

# **IMPROVED PREDICTION OF COASTAL FLOODING DUE TO TROPICAL CYCLONES: AN INTEGRATED MODELLING APPROACH FOR THE EAST COAST OF INDIA**

## **Abstract**

Tropical cyclones (TC) pose a significant threat to the densely populated coastal areas due to generation of storm surges (SS) and associated inundation. This threat becomes even more severe in deltaic regions, particularly when a cyclone crosses a river estuary, leading to compound flooding (CF) caused by the combined effects of downstream storm tide (ST), precipitation (Pcp), and upstream river discharge (RD). The thesis presents a comprehensive investigation into cyclone-induced SS and associated inland flooding along the east coast of India using a fully coupled hydrodynamic Advanced CIRCulation (ADCIRC), wave Simulating Wave nearshore (SWAN) and hydraulic Hydrologic Engineering Center's River Analysis System (HEC-RAS) models.

A standalone high-resolution ADCIRC model with 100 m nearshore resolution and 18 km in the open ocean is set-up along the east coast of India for the computation of SS and associated inundation. The model water elevations are validated well at various tide-gauge locations. A directional surface roughness parameterization is implemented to represent spatially varying wind and bottom stress derived from land use and land cover (LULC) data. The ERA5 reanalysis indicates that cyclonic winds over the coastal land are weaker by 29–50% compared to adjacent oceans during landfall period. A comparison of cyclonic wind speed after incorporating LULC data in the model is made with an automatic surface observation system (ASOS). It suggests about 15–29% reduction in the wind speed, which is consistent with ASOS. The inundated area computed for the cyclones advocates a significant reduction of about 15–50% due to LULC. Further, sensitivity experiments are performed to examine the impact of mangroves in the Krishna estuary located in between two concave-shaped coastal geometries. Replacing wetlands with Mangroves in the Krishna estuary region results in a simultaneous decline in the wind speed (12.5%) and inundated area (13.4%). It also highlights that bottom friction contributes (9.4%) in the inundated area against surface friction (4%). These findings underscore the crucial role of vegetation and land cover in mitigating cyclone-induced flooding and support the need for coastal ecosystem restoration and management.

The shape of the coastline, whether concave or convex, significantly influences the generation and propagation of SS during any extreme weather events like TC. A comprehensive investigation is made on the generation of SS along the coast in response to complex coastline geometry using a standalone ADCIRC model. The study deals with sensitivity experiments by using various idealized concave/convex model domains with the same intensity of parallel cyclone tracks. It demonstrates that a sharp curvature along with the landfall location of each track within the domain has more influence on the surge evolution. Peak surges (PS) are generated in the domain for the tracks possessing strong onshore winds, while intense alongshore winds are responsible for PS spreading along the coast. The propagation of energy density per unit length associated with surge waves is computed for concave coasts to explain the funneling effect. Development of PS is also seen with actual intricate coastal stretch having concave and convex coastlines along the east coast of India using parallel tracks, which is consistent with that of idealized experiments. Further simulations are carried out with real coastline with different approach angles of the track exhibit that maximum PS are not always aligned to the east of the track. Depending on approaching track angle, PS may also develop on the west side. Experiments with real coastline also indicate that PS in the concave coastline is more influenced by cyclone's radius of maximum winds. Surge generation with different radius of maximum winds is seen to the west side of the track though the cyclone is not making its landfall in this region. Simulation with a recent cyclone, Michaung reveals that occurrence of ST is also seen to west of the landfall as the track moves parallel to the coast, which agrees with the observations. This study signifies importance of local coastline configuration, particularly in the concave coasts, on the intensification of storm surges.

CF in any deltaic region is caused by complex interactions between ST, RD, and Pcp, in which impact of land-surface parameters is often undetermined. A coupled hydraulic HEC-RAS and hydrodynamic ADCIRC model is used to examine how land surface characteristics affect CF during Yaas cyclone. The model includes Brahmani, Baitarani, Subarnarekha, and Mahanadi River tributaries along east coast of India. CF is estimated using IMDAA, ERA5, GPM Pcp, evaporation, along with soil infiltration. Validation of inundation extent with satellite imagery suggests that Pcp is the leading cause of CF. As infiltration rate primarily depends on soil conservation service curve number (SCN) and minimum infiltration rate, sensitivity analysis shows that minimum soil infiltration and maximum SCN increase flooding due to lesser water penetration and higher runoff. Experiments are carried out to calibrate district-wise inundation with the observations by considering suitable minimum infiltration

rates and SCN values, leading to 50% increase in CF. Additional simulations with two more historical cyclones (Odisha Super cyclone and Phailin) demonstrate that incorporation of Pcp doubles the inundation compared to RD and ST forcing. The work enlightens significance of various responsible factors for CF along with uncertainties involved in it and emphasizes potential solutions to improve it further.

The relative contributions of different drivers of CF and their interaction with land-surface processes are still unclear, especially in different seasons along with basin morphology. Conventional hydrodynamic models commonly isolate their representation due to lack of Pcp data resulting in underprediction of inundation. To fill this gap, a fully coupled hydraulic, hydrodynamic and wind wave (ADCIRC+SWAN+HEC-RAS) modelling framework is utilized over three major river networks along the east coast of India: Hooghly, Mahanadi–Brahmani–Baitarani–Subarnarekha, and Krishna–Godavari basins, to quantify the combined influences of ST, RD, Pcp, and surface processes on CF. This is the first study in a multi-basin and seasonally stratified ocean during pre- and post-monsoon cyclone period along the coast. Simulations show that model winds and total water elevations match with the observations. The study shows that pre-monsoon CF is mainly caused by Pcp, but post-monsoon CF is a compound effect of high RD, Pcp, and ST. Further, sensitivity analysis depicts that accurate representation of river cross-sectional data is very critical, while default topographic datasets tend to overestimate flood extents. Inclusion of soil infiltration dynamics in the model reduces inundated area by 30–38%, and hence imperative to be considered in real-time simulations. It also reveals a standalone ADCIRC+SWAN underestimates total flooding by 47% due to the non-inclusion of RD and Pcp, compared to the fully coupled approach emphasizing the need of fully integrated modelling. Study also highlights constraints related to the data and methodological issues and uncertainties associated with fully coupled framework and possible ways to reduce it.

Overall, the thesis provides a multi-scale assessment of cyclone-induced flooding along the Indian east coast. It advances the understanding of how surface and bottom stress, coastline configuration, land-surface characteristics, and multi-driver interactions shape the spatial and temporal evolution of inundation. The findings have strong implications for coastal zone management, disaster preparedness, and the development of resilient coastal infrastructure in cyclone-prone regions.