

A numerical study of hypothetical storm surge and coastal inundation for AILA cyclone in the Bay of Bengal

R. Gayathri¹ · P. L. N. Murty² · Prasad K. Bhaskaran¹ ·
T. Srinivasa Kumar²

Received: 2 February 2015 / Accepted: 3 November 2015 / Published online: 7 November 2015
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Abstract The head Bay region bordering the Bay of Bengal is highly vulnerable to tropical cyclones. Catastrophic risks from storm surge and associated inundation are quite high due to high population density in coastal areas, socio-economic conditions, and shallow bathymetry. It features the world's largest deltaic system comprising of 'Sunderbans' bordered by West Bengal and Bangladesh. In a geomorphologic sense, the head Bay region is a low-lying belt comprising several barrier islands and river drainage systems, numerous tidal creeks, and mud flats having a high risk for widespread inundation. In addition, the high tidal range together with low-lying topography leads to high risk and vulnerability from storm surge inundation. During May 2009, a severe cyclonic storm *Aila* struck West Bengal causing enormous destruction to life and property along coastal belts of West Bengal and Bangladesh. It was the strongest pre-monsoon cyclone in the past two decades that had landfall in West Bengal. This work reports on a numerical study for hypothetical storm surge and associated inundation from *Aila* using the ADCIRC model. The study covers a comprehensive qualitative analysis on water level elevation and onshore inundation for West Bengal and Bangladesh regions. The estimated peak storm surge was about 4 m in the Sunderban region that propagated into all major riverine systems, inundating the river banks as well the inland areas. Numerical simulations indicate an average inland penetration distance of 350 m with a maximum of 600 m at various coastal locations in West Bengal and Bangladesh. The study emphasizes the need and importance of inundation modeling system required for emergency preparedness and disaster management.

Keywords ADCIRC model · Storm surge · Coastal inundation · *Aila* cyclone

✉ Prasad K. Bhaskaran
prasadlsu@yahoo.com; pkbhaskaran@naval.iitkgp.ernet.in

¹ Department of Ocean Engineering and Naval Architecture, Indian Institute of Technology Kharagpur, Kharagpur 721 302, India

² Earth System Science Organisation (ESSO)-Indian National Centre for Ocean Information Services (INCOIS), Hyderabad 500 090, India

1 Introduction

In coastal regions the damages from land-falling cyclones attribute to several factors such as torrential rainfall, extreme wind forcing, storm surges, and extreme water levels including the effects from wave-induced setup. Strong onshore wind from tropical cyclone piles up the water near coast causing severe inundation and flooding. The extent of damage that results from onshore inundation of seawater is enormous. In addition, coastal areas having river drainage systems also experience flooding along riverbanks due to surge penetration in the upstream direction. Especially during extreme weather events like cyclones, one can expect excess freshwater discharge from rivers caused by heavy rains. Hence, the abnormal rise of water level from storm surge inundation covering vast coastal areas is a matter of serious concern, and a major threat to the coastal community. Table 1 provides information on human death toll worldwide from tropical cyclones during the past three centuries. Both India and Bangladesh bordering the Bay of Bengal reported the major causalities in the world. In particular for the Bay of Bengal, the destruction from storm surge affects east coast of India, Bangladesh, Myanmar, and Sri Lanka. A detailed review on storm surge studies for the Bay of Bengal is reported by Ali [1], Rao [2], Roy [3], Murty et al. [4], Das [5], Dube et al. [6], Chittibabu [7], and Gonnert et al. [8].

Amongst all countries that surround the Bay of Bengal rim, Bangladesh suffered the maximum impact from storm surges. Major factors that contribute to disastrous surge in

Table 1 Human deaths reported from tropical cyclones

S. no.	Year	Countries	Deaths
01	1737	India	3,00,000
02	1780	Antilles (West Indies)	22,000
03	1822	Bangladesh	40,000
04	1833	India	50,000
05	1864	India	50,000
06	1876	Bangladesh	2,00,000
07	1886	China	3,00,000
08	1897	Bangladesh	1,75,000
09	1900	U.S.A.	6000
10	1923	Japan	2,50,000
11	1960	Bangladesh	5149
12	1960	Japan	5000
13	1961	Bangladesh	11,466
14	1963	Bangladesh	11,520
15	1963	Cuba	7196
16	1965	Bangladesh	19,279
17	1970	Bangladesh	3,00,000
18	1971	India	10,000
19	1973	India	5000
20	1977	India	10,000
21	1985	Bangladesh	11,069
22	1991	Bangladesh	1,40,000
23	1999	India	15,000

Source Recent developments in storm surge prediction models for the North Indian Ocean [9]

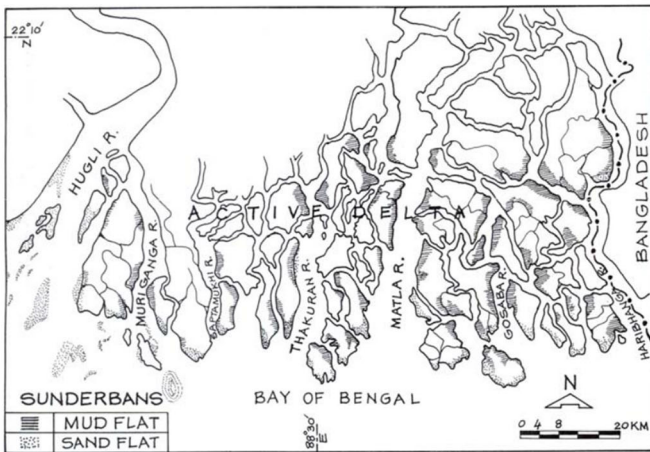
the head Bay region results from various physical mechanisms viz; shallow coastal waters, convergence of the bay, high astronomical tides, and numerous river drainage systems with several tidal creeks and inlets [9]. In a geomorphologic sense, the coastal belt of West Bengal and Bangladesh is a low-lying area, surrounded by complex barrier systems and several islands forming the world's largest deltaic environment. The near-shore areas in the head Bay region have a vast stretch of mangrove ecosystem referred as 'Sunderbans'. The Indian side of Sunderbans occupies the lower portion of the Gangetic Delta stretching about 274 km from brackish water environment of Hooghly estuary on the west, to fresh water of relative wider estuary from Meghna River in the east. Almost 30 % of Sunderbans lies in the Indian region, and the remaining 70 % in Bangladesh. The landscape features of Sunderbans (Fig. 1a) is a low lying, alluvial flat plain covered with thick impassable forest in conjunction with wide tidal variation along the north–south extent. Multiple river channels and tidal creeks are common along the east–west extent. Fig. 1b depicts the zones of active mud- and sand-flats found along Indian and Bangladesh side of the Sunderbans region.

As noticed from Fig. 1, complex coastline geometry and low-lying topography makes the head Bay region highly vulnerable to storm surge inundation. Physical variables such as storm surge amplitude, coastal slope, and vegetation characteristics determine the extent of onshore inundation. Storm surge amplitude depends on cyclone intensity, and peak surge on the landfall location and cyclone track. The present decade show an increasing trend on severe cyclone intensity in the Bay of Bengal basin [10]. The implications being higher storm surge and associated coastal inundation. It demands the need for a comprehensive location specific study on storm surges and associated envelope of onshore inundation. Notably the Bay of Bengal is quite conducive for cyclogenesis formation, and therefore the risk level from storm surge is relatively high for the coastal belts of east India, Bangladesh, and Myanmar compared to the west coast of India. As a first approximation, the shape for Bay of Bengal basin resembles a funnel that modulates storm surge amplitude for countries surrounding the head Bay rim. One can expect significant amplification due to the Bay shape, presence of numerous river drainage system, and shallow bathymetry. There are documented evidences that reports on changes in coastal geomorphic setting after an attack from a severe cyclone. Some of the recent documented cyclones that had landfall either in India or Bangladesh province of Sunderbans are Sidr (November 2007), Akash (May 2007), AILA (May 2009), Mahasen (May 2013).

