

# Long Term Morphodynamic Evolution of Kakinada Bay using Upscaling Methods

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## ABSTRACT

Kakinada Bay has evolved over the last century dynamically by the action of wind, waves, tides and currents. Formation of Hope Island and development of Coringa Mangroves are attributed to the hydrodynamic 'forcings' and sediment dynamics. This study aims to predict the future morphological development of Kakinada Bay for next 100 years. The morphological model was built up in the DELFT 3D package. Model setting parameters were fixed after analysing their effect on the simulation results. For reducing the computational time and effort for simulating long term morphological development, upscaling methods such as morphological acceleration factor (MORFAC) and morphological tide were incorporated in the morphological model. Morphological tide was formed using tidal constituents - M<sub>2</sub>, O<sub>1</sub> and K<sub>1</sub>. The MORFAC value for this study was chosen as 30 after undergoing the sensitivity test analysis using Brier Score Skill (BSS) Score. The model was run for 19 years for hindcasting and 100 years for forecasting. In order to establish confidence in the model, it was calibrated and validated using hindcast modelling. The hindcast simulation results were used to match the simulated shoreline with satellite observed shoreline from year 1988 to 2000, and 2006 to 2013 and the results were in good agreement. It was observed that the south-western part of

the bay has accreted more rapidly while south-eastern part of the bay has undergone slight erosion. Thereafter long term morphological model was run for 100 years to predict the future evolution of bay. Results of these simulations show the capability of the long term morphological model to predict the spatial and temporal geo-morphological changes.

**Keywords:** Shoreline, morphological tide, MORFAC, hindcast, forecast.

## INTRODUCTION

Kakinada bay is located in Andhra Pradesh on the East coast of India. The Bay has formed over the last century by the action of the hydrodynamic forcing by winds, waves, tides, currents and sediment influx brought by the river Godavari discharges. With time, flushing capacity of river Godavari reduced due to which more sediment has been brought inside the bay. This led to deposition of sediments and land advancement towards the sea. Sediments inside the bay are mainly fine grained and cohesive in nature, which leads to flocculation and settling thus helping mangrove seed propagules to grow and establish in mudflats. With time, these mangroves colonized at the bottom of the bay and formed the second largest Mangroves of East Coast of India. This shoreline advancement towards the sea has been studied over the

last few decades with the help of satellite imageries which showed that considerable amount of accretion has taken place in the western side of the bay. Coringa mangroves hold utmost importance as they have acted as protective shield for Kakinada Port and the city against natural calamitous actions of high waves and tsunamis. Hence, prediction of long term development of this bay will be highly useful as it will lead to better future planning for safeguarding the coast and the city from erosion.

For this, the process based hindcast and forecast morphological models have been developed to simulate the hindcast and forecast for 19 years and 100 years' time period respectively. Hindcast simulation was done for the time period of 19 years on the basis of bathymetries available for respective initial and final years given as input and validating the obtained morphological results, Dam et al., (2015) and Van der Wegen, M., and Roelvink, J. A. (2012) explained how morphological models have become robust tools for prediction of long-term development using hydrodynamic physical process principles and mathematical equations for mass conservation, water motion, sediment transport and change in bed. Morphological models calculate flow, sediment transport and bottom changes for predicting morphological development.

Since running model for predicting long time period takes lot of computational time and effort, it becomes infeasible to run the model for longer time periods. To overcome this, upscaling techniques have been developed for accelerating the morphological evolution, using morphological acceleration factor and morphological tide as input reduction method. MORFAC is one of the most commonly applied acceleration method developed by Lesser et al., (2009). It multiplies the calculated bed changes with the MORFAC factor. For example, a simulation over one-month (30days) with a MORFAC value 10 will result in 300 days of predicted morphological change.

