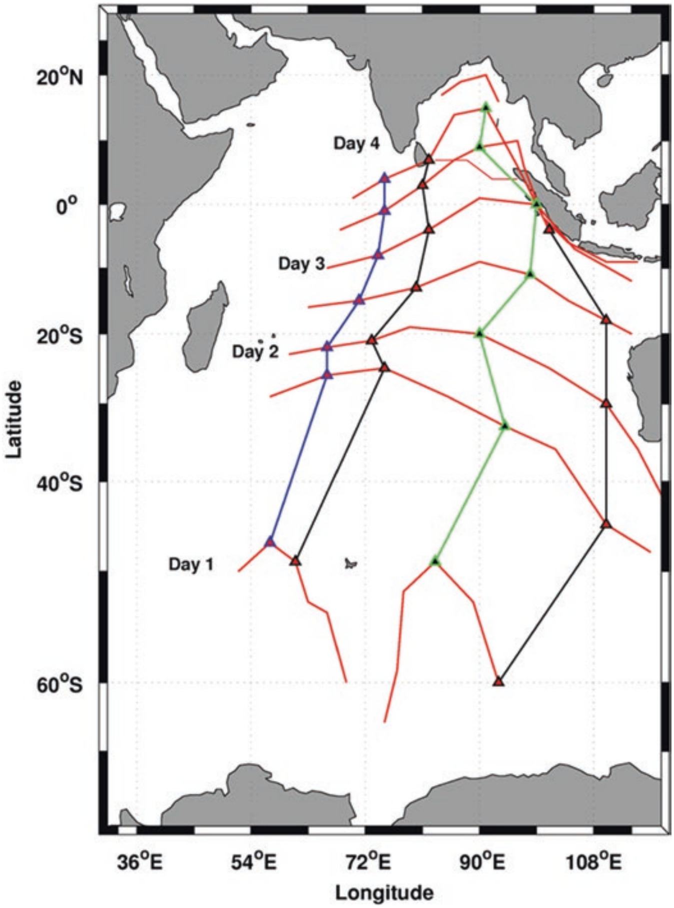

Fig. 2.4 Swell generation and advancement through Southern to Indian mainland (Nayak et al. 2013)

the government and media only when it affects the local population and causes damage to their property. So far, two theories were proposed for the 2005 kallakkadal event. First, the flooding is related to the seismic activities in Sumathra—Andaman Nicobar regions and observed a substantial flooding of TS canal during the 2005 kallakkadal event that was way similar to 2004 tsunami (Narayana and Tatavarti 2005) and the second theory was, these high wave activities are probably due to the storm occurred on the south west coast of Australia. The storm formed around 30° S and traveled toward south of Madagascar, then dissipated on 22 May (Baba 2005). Later, analysis of 2005 event confirmed that these remotely generated swells from Southern Ocean may interact with coastal current directed southward in the west coast of India and waves get amplified, leading to Kallakkadal with an inundation limit of 435 m along the Adimalathura coast (Kurian et al. 2009) (Fig. 2.5). The flooding impacts along the coast vary based on land topography and become more

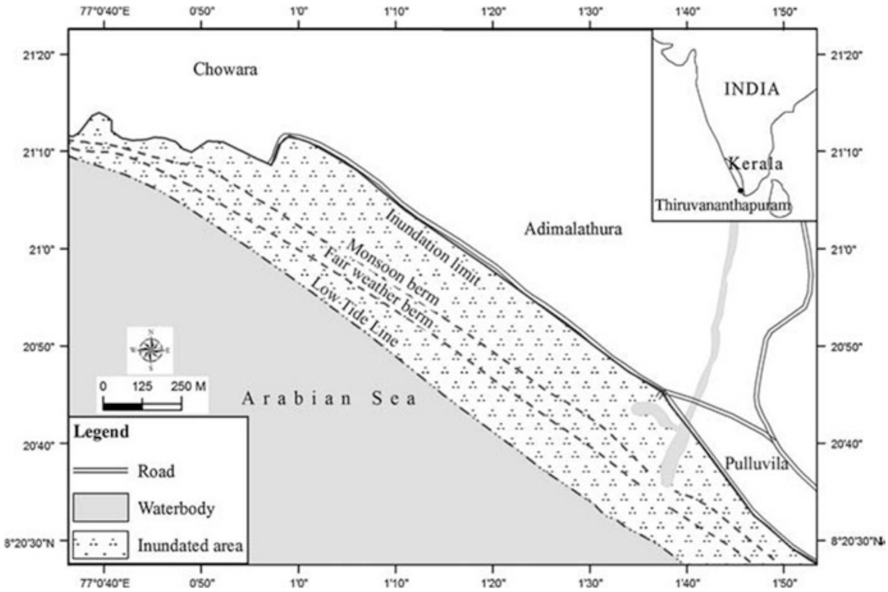

Fig. 2.5 Inundation limit of May 2005 Kallakkadal at Adimalathura, Thiruvananthapuram (Kurian et al. 2009)

severe when associated with high tide. Similar events appear severe and higher in frequency over southern Indian coast than in north mainly due to the orientation of the coast line.