Another factor that builds up the effect from disastrous surge is the high tidal amplitude in head Bay region. If storm surge coincides with the timing of astronomical high tide, one can expect the worst possible scenario. There are several studies conducted on storm surge for the head Bay region, however numerical studies pertaining to onshore inundation is absolutely lacking for the Indian region. With present day advancements in computational power, there is a need for high resolution coastal hydrodynamic model including suitable models for inundation especially for the head Bay region. Numerical models that provide realistic estimates of storm surge and inundation scenarios will be a value added product in an operational centre and will support future studies. Therefore, an inundation map for the head Bay region is of vital importance to understand the complex pattern of inland surge penetration. The head Bay region is a data void region and some areas in Sunderbans is a hostile environment lacking in situ measurements, hence one has to depend on remote sensing and modeling information. With this motivation the current study deals with a numerical model to understand hypothetical storm surge and onshore inundation associated with the 2009 *Aila* cyclone that had landfall in the West Bengal coast. The river discharge and precipitation run-off is not included in the present study. It is important to



(a)



(b)

Fig. 1 Landscape and geomorphologic features of Sunderbans in the head Bay region

include these components also into the modeling system, however due to lack of observational data the present study do not include these components. The authors will treat the parameters of river discharge and surface runoff from precipitation in a separate study. The Disaster Response Facility under the United Nations Development Programme [11] conducted a post-cyclone survey for *Aila* in the Bangladesh region. The survey covered affected areas of Gabura, Padmapukur and Burigoalini unions under Satkhira district, Kamarkhola and Sutarkhali unions under the Khulna district. *Aila* affected nearly 329,886 peoples in Bangladesh alone [11]. Massive inundation occurred in the coastal areas of

Satkhira and Khulna districts. Breaches in embankments have resulted in damage to houses and other infrastructure. The subsequent section provides more details on the *Aila* cyclone. The authors believe that an operational system providing periodic bulletins on storm surge and inundation scenarios for the head Bay region will be highly beneficial for emergency preparedness and evacuation measures.

1.1 Details of AILA cyclone

In the morning hours of May 22, 2009 a low-pressure system formed over the southeastern region in the Bay of Bengal coinciding with leading edge of the advancing monsoon current. It intensified into a depression almost 30 h later, and the India Meteorological Department (IMD) stated its geographical location centered around 16.5°N; 88.0°E at 0600 UTC on May 23, 2009. The IMD periodically monitored this system from satellite imageries and Doppler Weather Radar (DWR) located at Kolkata monitoring its trajectory towards the West Bengal coast. The system crossed the coast near Diamond Harbor ($\approx 21.5^\circ\text{N}$; 88.0°E) and further dissipated over the northern region of West Bengal after 0600 UTC on May 26, 2009. It attained the intensity of a ‘deep depression’ with wind speed exceeding 14 m s^{-1} on May 24, 2009 (0300 UTC) transforming into a ‘cyclonic storm’ (wind speed exceeding 17 m s^{-1}) during 1200 UTC of the same day. The IMD named this system as ‘*Aila*’. Thereafter, it intensified into a ‘severe cyclonic storm (SCS)’ with wind speed exceeding 25 m s^{-1} at 0600 UTC on May 25, 2009 just before its landfall in the West Bengal coast.

Aila experienced rapid intensification while approaching the coast retaining its intensity level of SCS for more than 12 h after the landfall. It is notable that *Aila* was the only cyclone in the past two decades to cross West Bengal coast during the pre-monsoon season. The IMD report states that *Aila* resulted in storm surge exceeding 2 m along Sunderbans in the Indian coast [12]. The surge level was about 3 m for the Bangladesh region [13]. The astronomical tide during time of landfall ranged between 4 and 5 m, and the cumulative effects from storm surge resulted in a total water level elevation exceeding 4 m that severely inundated the onshore regions. The loss of human life was about 100 in India and about 175 in Bangladesh. In addition, this severe cyclone also resulted in heavy rainfall covering several parts of West Bengal, Sikkim, Odisha, and Nepal.

The trajectory of *Aila* followed almost the northward direction (Fig. 2) towards West Bengal, which is the usual pre-monsoon climatology track for cyclones that have cyclogenesis in the southeast Bay of Bengal. From track details it is evident that the latitudinal displacement occurred from 16.5°N until 27.0°N, a linear distance of almost 10.5° with marginal variation along the meridian (Table 2). The average forward speed of translation was about 15.54 km h^{-1} in the northward direction.

2 Coastal inundation studies

Storm surge resulting from severe cyclones have attracted major attention from research community worldwide due to its catastrophic nature causing severe loss to life and property. The resulting coastal inundation is a matter of serious concern as it adversely affects the entire population dwelling in the vulnerable coastal belt. Often the coastal inundation extends to large areas along a coastal belt due to cyclone impact, and its effect may last for a longer period. The complexity of physical processes that cause coastal

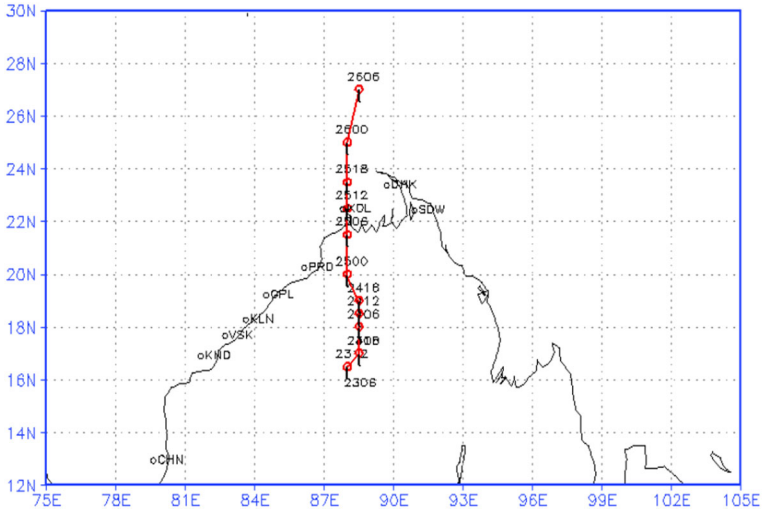


Fig. 2 Track of the *Aila* cyclone

Table 2 Observed parameters for the severe cyclonic storm *Aila* during 23–26 May, 2009 in the Bay of Bengal

Date	Time (UTC)	Category/grade	Central location of the eye	Central pressure	Maximum wind speed (in knots)
23 May, 2009	0600	D	16.5°N; 88.0°E	998	25
	1200	D	16.5°N; 88.0°E	994	25
	1800	D	17.0°N; 88.5°E	996	25
24 May, 2009	0000	D	17.0°N; 88.5°E	996	25
	0300	DD	18.0°N; 88.5°E	992	30
	0600	DD	18.0°N; 88.5°E	988	30
	0900	DD	18.0°N; 88.5°E	986	35
	1200	CS	18.5°N; 88.5°E	986	35
	1500	CS	19.0°N; 88.5°E	986	35
	1800	CS	19.0°N; 88.5°E	986	35
25 May, 2009	2100	CS	20.0°N; 88.0°E	984	40
	0000	CS	20.0°N; 88.0°E	980	40
	0300	CS	20.5°N; 88.0°E	978	50
	0600	SCS	21.5°N; 88.0°E	974	55
	0900	SCS	22.0°N; 88.0°E	968	60
	1200	SCS	22.5°N; 88.0°E	970	50
	1500	CS	23.0°N; 88.0°E	978	45
	1800	CS	23.5°N; 88.0°E	980	40
26 May, 2009	2100	CS	24.0°N; 88.0°E	981	35
	0000	CS	25.0°N; 88.0°E	982	30
	0300	DD	25.5°N; 88.0°E	988	25
	0600	D	27.0°N; 88.5°E	992	20
	0900	LOW	–	–	–

inundation and the need for tools to evaluate, identify, and understand the catastrophic risks in coastal areas have widely attracted the attention of scientists and engineers. Tropical cyclone induced storm surge depends on the geometry of coastline, topography, shoreline configuration of local area, and tropical cyclone characteristics such as the maximum sustained wind speed, storm size, and landfall location. The generation of storm surge also depends on the tropical cyclone forward motion, approach angle, and central pressure within the cyclone. Other factors such as the tidal range, tidal amplitude during the landfall time, increased water level due to local behavior of shoaling waves, river discharge, and rainfall-induced runoff effectively contributes to coastal inundation. Woodruff et al. [14] postulated using a linearized version of momentum conservation, and neglecting the bottom friction and other external forces, the wind induced storm surge is proportional to $U^2 \frac{W}{h}$. In this formulation [14], U represents the wind speed, W is the distance over which wind blows in same direction, and h is the mean water depth influenced by wind. It indicates that coastal regions having wide and shallow continental shelf areas are prone to extreme wind driven storm surge. The deltaic environment in the head Bay region, the domain in this study is a low-lying coastal belt highly susceptible to enhanced coastal flooding from tropical cyclones.

