Government of India
Ministry of Jal shakti
Department of Water Resources,
River Development and
Ganga Rejuvenation

सत्यमेव जयते

भारत सरकार
जल शक्ति मंत्रालय
जल संसाधन, नदी विकास
और गंगा संरक्षण विभाग

Technical Report No. 6173
October 2023

MATHEMATICAL MODEL STUDIES TO ASSESS IMPACT OF THE PROPOSED PORT DEVELOPMENT AT VADHAVAN ON FLOODING IN DAHANU CREEK AND NEARBY CONTROL AREA UNDER CYCLONIC CONDITIONS

केन्द्रीय जल और विद्युत अनुसंधान शाला, पुणे
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PORTS AND HARBOURS-II DIVISION

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Dr. R. S. Kankara

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REPORT DOCUMENTATION SHEET

Technical Report No: 6173 **Date:** October 2023

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Officers Responsible for conducting the studies:

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Name and address of Sponsoring Authority:

The Chief Manager, (PPD)
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Synopsis:

The major all-weather, Greenfield port is proposed to be developed offshore of the headland at Vadhavan in Dahanu Taluka of Palghar district in the state of Maharashtra at Lat. 19° 55.8′ N, Long. 72° 39.6′ E. The location of proposed port is at about 110 km north of Mumbai. The port will be developed through a joint venture between Jawaharlal Nehru Port (JNP) and Maharashtra Maritime Board (MMB). The port limit of the proposed port extends up to about 4 km on the north side of Headland at Vadhavan, while it is about 3 km on its south side of as well as it extends up to 26 m depth w.r.t. CD of Dahanu in the deeper part of the Arabian Sea. The finalized Master Plan layout of port consists of 10.3 km long breakwater, offshore reclamation of about 1262 ha. with its westward face located at about 6.5 km from headland at Vadhavan along with trestle approach connected to nearshore reclamation of about 222 ha. The tides in this region are of macro semi-diurnal with tidal range of about 6 m and waves are predominant from two quadrants namely North-West & South-West.

The mathematical model studies were carried out to assess the impact of proposed port at Vadhavan on flooding in control area (10 km radius) due to cyclones considering the cyclonic storm data obtained from IMD, ECMWF for past 50 years (1970-2020), wave and wind data from INCOIS along with oceanographic data collected near the proposed port site for non-monsoon (2017) & monsoon season (2020). The regional model covering the area from Lat. 8° N (Kerala) up to Lat. 23° N (Gujarat) and Long. 65° E (about 4500 m depth) to Long. 77° E (West Coast of India) inclusive of the area of proposed port at Vadhavan is calibrated for tides at Dahanu as well as for wave and wind data of cyclones occurred in 2001 & 2017 (INCOIS). The rise in water level at Diu, Gujarat for 1982 cyclone observed at site also compares well with that in model. The calibrated regional model was used for the simulation of 44 cyclonic events of past 50 years which are of significance to Vadhavan area to determine Significant wave height (Hs) & rise in water level.

The extreme value analysis (EVA) carried out by fitting the data set of cyclones for rise in water levels as well as (Hs) for various distribution functions (FT, Weibull) reveal that the predicted rise in water level will be 1.16 m, 1.60 m & 2.10 m, while the ‘Hs’ are as 5.54 m, 6.50 m & 7.46 m for 1 in 25 yrs, 1 in 50 yrs & 1 in 100yrs return periods respectively. The proposed port being on open coast & offshore of Vadhavan, the reliable estimation of flood level is necessary and is carried out by selection of simultaneous occurrence of such oceanic phenomena which are of significance viz. rise in water level & tides to arrive at storm tide level to assess the impact of proposed port development over the control area (10 km radius).

Thus a multivariate approach is adopted to arrive at storm tide level for three cases Viz. 1) occurrence of maximum rise in water level and corresponding tidal level, 2) occurrence of maximum rise in water level and the maximum high tide in proximity of the occurrence of maximum rise in water level and 3) occurrence of maximum rise in water level and the second-high tide in proximity of the occurrence of maximum rise in water level. The studies were carried out using well calibrated local model for the existing bathymetry and proposed port conditions for above three cases with two scenarios viz. 1) flooding due to cyclonic storms + rainfall occurred during cyclonic conditions and 2) flooding due to cyclonic storms + rainfall occurred during past 50 years each for 1 in 25 yrs, 1 in 50 yrs & 1 in 100 yrs return periods.

The model studies for all combinations/cases reveal that there is practically no variation /impact (less than 15 cm) in extent of flooding within control area (10 km radius) due to proposed development of port at Vadhavan than that observed for the existing condition.

Key Words: Control Area, Cyclone, Flooding, Impact, Multivariate, Return Period, Significant Wave

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MATHEMATICAL MODEL STUDIES TO ASSESS THE IMPACT OF PROPOSED PORT DEVELOPMENT AT VADHAVAN ON FLOODING IN DAHANU CREEK AND NEARBY CONTROL AREA UNDER CYCLONIC CONDITIONS

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1. INTRODUCTION

The major Greenfield, all-weather port at Vadhavan is proposed to be developed on the offshore of headland at Vadhavan in Dahanu Taluka of Palghar district in the state of Maharashtra at Lat. 19° 55.8′ N, Long. 72° 39.6′ E. The location of the proposed port is about 110 km north of Mumbai and will be developed through a joint venture between Jawaharlal Nehru Port (JNP), Govt. of India undertaking and Maharashtra Maritime Board (MMB), Govt. of Maharashtra undertaking. The port limit of the proposed port extends up to about 4 km on the north side of Headland at Vadhavan, while it is about 3 km on its south side of headland as well as it extends up to 26 m depth in the deeper part of the Arabian Sea. The area of proposed port is about 175 Sq. km. The location plan of proposed port is shown in FIG.1.The important oceanographic phenomena such as waves & tides prevail in this region are of significance as the port development being on the open coast. The waves approach to the port location predominantly from two quadrants namely North-West & South-West and tides in this region are of macro semi-diurnal in nature with tidal range of about 6 m.

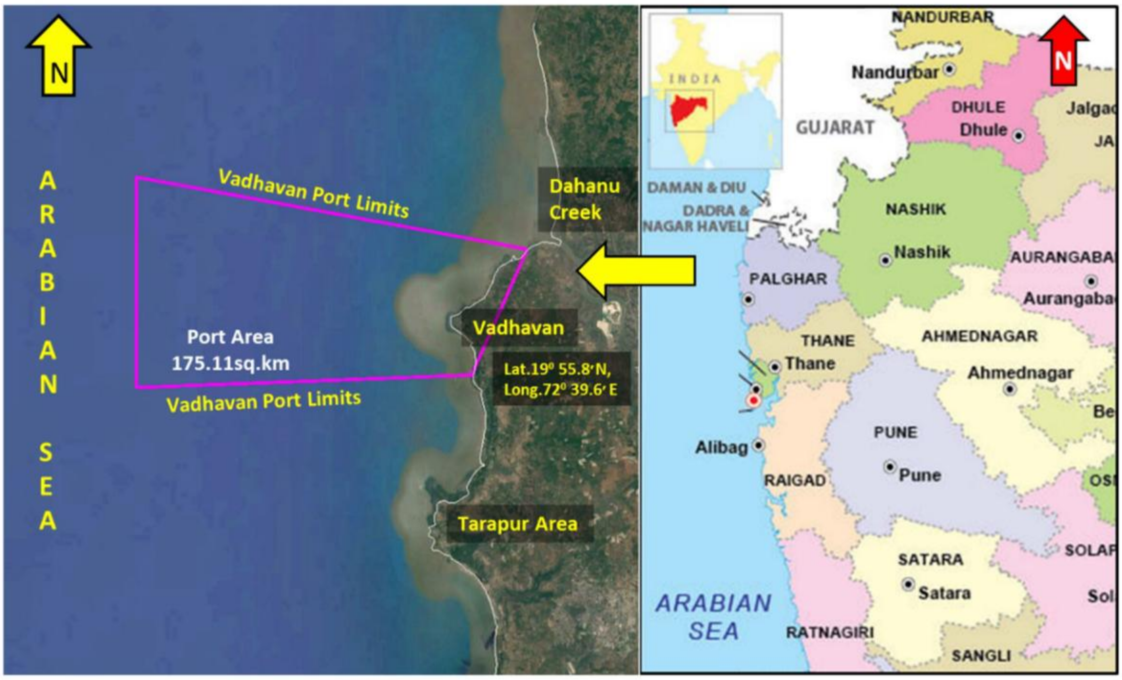


FIG.1: Location plan of proposed port at Vadhavan

The JN Port has undertaken the task of planning the configuration of the port layout, along with finalization of various components like alignment of breakwaters, berth structures, operational area, harbour basin, approach channel etc. to finalize the conceptual layout of the port. The port is proposed to be developed on the seaward side of the headland at

Vadhavan and the entry to the port will be from the Arabian Sea through the navigational channel.

The port Authority entrusted various hydraulic model studies to Central Water & Power Research Station (CWPRS) to study the concept layout prepared by the Consultant to JN Port for finalizing the layout for the proposed port at Vadhavan and to assess the impact of proposed development on Tarapur Atomic Power Station (TAPS) through model studies. CWPRS carried out following four studies to finalise the layout of port and the technical reports for the same were submitted to JN Port in year 2018.

- Hydrodynamics and siltation to finalize layout of port and estimate the siltation
- Wave transformation and tranquility for assessing wave conditions at berths
- Shoreline changes and littoral drift
- Design of breakwaters – Wave flume studies

The layout finalized in the year 2018 was considered to assess the impact of proposed port development on intake/outfall facilities of TAPS and technical reports for the same were also submitted to JN Port in year 2018-19.

The JN Port thereafter has submitted the proposal of the development of Port at Vadhavan to Ministry of Environment Forest and Climate Change (MoEF&CC) for Environmental Impact Assessment (EIA) clearance. The Expert Appraisal Committee (EAC) meeting was held by MoEF&CC, New Delhi on 26th August 2020 and recommended the project for the grant of TOR with conditions to carry out various additional studies. In this context to fulfil the TOR conditions, JN Port referred the following additional studies vide their letter dated 11th September 2020.

1) Assess the impact of proposed capital dredging on the flow field in the nearby area
2) Flooding and related impact on creek at Control area during the cyclonic storm

This report describes the studies carried out to assess the flooding and related impact on creek at Control area during the cyclonic storm due to the proposed development of Port at Vadhavan.

The JN Port officials, before complying the TOR conditions, altered the layout considering the operational efficiency/turnaround time of transport of containers from stack yard proposed on intertidal zone and berths in deeper depths. It was proposed to modify the shape of reclamation and desires to relocate the same immediately on the leeward side of container berths in deeper depths. The various layouts (10 Nos) were studied at CWPRS from tidal & wave hydrodynamic considerations and were discussed with project officials, their consultants from time to time through VC meetings and the layout finalised through model studies was reported in CWPRS Technical Report No. 5968 of November 2021 in detail.

The finalized master plan layout of the port consists of 10.3 km long breakwater, offshore reclamation of about 1262 ha. with its westward face located at about 6.5 km from headland at Vadhavan and shore connected reclamation of about 222 ha. on tidal flats near the headland at Vadhavan and is as shown in FIG.2.

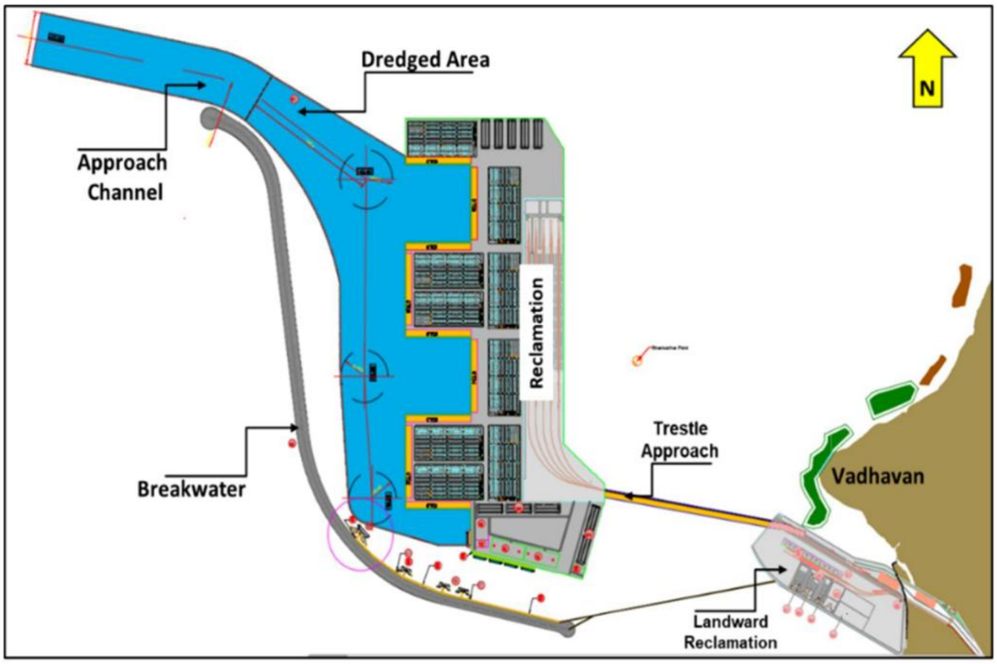


FIG.2: Finalised master plan layout of proposed port at Vadhavan

The mathematical model studies to assess the impact of cyclonic storms on flooding in the Dahanu creek and control area due to the development of proposed port at Vadhavan are carried out by developing the regional & local mathematical models wherein the use of past fifty (50) years of cyclonic storms data and rainfall/runoff events (hydrographs) as well tidal levels at Vadhavan is made and are described in this report.

2. SCOPE OF THE STUDIES

The mathematical model studies to assess the impact of cyclonic storms on flooding in the Dahanu creek and control area due to the development of proposed port at Vadhavan are proposed to be carried out by simulating the cyclonic storm conditions which are of relevance to the port site during past 50 years. The scope of the studies is as follows:

i) Develop a regional mathematical model covering area from Lat. 8° N (Kerala) up to Lat. 23° N (Gujarat) and Long. 65° E (about 4500 m depth) to Long. 77° E (West Coast of India) including the area of proposed port at Vadhavan, Dahanu creek along with shoreline within control area (within 10 km radius from Vadhavan point). The regional model is to be calibrated for the available oceanographic field data.

ii) Develop a local mathematical model covering the area up to Gholvad on north side as well as up to Nandgaon on the south side and up to about 30 m depth below CD in deeper part of Arabian Sea on the west-side, proposed port at Vadhavan, Dahanu creek along with shoreline within control area (within 10 km radius from Vadhavan point). The local model is to be calibrated for oceanographic field data collected near Vadhavan port site.

iii) Simulate the cyclonic conditions relevant to the port site at Vadhavan for past fifty (50) years (1970-2020) using regional model to estimate the rise in water level & significant wave heights near Vadhavan area in the domain area of local model.

iv) The extreme water levels & significant wave heights for return periods of 1 in 25, 1 in 50, 1 in 100 years are to be derived using appropriate statistical methods for last fifty (50) years cyclonic storm conditions.

v) The local model with existing bathymetry condition is to be used to determine the likely rise in water/ flood level in Dahanu creek and control area under the combined effect of cyclonic storms in the sea and rainfall-runoff for Scenario-1: Flooding due to cyclonic storms + rainfall (occurred during such stormy conditions only) for respective return periods (RP) of 1 in 25, 1 in 50 and 1 in 100 years along-with tide level and significant wave heights.

vi) The local model with existing bathymetry condition is to be used to estimate the likely rise in water/ flood level in Dahanu creek and control area under the combined effect of cyclonic storms in the sea and rainfall-runoff for Scenario-2: Flooding due to cyclonic storms + rainfall (considering past 50 years of rainfall data) for respective return periods (RP) of 1 in 25, 1 in 50 and 1 in 100 years along-with tide level and significant wave heights.

vii) The impact of development of port at Vadhavan on the water levels for above scenarios is to be studied by incorporating finalized layout of proposed port. The effect of proposed port on the likely variation/rise in water/ flood level in Dahanu creek and control area is to be assessed both for Scenario-1 and Scenario-2.

3. METHODOLOGY

The Indian coasts are typically characterized by monsoon wave climate and tropical storms. The wave climate is more severe during tropical storms in comparison to monsoon. The storms/cyclones which occur in the Indian Ocean are Tropical cyclones. The nomenclature “Tropical Cyclone” is based on its geographical origin and is a rapidly rotating storm system in tropics wherein the central pressure falls by 5 to 6 hPa from the surrounding with maximum sustained wind speed of about 34 knots (about 62 kmph). These cyclones generate extreme wind waves, storm surges (Rise in sea level due to wind stress and inverted barometric effect), heavy rainfall and coastal flooding. Storm Surge is the temporary rise in water level at the coastline during the cyclone. This temporary rise in the water level takes place only when the cyclonic wind blows over the continental shelf and pushes the water against the coastline. It also causes torrential rains that lead to flash flooding, abnormally high waves, storm surge and these phenomena causes major threat to the human life, property, damage to the coastal structures etc. The severity of storm i.e. wind speed, pressure gradient as well as water depth, width of continental shelf etc. governs the magnitude of storm surge. The generation of storm surge is site specific and depends on extreme storm climate in the vicinity of the site. Ideally, determination of extreme storm surge values & significant wave heights should be based on the statistical analysis of surge & wave datasets. Since the measurements of surges & waves, which occur during the stormy conditions, are seldom available, the extreme value analysis is carried out using past storm data for estimating the design storm surge (Rise in water level) & significant wave heights. The Indian Meteorological Department (IMD) provides the records of the storms in the form of synoptic charts (pressure distribution) and storm tracks for the moving storms. Similarly, European Centre for Medium-Range Weather Forecasts (ECMWF) provides data on spatial & temporal varying wind, pressure field with resolution of 0.25° x 0.25°. These storm data are useful for the simulation of cyclonic storm conditions while hindcasting of the storms occurred in the past is useful for extreme value analysis (EVA). The Extreme value analysis is carried out for predicting the Rise in sea level (SS) values & significant wave heights with 1 in 25 yrs, 1 in 50 yrs and 1 in 100 yrs return periods (RP) for the Vadhavan area. In order to determine the extreme water level at boundary condition for local model, the predicted maximum rise in water level is to be superimposed over tide level determined by joint probability distribution between tide data and rise in water level (SS).

The hindcast data on rise in water level (SS) & waves, obtained by considering the storms passing in the vicinity of the Vadhavan area between the years 1970 and 2020 (50 years) have been utilized for the studies. Extreme value analysis of hindcast (SS) & wave data was carried out to determine the rise in water level & wave conditions for various return periods at Vadhavan. The mathematical model TOMAWAC (Telemac suite) is used to arrive at the wave conditions obtained by the hindcast studies while rise in water levels (surges) obtained by the hindcast studies using Telemac2D mathematical model for the Vadhavan area. The predicted values of significant wave height & rise in water level for various return period viz. 100-years, 50-years and 25 years are determined by fitting the hindcast wave & surge data in extreme value distribution functions, which are normally adopted for oceanographic data fitting.

The wave and rise in water level data for various return periods along with tide level determined by Joint probability method (for tide and rise in water level) for the area at Vadhavan were used to assess the impact of flooding on control area and Dahanu creek due to the development of proposed port at Vadhavan.

4. FIELD DATA FOR MODEL STUDIES

The field data viz. bathymetry, topography, oceanographic parameters such as tides, current, bed samples etc. was collected and provided by JN Port to simulate the prevailing tidal hydrodynamic flow conditions for both monsoon and non-monsoon seasons. The non-monsoon field data was collected in January-February 2017, while monsoon field data was collected in September-October 2020. The data on wave & wind field from INCOIS, intake &

outfall discharges of Dahanu Thermal Power Plant, Dahanu Creek Bridge details etc. were also provided by JN Port. The flood hydrographs for 25 years, 50 years & 100 years return period estimated by CWPRS (CWPRS TR. No. 5985 of January 2022) were also used for the studies. The field data submitted to CWPRS is as follows:

1. Bathymetry survey of proposed port site w.r.t. CD of Dahanu
2. Topography of Dahanu creek and nearby region within Control Area up to +10m contour w.r.t. MSL of Dahanu
3. Tide data collected at Dahanu Creek Bridge at the entrance of Dahanu creek for non-monsoon and monsoon seasons
4. Tidal current data at ADCP location inside the port for non-monsoon and monsoon seasons
5. Grain size analysis of bed samples collected for non-monsoon and monsoon seasons
6. Wave & Wind data at three locations viz. SW01, CB03 & Versova Buoy from INCOIS
7. Intake & Outfall discharges for Dahanu Thermal Power Plant
8. Dahanu creek Bridge Details
9. Villages in Control Area of Port at Vadhavan

The locations of oceanographic field data collected are shown in FIG. 3.

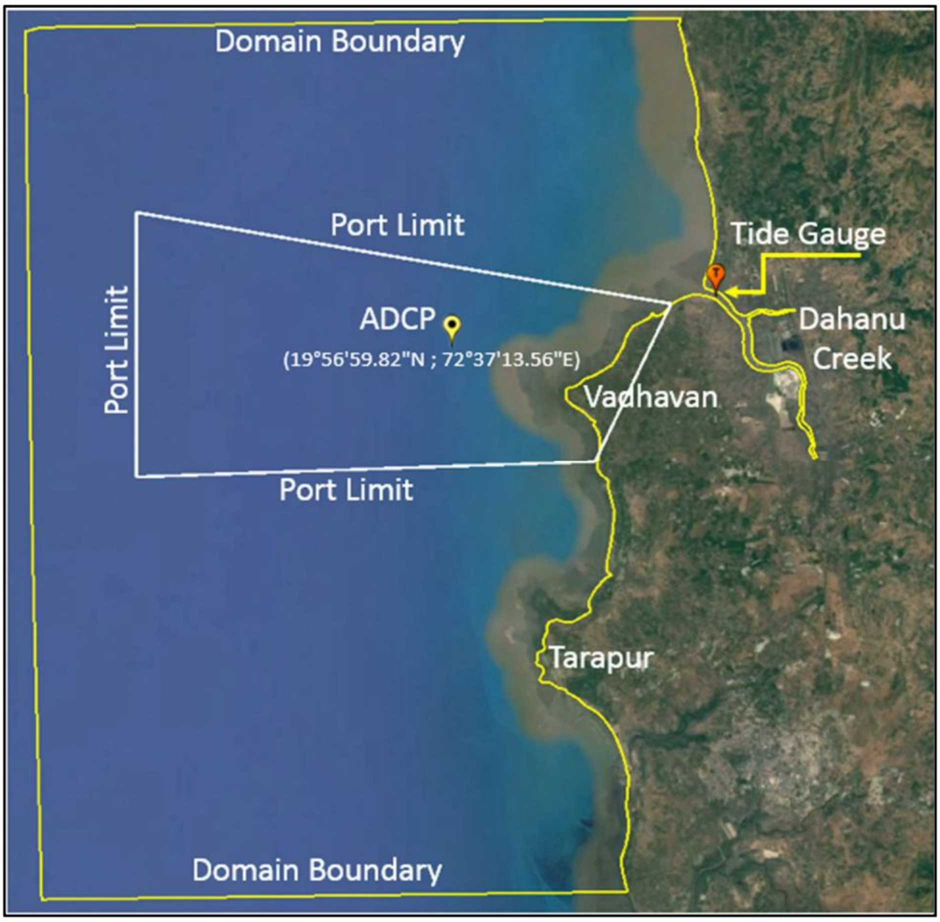


FIG.3: Locations of field data measurements for proposed port at Vadhavan

4.1 Bathymetry Data

The bathymetry data from GEBCO, Mike C-map (between Lat. 8° to 23° N and Long. 65° to 77° E) for the region of the Arabian sea (FIG.4) is used along with the hydrographic survey carried out by project Authorities during December 2016 to March 2017 for the proposed port area and the same is shown in FIG.5.

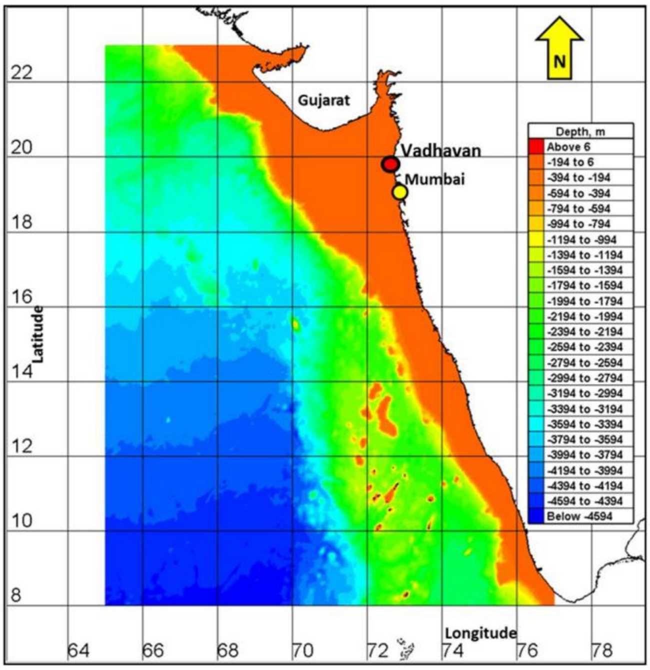


FIG.4: Bathymetry data from GEBCO & MIKE C-map

The above data indicate that the depths in the area under consideration vary between -4600 m and +6 m w.r.t MSL.

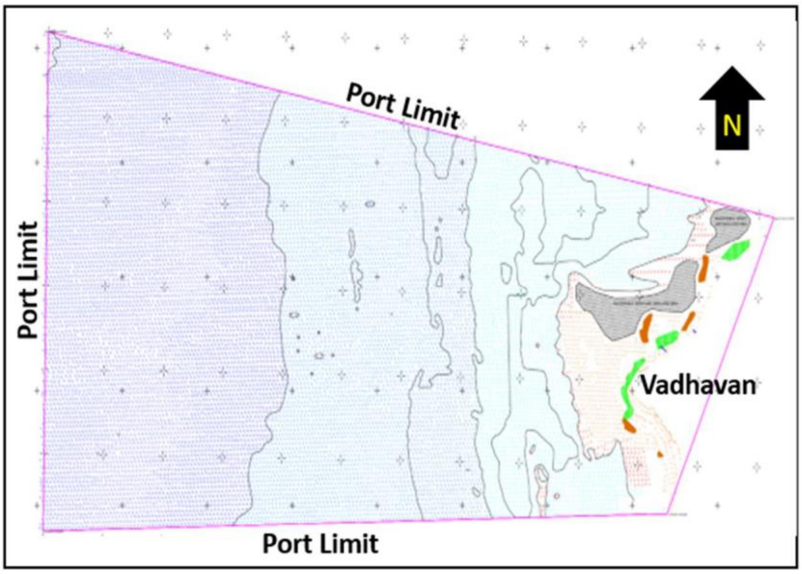


FIG.5: Bathymetry data for proposed port at Vadhavan

The depths within the port limit vary between -26 m and +2 m w.r.t. CD of Vadhavan area. The data shows some patches of rocky outcrops and areas of mangrove coverage near shoreline. The bathymetry in the areas like Dahanu creek, Vadhavan, Tarapur area was provided by JNP and part of this data is based on the hydrographic charts prepared by MMB in year 2003 for Tarapur site and Vadhavan headland area, while for Dahanu creek in year 2020.