While morphological acceleration

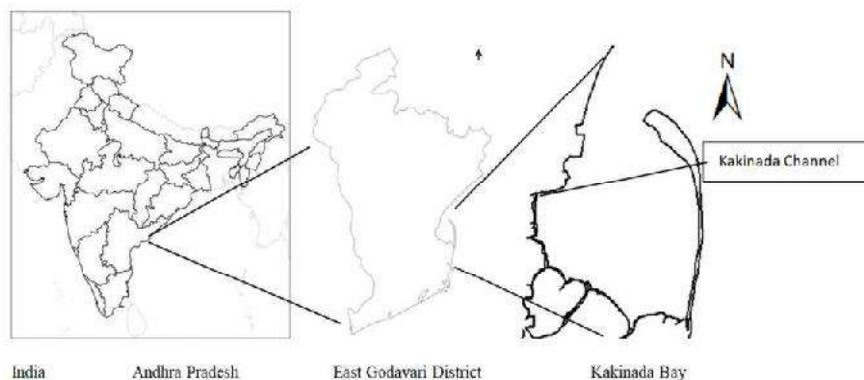


Figure 1: Coringa Mangroves and Kakinada Bay

factor accelerates the simulation, input reduction method is the technique to reduce the computational effort by applying a reduced set of input forcing conditions. For the input reduction method, morphological tide was formed using only those tidal constituents which represented a longer time signal and were majorly responsible for the bed level changes as explained by Luijendijk A.K. et al., (2019). Thus the combined usage of MORFAC with morphological tide helps

**Hence, prediction of long term development...  
...will lead to better future planning for safeguarding the coast and the city from erosion.**

in reducing the computational time and effort drastically for simulating the morphological development for decades and centuries.

## 2. STUDY AREA

Kakinada bay is located at  $82^{\circ}14'$  –  $82^{\circ}22'E$  longitude and  $16^{\circ}5'$  –  $17^{\circ}N$  latitude in East Godavari district of Andhra Pradesh state in India (Figure 1). It is a low-lying shallow region with approximately 132 sq. km in area, surrounded by Kakinada spit at the eastern side, Coringa mangroves and three tributaries of Godavari River; Gaderu, Corangi and Matlapalem at the southern side, Kakinada port and city on the western side. The mouth of the bay is opened to the sea on the

northern side. Kakinada has a semi-arid climate with an average rainfall of 1040 mm per annum and average temperature of 28 deg. C. Tides are semidiurnal and tidal amplitude in the bay varies between 2.3 m and 4.5 m. Prevailing winds in Kakinada are usually south-westerly for most of the year except during October-January, when they blow north-easterly. In this region, the waves approach predominantly from the south east during March-September and from the east during December-February. Being a large rice zone and also part of a Special Economic Zone and a proposed Petroleum, Chemical & petrochemical Investment Region, it holds great economic importance.

## 3. MODEL DESCRIPTION

DELFT3D is a hydrodynamic model package that helps in simulating hydrodynamic, sediment dynamics and wave dynamics. DELFT3D Flow model calculates non-steady flow by the action of winds, waves and tides. These equations along with initial and boundary conditions of water level and horizontal velocities are solved on a finite difference grid.

The horizontal momentum equations are represented as Eq. 1 and 2, where  $d$  is water depth below plane of reference (m),  $f$  is Coriolis Parameter ( $1.s^{-1}$ ),  $F_{x,y}$  is  $x$  and  $y$  component of external forces ( $N.m^{-2}$ ),  $U, V$  are depth averaged velocity ( $m.s^{-1}$ ),  $\rho_w$  is mass density of water ( $kg.m^{-3}$ ),  $\nu$  is diffusion coefficient (eddy viscosity) ( $m^2.s^{-2}$ ),  $\eta$  is water level variation above plane of reference (m),  $g$  is gravity of

acceleration ( $m.s^{-2}$ ),  $\tau_{bx,y}$  is x and y component of bed shear stress ( $N.m^{-2}$ )

The depth averaged continuity equation is represented as Eq.3

These equations along with initial and boundary conditions of water level and horizontal velocities are solved on a finite difference grid.

DELFT3D SWAN model is a stand-alone application used to simulate wind-generated waves in the coastal areas. SWAN stands for Simulating WAVes Nearshore. It simulates the evolution of random short-crested waves in estuaries, tidal inlets and lakes.

#### 4. MODEL SET UP

The hydrodynamic and wave model consists the area of Kakinada Bay represented by curvilinear orthogonal grid (M\*N) in horizontal plane using 433\*487 grid cells with grid size dx and dy 58m and 60m respectively as shown in Figure 2.

SWAN model has been used for studying the wave impacts inside the bay. Boundary input parameters for model were time-varying for wave height, wave period and wave direction for the month of September 2011. Wave heights entering inside the bay have been studied to see if they were significant. Wave model has been calibrated by varying constants to validate the input data by comparing with field data obtained from Kakinada seaports.