Numerical models such as Sea, Lake, and Overland Surges from Hurricanes (SLOSH) [15] and Advanced Circulation Model (ADCIRC) [16] is being widely used to understand the storm surge characteristics for the global ocean basins. Prior attempts on storm surge modeling considered the coastline as a vertical wall preventing the onshore flow thereby leading to overestimation of peak surges. Model refinements thereafter considered deforming coastline techniques to avoid this problem. In the Bay of Bengal region, prior studies by Johns [17], Dube et al. [18] adopted this technique to model storm surges for the Indian and Bangladesh coast. Thereafter, advancements in coastal inundation algorithm provided an opportunity to represent drying and wetting of grid points at different time steps improving numerical prediction of storm surge amplitude and associated inundation. The ADCIRC model used in the present study is an advanced state-of-art hydrodynamic model that employs sophisticated wetting and drying algorithm to compute realistic coastal inundation. Recent developments for the Indian Ocean region employ a coupled hydrodynamic modeling system that integrates ADCIRC with SWAN (Simulating Waves Nearshore) wave model [19, 20]. As mentioned above one can find very limited studies on coastal inundation modeling for the Indian Ocean region. A recent study by Bhaskaran et al. [21] emphasizes on the importance and need to model coastal inundation required for an operational storm surge prediction system.

3 The ADCIRC model

The development of ADCIRC model is a joint collaborative effort between the U.S. Army Corps of Engineers (USACE) Engineering Research and Development Centre, University of Notre Dame, and University of North Carolina. It solves the equation of motion for a moving fluid in a rotating coordinate system. The governing equations are formulated using Boussinesq approximation and discretized in space using finite element method, and in time using finite difference method. ADCIRC has the capability to run on a highly flexible unstructured grid in a two-dimensional depth integrated (2DDI) mode or in a three-dimensional (3D) mode. The model requires wind and pressure fields, and tidal forcing along open ocean boundary as essential inputs. The latest version of ADCIRC runs in a

parallel mode using message passing interface (MPI) library to operate at its highest efficiency. The readers can find more details on the ADCIRC model and its governing equations in the published work of Luettich et al. [22] and Dietrich et al. [23].

The model uses a sophisticated algorithm [24] for wetting and drying that activates and de-activates the near-shore grid elements during inundation and recession of the coastal topography. Dry grid points become wet when a balance is satisfied between water level gradients and bottom friction relative to the neighboring wet grid points on a triangular element. Likewise, the wet grid point becomes dry when the total water depth decreases below the minimum wetness height. If all the vertices are wet in a triangular element, the area within this triangular element is taken as wet else dry. For more details on the wetting and drying algorithm one can refer to the work of Luettich and Westerink [24]. Once the water level information updates, the wetting and drying algorithm activates and the vertically integrated momentum equations solves explicitly for the currents. The implementation of wetting and drying algorithm in ADCIRC model begins from a cold start mode defining the water level elevation (ζ) as zero at all wet nodes. The steady state velocity results from a balance between water level gradient and bottom friction between a wet and inactive node compared against a minimum wetting velocity (U_{\min}). The balance is expressed [25] as:

$$U = \frac{g(\zeta_{i-1} - \zeta_i)}{\tau_i \Delta x_i} \quad (1)$$

where, g is the gravity, ζ_{i-1} and ζ_i are the respective free surface elevation at adjacent node and the node under consideration, τ_i is the linear bottom friction coefficient, and Δx_i is the spacing between grids. The present study uses the parallel version of ADCIRC model, and in a parallel computing environment, the ADCIRC solution requires both local and global communication between computational cores.

3.1 Formulation for bottom friction

The bottom friction factor is extremely important in near-shore areas, and frictional dissipation of energy within the bottom boundary layer plays an important role in the momentum balance. It is also of wide interest to coastal engineers to have reliable estimates of friction factor to determine the sediment transport rates and other processes. In general, most of the two-dimensional models use standard quadratic bottom friction formulation of Manning's type friction formula both as a function of depth averaged velocity. The Manning's bottom frictional coefficient correlates to the overall bottom friction by the Chezy equation. The bottom topography plays an important role and greatly influences the hydrodynamic behavior of waves and currents in the near-shore environment, thereby modifying the bottom boundary layer. The bottom drag coefficient produces greater friction leading to slack in water movement during a tidal cycle. In the head Bay region, where *Aila* had its landfall, the hydrodynamic condition is dominated by tides. An interesting study carried out earlier by Chitra and Bhaskaran [26] for the Hooghly estuary in the head Bay region developed a varying bottom friction factor based on the hydrodynamic properties of sea bottom under the combined action of waves and currents. Their formulation [26] considered bottom friction factor having dependence on wave-current interaction and bottom sediment characteristics.

In the present study, the hybrid bottom friction factor used in ADCIRC for the simulation of *Aila* event in the head Bay region had a close similarity with the developed formulation by Chitra and Bhaskaran [26] that was verified using ENVISAT data for

significant wave heights. Based on a detailed model sensitivity study on bottom friction, the present study considers the hybrid bottom friction parameterization. In a separate study conducted using ADCIRC at various locations along the east coast of India, the hybrid bottom friction formulation performed the best based on validation against seven coastal tide gauge records. Therefore, the present study uses the hybrid bottom friction parameterization. In the recent years, spatially variable Manning’s n parameterization is also being used. A separate study will be required to skill assess and compare the bottom friction formulations with spatially variable Manning’s n value and hybrid bottom friction formulations.

The hybrid bottom friction coefficient used in this simulation considers the bottom stress proportional to local water depth, and is the best available information for bottom frictional formulation to simulate the flow around complex geometries in the near-shore waters of the head Bay region. The hybrid nonlinear bottom friction law used in this study assumes in deep water the friction coefficient is constant and a quadratic bottom friction law results. In shallow near-shore waters the friction coefficient increases as the water depth decreases as in Manning type friction law. Mostly in coastal applications, the recommended quadratic friction uses a drag coefficient of $C_f \approx 0.0025$, and in extremely shallow waters where wetting and drying algorithm is active, the hybrid bottom friction is recommended with $C_{fmin} \approx 0.0025$. The physical form of bottom stress (τ_*) in the barotropic run mode of ADCIRC is expressed in the form:

$$\tau_* = \frac{C_f(U^2 + V^2)^{0.5}}{H} \tag{2}$$

In Eq. 2, the bottom friction coefficient (C_f) is mathematically expressed as [27]:

$$C_f = C_{fmin} \left[1 + \left(\frac{H_{br}}{H} \right)^\theta \right]^{\lambda/\theta} \tag{3}$$

The parameter C_{fmin} is the minimum friction factor while approaching the deep water, wherein hybrid bottom friction reverts to quadratic bottom friction. H_{br} is the breaking depth that determines whether the hybrid function behaves like quadratic function or increase with depth similar to Manning’s type function; θ is a non-dimensional parameter determining the upper and lower bounds of the hybrid function; and λ is a non-dimensional parameter determining how rapidly the friction factor increases as water depth decreases. To understand coastal flooding and intrusion of storm surge for the Aila event, it is very essential to having spatial grids that refines very close to the coastline. Hence as the bathymetric depth approaches zero, the bottom friction factor reduces to the form: $C_{fmin} \left(\frac{H_{br}}{H} \right)^\lambda$ and for infinite water depth the hybrid and quadratic friction factors are similar to the form C_{fmin} . The present study uses the recommended values of θ and λ as 10 and 1/3 respectively [27, 28].

4 Methodology

The landscape features in Sunderbans comprises of low lying, alluvial flat plain covered with thick impassable forest in conjunction with wide tidal variation along the north–south extent, whereas multiple river channels and tidal creeks forms a part along the east–west

extent. This makes the region a unique ecosystem comprising of a network of tidal rivers and creeks, several islands (an archipelago of about 54 islands), mudflats and coastal dunes. The generation procedure for a high-resolution grid in the deltaic environment that effectively captures numerous tidal creeks, river drainage system, and shallow mudflats is a challenging task. Rapid topographic variation and complex coastline geometry demands a high-resolution grid for the realistic computation of storm surge and associated coastal inundation. The present modeling study uses a blended product of SRTM (Shuttle Radar Topography Mission) and GEBCO (General Bathymetric Charts of the Oceans) covering both land and water regions respectively (Fig. 3). The SRTM data has a horizontal resolution of 90 m, and the gridded bathymetry from GEBCO is a global 30 arc-second grid generated by combining quality controlled depth soundings with satellite derived gravity data.