4.2 Topography of Dahanu Creek and nearby region within Control Area

The topography survey of the Dahanu creek and nearby region within Control area from HTL up to +10 m contour has been carried out by Drone survey by JN Port (Report on Topography Survey by Drone in Vadhavan Area (March 2021) by VEFES Engineering Pvt. Ltd. & the latest data received vide JNPA e-mail dated 19/03/2023 & its report in August 2023). This data is used to reproduce the topographical details of Control area (10 km radius from headland at Vadhavan). The area over which topographic survey carried out is shown in FIG. 6 as blue portion. The data provided is w.r.t. MSL and is correlated to CD based on the relation between MSL and CD provided by JN Port.

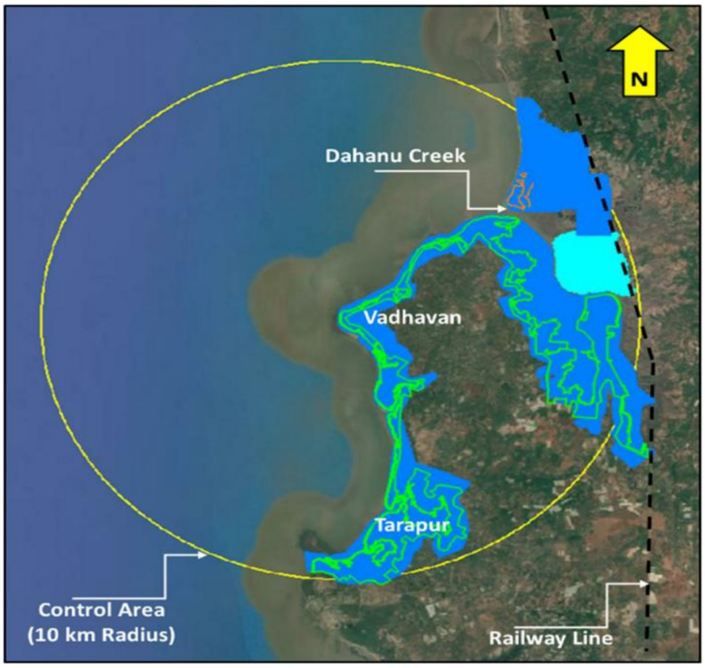


FIG.6: Topography data in control area for proposed port at Vadhavan

4.3 Tide Data

The TPXO Regional Tidal Solution is used to impose boundary conditions for model. The TPXO models include complex amplitudes of MSL-relative sea-surface elevations and transports/currents for eight primary (M2, S2, N2, K2, K1, O1, P1, Q1), two long periods (Mf, Mm) and 3 non-linear (M4, MS4, MN4) harmonic constituents.

Similarly, the tidal data was collected at 3rd pier of Bridge on Dahanu Creek for the duration of one month from 10/01/2017 to 10/02/2017 for non-monsoon season while for monsoon season it was collected from 11/10/2020 to 27/10/2020. The data was correlated with CD of Vadhavan area and the CD was correlated w.r.t. Benchmark established on the

Light House at Dahanu. The plots of tide data collected for non-monsoon & monsoon seasons are shown in FIG. 7(A) & 7(B).

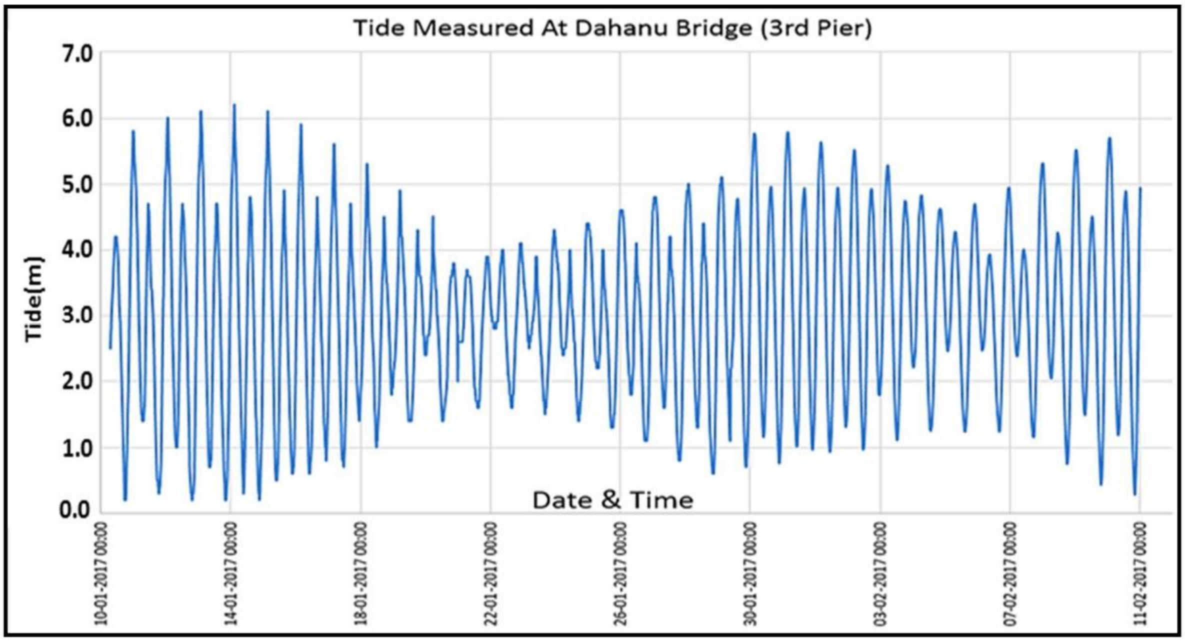


FIG.7(A) : Measured tide data at Dahanu Bridge location (Non-monsoon Season)

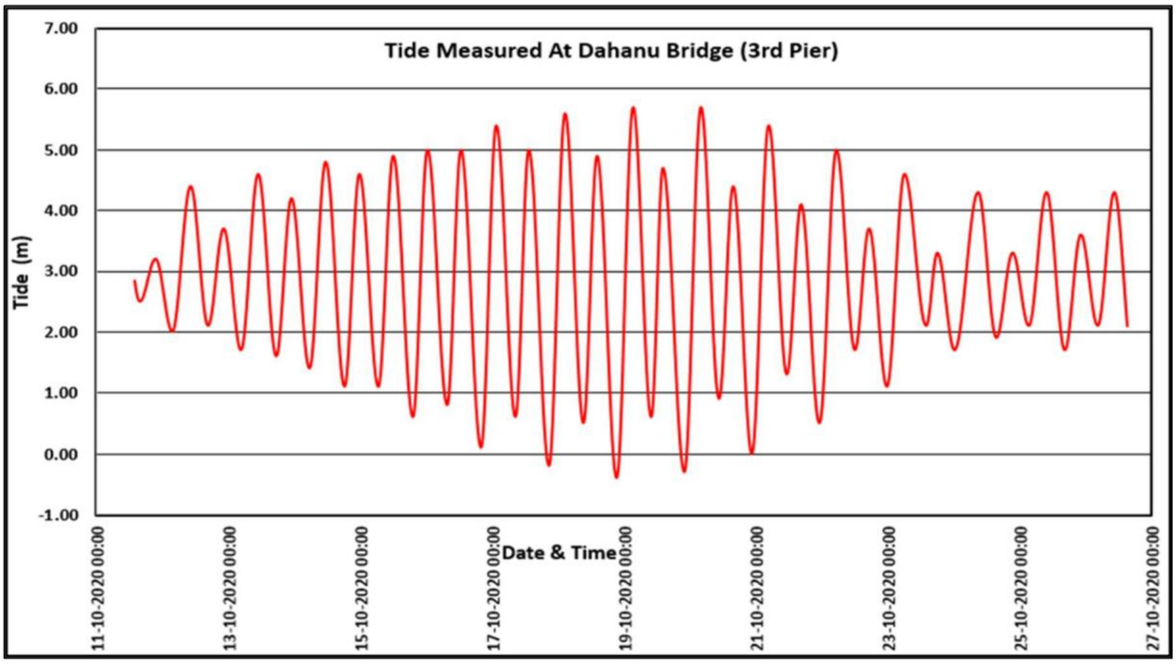
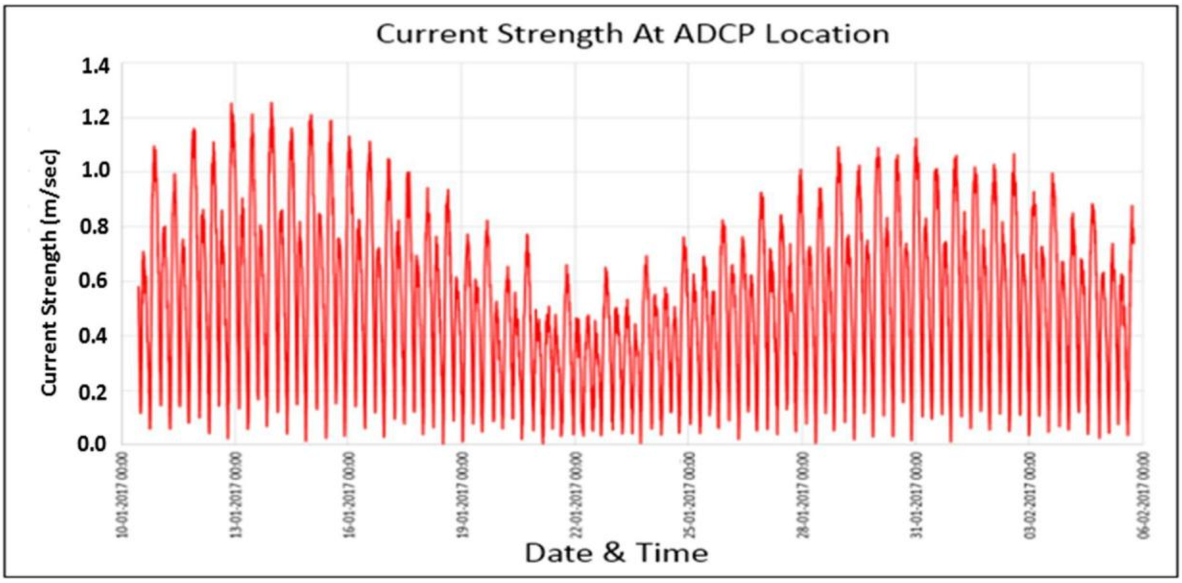


FIG.7(B) : Measured tide data at Dahanu Bridge location (Monsoon Season)

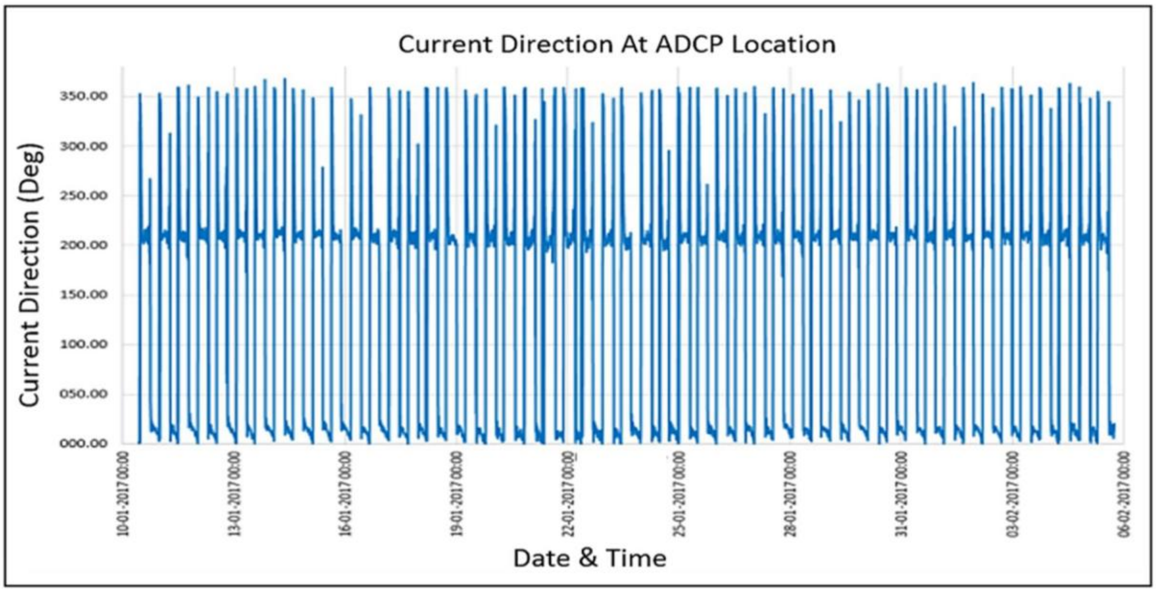
The analysis of measured tidal data was carried out and it reveal that the tides are semi-diurnal in nature with diurnal inequality for both non-monsoon and monsoon seasons. During non-monsoon season, the maximum tidal variation is about 5.87 m, while minimum tidal variation is about 2.10 m. Similarly, during monsoon season, the maximum tidal variation is about 6.0 m, while minimum tidal variation is about 1.14 m.

4.4 Current Data

The ADCP was deployed at Lat.19°56’59.82” N, Long. 72°37’13.56” E for the measurement of current (strength & direction) in the port limit both for non-monsoon and monsoon seasons. The plots of measured current data (strength & direction) at mid depth for non-monsoon and monsoon seasons are shown in FIG. 8 and FIG.9 respectively.



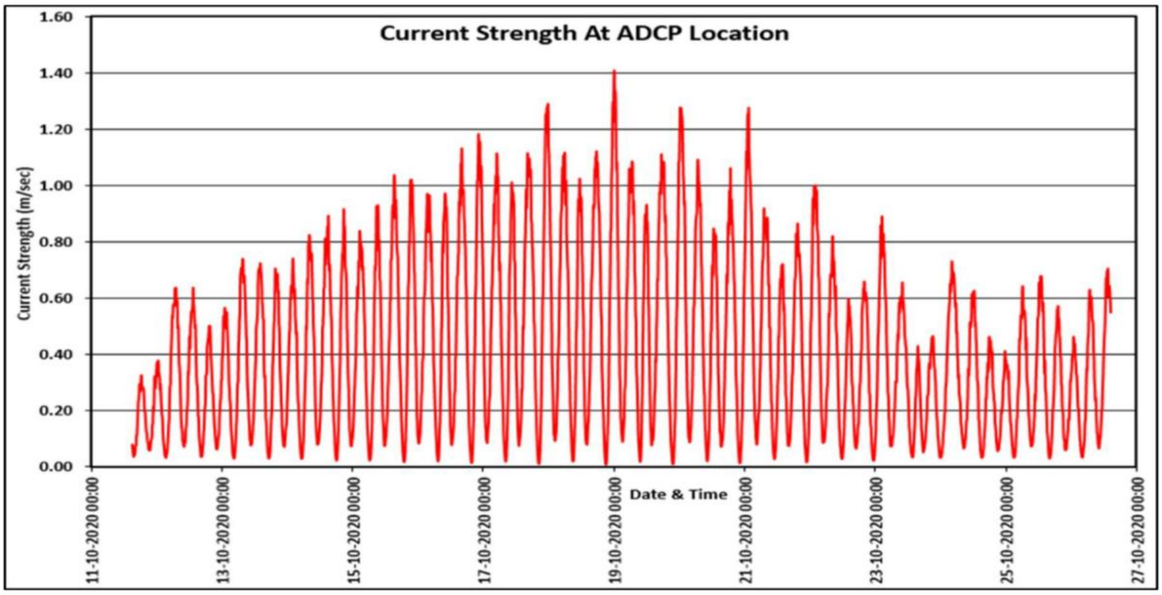
(A) Current strength at Mid depth



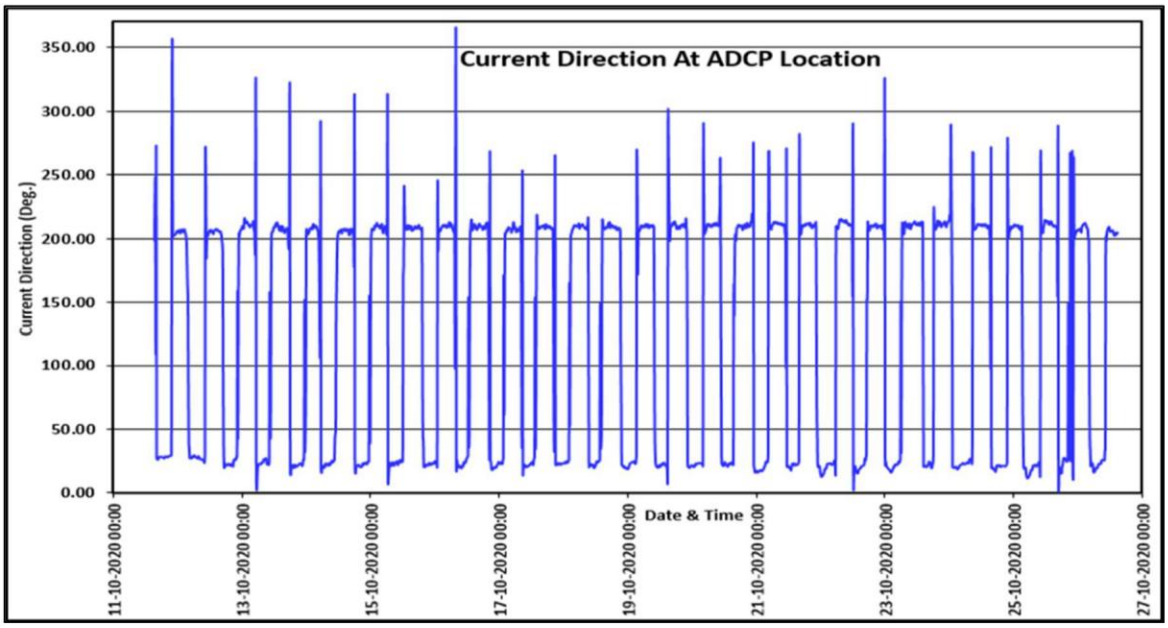
(B) Current Direction at Mid depth

FIG.8 : Measured current at ADCP location (Non-monsoon Season)

The analysis of current data for Non-monsoon season reveals that maximum current strength observed is 1.25 m/s during spring tide, while it is 0.50 m/s during neap tide. The current direction w.r.t. north varies between 3° and 23° during flood tide, while it is between 204° and 215° during ebb tide.



(A) Current strength at Mid depth



(B) Current Direction at Mid depth

FIG.9 : Measured current at ADCP location (Monsoon Season)

The analysis of current data for monsoon reveals that maximum current strength observed is 1.40 m/s during spring tide, while it is 0.40 m/s during neap tide. The current direction w.r.t. north varies between 16° and 23° during flood tide, while it is between 203° and 210° during ebb tide.

4.5 Grain Size Analysis of Bed Samples

The bed samples were collected at eight (8) locations in the vicinity of proposed port area during non-monsoon season and its grain size analysis carried out is presented in Table-I.

Table-I

Grain size analysis of bed samples (Non-monsoon)

Sr. No.	Description	Location		Sample retained on 75 Micron %	% Fines		D_{50}
		Easting	Northing		Silt %	Clay %	
1	Dandepada (A1)	252850.51 m E	2202778.18 m N	7.98	59.66	32.36	0.0100
2	Dandepada (A2)	252615.50 m E	2202745.80 m N	8.65	57.53	33.82	0.0115
3	Dandepada (A3)	252473.37 m E	2202714.44 m N	7.22	53.15	39.63	0.0050
4	Dandepada (A4)	252389.46 m E	2202644.83 m N	10.69	59.15	29.80	0.0076
5	Chinchani (B1)	254175.56 m E	2200735.42 m N	10.41	59.64	29.95	0.0150
6	Chinchani (B2)	252921.99 m E	2201004.30 m N	10.02	60.78	29.20	0.0114
7	Chinchani (B3)	252698.02 m E	2200930.75 m N	9.87	59.38	30.75	0.0113
8	Chinchani (B4)	252496.19 m E	2200560.39 m N	12.02	58.53	29.45	0.0138

The grain size analysis reveal that the bed material is clayey silt with D_{50} varies between 0.005 mm and 0.015 mm. A typical grain size analysis curve plotted to determine D_{50} of bed material is shown in FIG.10.

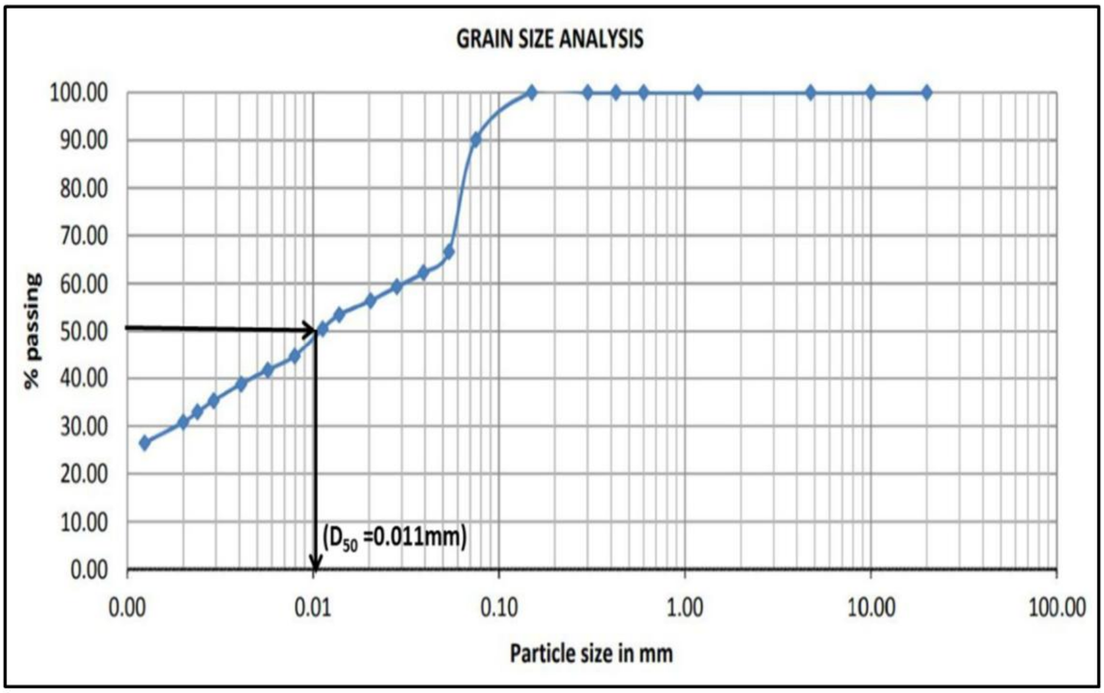


FIG.10: Typical plot of sieve analysis indicating D_{50} size of bed sample (Non-monsoon)

Similarly, bed samples were collected at nine (9) locations in the vicinity of proposed port area as well as in Dahanu creek area during monsoon season. The locations and its grain size analysis carried out is presented in Table. II.

Table-II
Grain size analysis of bed samples (Monsoon)

Sr. No.	Description	Location		Sample retained on 75 Micron %	% Fines		D_{50}
		Easting	Northhing		Silt %	Clay %	
1	Sea Bed Sample 1	260058.67 m E	2210556.01 m N	31.86	39.07	29.08	0.0193
2	Sea Bed Sample 2	260506.45 m E	2210118.04 m N	31.71	38.18	30.11	0.0250
3	Sea Bed Sample 3	260886.37 m E	2209899.71 m N	11.76	49.05	39.19	0.0050
4	Sea Bed Sample 4	261362.28 m E	2209702.34 m N	14.46	46.04	39.50	0.0060
5	Sea Bed Sample 5	261785.79 m E	2209410.27 m N	9.25	48.93	41.83	0.0043
6	Sea Bed Sample 6	262231.29 m E	2209010.97 m N	20.62	45.78	33.61	0.0107
7	Sea Bed Sample 7	262605.67 m E	2208663.69 m N	14.53	47.01	38.46	0.0065
8	Sea Bed Sample 8	262714.88 m E	2208258.59 m N	5.57	54.05	40.38	0.0050
9	Sea Bed Sample 9	262756.84 m E	2207799.91 m N	24.29	45.17	30.54	0.0150

The grain size analysis reveal that the bed material is also clayey silt with D_{50} varies between 0.005 mm and 0.0250 mm. The bed samples collected during monsoon as well as non-monsoon seasons indicate that the bed material is clayey silt. The information of bed material is of significance to decide the bed friction in the model domain.

The data on sea water temperature, density and salinity were also measured at site and the average sea water temperature is 23.5°C, average sea water density is 1024 kg/cum and average salinity is 35.5 PSU.

4.6 Wave Data

The wave data (height, direction & period) from Indian National Centre for Ocean Information Services (INCOIS) was obtained and is made available by JN Port at three locations viz. SW01(Lat. 20.89°N; Long. 71.5°E) for period of 15th -26th May 2001; at CB03 (Lat. 20.27802°N; Long. 71.87767°E) for the period 1st -15th June 2012 and Versova wave rider buoy (Lat. 19.11°N; Long. 71.74°E) for the period 01st – 10th December 2017. The above locations are shown in FIG.11.

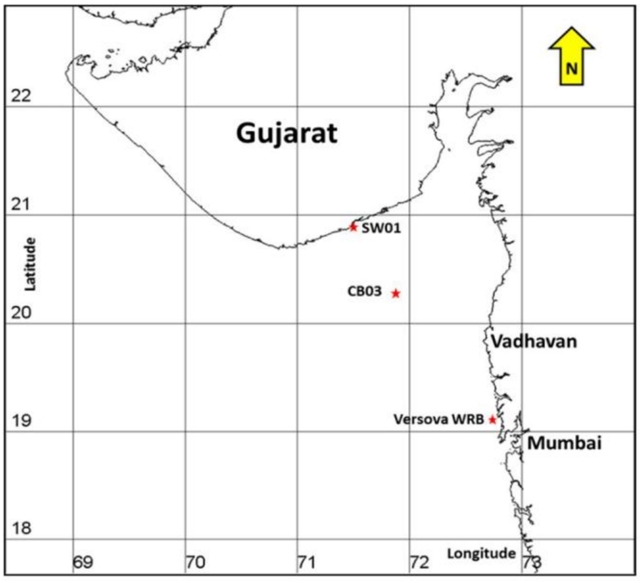


FIG.11 : Location plan for wave & wind data

The plot of significant wave height (Hs) & mean wave direction for SW01 location is shown in FIG.12.