In order to check the significant effect of waves inside the bay, inputs on waves were extracted from three points: at the model boundary, at the mouth of the bay and inside the bay. It was found that the wave heights of waves entering inside the bay were comparatively very less as shown in Figure 3. The reduced wave action inside the bay can be attributed to the action of breakwater.

The Figures 3 and 4 show the significant wave heights and wave direction inside the bay, respectively. It is observed that the significant wave heights entering inside the bay are very less. Hence effect of waves has not been considered in the morphological model.

$$\frac{\partial U}{\partial t} + U \frac{\partial U}{\partial x} + V \frac{\partial U}{\partial y} + g \frac{\partial \eta}{\partial x} - fV + \frac{\tau_{bx}}{\rho w(d+\eta)} - \frac{F_x}{\rho w(d+\eta)} - \nu \left( \frac{\partial^2 U}{\partial x^2} + \frac{\partial^2 U}{\partial y^2} \right) = 0 \quad (1)$$

$$\frac{\partial V}{\partial t} + U \frac{\partial V}{\partial x} + V \frac{\partial V}{\partial y} + g \frac{\partial \eta}{\partial x} + fV + \frac{\tau_{by}}{\rho w(d+\eta)} - \frac{F_y}{\rho w(d+\eta)} - \nu \left( \frac{\partial^2 V}{\partial x^2} + \frac{\partial^2 V}{\partial y^2} \right) = 0 \quad (2)$$

$$\frac{\partial \eta}{\partial t} + \frac{\partial [d+\eta]U}{\partial x} + \frac{\partial [d+\eta]V}{\partial y} = 0 \quad (3)$$

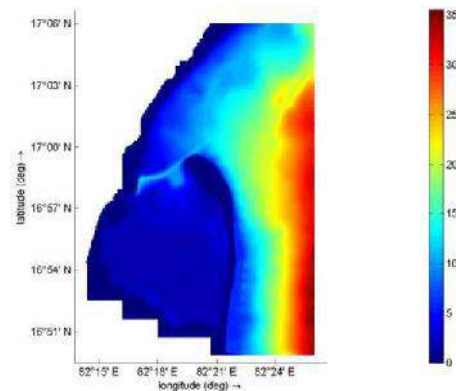


Figure 2: Grid and Bathymetry of Wave and Flow model

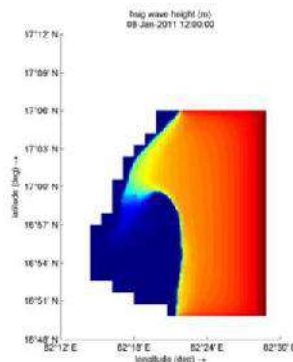


Figure 3 Significant Wave Height

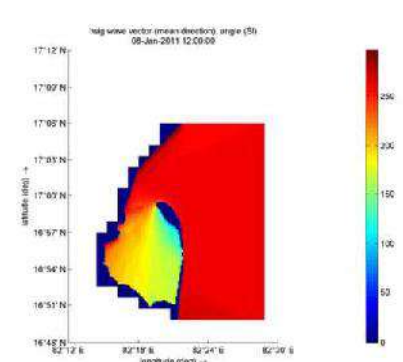


Figure 4 Significant Wave Direction

#### 4.1 Validation of Flow model

Flow model was validated by comparing the tidal water levels obtained from model with the observed tidal water level. To achieve this, the flow model was run for the month of September 2011 giving open boundary conditions as astronomical water level tidal constituents. The astronomical tides are generated from the gravitational effect of Earth, Sun and Moon without any atmospheric influence.

In order for a model to represent an original field, various parameters like bed roughness, eddy viscosity, eddy diffusivity, etc., were defined with a certain value that would represent the

actual field. For this various simulations were performed by giving various values for tuning these parameters so that the obtained flow model results are in good agreement with the data obtained from field work. This process is called as Model calibration. The bottom roughness was given a value of 74 as Chezy coefficient. Value for bottom horizontal eddy viscosity and eddy diffusivity were given as  $1 m^2.s^{-1}$ . This way, the flow model was validated.

For understanding sedimentation occurring inside the bay, various parameters were tuned for matching well with the actual field data. Cohesive silt sediments were given as boundary conditions with a sediment size D50 equal to  $200\mu m$ . Specific sediment

density was set as 2650 kg/m<sup>3</sup> and dry bed density as 500kg/m<sup>3</sup>. The sediment model was validated by comparing the suspended sediment concentration of observed field data with the predicted model data. It was found to be reasonably matched, hence the sediment parameter was incorporated in flow model to further form the morphological model.