A realistic simulation of inland seawater penetration requires a high-resolution data product for coastal areas and its hinterland. The authors believe the hybrid-blended product used in this study is of superior quality that provides a reasonable good estimate of hypothetical surge development and coastal inundation. The model domain covers the area from Paradip in Odisha state until the Bangladesh–Myanmar border in the east. The domain extends nearly 500 km from the coastline to offshore open ocean boundary as shown in Fig. 4a. This offshore distance captures the entire life history of *Aila* cyclone as shown in Fig. 2. The finite element mesh comprises of 317,589 nodes with 627,191 triangular elements enveloped by a rectangular offshore boundary (Fig. 4a). The advantage in choosing a rectangular boundary is to avoid computational instability along the corner nodes. Extent of the onshore boundary is limited to +10 m topo line, assuming that flooding does not cross this boundary limit. In spatial dimension, the +10 m onshore

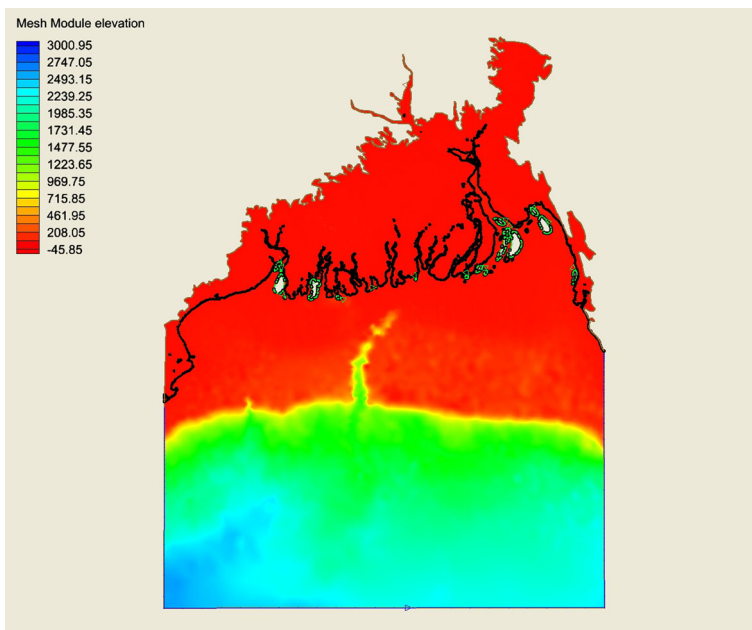


Fig. 3 Blended topography (SRTM + GEBCO) of the study area

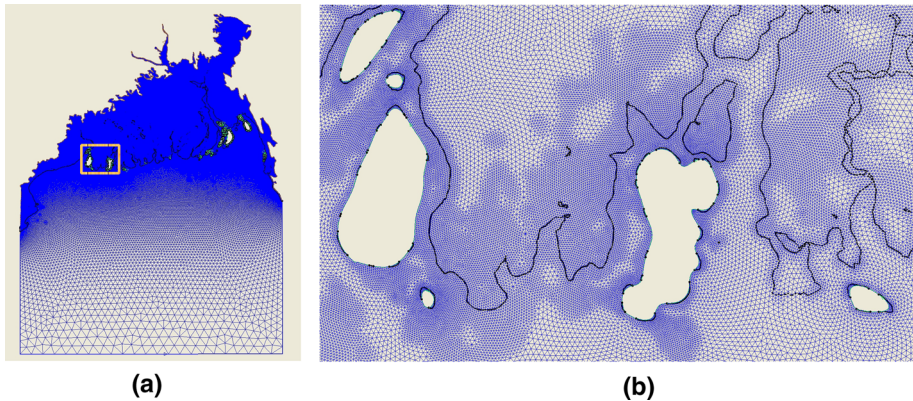


Fig. 4 Flexible finite element mesh **a** for entire study domain, **b** enlarged view for the Indian Sunderbans covering tidal creeks and regions of mudflats

elevation extends up to a distance of nearly 5 km inland. The finite element grid structure is highly flexible dynamically adjusting with the bathymetric data. It has a resolution of about 20 km in the open ocean boundary, and refines to about 250 m along the coastal regions (Fig. 4b).

Coastal landscape features such as barrier islands, bays, wetlands, and natural ridges affect the intensity and spatial pattern of storm impacts. It is therefore important to have optimum horizontal mesh size that represents well the hypothetical surge development and system response. There were prior studies that used different hydrodynamic models with varying grid resolutions to assess the development of storm surge. A notable work by Blain et al. [29] investigated the influence of grid spacing, shoreline configuration, coastline resolution, and characteristics of meteorological forcing on the resultant storm surge computation. An optimum grid size of 250 m along coast could capture the development of storm surge characteristics. Another study by Rao et al. [30] for the east coast of India also mentioned that an optimum grid size of 250 m along coast captured the surge development. As seen from Fig. 4b, the flexible grid represents well the river drainage systems such as Rupnarayan, Hooghly, Matla etc. in accordance with the topography data. In addition, the mesh resolution of 250 m also represents the near-shore landforms as seen from the high-resolution maps thereby preserving the coastal geomorphic features for inundation studies. The wetting and drying of onshore regions arising from surge development is also visible from model computation. There are some recent studies conducted elsewhere choosing very high resolution grid sizes of 10–20 m for the inland regions. Such high spatial resolution demands very high computational power, and keeping in view the coastal landforms and geomorphology for the head Bay region, the resolution of 250 m used in the present study is reasonable.

In a modeling perspective, a grid size of 250 m along coast has inherent limitations in representing physical mechanisms such as the wave induced setup generated from the radiation stress of near-shore wave breaking. In this context, the total water level elevation is a non-linear combination between tides, storm surge, and wave induced setup. It is imperative to have a coupled wave-hydrodynamic modeling system to model these combined effects. The coupled model demands the necessity of a high resolution grid preferably less than 50 m to resolve features such as basin geometry, bathymetry,

topography, and nonlinear coupling of physical processes including wind-wave radiation stress induced setup [31]. In another study conducted by the Joint Research Centre (JRC), European Commission used a finite volume model HyFlux2 to investigate storm surge and inundation utilizing nested grids [32]. It evaluated the storm surge development and response for three severe tropical cyclones such as Katrina (using NOAA best track data), Nargis and Yasi (using advisory bulletins from GDACS database). The nested simulation used a grid size of 450 m to generate inundation maps and maximum storm surge height, and further validated with observed data [32]. The storm surge height and inundation computed for the Katrina event in the Gulf of Mexico using 450 m grid size showed a good consistency with observed data. However, there are differences noticed in the area of New Orleans due to the levee system that demands a very high resolution grid. The readers can refer to the NOAA storm surge report that covers a complete storm surge analysis for the Katrina event [33].

The scope of work in the present study limits to understand the spatial variability of hypothetical storm surge development and associated inundation using the ADCIRC hydrodynamic model in a standalone mode. In addition, the nonlinear effects from wave induced setup on total water level elevation is not a part of this study, hence the grid spacing of 250 m would be ideal to represent the development of storm surge and the system response. Due to constraints in grid spacing of 250 m along coast, the present study has limitation in proper representation of the hydrodynamic and hydrological features associated with sub-grid obstacles and tidal inlet dynamics. It is beyond doubt that high resolution grids is very critical to capture small scale features such as tidal inlets, sub-grid scale obstructions such as levees, and navigation channels in coastal flood plain areas. In a modeling perspective, the computational time required for storm surge and inundation depends on the number of ADCIRC grid nodes, the model time step, and number of available CPUs. The simulation for *Aila* event was performed using a High Performance Computing (HPC) cluster IBM, 9125-F2A system that has a processor clock speed of 4704 MHz available at INCOIS (Indian National Centre for Ocean Information Services), Hyderabad. The computational time is bound to increase when the number of finite element nodes in the study domain is further refined. The computation time using one node (64 processors) of HPC comprising of 0.3 million ADCIRC nodal points (250 m resolution along coast) for a 5 day simulation run consumes about 45 min clock time. Mesh refinement from 250 to 50 m along coast results in total grid nodes exceeding 1.0 million nodes that is computationally expensive with a clock time of about 240 min.