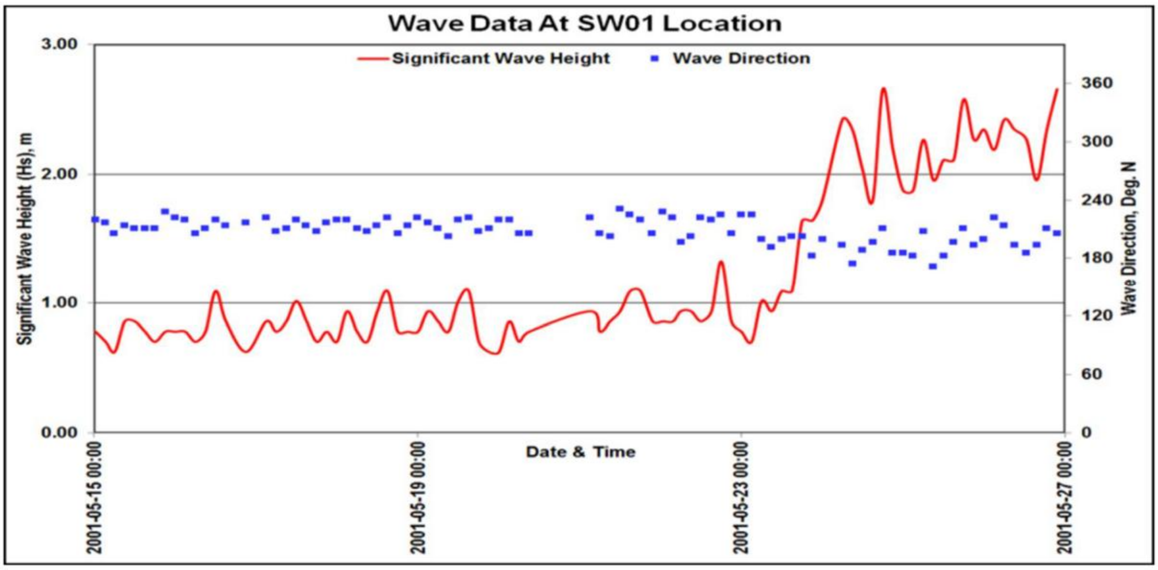


FIG.12 : Significant wave height (Hs) at SW01 location

The data at SW01 location available with INCOIS is for the period during which the cyclonic storm (Extremely Severe Cyclonic Storm) passed the coast of Gujarat and occurred in Arabian sea from 21st to 29th May 2001.The highest significant wave height observed at SW01 location in the data is 2.65 m.

Similarly, the plot of significant wave height (Hs) & mean wave direction for CB03 location is shown in FIG.13.

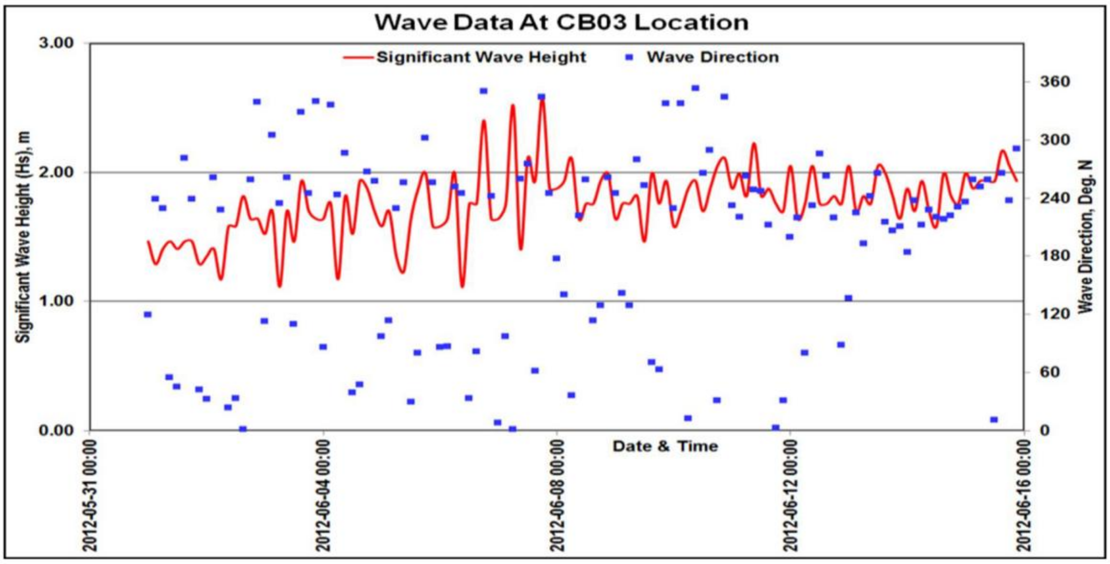


FIG.13 : Significant wave height (Hs) at CB03 location

The above data at CB03 location available with INCOIS is for the calm period and the average significant wave height observed at the said location in the data is 1.76 m.

The data at Versova wave rider buoy location available with INCOIS is for the period during which the cyclonic storm Ockhi (Very Severe Cyclonic Storm) occurred in Arabian sea from 2nd to 6th December 2017. The highest significant wave height observed at the said location in the data is 2.61 m. The plot of significant wave height (Hs) & mean wave direction for Versova Buoy location is shown in FIG.14.

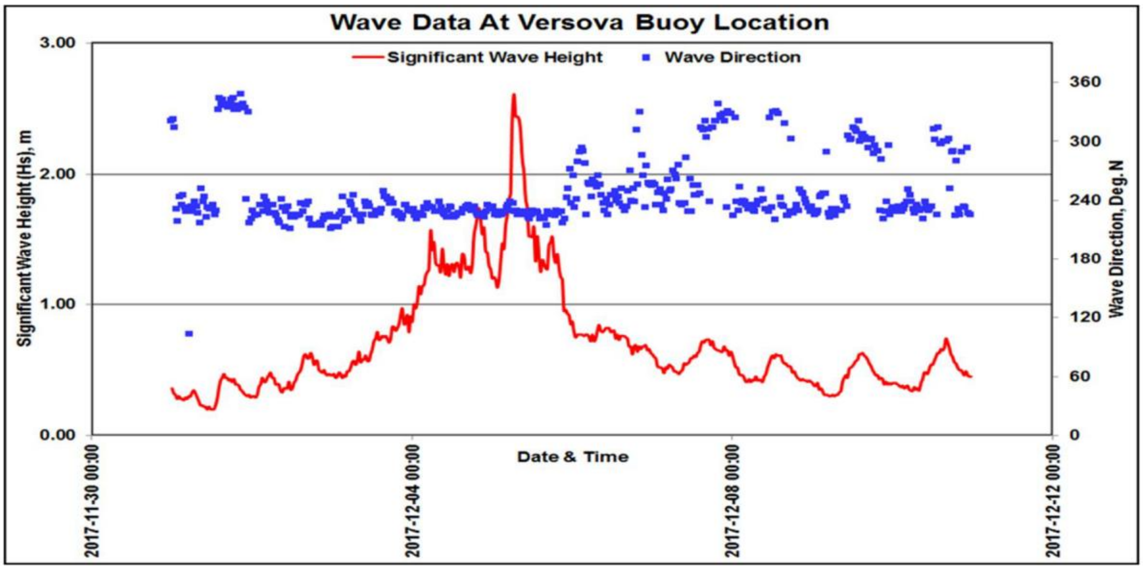


FIG.14: Significant wave height (Hs) at Versova location

4.7 Wind Data

The wind data (speed & direction) was obtained from Indian National Centre for Ocean Information Services (INCOIS) and made available by JN Port at two locations viz. SW01 (Lat. 20.89°N; Long. 71.5°E) for period of 15th -26th May 2001 and at CB03 (Lat. 20.27802°N; Long. 71.87767°E) for the period 1st -15th June 2012. The above locations are shown in FIG.11.

The plot of wind speed & direction at SW01 location is shown in FIG.15.

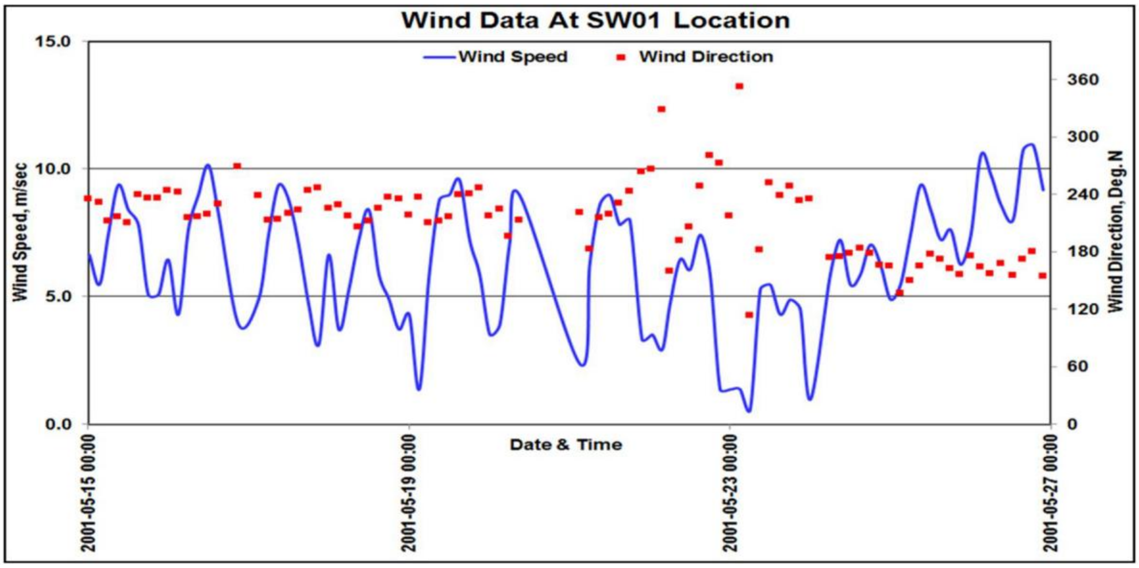


FIG.15 : Wind data at SW01 location

The wind speeds during this period varies from 0.6 m/s to 11.0 m/s with the majority of wind blows from 200°- 250° N.

Similarly, the plot of wind speed & direction at CB03 for the period 01/06/2012 to 15/06/2012 is shown in FIG.16.

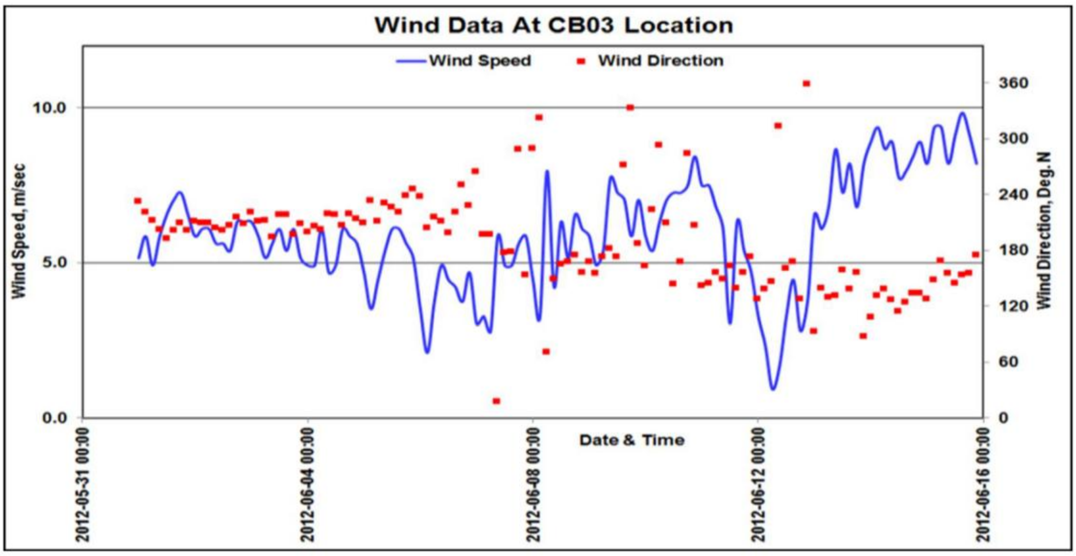


FIG.16 : Wind data at CB03 location

The wind speeds during this period varies from 0.94 m/s to 9.85 m/s with the wind direction varies from 100°- 340° N.

4.8 Cyclonic Storm Data:

The port at Vadhavan is proposed to be developed on the West coast of India near headland at Vadhavan facing the Arabian sea. The cyclonic storms generated in North Indian Ocean and passing through the area in the close vicinity of Vadhavan will have impact on the proposed port as well as on the coastline at Vadhavan. The storms are classified by Indian Meteorological Department (IMD) based on atmospheric pressure difference and maximum sustained wind speed and its nomenclature is given in the Table-III.

Table-III
Nomenclature for cyclonic storms (Source: IMD)

System	Pressure Deficient (hPa)	Associated Wind Speed In knots (kmph)
Low Pressure Area	1.0	< 17 (<31)
Depression	1.0 – 3.0	17 to 27 (31-49)
Deep Depression	3.0 – 4.5	28 to 33 (50-61)
Cyclonic Storm	4.5 – 10.0	34 to 47 (62-88)
Severe Cyclonic Storm	10.0 – 15.0	48 to 63 (89-117)
Very Severe Cyclonic Storm	15.0 – 29.4	64 to 90 (118-167)
Extremely Severe Cyclonic Storm	29.4 – 65.6	91 to119 (168-221)
Super Cyclonic Storm	> 65.6	120 and above (>222)

The cyclonic storm data for the past 50 years (1970-2020) is considered for the studies under reference. There were 125 storm events occurred during the above period in the Arabian Sea. The storms which were passing through the area in the close vicinity of

Vadhavan or which are of significance for Vadhavan coast were identified and 44 storms were considered for the studies. The list of cyclonic storms relevant to Vadhavan is given in Table-IV.

Table-IV

List of cyclonic storms relevant to Vadhavan to be considered for the studies (1970 – 2020)

Sr. No.	Date & Year of Storm	Type of Storm
1	29 – 31 May 1970	Severe Cyclonic Storm
2	20 – 24 September 1974	Deep Depression
3	01 – 11 May 1975	Extremely Severe Cyclonic
4	30 – 31 May 1975	Deep Depression
5	24 – 25 June 1975	Deep Depression
6	20 – 22 October 1975	Very Severe Cyclonic Storm
7	30 May – 05 June 1976	Extremely Severe Cyclonic
8	09 – 11 June 1977	Severe Cyclonic Storm
9	25 – 29 November 1978	Super Cyclonic Storm
10	18 – 22 September 1979	Severe Cyclonic Storm
11	04 – 06 June 1980	Depression
12	29 October – 02 November 1981	Very Severe Cyclonic Storm
13	05 – 09 November 1982	Extremely Severe Cyclonic
14	28 – 30 May 1985	Cyclonic Storm
15	06 – 09 October 1985	Depression
16	09 – 12 June 1989	Deep Depression
17	12 – 15 November 1993	Very Severe Cyclonic Storm
18	05 – 08 June 1994	Severe Cyclonic Storm
19	12 – 16 October 1995	Cyclonic Storm
20	17 – 20 June 1996	Severe Cyclonic Storm
21	22 – 27 October 1996	Severe Cyclonic Storm
22	04 – 09 June 1998	Extremely Severe Cyclonic
23	16 – 17 October 1998	Cyclonic Storm
24	16 – 21 May 1999	Extremely Severe Cyclonic
25	21 – 29 May 2001	Extremely Severe Cyclonic
26	05 – 10 May 2004	Severe Cyclonic Storm
27	30 September – 03 October 2004	Severe Cyclonic Storm
28	14 – 16 September 2005	Depression
29	21 – 23 September 2006	Severe Cyclonic Storm
30	01 – 04 June 2007	Super Cyclonic Storm
31	23 – 25 June 2009	Depression
32	09 – 11 November 2009	Cyclonic Storm
33	11 – 12 June 2011	Depression
34	27 – 30 November 2011	Deep Depression

35	10 – 12 June 2014	Cyclonic Storm
36	25 – 30 October 2014	Extremely Severe Cyclonic
37	07 – 09 June 2015	Cyclonic Storm
38	22 – 24 June 2015	Deep Depression
39	02 – 06 December 2017	Very Severe Cyclonic Storm
40	10 – 17 June 2019	Very Severe Cyclonic Storm
41	22 – 23 September 2019	Very Severe Cyclonic Storm
42	24 – 28 October 2019	Super Cyclonic Storm
43	01 – 07 November 2019	Extremely Severe Cyclonic
44	01 – 04 June 2020	Severe Cyclonic Storm

The breakup of these 44 storms based on their intensity (IMD classification) is given in Table-V.

Table-V
Classification of cyclonic storms based on intensity

Depression	5
Deep Depression	6
Cyclonic storms	6
Severe Cyclonic Storms	10
Very Severe Cyclonic Storms	6
Extremely Severe Cyclonic Storms	8
Super Cyclone	3

Similarly, monthly and year-wise distribution of the storm events is shown in FIG.17 and FIG.18 respectively.

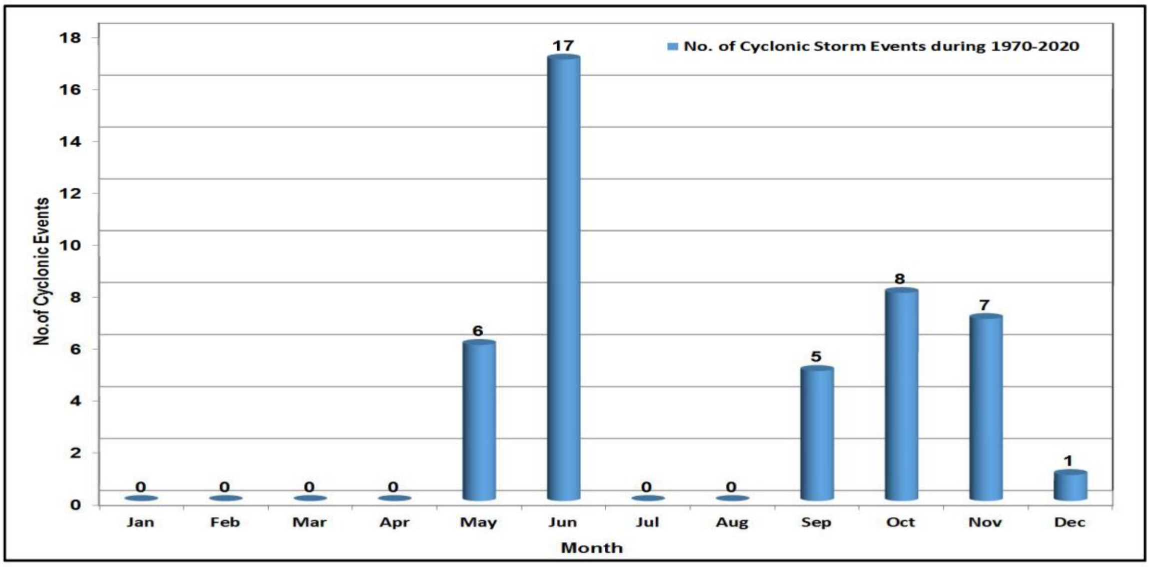


FIG.17: Monthly distribution of storm events

It is observed from above plot that all storms which are of significance for Vadhavan area have occurred in the months of May & June and September to November.

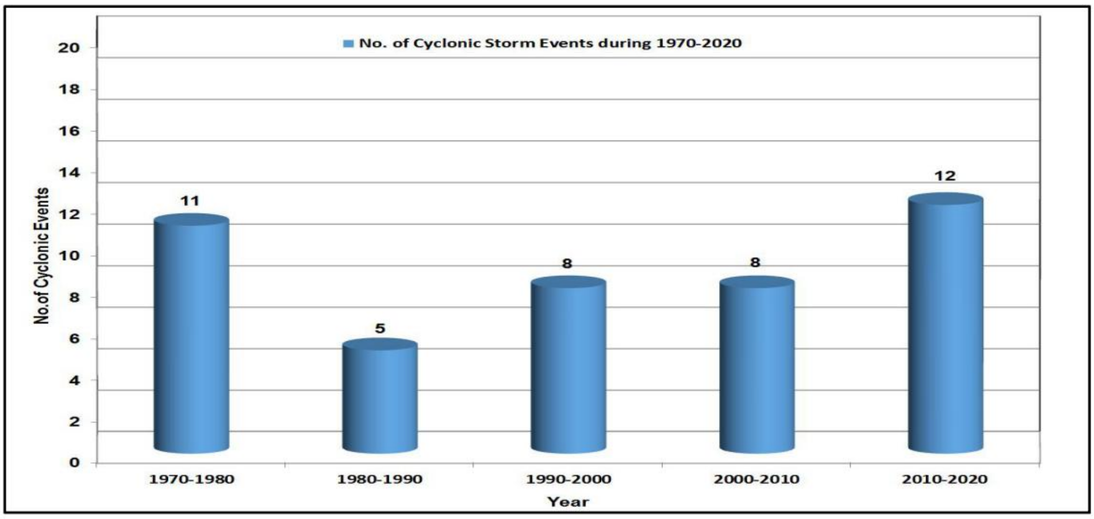


FIG.18: Year-wise distribution of storm events

It is observed from above plot that there were about 8 cyclonic events on an average in every decade since 1970.

The information on storm track (IMD data), central pressure as well as maximum sustained wind speed etc. for the cyclonic storms available for year 1982-2020 is used for the studies along with Joint Typhoon Warning Centre (JTWC) best track information for the remaining period from 1970-1981. The storm tracks of the storms considered for the studies are shown in Fig. 19(A) to 19(E).