### 5. MORPHOLOGICAL MODEL

Morphological model has been formed in the flow model of DELFT3D for predicting long term changes using Input Reduction method and MORFAC. Input reduction method has been applied by creating morphological tide comprising of tidal constituents M2, and C1, where C1 is the combined constituent of O1 and K1. This morphological tide has been incorporated in the model with period of M2 and C1 constituent kept at 745 minutes and 1490 minutes respectively, so that the residual sediment transport obtained can be same as that of the astronomical tide.

Water level has been compared for model with harmonic morphological tide including M2 and C1 as input boundary condition and run with full astronomical tide for month of September 2011. Current velocity has been validated comparing astronomical tide with morphological tide. In order to amplify the total energy by combined interaction of M2, O1 and K1, a scaling factor 1.3 was multiplied to M2 which was determined after multiple trial and error comparisons with brute force simulation. This way morphological tide was formed.

In order to choose morphological acceleration factor, a sensitivity analysis for morphological factor was carried out using Brier Score Skill as discussed by Sutherland et al. (2004) which provides quantitative analysis of skill of model, where skill is the accuracy of prediction by model relative to the baseline prediction. Formulation of BSS is represented by Eq. (4).

Where Y is a prediction, X is an observation;

B is the baseline prediction against

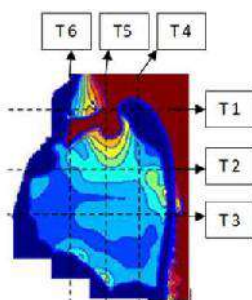


Figure 5 Transects casted in NS and EW Directions

Transects	BSS for	BSS for	BSS for
	MORFAC	MORFAC	MORFAC
	20	30	40
T1	0.94	0.93	-2.15
T2	0.97	0.99	-3.45
T3	0.94	0.94	-3.55
T4	0.95	0.98	-3.38
T5	0.86	0.89	-2.61
T6	0.94	0.95	-2.75

Table 1: BSS for various MORFAC values for transects

which the model prediction is evaluated.

<>denotes the arithmetic mean.

BSS with a value of 1 implies that the morphological change predicted by model is perfectly identical to the benchmark simulation.

Morphological model was run using various MORFAC values like 10, 20, 30 and 40 for predicting morphological evolution for one month. Bed level results were compared with MORFAC 1 simulation at the exact same morphological time of one month for six

**Hindcast modelling has been done using the morphological model with morphological tide and morphological acceleration factor.**

transects casted in North-South and East-West directions as shown in Figure 5. BSS score for simulation with MORFAC 20 and 30 were greater than 0.9 for all transects as presented in Table 1. In order to run morphological model for less time for simulating larger time period, MORFAC value was chosen as 30; as higher the acceleration factor, lesser the computational time.

Bathymetry values were compared for brute force and morphological simulation results. Regression Coefficient was calculated to develop the confidence level in the model. The regression coefficient value obtained

$$BSS = 1 - \frac{\langle(Y-X)^2\rangle}{\langle(B-X)^2\rangle} \quad (4)$$

was 0.99 for all the transects. Hence the morphological model was well formed with reasonable results obtained using morphological acceleration factor and morphological tide.

### 6. HINDCAST MODELLING

Hindcast modelling has been done using the morphological model with morphological tide and morphological acceleration factor. Simulation was run for time periods of 1988-2000 and 2006-2013 with corresponding initial bathymetry to assess the accuracy of long term morphological simulations. Hindcast models were set up giving input bathymetry for the starting years 1988 and 2006 and were run with MORFAC 30 to predict morphological development for the final years 2000 and 2013 respectively. The hindcast results were used to extract the predicted bathymetries. Further from the extracted resultant bathymetries, land-water shorelines were delineated. These model-delineated-simulated shorelines were compared with the satellite shorelines by superimposing them together on the satellite imagery of the year the prediction was done for. As shown in Figures 6 and 7, the simulated shorelines for year 2000 and 2013 respectively were superimposed with the satellite shorelines of the same year on the satellite imagery of the predicted year. The Figures show the initial shoreline of the input bathymetry, the satellite and simulated shorelines for the predicted year. This gives a clear picture how hindcast morphological model has been able to predict the

morphological development. The hindcast model is validated as the simulated shoreline has been well predicted as the satellite shoreline.