In the present study, the wind field for ADCIRC computation uses the Jelesnianski formulation [15]. The best track information of *Aila* from IMD is used. The relation proposed by Garratt [34] converts the wind speed in terms of wind stress, and provided as input to ADCIRC. The present study used forcing from thirteen tidal constituents in ADCIRC spanning a period of 2 months along the open ocean boundary to reach a final steady state condition. The head Bay region located in the Bay of Bengal is a data sparse region and has no network of observational data to monitor the hydrodynamic fields. Therefore, it was not possible in this study to validate numerical output with measured data for the *Aila* event. The ADCIRC model initially was run for 60 days (cold-start) with tidal forcing along the open boundary, which provided the initial condition for hot-start during this event. A separate study conducted with ADCIRC for other coastal locations along the east coast of India signify that a period of 60 days cold start was ideal to provide realistic estimates of water level elevations. A comprehensive validation exercise carried out using observed tide gauge data at four different locations at Chennai, Ennore, Visakhapatnam, and Paradeep located along east coast of India revealed the performance and skill level of

ADCIRC simulations. The overall statistics showed a very good match between ADCIRC simulated water level and measured tide gauge data at these four stations. The obtained correlation coefficient was 0.96 at Chennai, 0.93 at Ennore, 0.98 at Visakhapatnam, and 0.93 at Paradeep. The Root Mean Square Error (RMSE) was 0.12 m at Chennai, 0.11 m at Ennore, 0.06 m at Visakhapatnam, and 0.18 at Paradeep respectively. In addition, the ADCIRC simulations at these four stations well captured the phase and amplitudes of the tidal wave. Based on this statistics between model computation and observation, the 60 days period was set as the cold start condition to simulate *Aila* for the head Bay region, and subsequently used to hot-start ADCIRC. The authors believe this steady state information provides a better representation on water level elevations, eventually used to simulate the *Aila* event. The resultant water level elevation derived at the end of 2 months period is stored and used for the subsequent hot start mode. The ADCIRC model executes for a period of 5 days in a hot start mode, starting from May 22, 2009 (1800 h) until May 26, 2009 with a time step of 3 s. The hybrid bottom friction coefficient used in ADCIRC considers the bottom stress as proportional to the local water depth. It provides a better description on the bottom stress condition compared to the linear and quadratic bottom friction formulations and more accurate in shallow water when wetting and drying of grid elements occur [27]. The model outputs at every 0.5 h interval the net water level elevation and depth averaged currents for the analysis of surge and flooding characteristics. As mentioned above, the computation of inundation used the advanced wetting and drying algorithm enabling alternate wetting and drying of grid points as the computation progress with each time step. According to model simulations the maximum water surface elevation information provides information on the location of peak surge and associated inundation along the coastal head Bay region. This study also provides a comprehensive analysis on the inundation scenarios at various locations along India and Bangladesh coast.

5 Results and discussion

State-of-art numerical models such as ADCIRC have proven wide applications in disaster planning, management, and coastal engineering studies. The storm surge amplitude at a coastal location can be determined from the maximum water level elevation maps. For the *Aila* event, the model computed hypothetical maximum surge was about 4 m along the regions of Dongajara and Sunderbans. According to the media reports and as well documented by the IMD, the storm surge was 3 m along the western parts of Bangladesh that submerged several villages. It also mentions that resultant storm surge over Sunderbans in West Bengal exceeded 2 m. Presence of numerous river drainage systems with several tidal creeks along coastal stretches in head Bay region had enabled surge propagation into the river systems. Model simulations show that surge propagated into most of the river systems. The surge amplitude in rivers such as Matla, Bidyadhari, and Garal reached nearly 4 m. Model computation also indicate that surge propagated up to 40 km upstream in these rivers and inundated the banks far away from the coast. The worst affected areas with highest surge amplitude were the Sunderbans along India and Bangladesh sector. A study by Pradhan et al. [35] used observations from DWR located at Kolkata to evaluate storm surge height from DWR measured radial winds after its landfall. The maximum observed radial wind velocity was 120 km h^{-1} , and the DWR estimated storm surge height was 2.784 m.

Figure 5 shows the model computed maximum water level elevation for the head Bay region. The black solid line indicates the *Aila* track, and maximum surge occurred along the right side of the storm track. Surge amplitude depends on variety of factors. The wind intensity, central pressure of storm, location, and direction of landfall are few amongst the causative factors. In particular, for the Bay of Bengal region, Dube et al. [18], Das [5], and Rao et al. [36] conducted modeling studies to investigate factors governing the surge amplitude.

The funneling effect of the Bay together with high tidal amplitude and presence of numerous inlets and river discharge locations are the significant causative factors. Therefore, the effect of tidal propagation and its interaction with storm surge is a matter of major concern and important in context to regions along the head Bay. Tidal propagation in river creeks and inlets is a complex nonlinear phenomenon. Cumulative effects from storm surge add to this complexity, and therefore tide-surge interaction is a problem of great interest in such locations.

In order to investigate the tide-surge interaction phenomena, the present study attempts to compare qualitatively the tide and surge amplitudes at eight different locations (locations are marked in Fig. 6) along the Bangladesh coast. The comparison signifies that at most locations the storm-tide and astronomical tide matched their phase having varying amplitudes. It is imperative that observational data is an essential pre-requisite to verify numerical models. Unfortunately there are no observational data available for *Aila* event to compare the numerical simulations. Therefore, the simulation presented in this study is a hypothetical scenario of storm surge height and associated inundation. For the Bangladesh region, the hydrographic Department of BIWTA (Bangladesh Inland Water Transport Authority) collects the water level data at different coastal locations using manual gauge readers. During the severe cyclone *Aila*, there was paucity of measured data from these gauge stations, as it was not possible to make any manual measurements [37]. Therefore, water level data for this severe storm periods are not available for validation. Information collected from other sources such as the Wikipedia website (<http://en.wikipedia.org/wiki/>

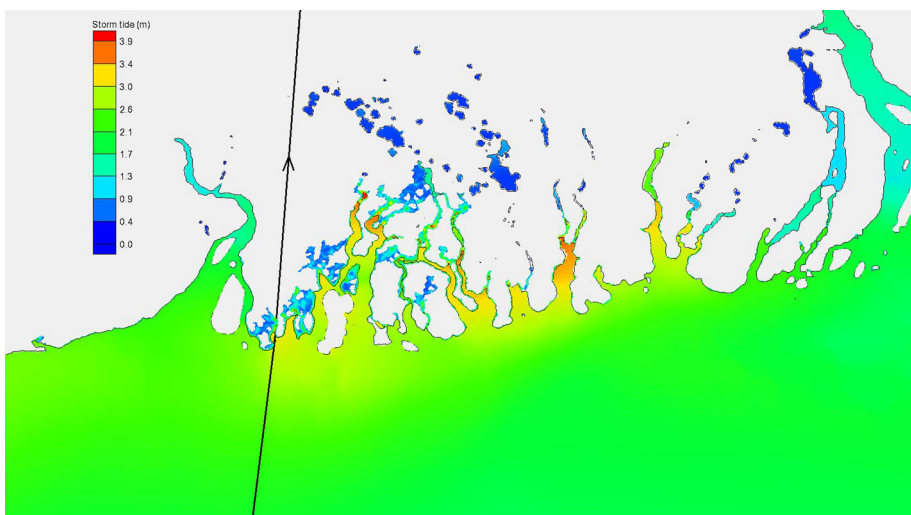


Fig. 5 ADCIRC model computed maximum water level elevation (in meters) for the head Bay region



Fig. 6 Geographical locations along the Sunderbans for water level comparison

Cyclone_Aila) suggests that surge height was about 3 m along the western regions of Bangladesh. Therefore, the result presented in this study is a hypothetical scenario on the development of storm surge height and associated coastal inundation.

The difference in surge amplitude was evident as *Aila* approached its landfall location. For the locations Hiron Point, Tiger Point, and Basakhali, the difference between tide and storm-tide was more than 1.25 m (Fig. 7) when the cyclonic system approached towards the coast. The rise in storm surge is evident at all the eight stations during landfall, and found weaker when *Aila* was far away from the coast. For locations such as Kuakata, Char Chenga, Chittagong, and Sandwip located far off from *Aila* track, the surge amplitude was about 0.65 m. Another notable feature is the phase difference in resurgence time at most of the locations. The water levels were constantly higher for storm tide simulation almost 4 days prior to landfall at Char Jabar location. The relative water level heights were lower as compared to the remaining stations (Fig. 7). At Char Jabar, the water level height was about 0.6 m prior to landfall. The build-up of water level is evident increasing to about 1.0 m according to model simulations during the landfall time. In particular, the station Char Jabar is located in a very shallow water depth and bordered by shallow shoals and island barriers, unlike the case with remaining stations (Fig. 6). The shallow nature of this location along with bordering irregular islands itself provides a complex pattern of tidal propagation. The difference in water level compared to the remaining stations attributes due to the grid resolution used in the present study. There is a demand for high resolution grids in these areas to model shoals of smaller dimensions.