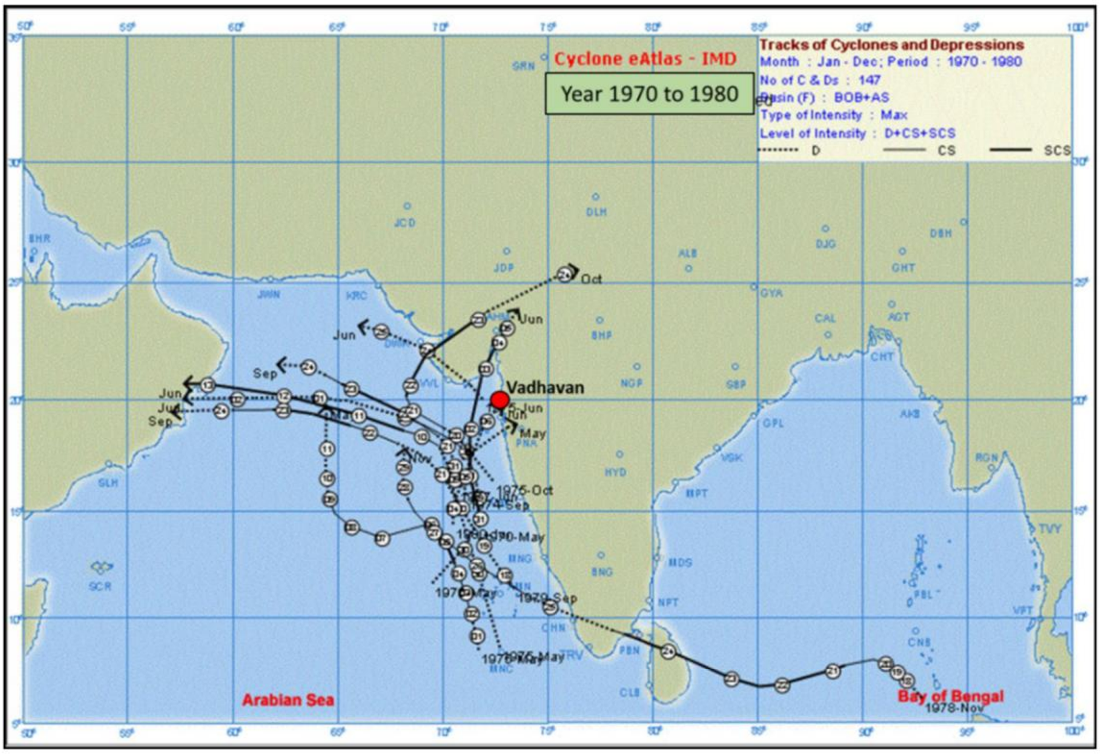


FIG.19(A): Storm tracks of cyclonic storms during 1970-1980

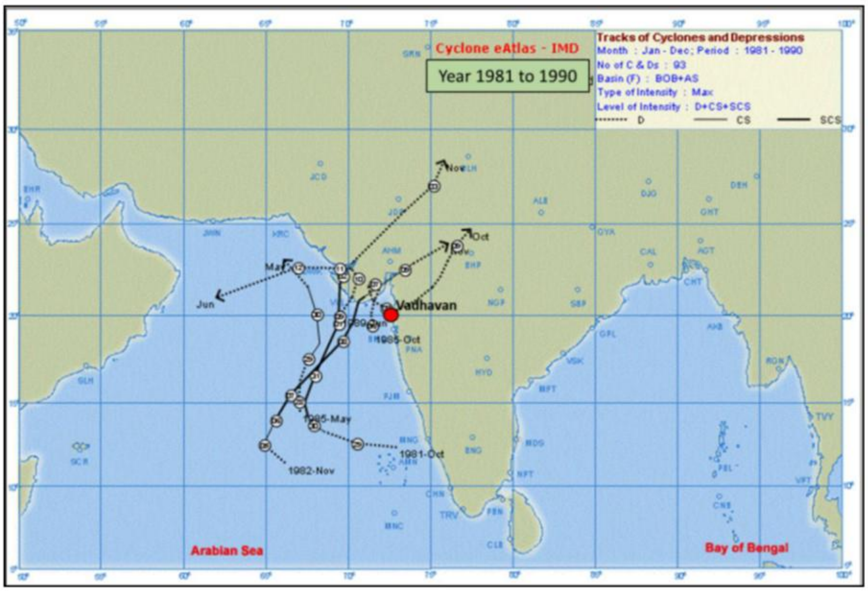


FIG.19(B): Storm tracks of cyclonic storms during 1981-1990

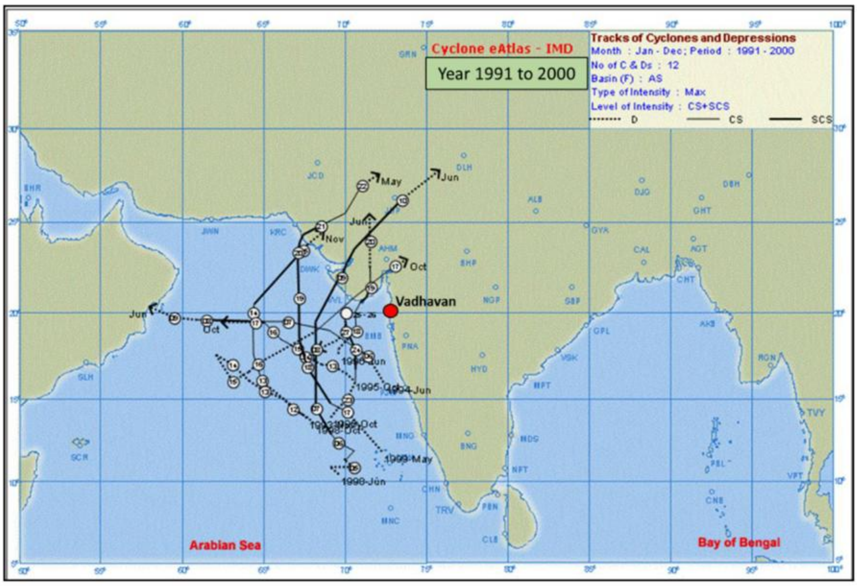


FIG.19(C): Storm tracks of cyclonic storms during 1991-2000

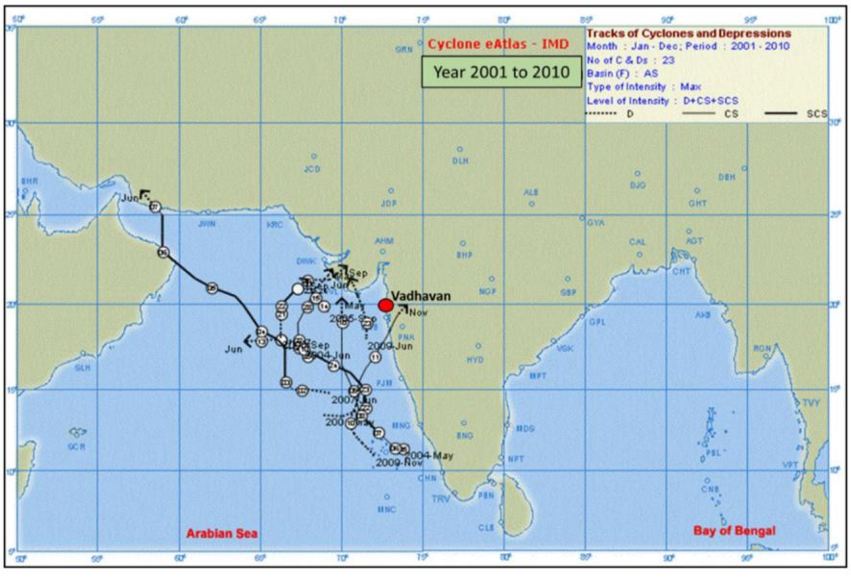


FIG.19(D): Storm tracks of cyclonic storms during 2001-2010

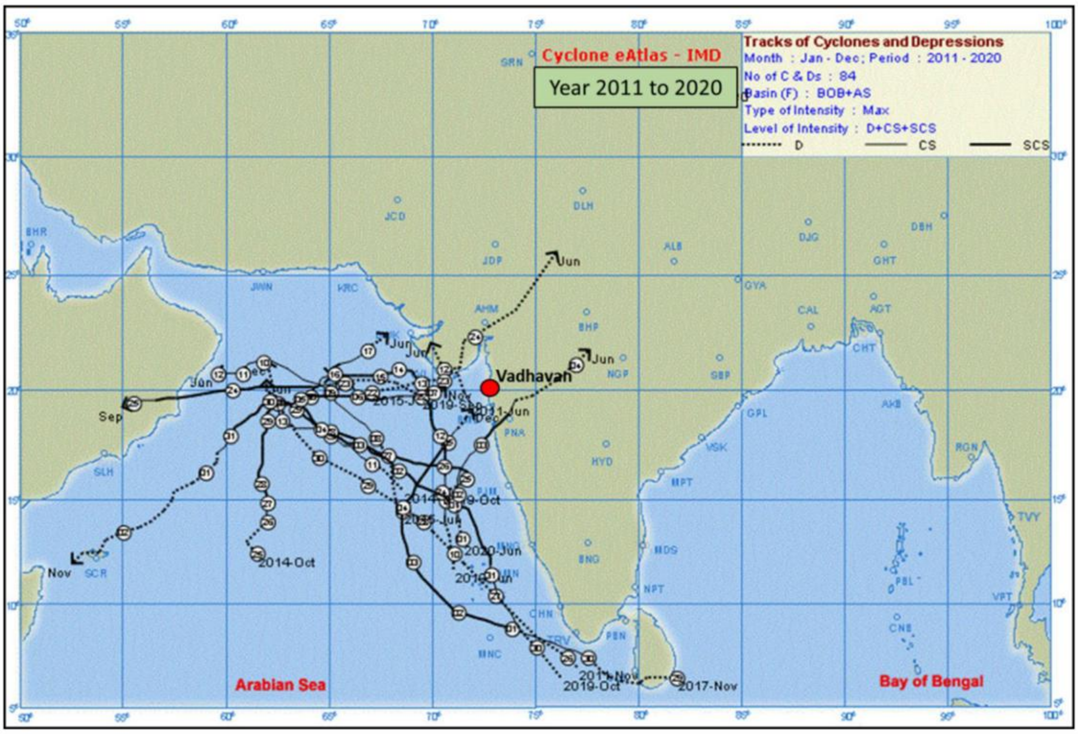


FIG.19(E): Storm tracks of cyclonic storms during 2011-2020

A typical synoptic chart for November 1982 cyclone, June 2019 – Vayu and June 2020 – Nisarga cyclones (IMD Data) are shown in Fig. 20(A) to 20(C).

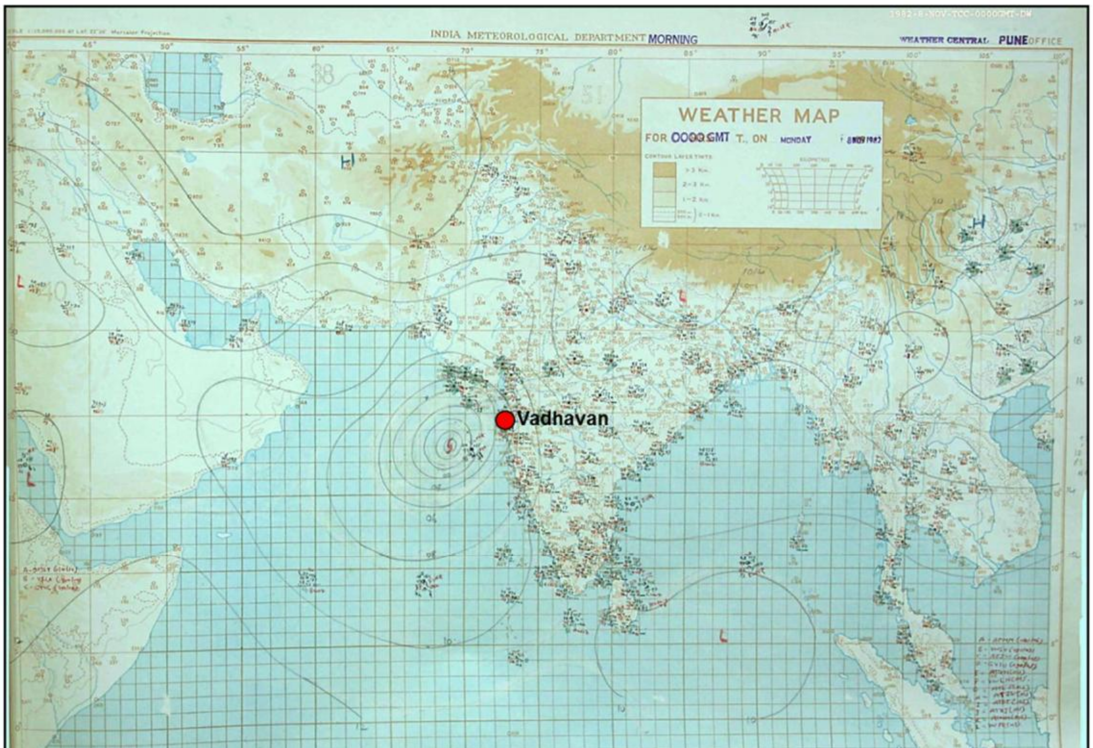


FIG.20(A): Synoptic chart for November 1982 Cyclone

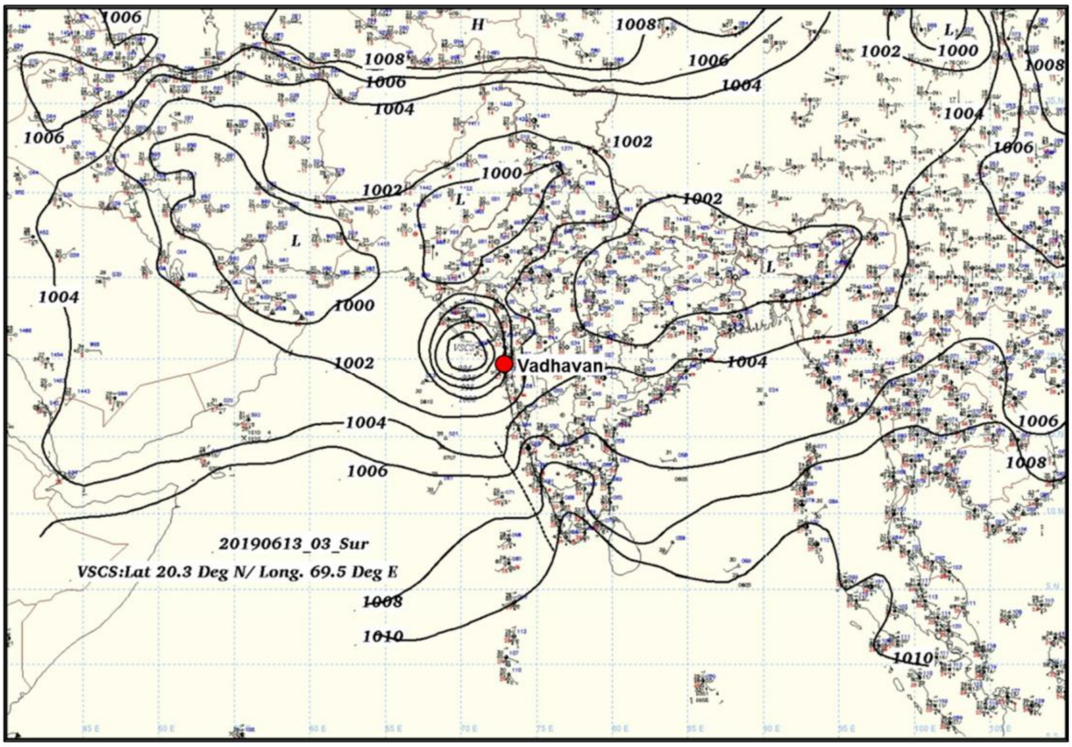


FIG.20(B): Synoptic chart for June 2019 – Vayu Cyclone

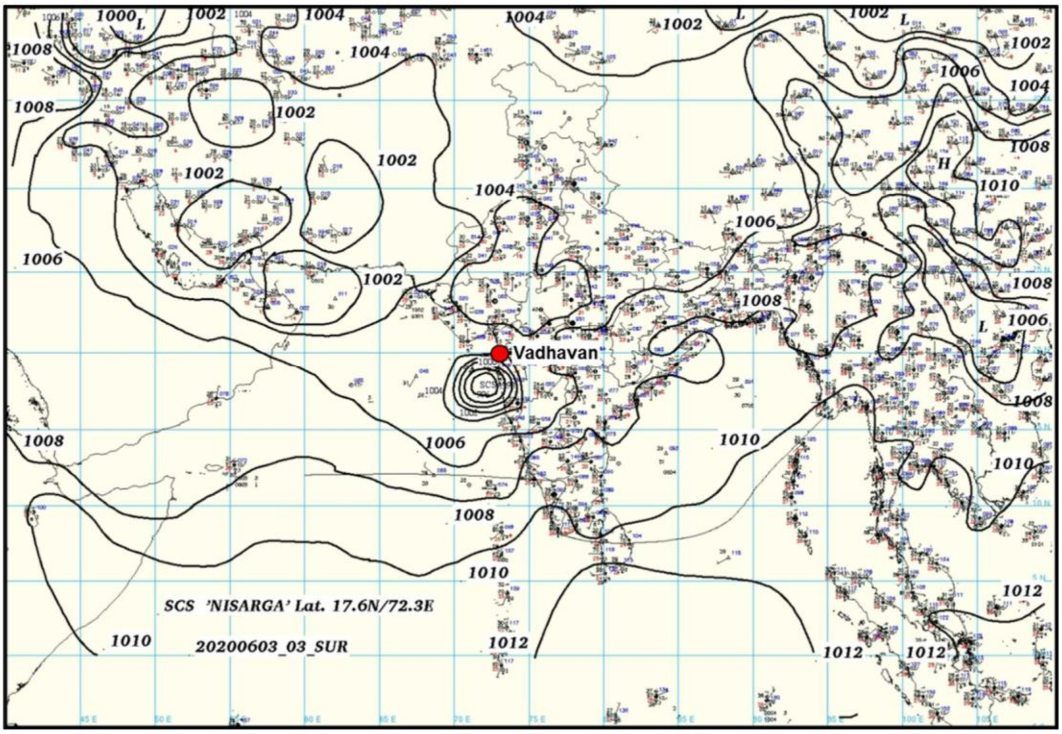


FIG.20(C): Synoptic chart for June 2020 – Nisarga Cyclone

The temporally & spatially varying data on wind and barometric pressure obtained from latest global atmospheric reanalysis of ECMWF in association with data on central pressure and wind information from IMD is used to carry out the simulation of cyclonic storms. The data on wind and barometric pressure is provided as one hourly spatially distribution. The spatial resolution of the data is 0.25º x 0.25º latitude/longitude (approximately 28 km x 28 km).

4.9 Flood Hydrographs:

The cyclonic storms are generally associated with high winds and heavy downpour in the peripheral coastal areas of storm. The storm surges developed due to storms, high river flows due to heavy downpour and tides can act either alone or in combination to produce high water levels during storm which creates a risk of flooding in low lying areas in the creek/estuaries. The accurate flood hydrograph estimation will be helpful to assess the impact of cyclonic storms on the important structures/ control areas in coastal region. The studies were carried to estimate flood hydrographs for 25 years, 50 years & 100 years return period by considering two scenarios viz. (i) Flooding due to cyclonic storms + rainfall (occurred during such stormy conditions only) and (ii) Flooding due to cyclonic storms + rainfall (considering past 50 years of rainfall data). These studies were carried out by HMET Division of CWPRS (CWPRS TR. No. 5985 of January 2022). The flood hydrographs were derived at six (6) locations (A-F) shown in FIG.21 for above two scenarios.

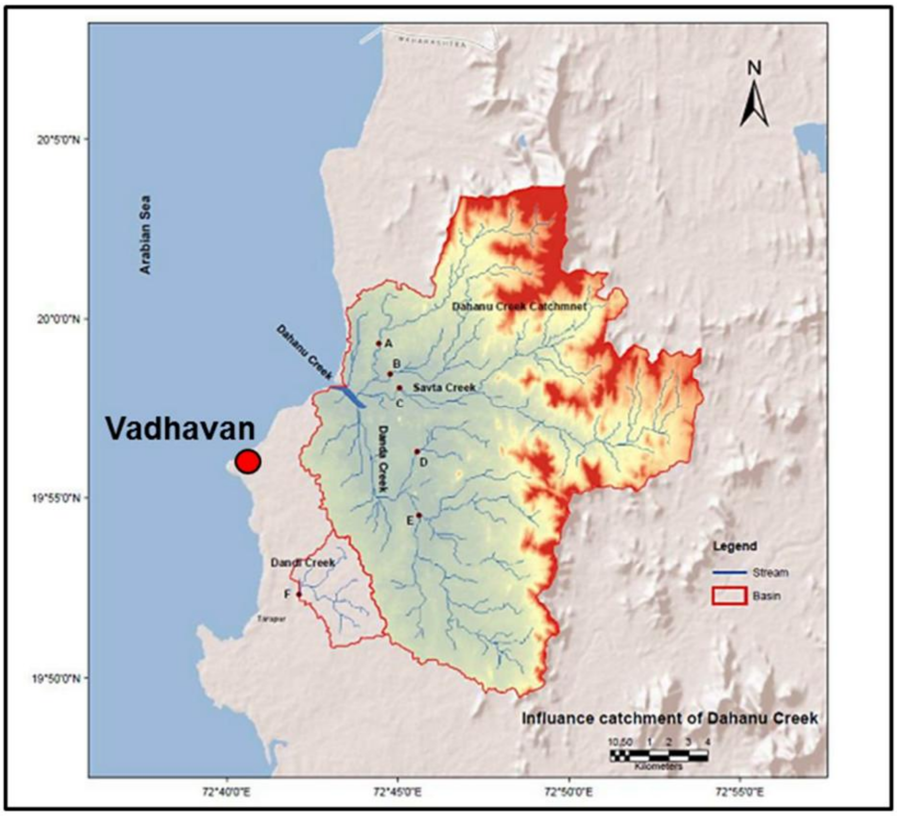
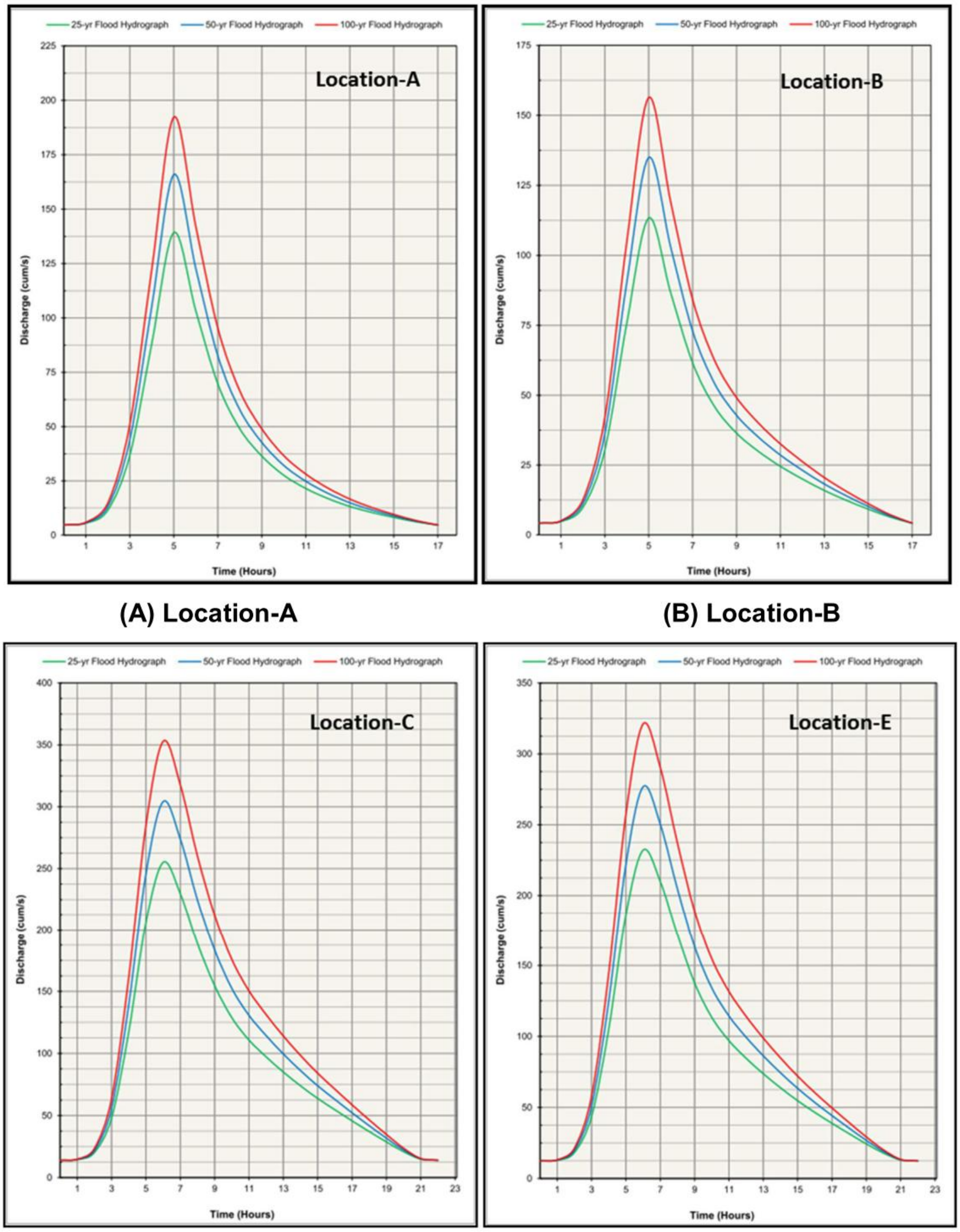


FIG.21: Locations of flood hydrographs

The flood hydrographs derived for locations A, B, C & E for Scenario-1 i.e. Flooding due to cyclonic storms + rainfall (occurred during such stormy conditions only) for respective return periods of 1 in 25, 1 in 50 and 1 in 100 years are shown in FIG.22. The peak flood discharges for return period of 25 years, 50 years & 100 years for location D are 66.12 m^3/s,78.33 m^3/s & 90.44 m^3/s respectively while for location F are 86.54 m^3/s,102.52 m^3/s & 118.38 m^3/s respectively.

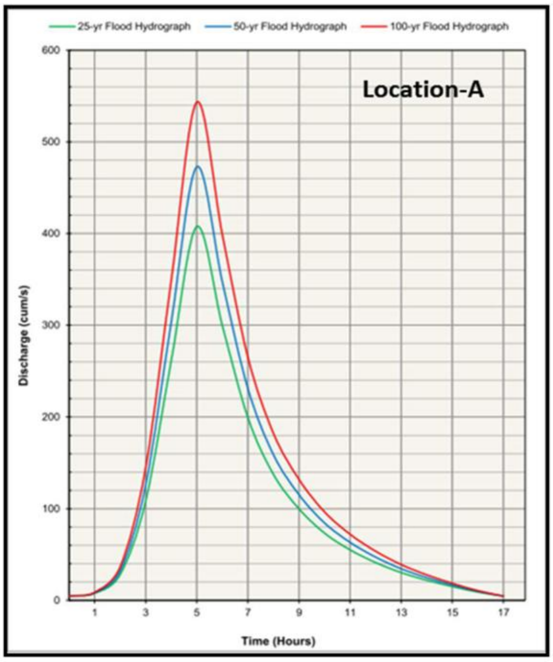


(A) Location-A **(B) Location-B**

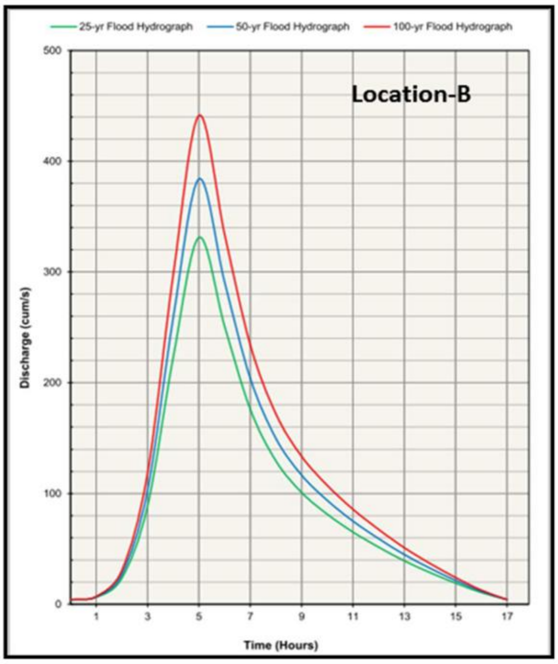
(C) Location-C **(D) Location-E**

FIG.22: Flood hydrographs for Scenario-1

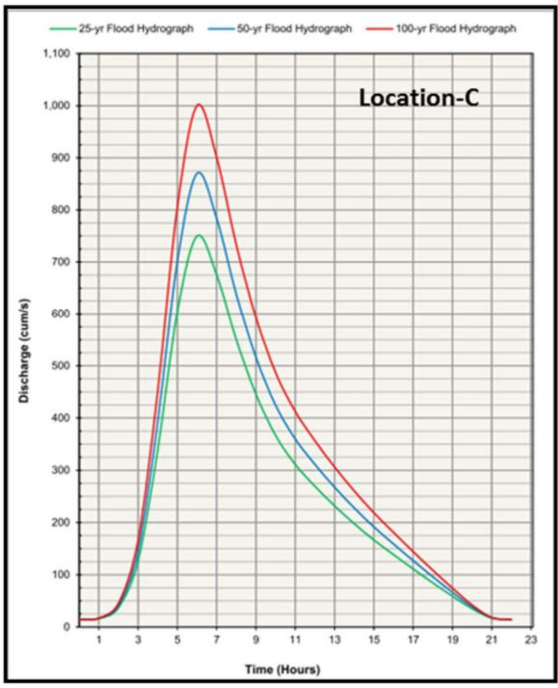
The flood hydrographs derived for locations A, B, C & E for Scenario-2 i.e. Flooding due to cyclonic storms + rainfall (considering past 50 years of rainfall data) for respective return periods of 1 in 25, 1 in 50 and 1 in 100 years are shown in FIG.23. The peak flood discharges for return period of 25 years, 50 years & 100 years for location D are 189.21 m^3/s, 219.13 m^3/s & 251.53 m^3/s respectively while for location F are 247.64 m^3/s, 286.81 m^3/s & 329.22 m^3/s respectively.



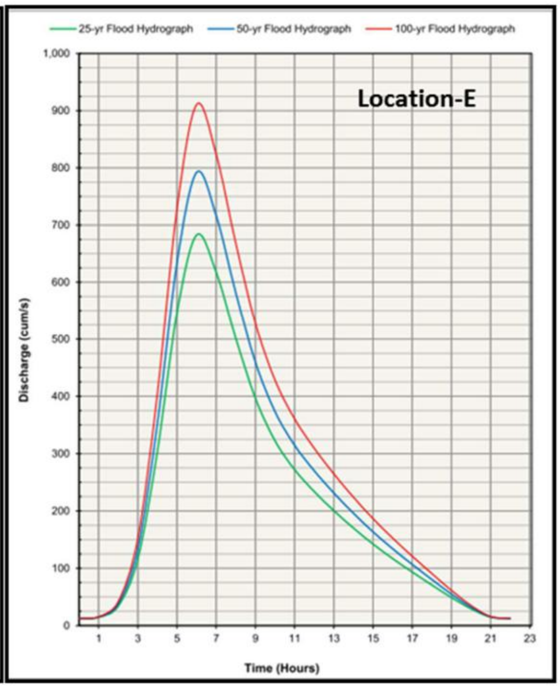
(A) Location-A



(B) Location-B



(C) Location-C



(D) Location-E

FIG.23: Flood hydrographs for Scenario-2

It is observed from above data that the runoff discharges for Scenario-2 are higher than that for Scenario-1. This is due to the fact that for the Scenario-2, discharges consider complete year rainfall data of past 50 years; while Scenario-1 takes into account the rainfall during stormy conditions only. The above flood hydrograph data are utilised for the model studies under consideration in combination with other oceanographic parameters.

Similarly, the intake requirement of Dahanu Thermal Power Plant located in Dahanu creek is 80,000 cum/hr and as the design is 'once through system' the outfall discharge is same as that of intake. This was submitted by JN Port based on the letter submitted by M/s Adani Electricity of Dahanu Thermal Power station (letter dated 25/11/2020). The data on various levels of Dahanu Thermal station provided by JN port vide their e-mail dated 14th March 2022 are as follows:

1) General ground level: 2.7 m above MSL
2) Main plant area: 3.5 m above MSL
3) Invert level for outfall: 0.5 m below MSL
4) Top level of the bund constructed by thermal power station: 4 m above MSL

4.10 Details of Bridge on Dahanu Creek:

The Dahanu creek bridge details were obtained from PWD of Maharashtra government by JN Port and were provided to CWPRS. The bridge spans across Dahanu Creek between Dahanu & Dhakti Dahanu. The location plan of the bridge is shown in FIG.24.