Referring to Figure 6 and 7, it was observed from the hindcast results that sedimentation has occurred at the western side of the bay while there are very negligible changes on the eastern side at the bottom of the bay. Simulated shorelines have matched well with that of shorelines derived from satellite imageries independently.

## 7. FORECAST MODELLING

Forecast model was prepared with reduced morphological tide using morphological acceleration factor 30 for predicting future development for next 100 years from year 2019 to 2119. The resultant bathymetry of the region has been extracted from simulation result and has been compared with the initial bathymetry of year 2019 in Figures 8 and 9.

Figures 8 and 9 show the bathymetry of the years 2019 and 2119 respectively. The morphological changes inside the bay for 100 years are compared. It is observed that the long term morphological model has predicted sedimentation and siltation inside the bay leading to reduction in the depth of the bay. It is seen from the Figure 9 that the width of the spit has reduced considerably with extreme erosion at the centre, which has allowed the water to flow through. This has resulted in the increased water level in the areas around. Morphological evolution at the bottom of the bay shows that there are two areas at the mouth of the creeks with less sedimentation.

## 8. RESULT AND CONCLUSION

Long term morphological development of Kakinada Bay has been predicted using morphological model in DELFT3D system. The 100 years long time prediction has been able to perform using input reduction technique with morphological tide and accelerating the simulation using morphological acceleration factor. Both the techniques combined together have been used to calibrate the model by comparing the simulation results of both non-accelerated model and

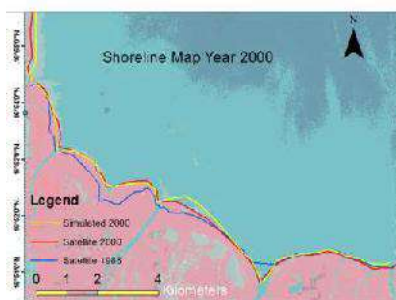


Figure 6 Simulated and Satellite imagery Y2000

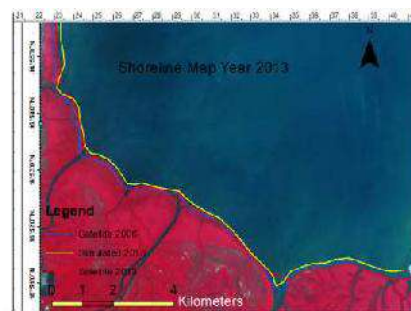


Figure 7 Simulated and Satellite imagery Y2013

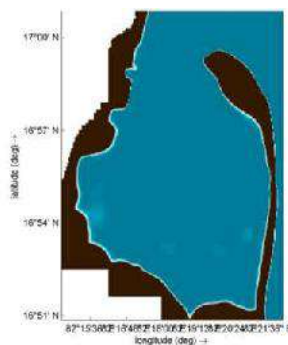


Figure 8 Bathymetry for year 2019

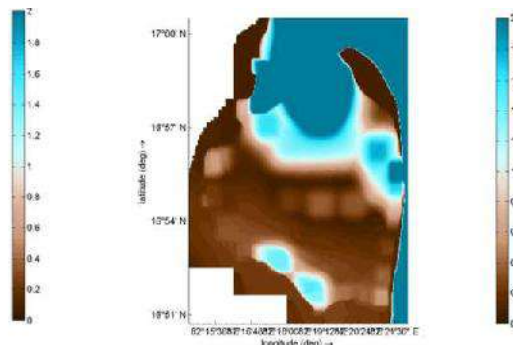


Figure 9 Bathymetry predicted for year 2119

accelerated morphological model. Confidence in the model was established by running Hindcast model for periods 1988-2000 and 2006-2013. The simulated results were used to extract the resultant shoreline to compare with the satellite shoreline of that predicted year, together superimposed on the year's satellite imagery. The matched simulated and satellite shoreline built confidence in the morphological model, which was further used for predicting for next 100 years from year 2019 to 2119. The predicted results showed considerable siltation and sedimentation inside the bay with narrowing of spit's width. Thus the morphological model has simulated most of the observed morphological changes in the bay and has performed well for predicting the long term century scale morphological development.

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(Note: The listed References have been used for the study and acknowledged though not cited in the paper).

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