The comparison of storm-tide amplitudes (Fig. 8) indicates a significant phase difference in the surge characteristics. The locations Basakhali and Hiron Point (Fig. 8) exhibited a perfect match in both surge amplitude and phase. In addition, the surge amplitude decreased as one progress from west to east, proportional to relative distance of locations from *Aila* track. The phase difference in surge characteristics (Fig. 8) is evident as one progress towards east from the *Aila* track. It is clear from Fig. 7 that the surge amplitude at locations Hiron Point, Basakhali, and Tiger Point are comparatively higher than other locations, with a smaller resurgence time. During the landfall time, the surge amplitude was 2.75 m at Hiron point reducing to 1.10 m at Char Chenga.

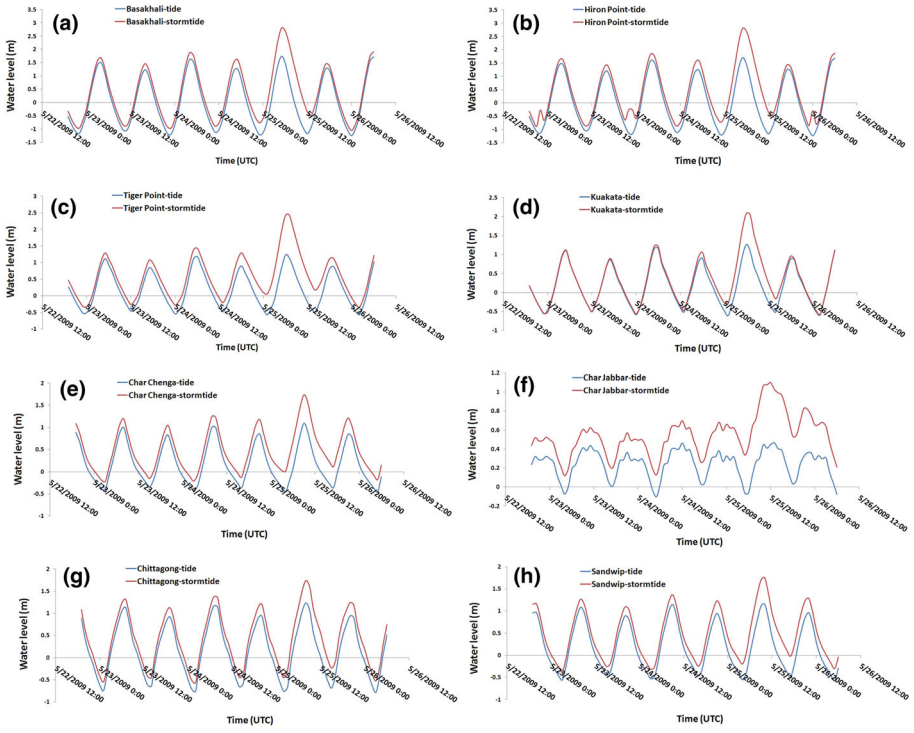


Fig. 7 Comparison between storm-tide and astronomical tide along various locations in the Sunderbans

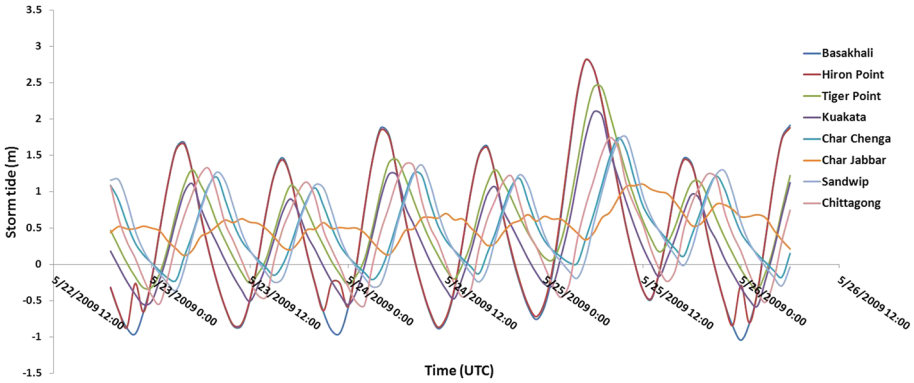


Fig. 8 Model computed amplitude and phase difference of storm-tide component at various locations in the Sunderbans

Figure 9 provides a time series information on the potential storm surge for all the nine locations marked in Fig. 8. The four stations located near-shore (Basakhali, Hiron Point, Tiger Point, and Kuakata) experienced higher surges, compared to remaining five stations located within the river environment. The model could represent the time lag in occurrence of peak surge (Fig. 9) at these four stations. The surge propagation into the river system

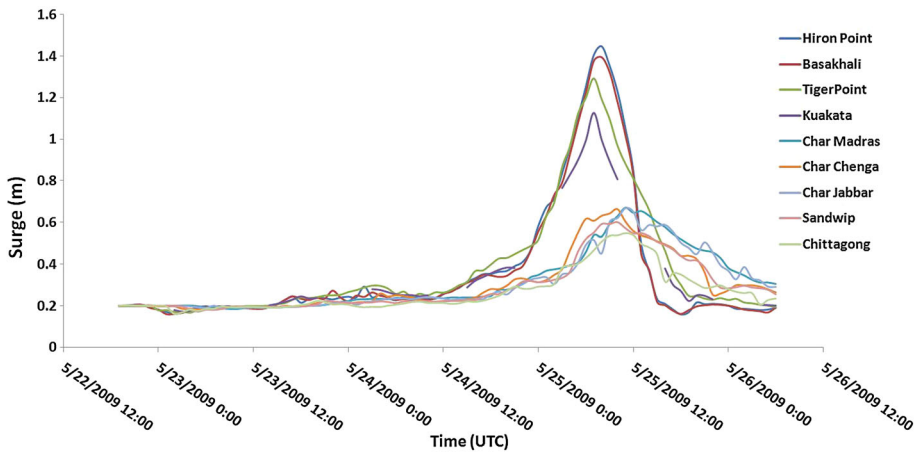


Fig. 9 Time series information of model computed peak surge (in meters) along various locations for the *Aila* episode

requires a detailed investigation. Numerical modeling of river-surge interaction demands precise information of riverbed topography, and the river discharge data. Discharge rates from river could significantly affect the storm surge amplitude. A detailed study on tide-surge-river interaction is available in the published work by Johns and Ali [38], Johns et al. [39], and Sinha et al. [40, 41].

As stated above, the most devastating effects from storm surge is inundation along the coast. It depends on the surge amplitude, and the beach slope is a determinant for the extent of inundation. Very recently, a comprehensive study by Bhaskaran et al. [21] highlighted the importance of beach slope and extent of coastal inundation for the *Thane* cyclone event in the Tamil Nadu state, east coast of India. Compared to any other regions in the east coast of India, the head Bay poses a major challenge to determine the extent of inundation owing to complex coastline geometry, high tidal range and numerous tidal creeks. In order to determine the extent of inundation, it is imperative to know the distance the seawater progressed onshore beyond the coastline. The current study uses the zero contour line as the reference line to determine the extent of inundation. The blended SRTM–GEBCO data provides this information. Model results of hypothetical storm surge signify extremely high levels of flooding in the Sunderban region, with intrusion distance reaching up to half a kilometer inland. The inundation maps from ADCIRC computation (Fig. 10) reveals that the entire coastal stretch in head Bay region including Bangladesh were badly affected. Severe inundation from peak storm surge occurred at locations close to the surge envelope. The low-lying topography of deltaic environment and surge propagation through complex riverine systems intensified the inundation scenario. The regions marked with red color in the top panel (Fig. 10a) indicate the overall scenario of coastal inundation. The bottom panel (Fig. 10b) is the corresponding illustration of storm surge envelope for the region marked by box in Fig. 10a.