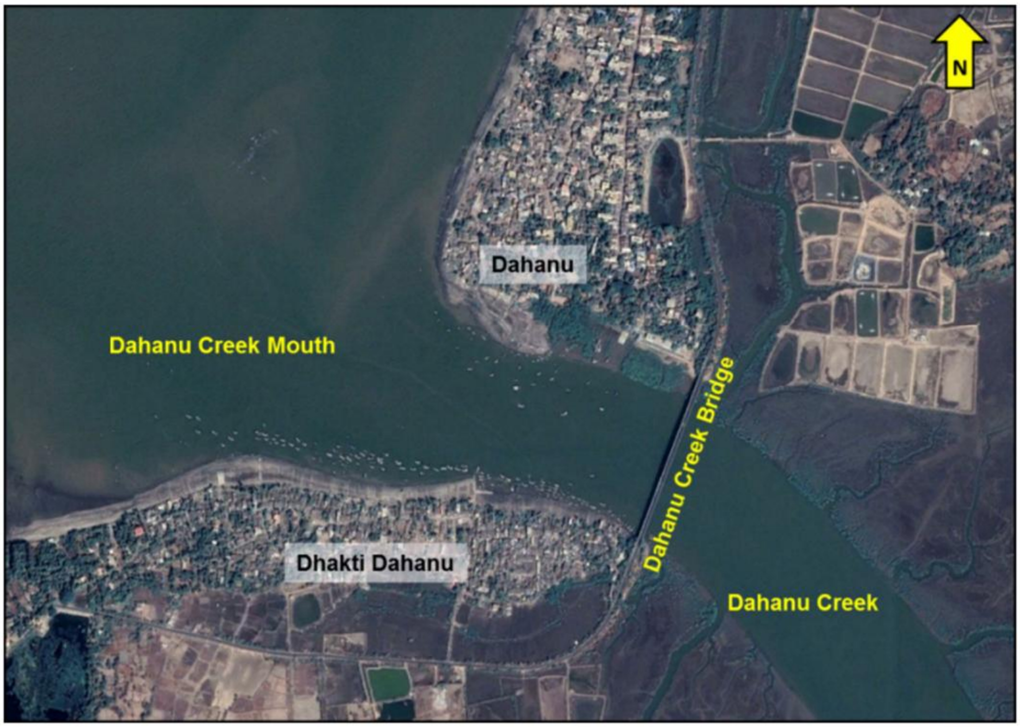


FIG.24: Location plan Dahanu Creek Bridge

The details of the bridge are as follows:

A) Total Length = 400 m

B) No. of piers = 9 Nos.

C) No. of abutments = 2 Nos.

D) Clear distance between two consecutive piers = about 40 m

E) Size of piers = 2.75 m X 2.75 m

F) Soffit level at Centre = 11.72m

4.11 Villages in Control Area of Port at Vadhavan:

The region in 10 km radius from Vadhavan point is considered as Control Area. There are 25 villages falling within the 10 km radius i.e. the control area and out of which 16 villages are associated with fishing and fishing related activities along the coastline. The list of 16 villages is given in Table-VI and control area & locations of 16 villages are shown in FIG.25.

Table-VI

List of villages associated with fishing in control area

Sr. No.	Name of Village	Sr. No.	Name of Village
1	Narpad	9	Chinchani
2	Agar	10	Tarapur
3	Dahanu	11	Kambode
4	Dhakti-Dahanu	12	Ghivali
5	Tadiyale	13	Dhumket
6	Gungwada	14	Abhram
7	Varor	15	Matgaon
8	Dandepada	16	Asangaon

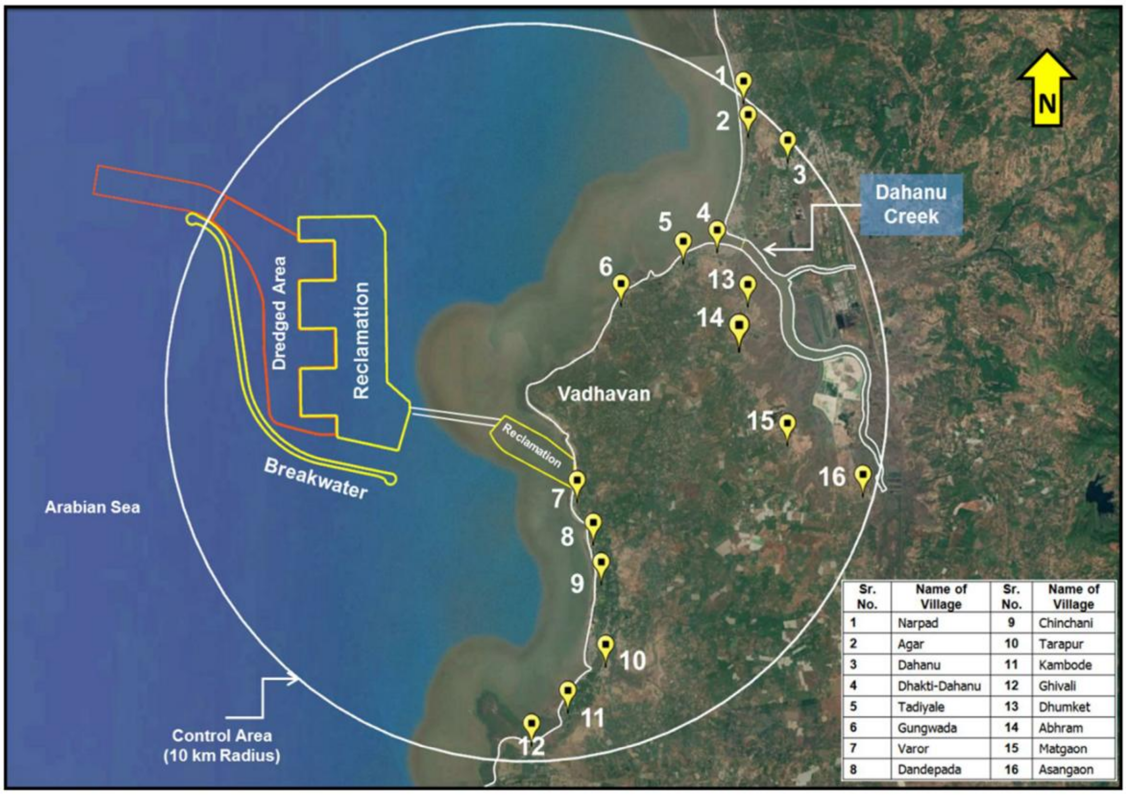


FIG.25: Locations of villages in control area

The visit to the proposed port site at Vadhavan Headland & surrounding area has been carried out by CWPRS officials along with JNPA officials from 18/05/2022 to 20/05/2022.

5. MATHEMATICAL MODEL STUDIES

The mathematical model studies were carried out for simulation of cyclonic storms generated in the Arabian Sea by considering temporally & spatially varying wind & barometric pressure as driving force and TPXO tidal database as boundary conditions. The regional model covering the area from Kerala to Gujarat in the Arabian Sea and local model within the regional model covering the area of proposed port at Vadhavan were developed. The impact of development of proposed port at Vadhavan on the rise in water levels due to cyclonic storms was assessed. The mathematical model studies provide the information on simulation of tidal & wave hydrodynamics under cyclonic storm conditions by considering the flood discharges (Hydrographs) for various return periods as an input from rivers meeting the Dahanu creek area. The studies were carried out by using TELEMAC software suite available at Central Water & Power Research Station (CWPRS), Pune.

5.1 Mathematical Model for Tidal Hydrodynamics

The TELEMAC-2D is finite element software, which considers solution of hydrodynamic equations of Saint Venant's. The model considers depth-averaged velocities. The equations are solved by solving matrices element by element at number of nodes of finite element, which is an unstructured triangular mesh. The TELEMAC-2D code solves the following three hydrodynamic equations simultaneously.

$$\frac{\partial h}{\partial t} + \vec{u}.\vec{\nabla}(h) + h\,div(\vec{u}) = S_h$$ ---------------- Continuity

$$\frac{\partial u}{\partial t} + \vec{u}.\vec{\nabla}(u) = -g\frac{\partial Z}{\partial x} + S_x + \frac{1}{h}div(h\nu_t\vec{\nabla}u)$$ ---------------- Momentum along x

$$\frac{\partial v}{\partial t} + \vec{u}.\vec{\nabla}(v) = -g\frac{\partial Z}{\partial y} + S_y + \frac{1}{h}div(h\nu_t\vec{\nabla}v)$$ ---------------- Momentum along y

in which,

h	(m)	--------------------------------	depth of water
u, v	(m/s)	--------------------------------	velocity components
g	(m/s^2)	--------------------------------	gravity acceleration
ν_t	(m^2/s)	--------------------------------	momentum diffusion coefficient
Z	(m)	--------------------------------	free surface elevation
t	(s)	--------------------------------	time
x, y	(m)	--------------------------------	horizontal space coordinates
S_h	(m/s)	--------------------------------	source or sink of fluid
S_x, S_y	(m/s^2)	--------------------------------	source and sink terms in dynamic equations

u, v are the unknowns

The equations are given in Cartesian Co-ordinates. They can also be processed using spherical co-ordinates.

S_x and S_y are source terms representing the wind, Coriolis force, bottom friction, a source or sink of momentum within the domain. The different terms of these equations are processed in one or more steps (in case of advection by method of characteristics).

1. Advection of h, u and v
2. Propagation, diffusion and source terms of the dynamic equation

5.2 Mathematical Model for Wave Transformation

The numerical wave model TOMAWAC, which is a third generation spectral model solves the wave action density balance equation and was used to transform the waves from deep water towards coastline. It models the evolution in space and time of the directional wave spectrum under unsteady wind forcing. It can take into account the input of energy from the wind, nonlinear wave-wave interactions, wave-current interaction, dissipation of energy due to white-capping, bottom friction, depth-induced breaking in shallow water etc. TOMAWAC is suitable for coastal modeling applications as the computations are performed on unstructured grids which can simulate curved boundaries of coast/estuary effectively. The wave action balance equation is given as follows:

$$\frac{\partial N}{\partial t} + \frac{\partial(\frac{\partial \Omega}{\partial k_x} N)}{\partial x} + \frac{\partial(\frac{\partial \Omega}{\partial k_y} N)}{\partial y} + \frac{\partial(-\frac{\partial \Omega}{\partial k_x} N)}{\partial k_x} + \frac{\partial(-\frac{\partial \Omega}{\partial k_y} N)}{\partial k_y} = Q(k_x, k_y, x, y, t)$$

Where *N* is directional spectrum of wave action density, and $\Omega(k, x, t) = \sigma + k.U$. Wherein *U* denotes the current velocity (depth-integrated); σ denotes the intrinsic or relative angular frequency; *k* is the wave number vector = (k_x ; k_y) = (*k.sinθ; k.cosθ*) for directional spectrum discretization, *θ* is denoting the wave propagation direction (direction in which the waves travel); *t* is time (TOMAWAC user manual). The *Q* denotes source and sink terms and can be defined as follows:

$$Q = Q_{in} + Q_{ds} + Q_{nl} + Q_{bf} + Q_{br} + Q_{tr} + Q_{veg}$$

Q_{in} is wind-driven wave generation; Q_{ds} is whitecapping-induced energy dissipation; Q_{nl} is non-linear quadruplet interactions; Q_{bf} is bottom friction induced energy dissipation; Q_{br} is bathymetry breaking induced energy dissipation etc.

5.3 Discretisation of the Domain Area

The regional model domain covers the area from Lat. 8° N (Kerala) up to Lat. 23° N (Gujarat) and Long. 65° E (about 4500 m depth) to Long. 77° E (West Coast of India) along with the area of proposed port at Vadhavan. The model domain is discretised using finite elements (FE) with resolution of 5 km X 5 km in the overall area except local model area where it is discretised with resolution of 2 km X 2 km. The total domain area considered is about 1.6 Million sq. km. The mesh generated for the domain is shown in FIG. 26(A).

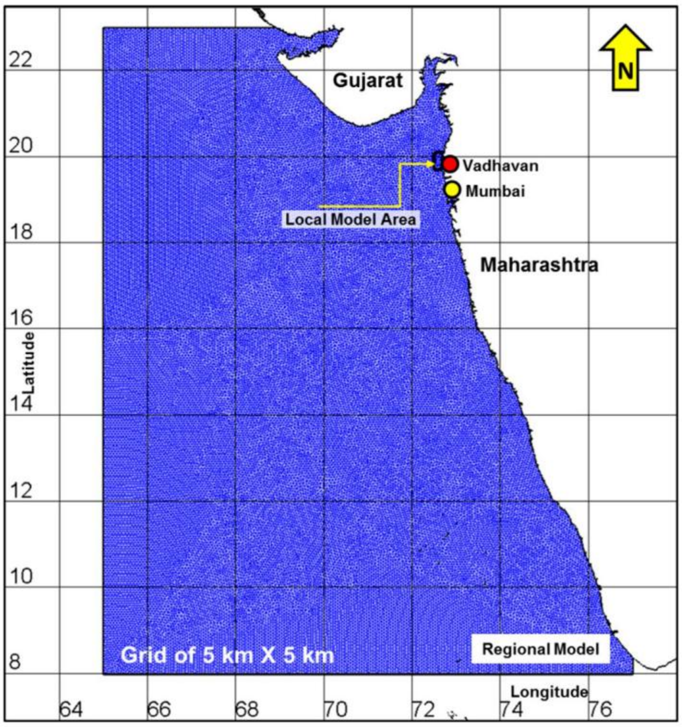


FIG.26(A):Finite element mesh for regional model domain

The bathymetry data supplied by JNP for proposed port area, bathymetry data from GEBCO/MIKE C-map for the Arabian Sea were used for reproducing the bathymetry in the domain area under consideration. The bathymetry of the regional model domain along with Vadhavan location is shown in FIG. 26(B). The interpolated depths were assigned at nodal points of the finite elements to represent the depths in model and hydrodynamic equations in terms of water depth and velocity are solved. Thus, mesh generated can effectively reproduce hydrodynamic conditions prevailing at site.

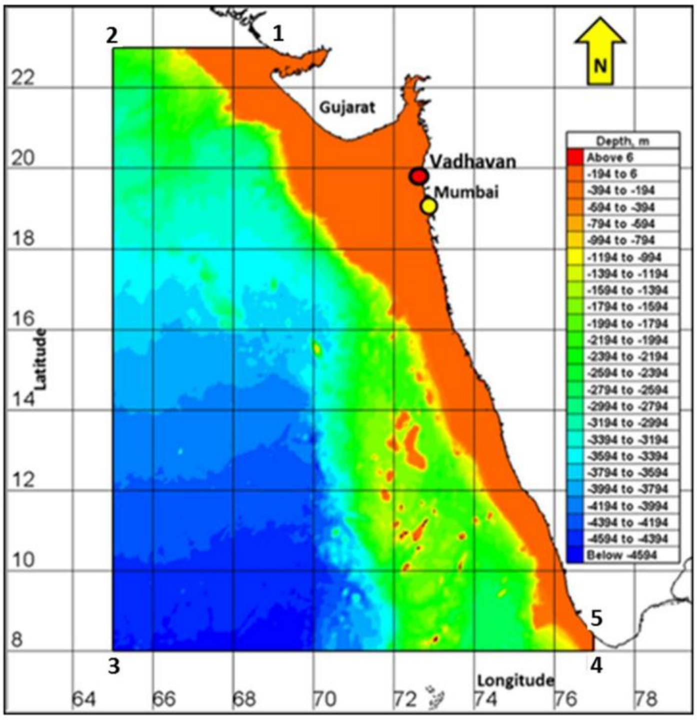


FIG.26(B):Bathymetry of regional model domain

5.4 Simulation and Calibration of Cyclonic Storm Model

The tidal hydrodynamic simulation for regional model is carried out by considering TPXO tides as boundary conditions along "1-2-3-4-5" boundaries (FIG.26(B)). The water level data at Vadhavan is extracted from model and is compared with the tide data collected at Dahanu bridge location. The comparison of water levels observed in mathematical model and that prevailing at site based on field data for non-monsoon season (year 2017) & monsoon season (year 2020) is shown in FIG.27 (A) & 27(B) respectively.

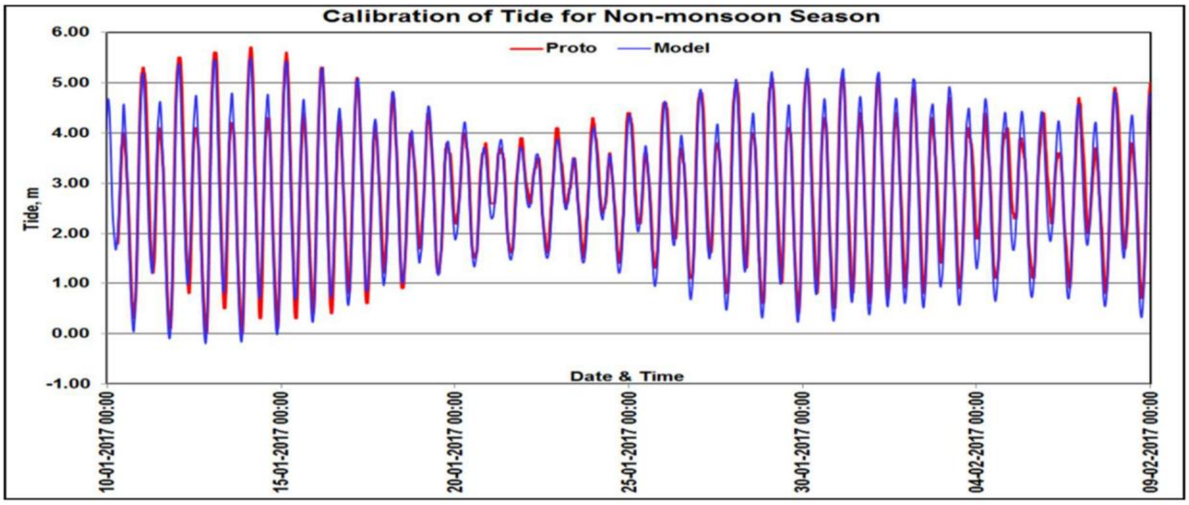


FIG.27(A): Comparison of proto and model tide at Dahanu (Non-monsoon)

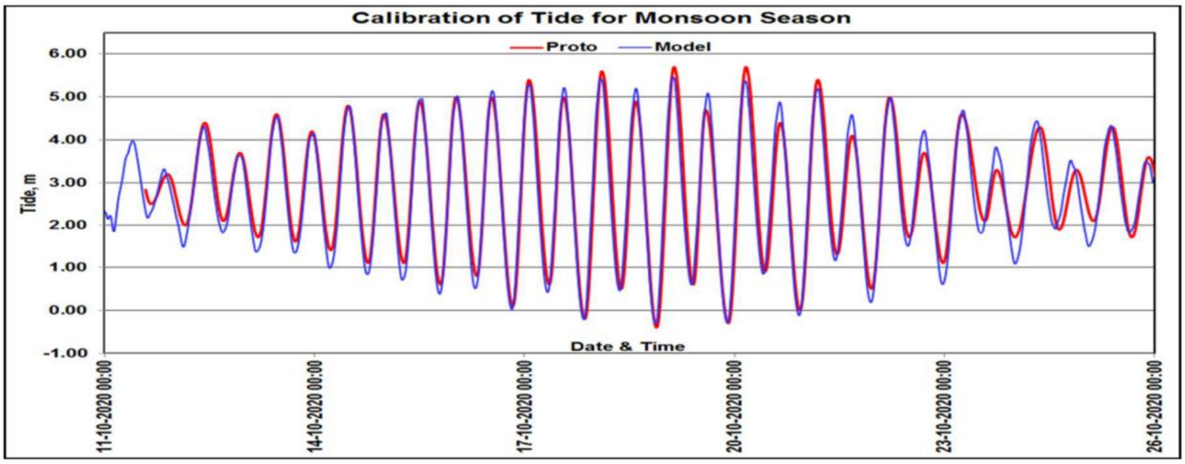


FIG.27(B): Comparison of proto and model tide at Dahanu (Monsoon)

It can be seen from the above figures that measured and computed water levels at Dahanu compares well for both non-monsoon & monsoon seasons. Hence, it can be inferred that mathematical model is reasonably well calibrated with respect to water level in the area under consideration. Thus, the TPXO tidal database is used for further studies.

The wind data considered for simulating cyclonic storm condition for year 2001 was compared with that collected at SW01 location for year 2001. The comparison of wind speed and direction for year 2001 is shown in FIG.28.

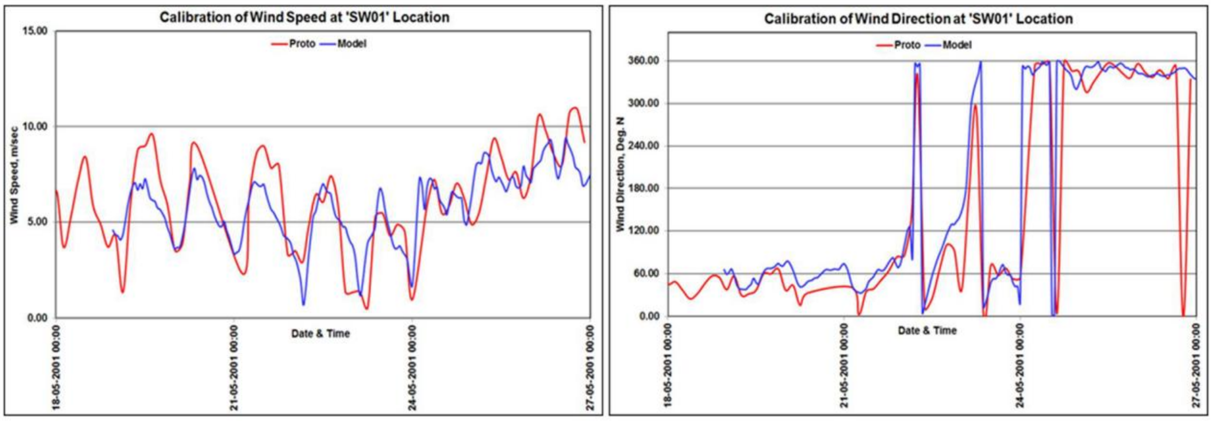


FIG.28: Comparison of proto and model wind at SW01 location

It can be seen from the above figure that measured wind at SW01 location and wind data from ECMWF reanalysis considered for simulation matches well and thus can be used for simulating wind field to determine rise in water level under cyclonic conditions as well as to determine wave condition in the region under consideration.

The simulations were carried out by coupling the wave model with the tidal hydrodynamic model so as to include the effect of waves which were generated due to cyclonic storms under prevailing tidal hydrodynamic conditions at that time. The simulations were carried out for year 2001 & 2017 storms. The data on significant wave height (Hs) & direction was also extracted from model at the locations of SW01 & Versova Buoy and is compared with the prevailing wave data collected at these locations for year 2001 & 2017 respectively. The comparison of significant wave height (Hs) & direction from proto and model at SW01 location for year 2001 cyclonic storm is shown in FIG.29(A) while comparison of significant wave height (Hs) & direction from proto and model at Versova Buoy location for year 2017 cyclonic storm is shown in FIG.29(B) respectively.

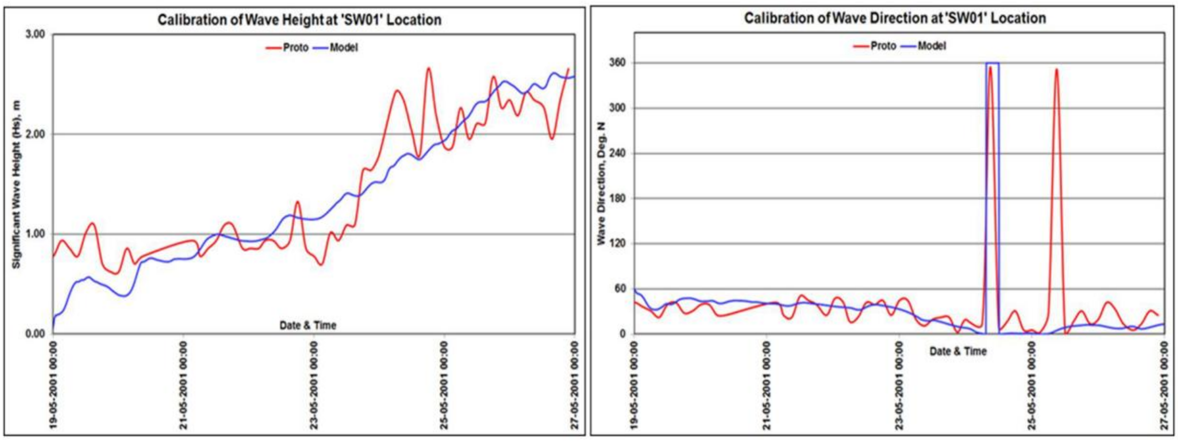


FIG.29(A): Comparison of proto and model significant wave height & direction at SW01 location for 2001 cyclone

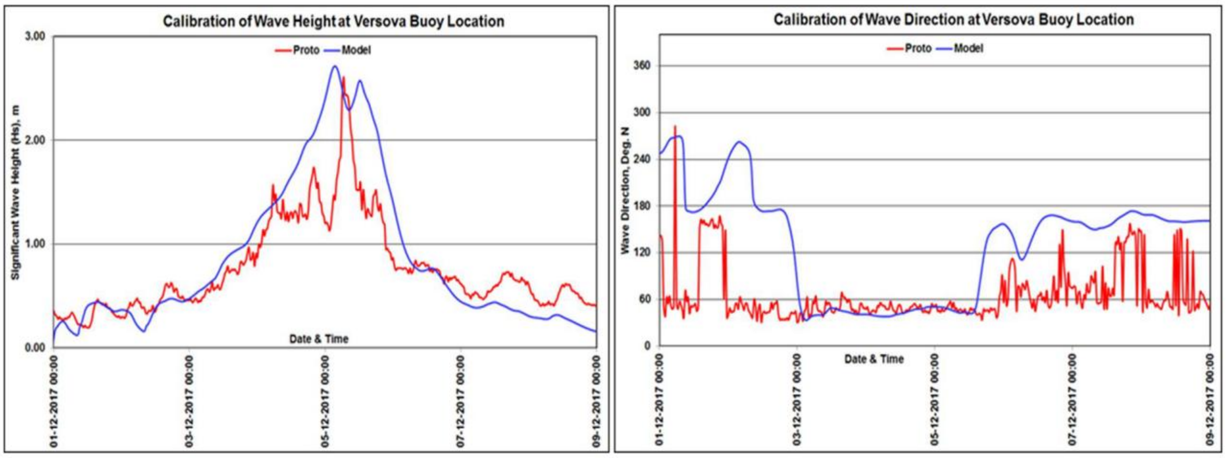


FIG.29(B): Comparison of proto and model significant wave height & direction at Versova buoy location for 2017 cyclone

It can be seen from the above figures that measured and computed significant wave heights & directions at SW01 & Versova Buoy locations compares well for 2001 & 2017 cyclonic storms respectively.