Intense wind system that provides larger fetch for longer duration is required for the generation and subsequent propagation of long period swells, like SIO swells (Munk et al. 1963). Such strong surface winds and associated ocean turbulence exhibit Cut of lows (COL), that initiates high waves (McInnes and Hubbert 2001) and these long period swells sometimes cause flash floods along the coast (Lupo and Smith 1995; Wiedenmann et al. 2002). Such planetary scale wind patterns associated with the strong westerly winds prevailing over the Southern Ocean, as blocking patterns, acted as a strong wind system for the generation of these SIO swells (Murty and Kurian 2006; Remya et al. 2016). Another noticeable Kallakkadal event occurred during 2012 September (Fig. 2.6) (The Hindu, Alappuzha, Kerala, 2012, Sep. 4).

Both the cases (2005 and 2012) had similar characteristics of tsunami where, the sea receded several meters landward and cause large amount of sediment transport with severe erosion. However, the Kallakkadal event is observed only along the SW coast of India and is mostly found along South Kerala coast.

Fig. 2.6 Flooding event during September, 2012 along Kerala coast

2.4 Recent Coastal Flooding Along SW Coast of India

Some of the identified coastal flooding events during the years 2017 to 2019 along the SW coast of India are given in Fig. 2.7. The flooding associated to cyclone OCKHI (Fig. 2.7a) during 1 December 2017 along the Trivandrum coast was the first reported flooding event of 2017 due to cyclone. During 24 April 2018 (Fig. 2.7b), waves of period more than 20s, that persisted for more than a day, caused flooding and could be identified as a swell-induced coastal flooding of pre-monsoon. Wind, wave, and tide have a combined effect on the coastal flood and Fig. 2.7c indicates the erosion after the event. During the calm conditions of March 2019, the coast witnessed the flash flood that lasted for a day (Fig. 2.7d), as an effect of three cyclonic storms occurred over the SIO (30° S). The increased frequency of coastal floods along with monsoonal rough seas and cyclones is taking a toll on the livelihoods of coastal community especially on small-scale fishermen.

Fig. 2.7 Different flooding events along the SW coast. (**a**) High wave activity on the Trivandrum coast during the cyclone Ockhi of 1 December 2012. (**b**) High period swells lashing over the Valiyathura-Shangumugham coast on 24 April 2018. (**c**) The flooding signatures at the Valiyathura beach during 28 September 2018. (**d**) High intensity waves during 20 March 2019 along Valiyathura that caused flooding and severe erosion

2.5 Conclusions

This chapter explains various types of coastal flooding events in Indian context and concludes that BoB is more influenced by synoptic scale flooding while the AS is experiencing more flooding due to remote forcing. The flooding due to storm surges is indeed due to the impact of high frequency and high amplitude waves which lasts on an average of 2–3 days leaving behind an erosive beach along with devastating destructions. The high period long waves (peak wave period more than 18 s) with an average H_s nearly 1.5–3 m were found responsible for flooding due to remote forcing and last from few hours to days extending from few kilometers to thousand kilometers. So far, the meso-scale flooding named rissaga has not been identified in Indian coasts. This chapter also emphasizes on the major drawback of all the previous studies regarding coastal flooding along the Indian coast, in which most of the studies discussed about cyclones and Southern Indian Ocean swells and no one could explain the proper reasons behind it. All the studies are mainly related to originating and propagating of Southern Indian Ocean swells, but none of these studies could answer clearly what is the forcing factor behind Kallakkadal and why this is reporting only along Kerala coast. Apart from the SIO swells, increased number of cyclones over AS and predicted sea-level rise along the Indian Ocean in the near future are also creating an alarming situation of coastal flooding. Hence, it is concluded that coastal flooding may also have other features rather than kallakkadal, especially on the increasing tendency of storm events in the tropical Indian Ocean and rising sea-level warnings and it is in high demand to establish a continuous monitoring network and therefore developing an early warning system for flash floods along Indian coast.

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