To verify the extent of inundation and the affected areas, the current study used the published results from Brakenridge et al. [42] that dealt with the potential flooding regions from *Aila* cyclone using satellite-mapping techniques. Their study [42] used eight MODIS image to obtain the inundation map for the Ganges–Brahmaputra delta (shown in Fig. 11a). The current study reports a qualitative comparison of the inundation scenarios

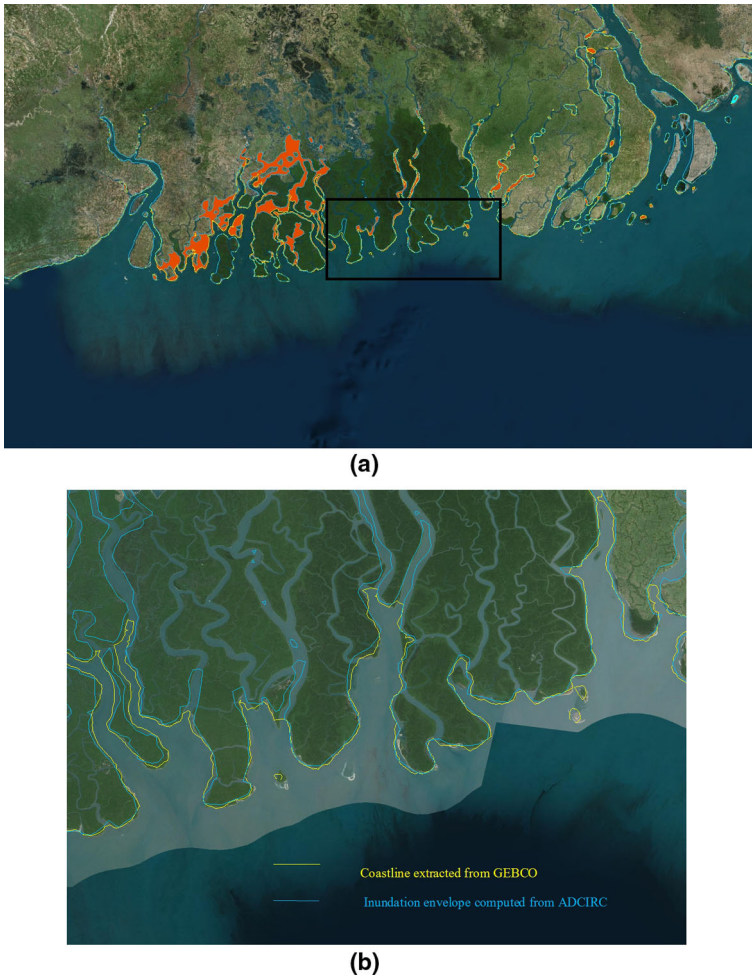
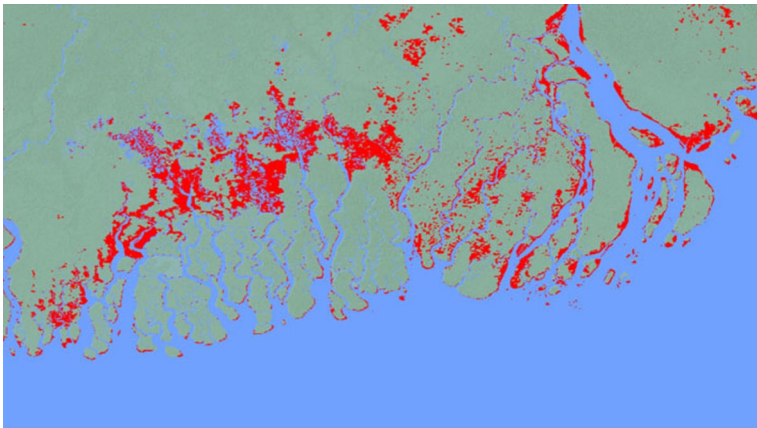


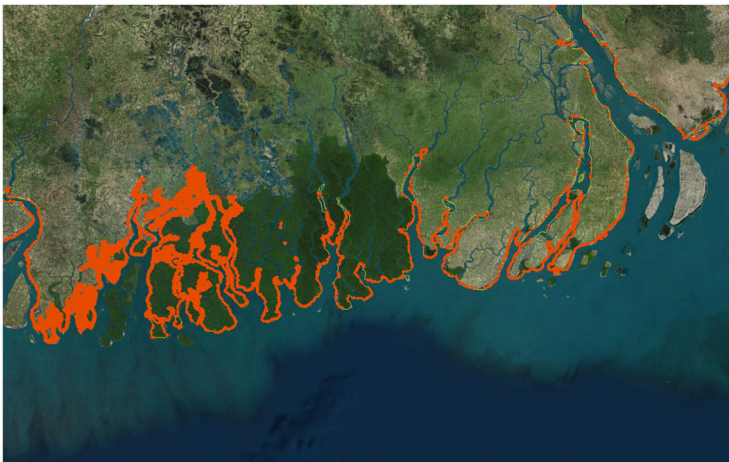
Fig. 10 Model computed maps of onshore inundation **a** for entire head Bay, **b** inundation envelope for Sunderbans marked as *rectangular box* in the *top panel*

from ADCIRC model (Fig. 11b) and the satellite imagery. The highlighted color patch shown in Fig. 11a, b indicates the extent of onshore inundation. The MODIS image shows the flooding to be quite intense (Fig. 11a); however, this imagery corresponds to the ground truth after 4 days of *Aila* passage. The inundation scenario in this imagery also supplements the flooding that resulted from heavy rainfall, which is not accounted in the ADCIRC simulations. For the benefit of the coastal community, the inundation extent was assessed for several locations in the head Bay region. Model results signify that flooding occurred mostly along the eastern region of West Bengal, and at western parts of Bangladesh covering a larger portion in the Sunderbans province. The inundation levels over the eastern sectors in Bangladesh were quite marginal.

Table 3 provides a detailed information on the hypothetical scenario of coastal inundation from ADCIRC computation for selected 38 locations in the head Bay region. These



(a)



(b)

Fig. 11 Comparison of inundation scenarios **a** MODIS imagery of onshore inundation, **b** ADCIRC computed inundation for the *Aila* cyclone

locations confine only to the Indian coast and the Sunderbans in Bangladesh. The geographical coordinates of these locations are shown along with their distance from the coastline. The distance of respective locations from coastline (fourth column in Table 3) refers to the nearest point where human settlements, habitation, and wildlife are present. The inundation distance (last column in Table 3) is the horizontal extent that water penetrated onshore with reference to the nearest water source. Numerical results signify that the highest inundation levels occurred at Sunderbans, geographically a site of heritage rich in biodiversity and ecological importance. The locations within Sunderban complex is referred as ‘SNP’ (Sunderban National Park), as these areas are void from any human settlements. The average horizontal extent of inundation at SNP was about 350 m according to the model simulations. At Bakkali, Bindapadmapur, Brojaballabpur, Lothian Island the extent of inundation exceeded 0.5 km. In SNP-2, the seawater intruded nearly

Table 3 Details of coastal location with their respective inundation extent and the distance from coastline

S. no.	Location	Geographical coordinate	Distance from coastline/major features	Inundation (distance in meters)
1	Bindapadmapur	21°36'12.95"N 87°27'32.99"E	0.48 km from coastline, Populated area with fishing jetty	536.970
2	Udaypur	21°36'35.74"N 87°27'52.96"E	0.12 km from coastline, populated area	296.634
3	Digha	21°36'36.32"N 87°31'44.56"E	0.81 km from coastline, thickly populated area of recreational importance	347.478
4	Jamra Shyampur	21°38'28.11"N 87°35'07.08"E	0.20 km from coastline, moderately populated	356.191
5	Tajpur	21°38'39.24"N 87°36'43.83"E	Along coastline, moderately populated with moderate vegetation	276.542
6	Bera Khana	21°38'51.28"N 87°36'53.81"E	0.27 km from coastline, thickly vegetated and forest	272.289
7	Silampur	21°38'51.73"N 87°39'19.51"E	1.6 km from coastline, Bank of Champa river, moderate agricultural farms	303.284
8	Sona Muhi	21°38'48.07"N 87°39'44.62"E	0.86 km from coastline, populated with agricultural farms	297.497
9	Mandaramani	21°39'57.69"N 87°42'17.72"E	0.27 km from coastline, populated area of recreational importance, agricultural farmlands	224.112
10	Dakshin Purushottampur	21°40'51.51"N 87°44'01.20"E	2 km from coastline. Thickly populated coastal regions	480.292
11	Birampur	21°43'32.88"N 87°49'08.35"E	2.26 km from coastline. Populated region with agricultural farms	201.642
12	Bhogpur	21°45'20.83"N 87°51'06.40"E	0.90 km from coastline. Populated region having thick vegetation and agriculture farms	211.106
13	Kaluraybar	21°45'42.38"N 87°51'36.75"E	0.72 km from coastline. Vegetation and farmlands with scattered residential areas	264.369
14	Sundarpur	21°47'48.19"N 87°53'44"E	0.90 km from the coastline. Slightly populated with thick vegetation	360.843
15	Thana Berya	21°49'16.73"N 87°55'51.27"E	0.16 km from coastline. Mostly barren with scattered vegetation	364.523
16	Sastimali	21°50'06.89"N 87°56'44.35"E	0.49 km from coastline. Agricultural land	324.390
17	Baman Chak	21°50'58.70"N 87°57'42.37"E	0.36 km from coastline. Mostly barren land	370.449
18	Saheb Nagar	21°52'11.95"N 87°58'35.29"E	2.2 km from coastline. Moderately populated land	235.922
19	Kharidabad char	21°52'59.77"N 87°58'30.40"E	1.2 km from coastline. Scattered agricultural farmlands	222.000
20	Usman Chak	21°58'11.47"N 88°01'26.72"E	2.51 km from coastline. Agricultural lands	278.263
21	Kendra Mari Jalpai	21°59'38.37"N 88°02'15.37"E	2.76 km from coastline. Populated land having dense vegetation	235.813
22	Durgachak	22°03'35.37"N 88°08'10.56"E	1.26 km from coastline. Thickly populated. Industrial units	246.220
23	Baneswar Chak	22°05'30"N 88°10'43"E	0.88 km from coastline. Moderately populated with industries along the coast	231.000