Hence, it can be inferred that cyclonic storm model is reasonably well calibrated with respect to water level, wind field, significant wave heights & direction in the area under consideration.

The wave & tidal hydrodynamic simulations were carried out with cyclonic storm (Wind & Barometric pressure) condition and without cyclonic storm conditions along with TPXO tides as boundary conditions. The 44 cyclonic storm events which are of relevance to Vadhavan site were considered (Mentioned in the Paragraph 4.8). The detailed information about the simulation carried out for Cyclone of November 1982 is described as below.

5.4.1 Simulation of Cyclonic Storm of November 1982

The Extremely Severe Cyclonic Storm for the year 1982 developed in the Arabian Sea on 4th November was initially a depression. This further moves north-eastwards and gets intensified into Cyclonic storm by 5th November morning. It further, intensified into Extremely Sever Cyclonic storm on 8th November morning with the sustained wind speed of 90 knots (46.3 m/s) and central pressure of 962 hp. The cyclone crossed South Gujarat coast near Veraval, India on the 8th November evening and weakened into cyclonic storm by 9th November morning and further turned into low pressure area by 10th November morning. As reported in Mausam Journal (1984) Vol.1 of IMD that according to the report of the touring officer estimated tidal wave above the normal tide (Storm Surge) was about 2 m at Diu. The track of this cyclone taken from IMD eAtlas is shown in FIG.30 while synoptic chart of 8th November at 00:00 GMT (05:30 IST) for the cyclone is shown in FIG. 31.

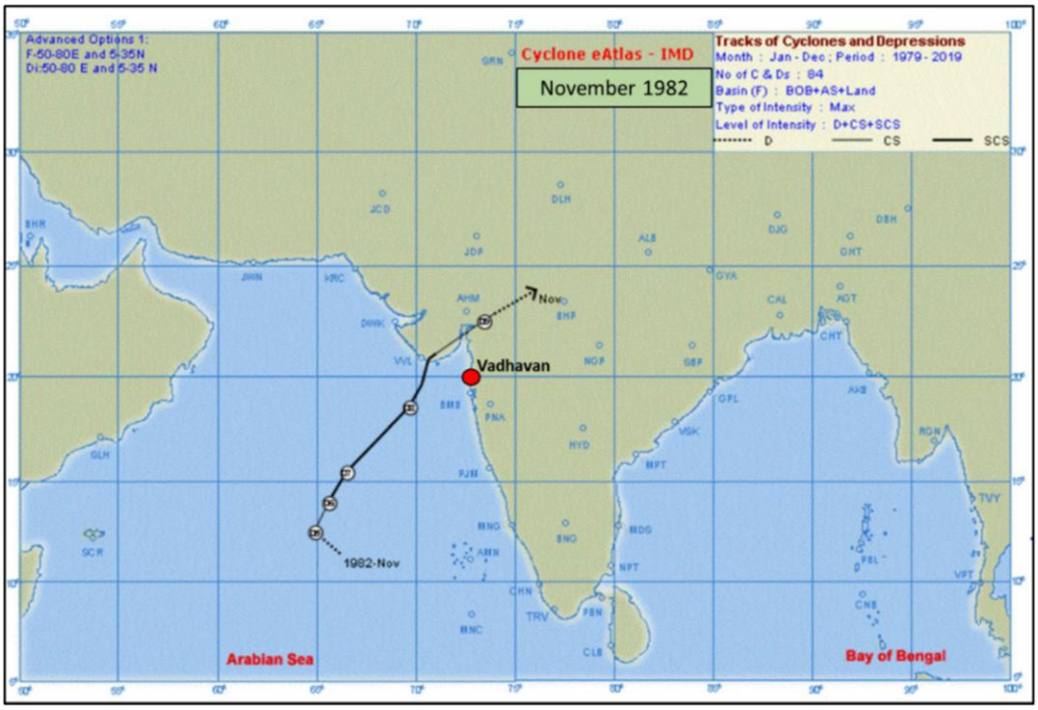


FIG.30: Storm track of cyclone of November 1982

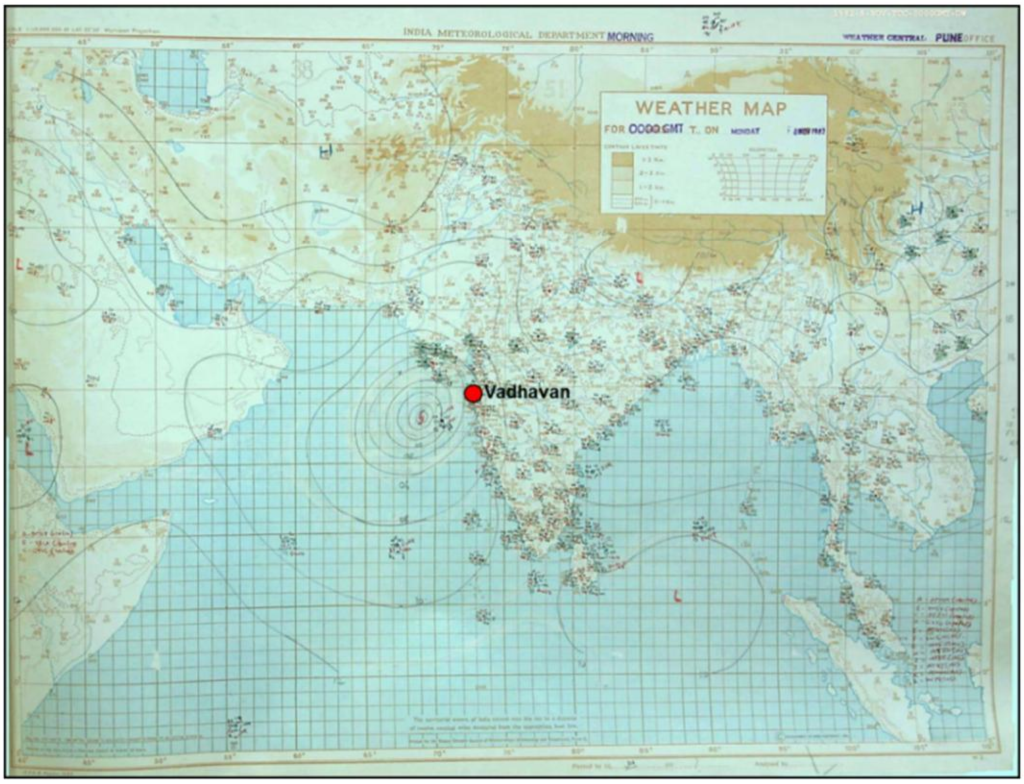


FIG.31: Synoptic chart for cyclone of November 1982

The calibrated cyclonic storm model was used to simulate cyclonic storm from 3rd November to 11th November 1982 considering temporally & spatially varying wind & barometric pressure field obtained from IMD best track data and latest reanalysis dataset of ECMWF along with TPXO tides as boundary conditions. The temporally & spatially varying wind field considered for typical time step for the studies is shown in FIG.32.

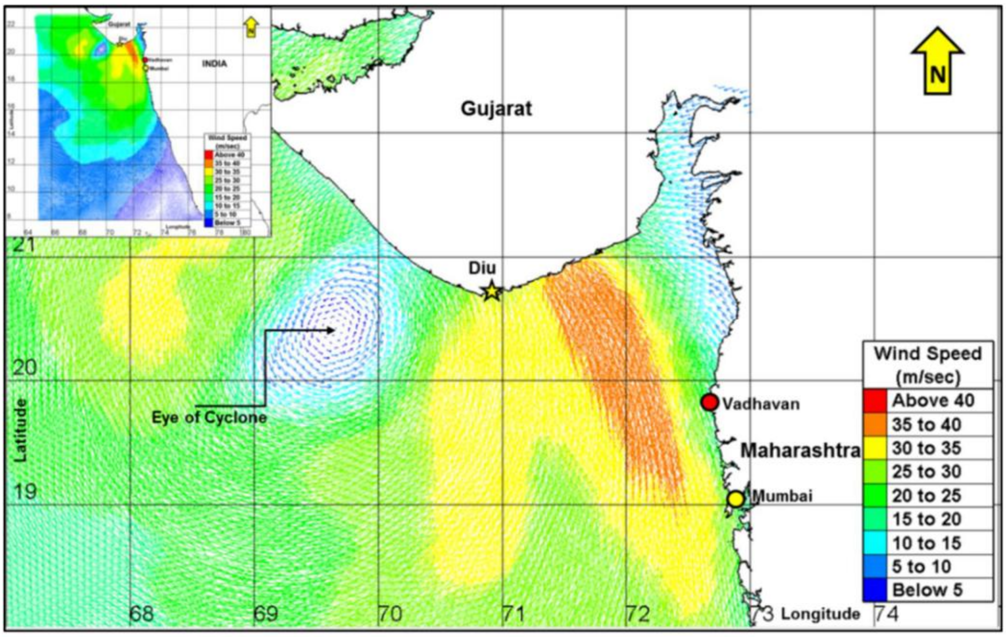


FIG.32: Wind field of November 1982 cyclone from model

The wave & tidal hydrodynamic simulations were carried out for with and without cyclonic storm event and rise in water levels due to cyclone observed in model 1-hr before landfall is shown in FIG.33.

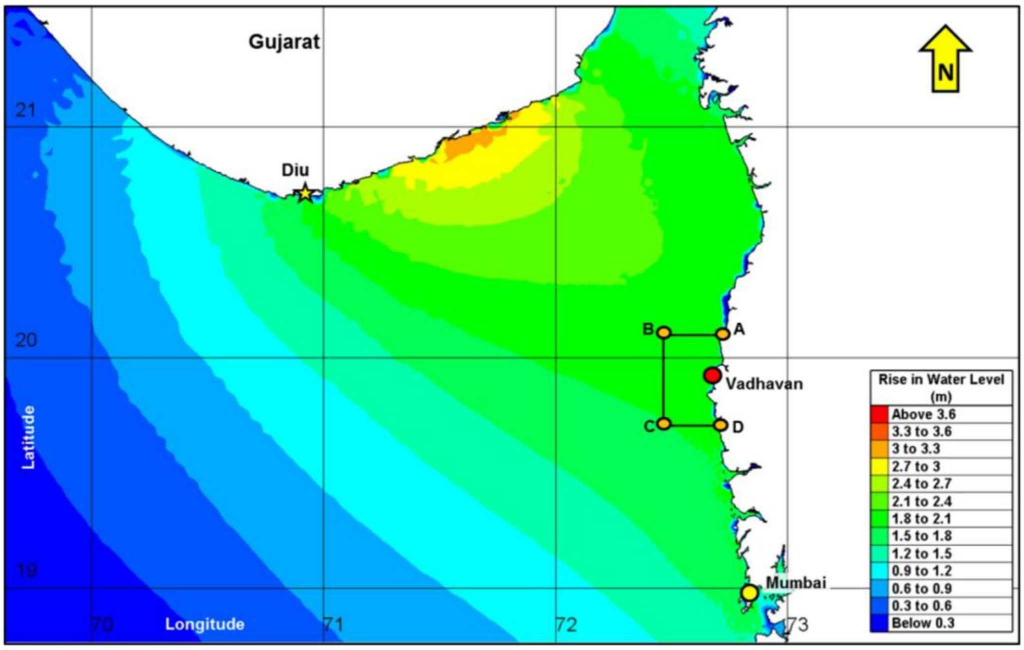


FIG.33: Rise in water level due to November 1982 cyclone from model

The data on water levels for both conditions was extracted and it is inferred that the rise in water level in the model (about 2.1 m) near Diu, Gujarat is comparable with that observed at site (2.0 m). The data on water levels and wave field were extracted in the model domain of local model. The data on water levels extracted indicate that the maximum rise in water level is about 2.4 m & significant wave height is about 6.9 m in the depth of 30 m.

5.4.2 Hindcasting of Cyclonic Storms for 1970-2020

The simulations for remaining 43 cyclones were carried out by adopting the procedure considered for November 1982 cyclone. The respective wind & barometric pressure fields as well as TPXO tides were considered for with cyclonic storm and without cyclonic storm conditions. The data on water levels and significant wave heights were extracted in the domain of the local model (FIG.33). The comparison of water levels with and without cyclonic storm conditions gives the rise in water level due to cyclonic storm. The data on significant wave heights & rise in water level obtained in the domain of local model are given in Fig.34 (A) & Fig. 34(B) respectively.

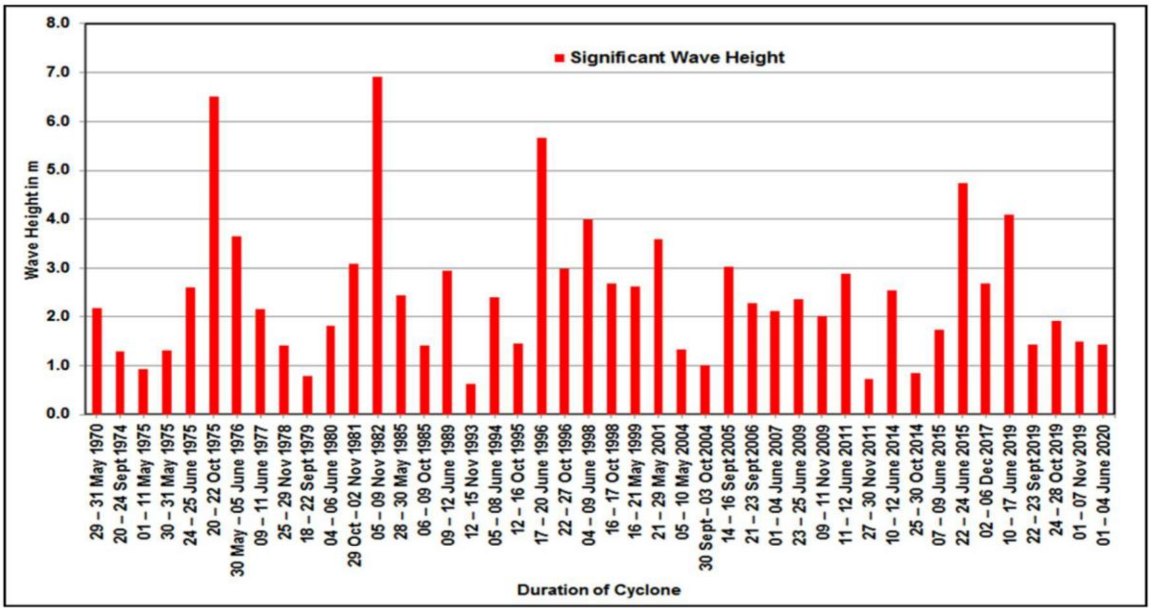


FIG.34(A): Significant wave heights due to cyclonic storms from regional model

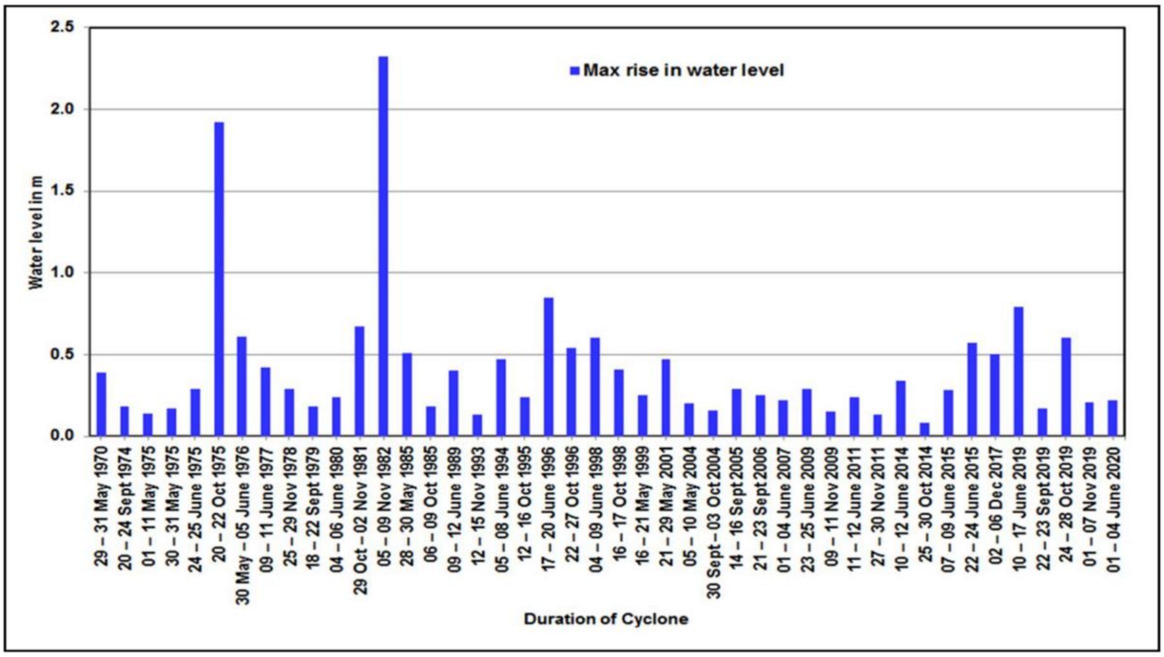


FIG.34(B): Maximum rise in water levels due to cyclonic storms from regional model

6. EXTREME VALUE ANALYSIS OF WAVES & RISE IN WATER LEVELS

Extreme value analysis (EVA) is a statistical procedure to estimate the likelihood of the occurrence of extreme values based on a few basic assumptions and observed/measured data. The observed/measured data is seldom available for longer duration during cyclonic conditions and hence hindcasting of the data is carried out by developing mathematical model of the region. The extreme value of the data which occurs on an average once in 100 years, will have a 100 year return period (RP) or recurrence interval. The data considered for the statistical analysis of past 25 years, 50 years are called sample. The important requisite for a statistical sample is independency. It means that individual dataset in a sample must be statistically independent of each other. Another important requisite is homogeneity. Individual dataset in a sample must have a common parent distribution, all datasets belonging to a single group of dataset.

6.1 Extreme Value Analysis of Storm Wave data for 1970-2020

The extreme value analysis of storm waves has been carried out by extracting maximum value of significant wave height during each storm event from the regional model near Vadhavan Port site for 44 cyclones covering period of past fifty (50) years (1970-2020) and plot of maximum significant wave height during each storm is given in FIG.34(A). Data series for the maximum significant wave height during the storm duration was checked for independence, homogeneity and found independent, stationary & homogenous. There were several methods of fitting a theoretical distribution function to a sample of extreme data and estimating the parameter values. The method of least squares described by Goda (Goda, 2000) was used for the extreme value analysis. The Peak-over-threshold (POT) method was used to determine the extreme observations over a certain threshold value for further analysis.

For the significant wave height data, the threshold value for POT was chosen as 2.5 m. As the data is during 1970 to 2020, the parameter K= 50 years, the number of events during the period K i.e. N_T= 44 and using POT method, the number of events taken for analysis, N=17. The mean rate of the extreme events is given by $\lambda = \frac{N_T}{K} = 0.88$. The censoring parameter denoted by $\nu = \frac{N}{N_T} = 0.3864$. FT-I, FT-II and Weibull distributions are considered for the fitting with different values of shape parameter k, location and scale parameters of the distribution estimated using the method of least squares (Annexure-A). The FT-I distribution was found to be the best fitted distribution for significant wave height data. Using this best fitted distribution, the significant wave heights for 25, 50 & 100 yrs return periods were estimated. The results are given in Table-VII.

Table-VII

Extreme significant wave heights for various return periods

Return Period (Yrs)	Significant Wave Height in m computed using FT-I distribution
25	5.54
50	6.50
100	7.46

6.2 Extreme Value Analysis of Maximum Rise in Water level for 1970-2020

The extreme value analysis of rise in water level has been carried out by extracting maximum value of rise in water level during each storm event from the regional model near Vadhavan Port site for 44 cyclones covering period of past fifty (50) years (1970-2020) and plot of maximum rise in water level during each storm is given in FIG.34(B). Data series of the maximum rise in water level during the storm duration was checked for independence, homogeneity and found independent, stationary & homogenous. The method of least squares described by Goda (Goda, 2000) was used for the extreme value analysis. The Peak-over-threshold (POT) method was used to determine the extreme observations over a certain threshold value for further analysis.

For the rise in water level data, the threshold value for POT was chosen as 0.3 m. As the data is during 1970 to 2020, the parameter K= 50 years, the number of events during the period K i.e. N_T= 44 and using POT method, the number of events taken for analysis, N=19. The mean rate of the extreme events is given by $\lambda = \frac{N_T}{K} = 0.88$. The censoring parameter denoted by v=$\frac{N}{N_T}$ =0.4318. The various probability distributions are considered for the fitting with different values of shape parameter k, location and scale parameters of the distribution estimated using the method of least squares (Annexure-B). The best fitted distribution for maximum rise in water level is FT-II distribution with k=2.5. Using this best fitted distribution, the rise in water level for 25, 50 & 100 yrs return periods were estimated. The results are given in Table -VIII.

Table-VIII

Extreme rise in water level for various return periods

Return Period (Yrs)	Extreme Rise in Water Level in m computed using FT-II distribution (k=2.5)
25	1.16
50	1.60
100	2.10

7. JOINT PROBABILITY ANALYSIS OF RISE IN WATER LEVEL (SS) AND TIDE

The Joint probability determines the chance of two or more events occurring concurrently that may combine and produce a critical situation. Joint probability is nothing but the probability of simultaneous occurrence of two or more events. A methodology capable of correlating the linkage between extremes of primary variables and estimating the probability of their simultaneous occurrence is called statistical dependence. Dependence determines the extent to which an observation of one variable is reliant on a value of another variable. This is essential for a joint probability calculation. Dependence indicates the likelihood of two variables, (such as storm surge, tide or significant wave height), producing high or extreme values at the same time (worst case scenario).(Petroliagkis, Voukouvalas, Disperati, & Bidlot, 2016).

The cyclonic storms are commonly associated with creation of low pressure weather system along with generation of high speed winds and heavy downpour in the peripheral coastal areas of storm. The rise in water level (storm surge) developed due to storms, high river flows due to heavy downpour and tides can act either alone or in combination to produce high water levels during storm which creates a risk of flooding in low lying areas in the creek/estuaries. The joint probability analysis determines the chances of simultaneous occurrence of these phenomena, depending on the location of the site, which may create worst situation like flooding.

The site of proposed port at Vadhavan is about 6 km offshore from Vadhavan headland at the coastline and to determine flood prone area in Dahanu creek and control area, the phenomena viz. tides and rise in water level due to cyclonic event (storm surges) are more dominant and joint probability of simultaneous occurrence of these phenomena needs to be considered to determine the flooding in Dahanu creek and control area due to development of proposed port at Vadhavan.

In the present study as the historical measured water level near the Dahanu creek is not available during cyclonic events, the hindcasting of rise in water level (SS) for past fifty years' historical storm events (1970-2020) which are of relevance of Dahanu creek and control areas were considered to estimate the rise in water level due to cyclonic events. The plot of rise in water level and the corresponding tidal level for the major cyclonic event analysed is shown in Fig 35.

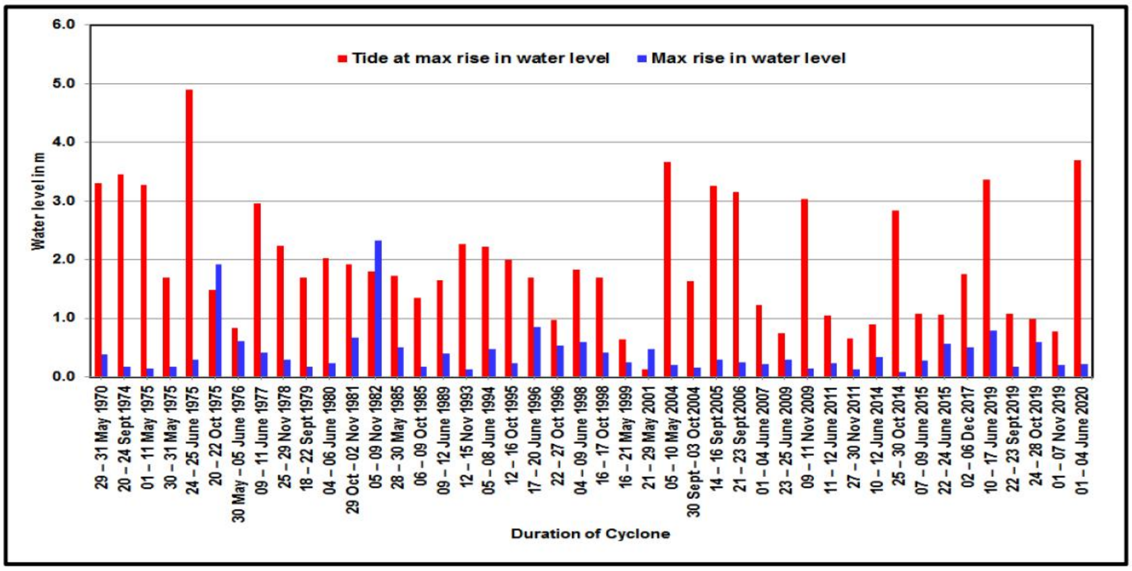


FIG. 35: Plot of rise in water level and corresponding tide during cyclonic event

The above plot indicates that most of the time the rise in water level during cyclonic event has occurred when the tide level is below mean sea level mainly during low to mean low water level. However, it has been observed that for some cyclonic event (for e.g. June 1998), wherein the storm is stationary for a duration of more than 6 hrs, the occurrence of rise in water level has also found to occur even during high tide also. The plot of rise in water level and the tide for the cyclonic event for cyclone of June 1998 is shown in Fig. 36.

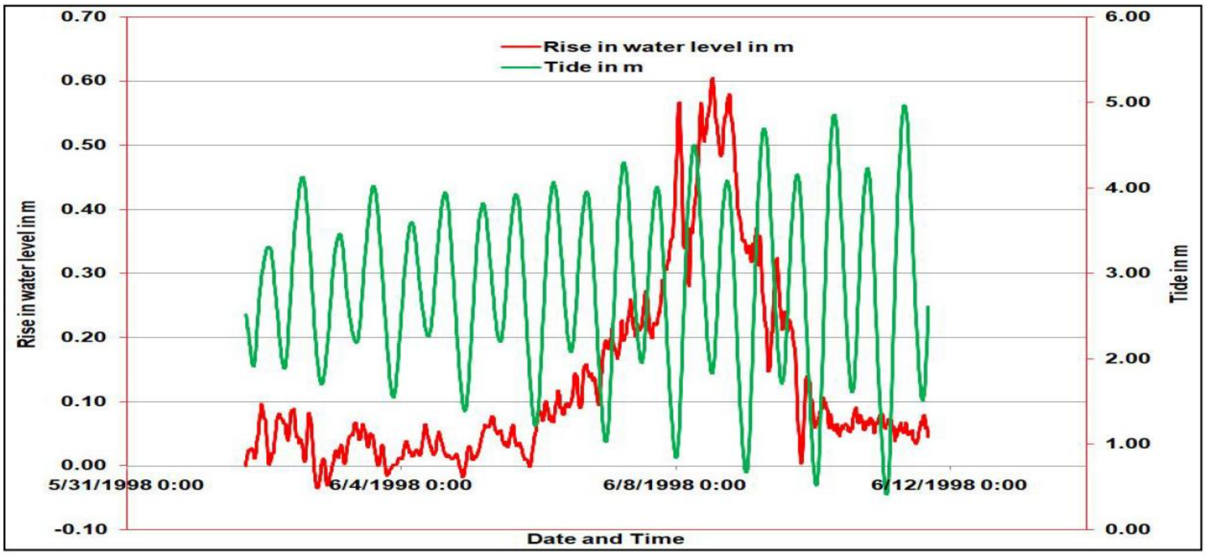


FIG.36: Plot of rise in water level and tide during extremely severe cyclonic storm (4th – 10th June 1998)

It is also observed that out of 44 cyclonic events, 22 times either maximum rise in water level had occurred in proximity of maximum high tide during cyclonic events or maximum rise in water level had occurred in proximity of second high tide during cyclonic events. As such in the present study, the joint probability of occurrence of tide and rise in water level for three cases have been estimated for various return periods (25/50/100 year) and are as follows:

Case-1: The joint probability of occurrence of maximum rise in water level and corresponding tidal level (shown in Fig 37(A)).

Case-2: The joint probability of occurrence of maximum rise in water level and the maximum high tide in proximity of the occurrence of maximum rise in water level (shown in Fig 37(B)).

Case-3: The joint probability of occurrence of maximum rise in water level and the second-high tide in proximity of the occurrence of maximum rise in water level (shown in Fig 37(C)).

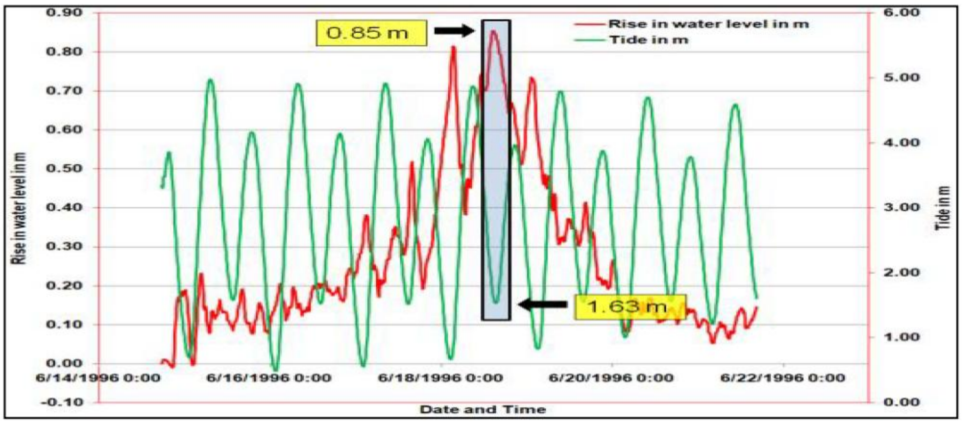


FIG.37(A): Plot of rise in water level and corresponding tidal level at maximum rise in water level

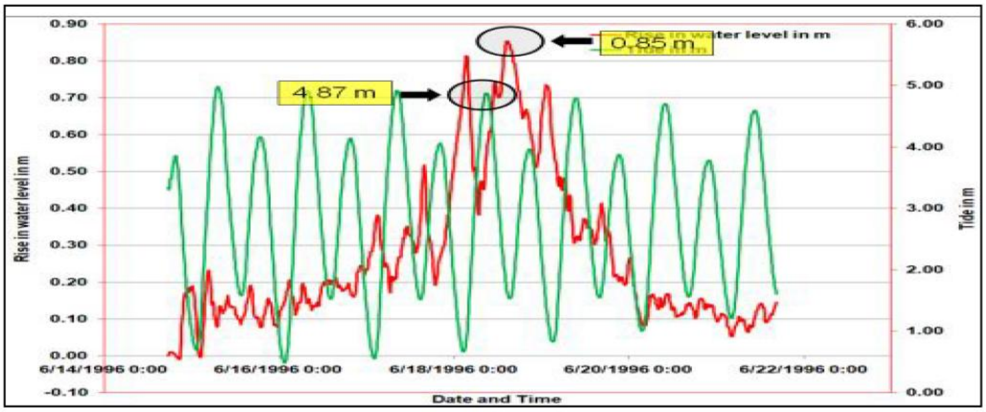


FIG.37(B): Plot of rise in water level and the maximum high tide in proximity of the occurrence of maximum rise in water level

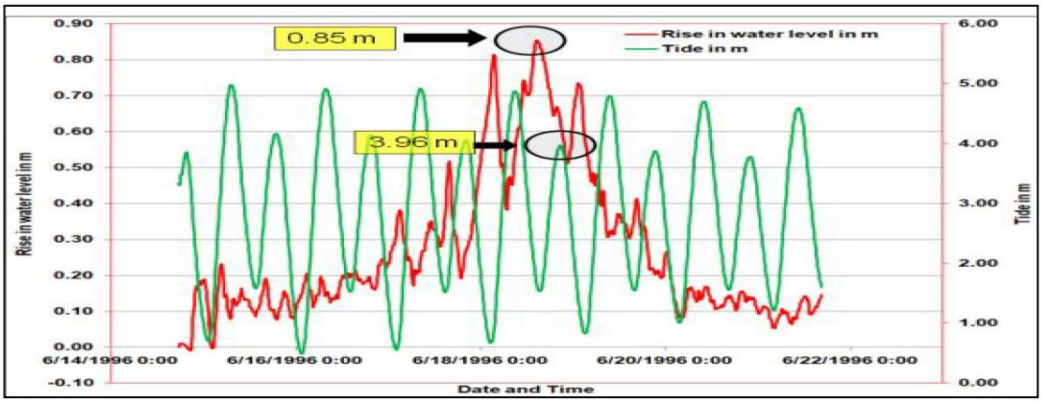


FIG.37(C):Plot of rise in water level and the second-high tide in proximity of the occurrence of maximum rise in water level

Joint probability distribution for all three cases was computed using statistical methods with the estimation of the individual marginal distributions and their joint probability of exceedance of rise in water level and tidal level for the various return periods. The estimation of joint probability using Copula distribution function is used for the studies and briefly described in Annexure-C. The results of joint probability distributions for all three cases are presented in Table-IX to Table-XI respectively.

Table-IX
Case-1: The joint probability of occurrence of maximum rise in water level and corresponding tidal level

Return Period in year	Tide Corresponding to peak rise in water level in m	Maximum rise in Water Level in m	Storm Tide in m
25	2.02	1.16	3.18
50	2.03	1.60	3.63
100	2.10	2.10	4.20

Table-X
Case-2: The joint probability of occurrence of maximum rise in water level and the maximum high tide in proximity of the occurrence of maximum rise in water level

Return Period in year	Nearby maximum high tide occurred during maximum rise in water level in m	Maximum rise in Water Level in m	Storm Tide in m
25	4.65	1.16	5.81
50	4.66	1.60	6.26
100	4.70	2.10	6.80

Table-XI
Case-3: The joint probability of occurrence of maximum rise in water level and the second-high tide in proximity of the occurrence of maximum rise in water level

Return Period in year	Nearby minimum high tide occurred during maximum rise in water level in m	Maximum rise in Water Level in m	Storm Tide in m
25	4.19	1.16	5.35
50	4.20	1.60	5.80
100	4.21	2.10	6.31

These storm tides were considered as boundary conditions for local model and are used for estimating flooding in Dahanu creek and control areas due to the proposed development of port at Vadhavan during cyclonic storm events.

8. MODEL STUDIES FOR FLOODING WITH LOCAL MODEL

The local model domain covers area of proposed port at Vadhavan, Dahanu Creek and other locations within the 10 km radius of the control area. The north side of the model extends up to Gholvad, while south side up to Nandgaon and up to about 31 m depth in deeper part of Arabian Sea on the West side. The Dahanu creek along with topography up to +10 m contour w.r.t. CD in the control area is also considered in the model. The model domain is discretised using finite elements (FE) and is developed to simulate the existing bathymetry condition. The total domain area considered is about 1150 sq. km. The mesh generated for the domain is shown in FIG. 38(A).

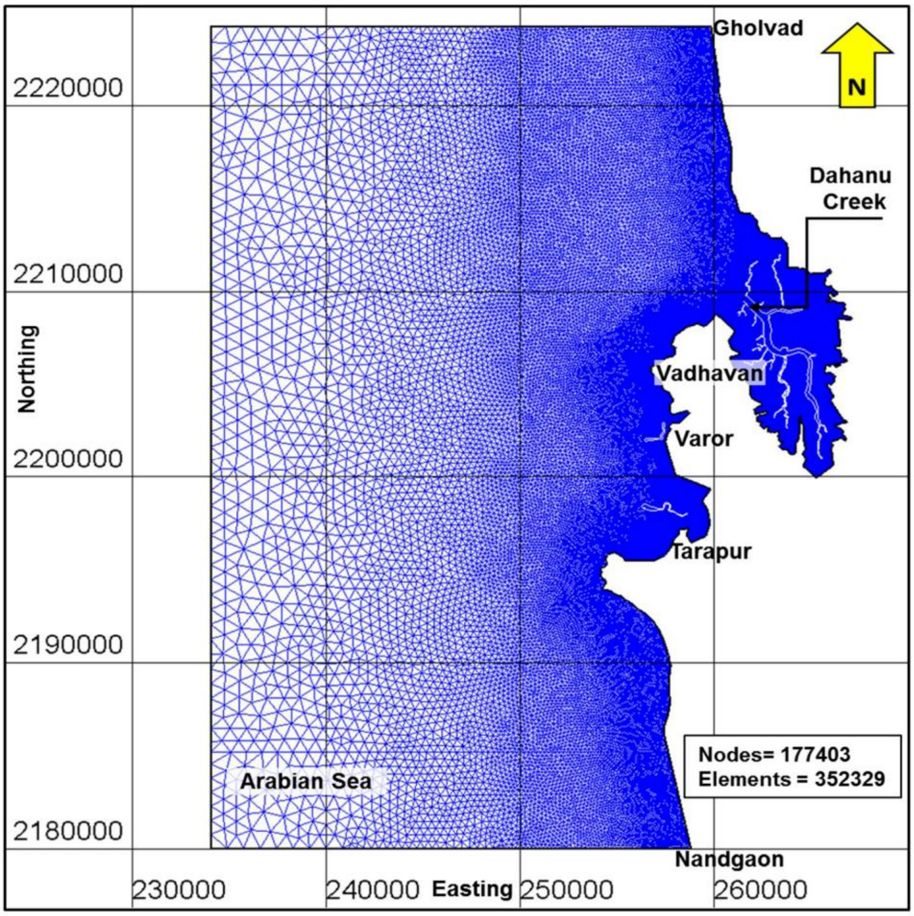


FIG.38(A):Finite element mesh for local model

The triangular finite elements with fine resolution near shoreline, in the creek-lets of Dahanu creek area etc. were adopted for true simulation of all water areas, steep slopes, rocky outcrops and coarser resolution in deeper areas to optimize the number of elements for minimizing the simulation time. Thus, mesh generated can effectively reproduce hydrodynamic conditions without compromising on the quality of results. The variable element sizes in proportion to bathymetry were also adopted to schematize the navigational channels, deeper depths and land boundaries. The bathymetry data supplied by JNP for proposed port area, C-map data (DHI) for deeper part of the sea and charts prepared by MMB for Dahanu Creek (Year 2020), Tarapur and Vadhavan (Year 2003) were used for reproducing the bathymetry in the domain area under consideration. The topography data from HTL up to +10m contour is also considered to represent the detailed topography of the Dahanu creek area. The bathymetry of the Vadhavan area along with the tide/current data measurement locations is shown in FIG. 38(B).

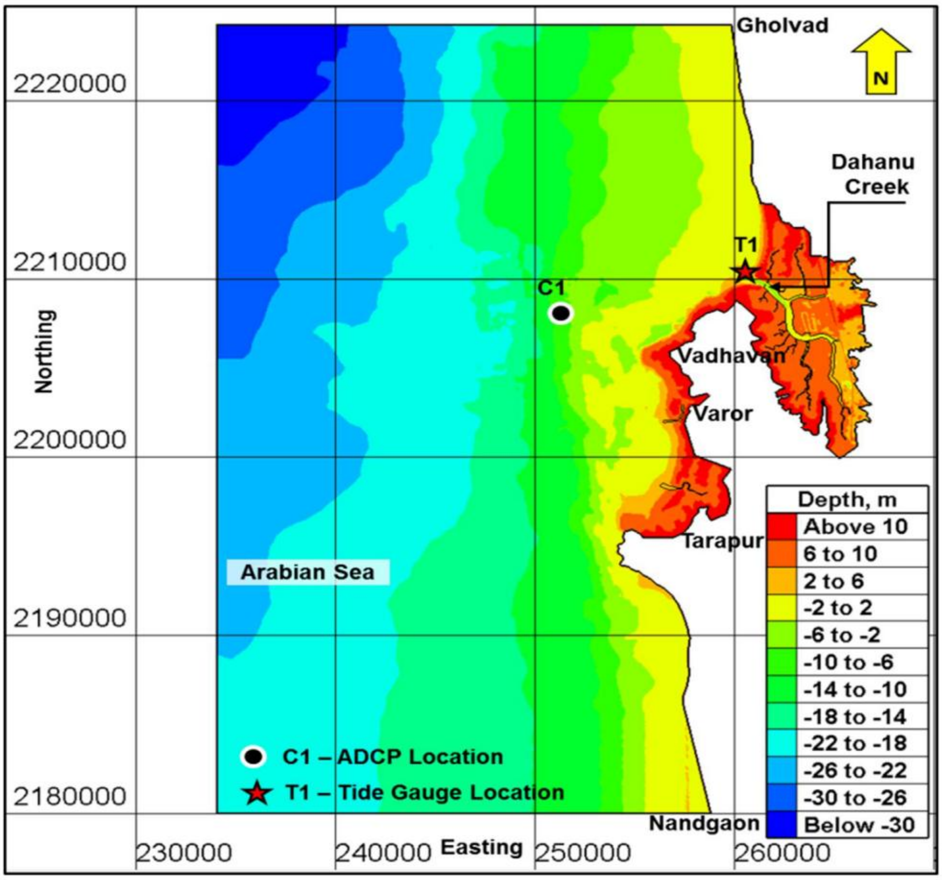


FIG.38(B):Bathymetry of Vadhavan area simulated in local model

The interpolated depths were assigned at nodal points of the finite elements to represent the depths in model and hydrodynamic equations in terms of water depth and velocity are solved. Thus, mesh generated can effectively reproduce hydrodynamic conditions prevailing at site.

8.1 Calibration of Local Model

The observed tidal data for non-monsoon season is used as northern boundary condition and tidal data with lag is adopted as southern boundary condition for existing bathymetry to simulate the hydrodynamics prevailing in the domain area by mathematical model. Information on grain size for bed samples provided by JN Port is used to consider the appropriate bed friction and the simulation of tidal flow in the model is carried out. The current data and water level data in model were obtained at locations wherein field data for current at ADCP location & tide data at Dahanu bridge site was collected. The comparison of water levels and current (strength & direction) observed in mathematical model and that prevailing at site based on field data for non-monsoon season is shown in FIG.39 (A), 39(B) & 39(C) respectively.

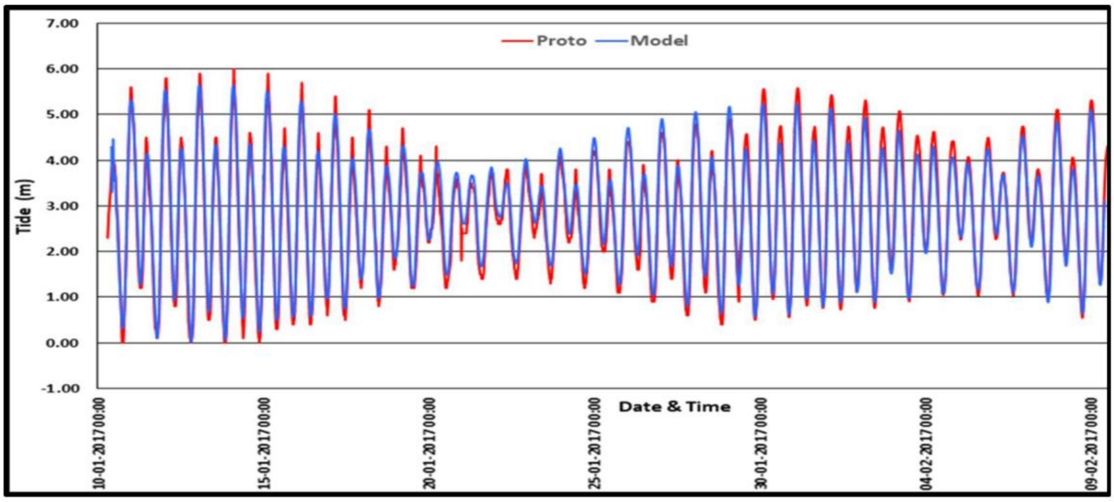


FIG.39(A): Comparison of proto and model tide at T1 location (Non-monsoon)

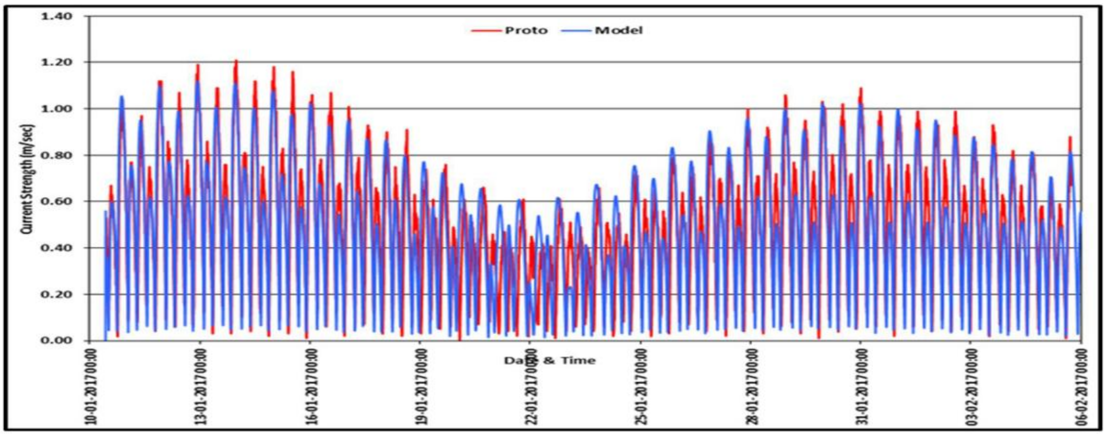


FIG.39(B): Comparison of proto and model current strength at C1 (Non-monsoon)

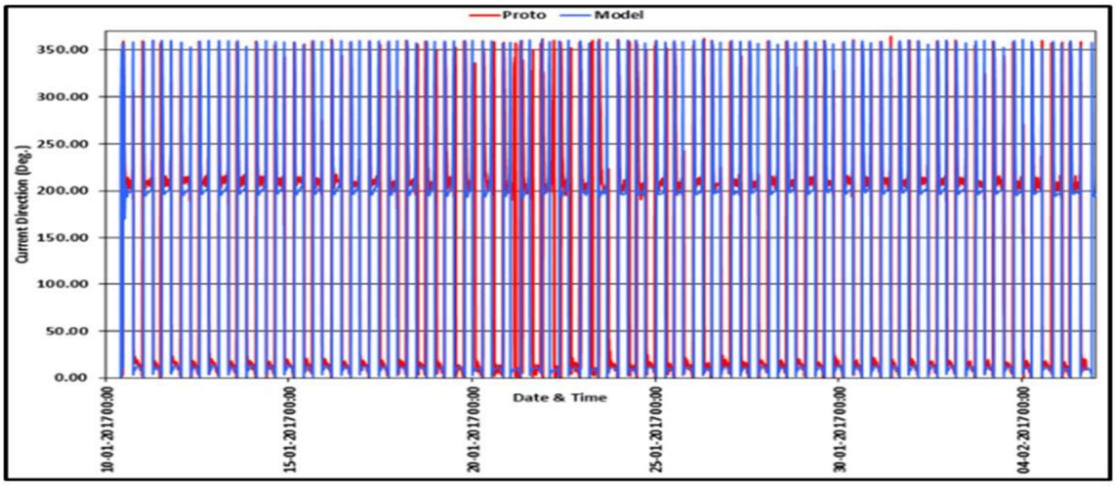


FIG.39(C): Comparison of proto and model current direction at C1 (Non-monsoon)

Similarly, the tidal hydrodynamic simulation for existing bathymetry condition for monsoon season is also carried out. The current data and water level data in model were obtained at locations wherein field data for current & tide is available. The comparison of water levels and current (strength & direction) observed in mathematical model and that prevailing based on field data for monsoon season is shown in FIG.40 (A), 40(B) & 40(C) respectively.

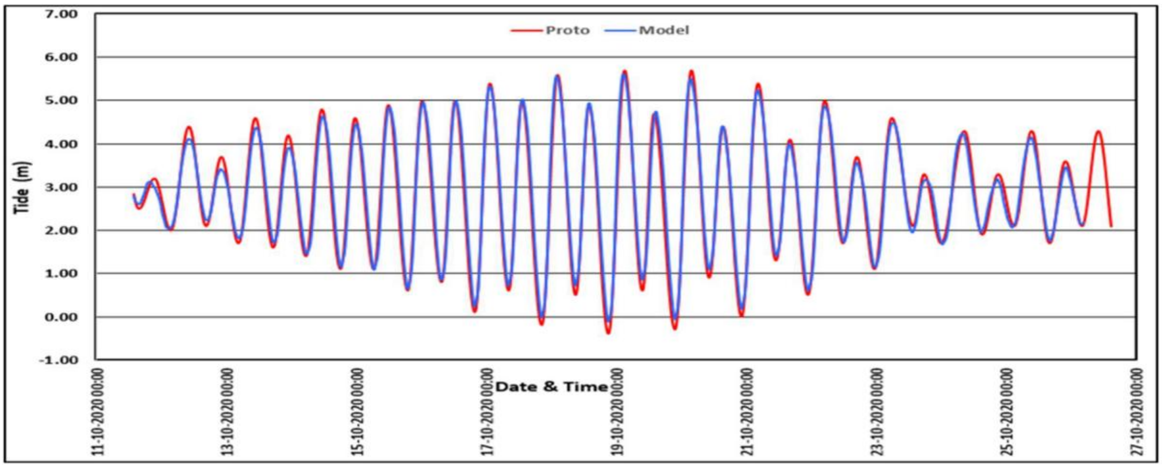


FIG.40(A): Comparison of proto and model tide at T1 location (Monsoon)

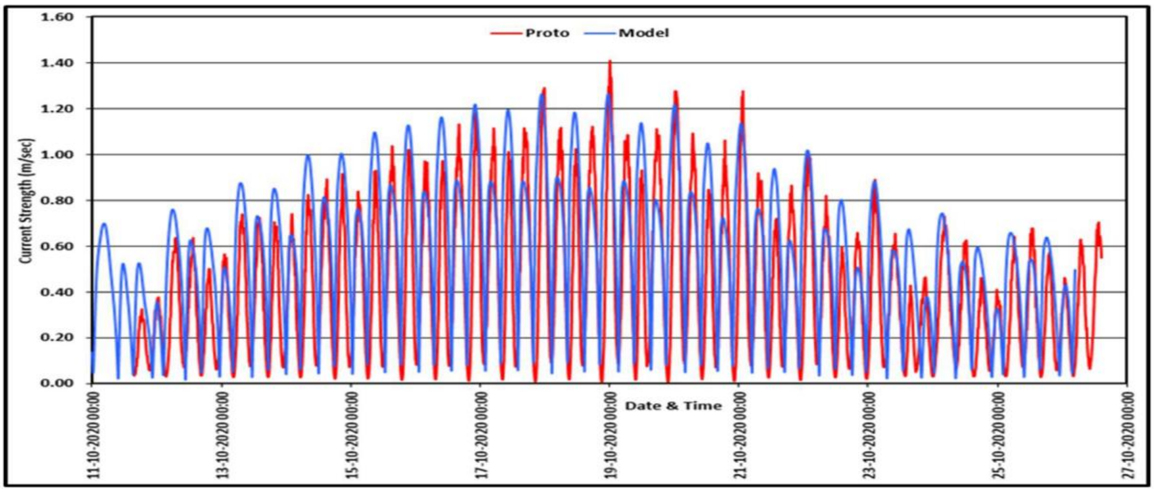


FIG.40(B): Comparison of proto and model current strength at C1 (Monsoon)