Table 3 continued

S. no.	Location	Geographical coordinate	Distance from coastline/major features	Inundation (distance in meters)
24	Begunbere	22°05'30"N 88°10'43"E	1.14 km from the bank of Hoogly river. Agricultural lands in coastal region and slightly populated inland	249.015
25	Dakshin Bhagabanpur	22°08'23"N 88°13'12"E	1.2 km from the coastline. Mostly agricultural land	173.221
26	Kalinagar	22°08'23"N 88°13'12"E	0.76 km from coastline. Thick vegetation and moderately populated	249.16
27	Kakadwip	22°08'23"N 88°13'12"E	1.92 km from coastline. Thickly populated area with industrial units and fishing harbors	300.140
28	Southern tip of Lothian Island	21°37'13"N 88°19'01"E	Deserted. Thick forest	589.703
29.	Bakkhali	21°33'37"N 88°15'33"E	0.30 km from the coastline. Agricultural land	650.000
30	Brojaballabpur	21°41'53"N 88°20'52"E	1.78 km from the coastline. Sparsely populated	560.897
31	SNP 1 ^a	22°02'08"N 88°45'37"E	0.5 km from the coast. Thick forest area	431.811
32	SNP 2	22°48'22"N 88°42'48"E	0.5 km the coast. Mangroves and vegetation	638.720
33	SNP 3	21°40'12"N 88°42'37"E	0.5 km from the coast. Forest and vegetation	270.152
34	SNP 4	21°38'21"N 88°45'42"E	0.5 km from the coast. Forest and vegetation	365.435
35	SNP 5	21°39'42"N 88°51'53"E	0.5 km from the coast. Forest and vegetation	309.404
36	SNP 6	21°39'16"N 88°53'42"E	0.5 km from the coast. Forest and vegetation	196.018
37	SNP 7	21°36'28"N 89°00'19"E	0. 5 km from the coast. Forest and vegetation	155.921
38	SNP 8	21°37'20"N 89°03'15"E	0.5 km from the coastline. Forest and vegetation	523.465

^a Location in Sunderban National Park

630 m. Places such as Kakwdip, Silambur experienced inundation almost 1–2 km inland from coast, primarily from the riverbank flooding. Figure 12 shows the 38 locations along the coastal belt based on the inundation range. The modeling study signifies that most of the locations experienced seawater penetration ranging between 200 and 400 m. The horizontal extent of inundation depends not only on onshore topographic elevation, but also on the roughness characteristics from vegetation cover such as the mangrove ecosystem dominant in Sunderbans. Accurate estimation of inundation scenario incorporating vegetation characteristics, and its resistance to time-varying flow field is a challenging task that requires further investigation and a separate study. To model the flow field in complex near-shore environment such as Sunderbans, it is necessary to have precise data on mangrove types, their characteristics, information on primary and

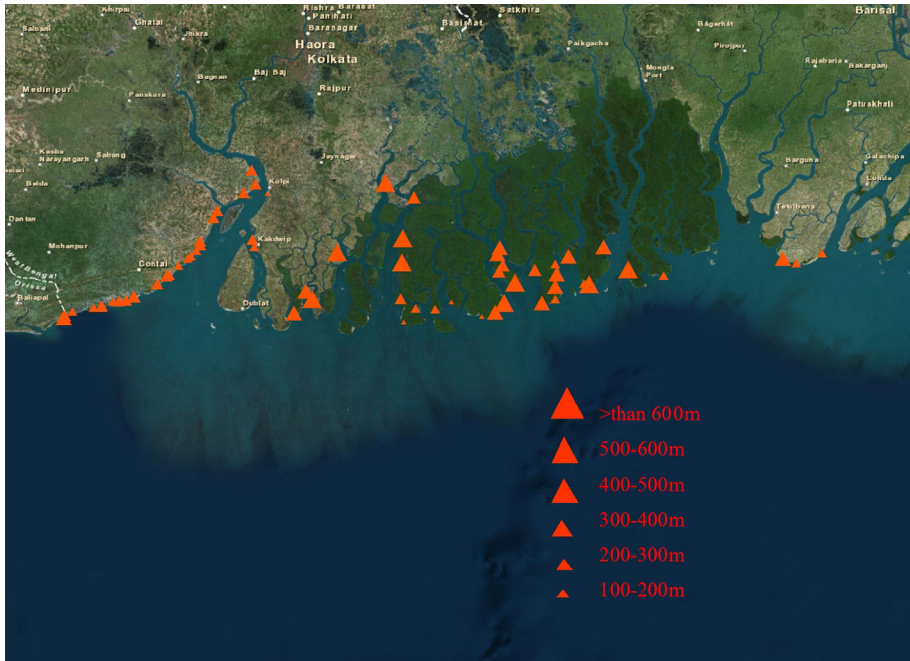


Fig. 12 Storm surge affected areas and associated onshore inundation range (in meters) for the head Bay region

secondary offshoots and their spacing, etc. along with details of accurate topography for the near-shore environment.

6 Summary and conclusions

This study reports on the application of ADCIRC model to compute the hypothetical peak surge and coastal inundation for the head Bay region associated with a severe tropical cyclone *Aila* that had landfall near Sagar Islands in West Bengal coast bordering west Bangladesh on May 25, 2009. *Aila* developed as a tropical depression approximately 950 km south of Kolkata on May 21, 2009 and intensified into a SCS moving in the northward direction. The Jelesnianski formulation generated the wind field for *Aila* event using the primary information of best track details from IMD. The model executes in a hot start mode using the tidal forced realistic boundary information of water level elevation. The formulation for bottom resistance used in ADCIRC is a hybrid version of the bottom friction coefficient having strong dependence on local bathymetry. Model simulations for the *Aila* event covered a period of 5 days starting from May 22, 2009 (18 h) until May 26, 2009 (06 h) with a prescribed time step of 3 s fulfilling the model stability criterion. The simulated output includes peak storm surge, maximum water level elevation, and depth averaged currents obtained at a regular 30 min interval. The model computed storm surge was about 4.0 m for the coastal stretch of Sunderbans. Unfortunately, there exists no measured data for model validation along the Indian and Bangladesh coast during the *Aila* event. The tide

gauges manually operated along the Bangladesh coast could not collect any data during this event. Therefore, the present study provides only a hypothetical scenario on the storm surge development and associated coastal inundation. The aftermath from *Aila* cyclone produced storm surge experienced all over the head Bay region causing widespread inundation. Especially the regions in Sunderban National Park (SNP) that possesses rich natural biodiversity and ecosystem faced the highest catastrophe. According to model simulations, the extent of inundation on an average was about 350 m for the Sunderban region. Several locations such as Silampur, Kakadwip, etc. were the worst affected and experienced flooding up to 600 m. The authors believe that a numerical modeling system that couples storm surge prediction along with onshore inundation will significantly benefit coastal engineers, coastal zone management authorities, and operational forecasts.

Acknowledgments This research work is a part of the High-resolution Operational Ocean Forecast and Reanalysis System (HOOFS) project funded by the Indian National Centre for Ocean Information Services (INCOIS). The authors gratefully acknowledge INCOIS, Hyderabad under the Ministry of Earth Sciences, Government of India for funding this research work and also the development team of ADCIRC model.

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