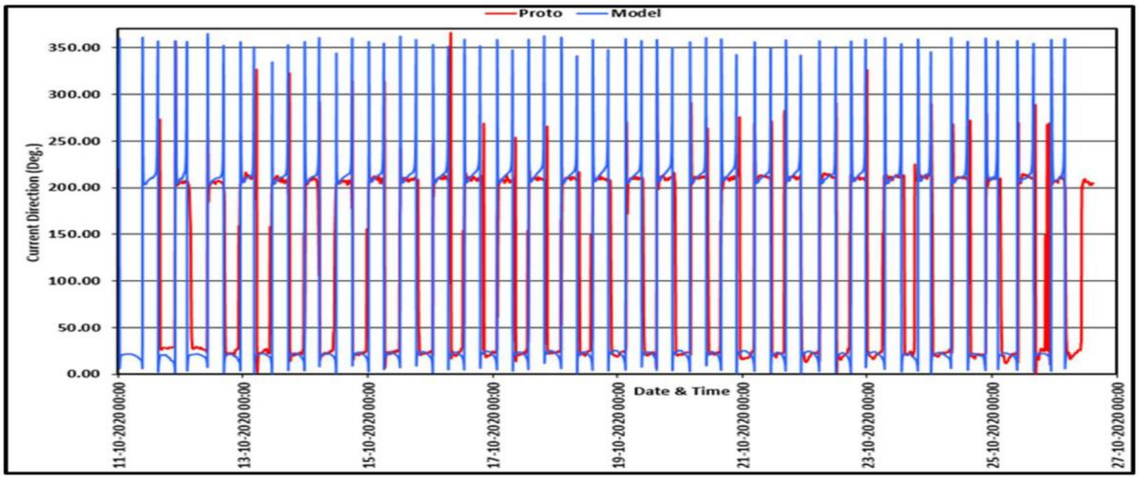
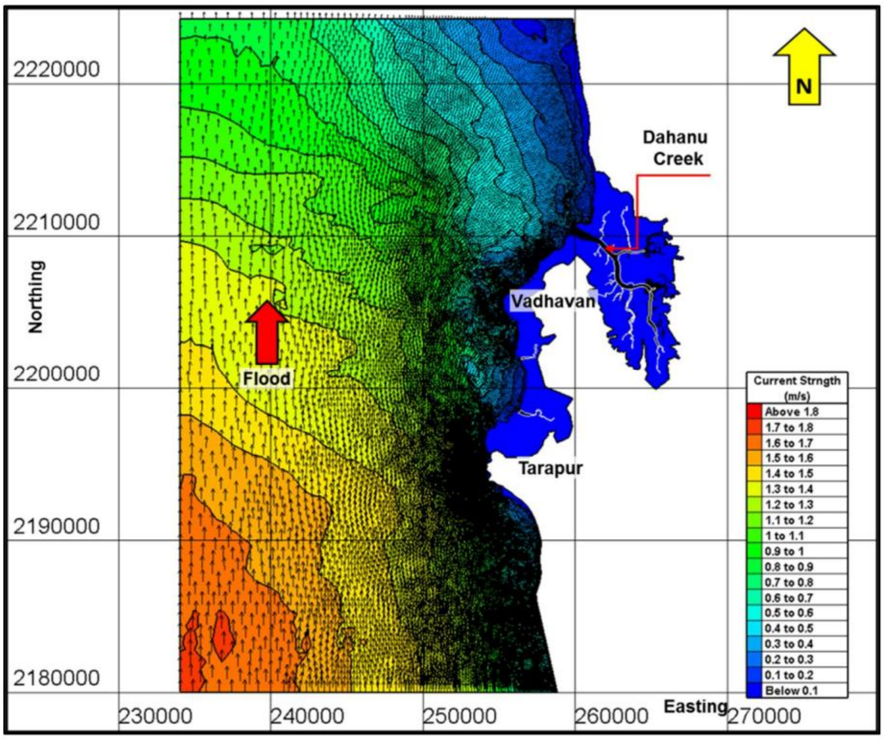
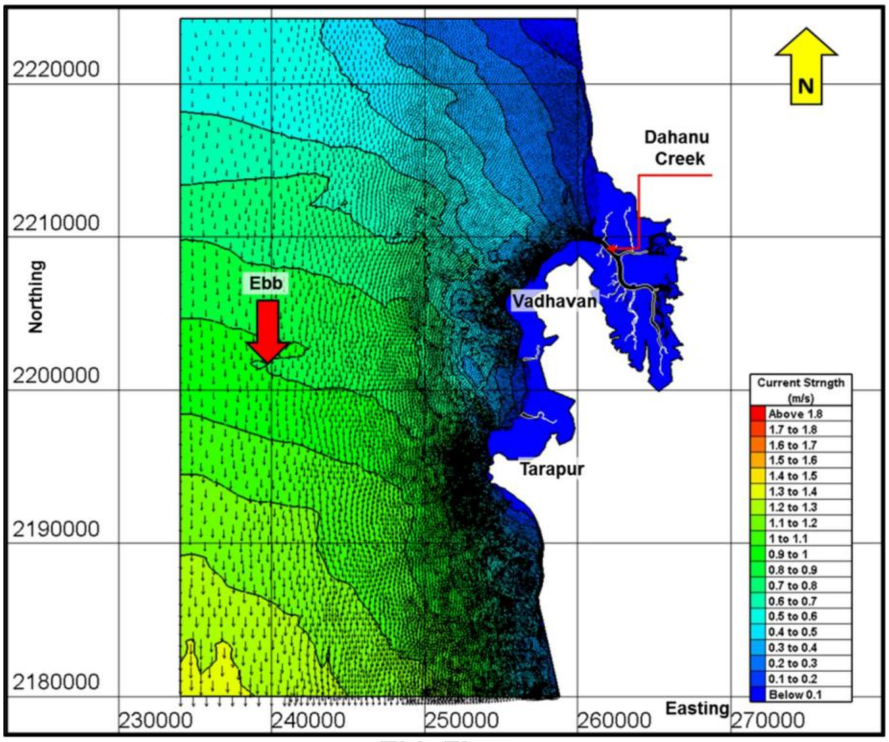


FIG.40(C): Comparison of proto and model current direction at C1 (Monsoon)

It can be seen from the above figures that measured and computed water levels as well as current at corresponding locations compares well for both non-monsoon & monsoon seasons. Hence, it can be inferred that the local model is also well calibrated with respect to water level and current in the area under consideration. The flow patterns observed in model during flood & ebb are shown in FIG.41.



Flood Flow



Ebb Flow

FIG.41: Flow patterns observed during flood & ebb for existing bathymetry condition

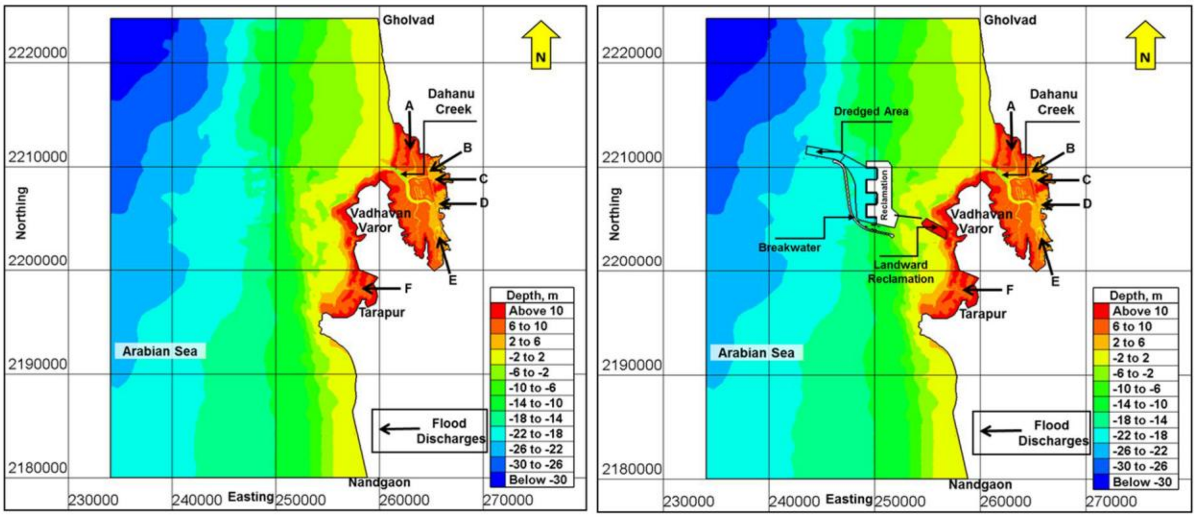
8.2 Model Studies for Flooding with Scenario-1

The model studies were carried out considering the local model with existing bathymetry condition as well as with finalised Master Plan layout of Port condition (CWPRS TR No.5968 of Nov. 2021) for Scenario-1. The Scenario-1 considers the simulation of the combined effect of storm tide (Rise in water level due to storm + tidal level for Case-1 to 3) +

Runoff discharges in the form of Hydrographs (Rainfall occurred during such stormy conditions only) for respective return periods of 1 in 25, 1 in 50 and 1 in 100 years and respective various return period significant wave heights also. The storm tides were considered at boundaries for simulation of flooding due to cyclonic storms along with parameters considered for calibration of the model. The likely rise in water/ flood level in Dahanu creek and control area were determined for these return periods and are described in following paragraphs.

8.2.1 Studies for Flooding with Scenario-1 for 1 in 25 yrs RP

The studies were carried out to assess the impact of proposed development of port at Vadhavan on the flooding in control area by carrying out simulation for existing bathymetry condition as well as finalised Master Plan layout condition. The bathymetry for existing condition and finalised Master Plan layout of Port condition are shown in FIG.42.



(A) Existing Bathymetry Condition **(B) Master Plan Layout Condition**

FIG.42: Bathymetry for existing & master plan layout conditions

The significant wave height for 1 in 25 yrs RP estimated from EVA is 5.54 m while rise in water level is 1.16 m. The storm tides for 1 in 25 yrs RP mentioned in Table-IX to Table-XI were considered as boundary conditions along with flood hydrographs for Scenario-1 (mentioned under heading 4.9 on page no. 23) at various locations for 1 in 25 yrs RP. These parameters along with intake/outfall discharges of Dahanu Thermal Power Plant were used for the studies.

The simulations for existing bathymetry condition as well as finalised Master Plan layout condition for Scenario-1 were carried out and the extent of flooding is determined in terms of ground level in meters w.r.t. CD of Dahanu up to which water is likely to spread. The regions where data on the extent of flooding was extracted is shown in FIG. 43(A) while zoomed portions of the same are shown in FIG. 43(B), 43(C) & 43(D).

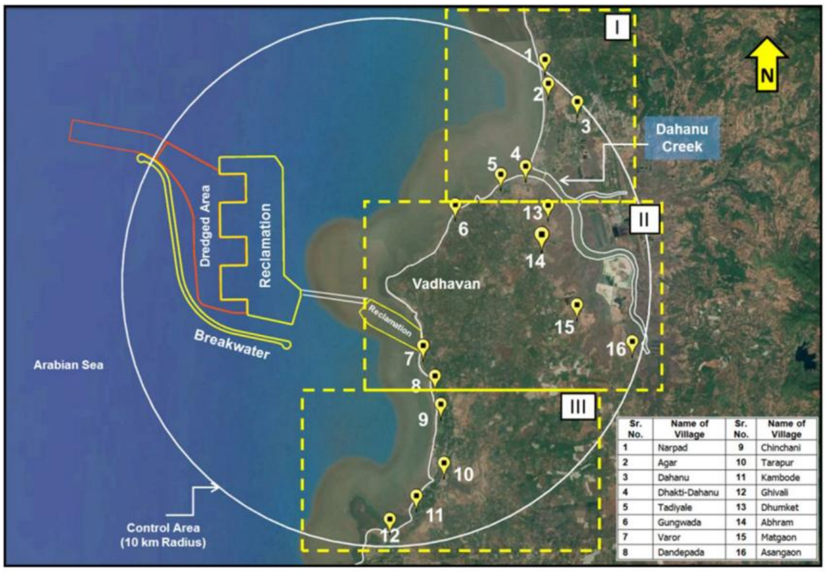


FIG.43(A) : Regions for data extraction on extent of flooding

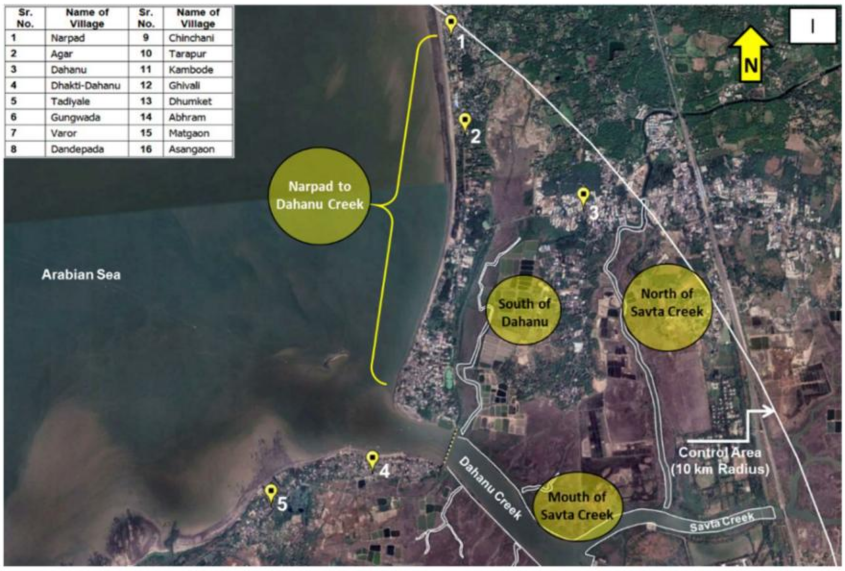


FIG.43(B) : Zoomed portion of Part-I

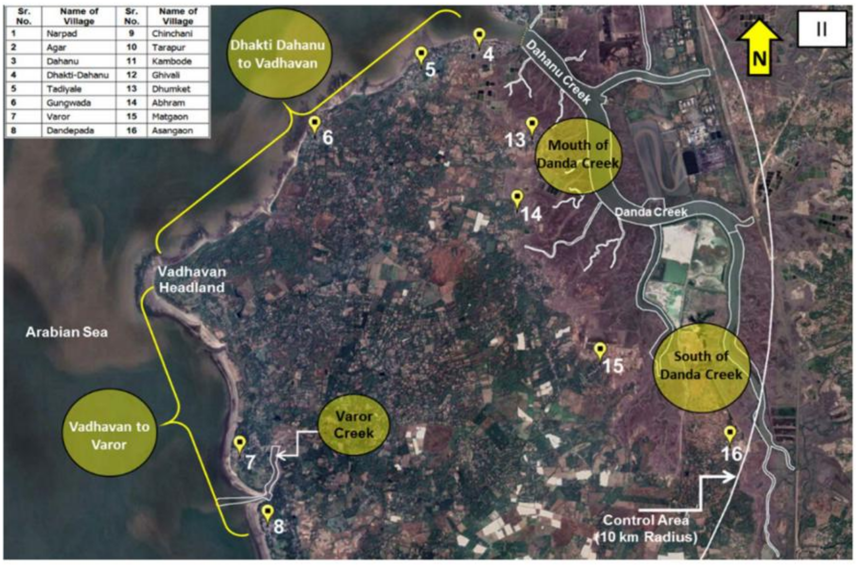


FIG.43(C) : Zoomed portion of Part-II

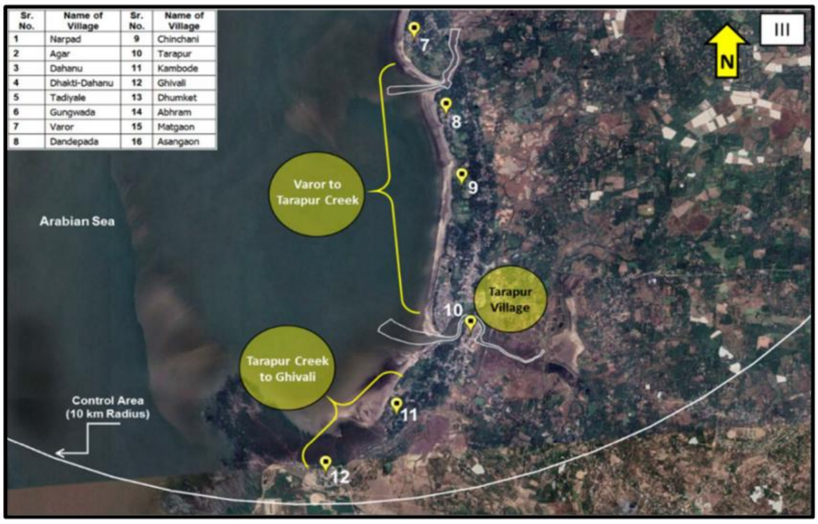


FIG.43(D) : Zoomed portion of Part-III

The data extracted from model for existing & port conditions is represented in the form of bar charts and are shown in FIG. 44(A) & 44(B) respectively.

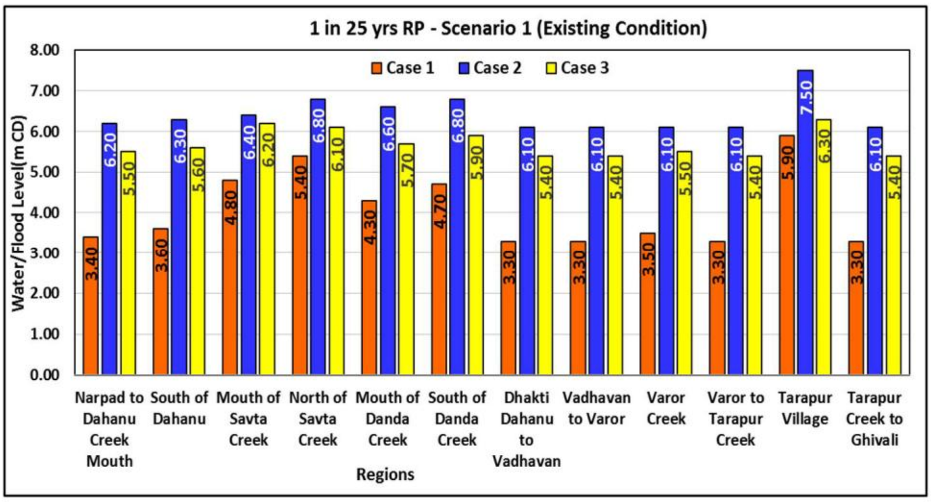


FIG.44(A) : Data on extent of flooding 1 in 25 yrs RP –Scenario 1 (Existing Condition)

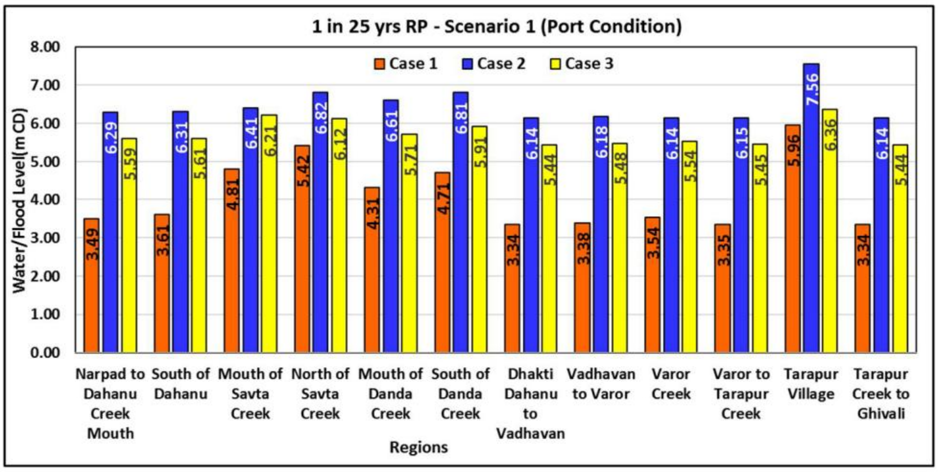


FIG.44(B) : Data on extent of flooding 1 in 25 yrs RP –Scenario 1 (Port Condition)

It can be inferred from above plots that there is practically no / insignificant impact due to development of port at Vadhavan on flooding in Dahanu creek and control area for 1 in 25 yrs. RP (Scenario-1) condition.

8.2.2 Studies for Flooding with Scenario-1 for 1 in 50 yrs RP

The studies were carried out to assess the impact of proposed development of port at Vadhavan on the flooding in control area by carrying out simulation for existing bathymetry condition as well as finalised Master Plan layout (FIG.42) conditions for 1 in 50 yrs RP (Scenario-1).

The significant wave height for 1 in 50 yrs. RP estimated from EVA is 6.50 m, while rise in water level is 1.6 m. The storm tides for 1 in 50 yrs RP mentioned in Table-IX to Table-XI were considered as boundary conditions along with flood hydrographs for Scenario-1 (mentioned under heading 4.9 on page no. 23) at various locations for 1in 50 yrs RP. These parameters along with intake/outfall discharges of Dahanu Thermal Power Plant were used for the studies.

The simulations for existing bathymetry condition as well as finalised Master Plan layout condition for Scenario-1 were carried out and the extent of flooding is determined in terms of ground level in meters w.r.t. CD of Dahanu up to which water is likely to spread. The data on likely spread of flood water was extracted from regions shown in FIG. 43(A).

The data extracted from model for existing & port conditions is represented in the form of bar charts and are shown in FIG. 45(A) & 45(B) respectively.

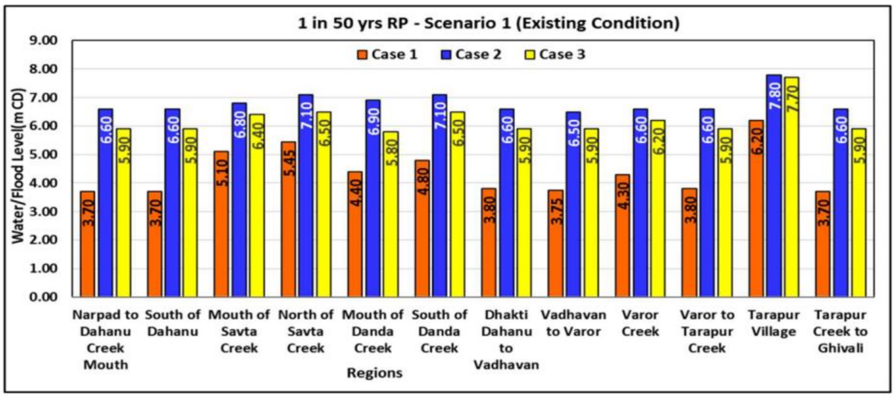


FIG.45(A) : Data on extent of flooding 1 in 50 yrs RP –Scenario 1 (Existing Condition)

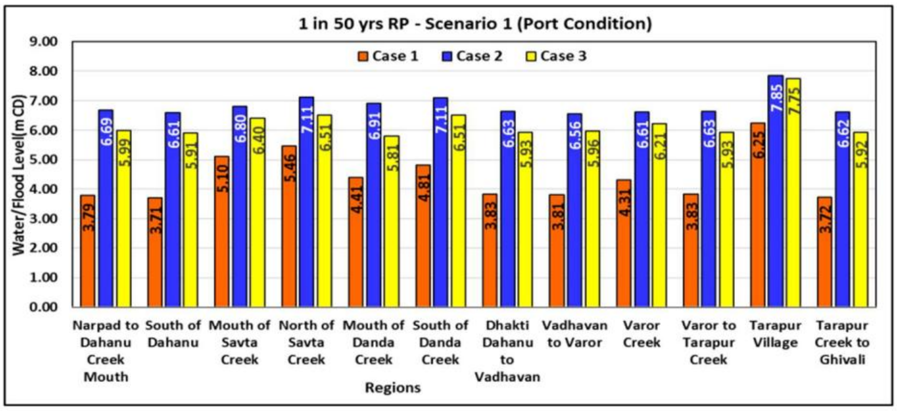


FIG.45(B) : Data on extent of flooding 1 in 50 yrs RP –Scenario 1 (Port Condition)

It can be inferred from above plots that there is no significant change in the extent of flooding due to development of port at Vadhavan in Dahanu creek and control area for 1 in 50 yrs RP (Scenario-1) condition.

8.2.3 Studies for Flooding with Scenario-1 for 1 in 100 yrs RP

The studies were carried out to assess the impact of proposed development of port at Vadhavan on the flooding in control area by carrying out simulation for existing bathymetry condition as well as finalised Master Plan layout (FIG.42) conditions for 1 in 100 yrs RP (Scenario-1).

The significant wave height for 1 in 100 yrs RP estimated from EVA is 7.46 m, while rise in water level is 2.1 m. The storm tides for 1 in 100 yrs RP mentioned in Table-IX to Table-XI were considered as boundary conditions along with flood hydrographs for Scenario-1 (mentioned under heading 4.9 on page no. 23) at various locations for 1in 100 yrs RP. These parameters along with intake/outfall discharges of Dahanu Thermal Power Plant were used for the studies.

The model studies were carried out for existing bathymetry condition as well as finalised Master Plan layout condition for Scenario-1 and the extent of flooding is determined in terms of ground level in meters w.r.t. CD of Dahanu up to which water is likely to spread. The data on likely spread of flood water was extracted from regions shown in FIG. 43(A).

The data extracted from model for existing & port conditions is represented in the form of bar charts and are shown in FIG. 46(A) & 46(B) respectively.

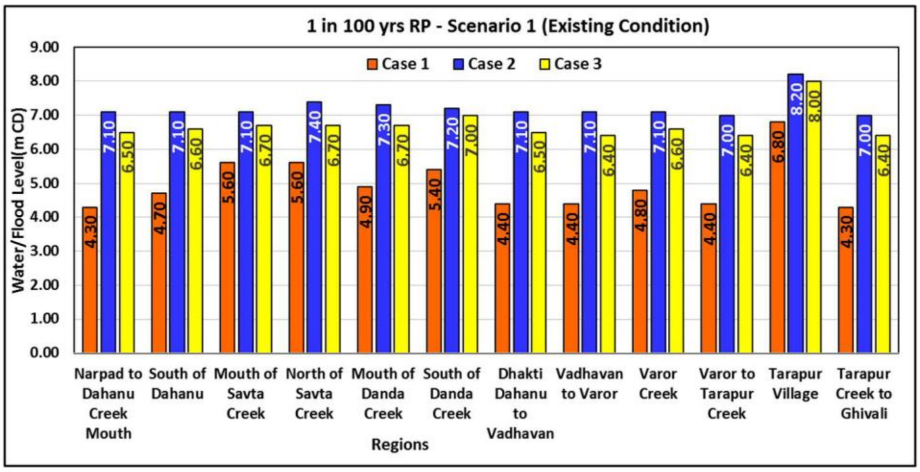


FIG.46(A) : Data on extent of flooding 1 in 100 yrs RP –Scenario 1 (Existing Condition)

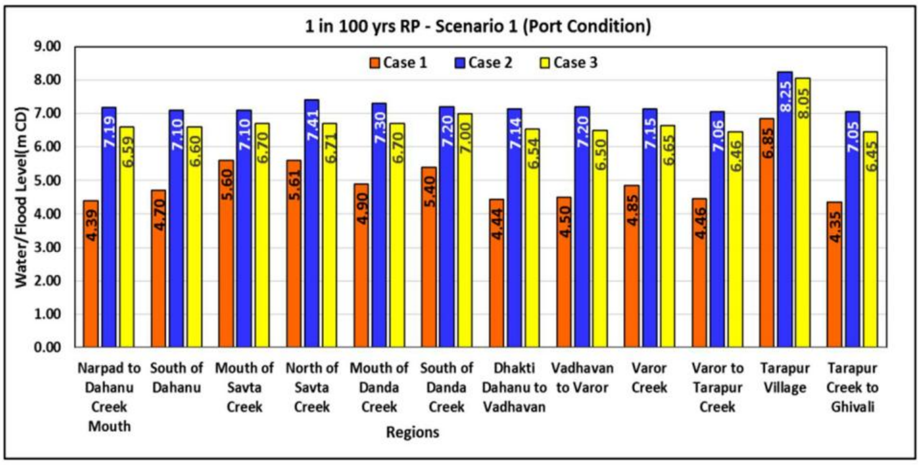


FIG.46(B) : Data on extent of flooding 1 in 100 yrs RP –Scenario 1 (Port Condition)

The above plots indicate that there is practically no change in the extent of flooding due to development of port at Vadhavan in Dahanu creek and control area for 1 in 100 yrs RP (Scenario-1) condition. It is also observed that the runoff discharges contribute significantly in flooding only inside the Dahanu & Tarapur creek area and not along the open coast.

8.3 Model Studies for Flooding with Scenario-2

The model studies were carried out considering the local model with existing bathymetry condition as well as with finalised Master Plan layout of Port condition for Scenario-2. The Scenario-2 considers the combined effect of storm tide (Rise in water level due to storm + tidal level for Case 1 to 3) + Runoff discharges (considering past 50 years of rainfall data) for respective return periods of 1 in 25, 1 in 50 and 1 in 100 years. The storm tides were considered at boundaries for simulation of flooding due to cyclonic storms along with parameters considered for calibration of the model. The likely rise in water/ flood level in Dahanu creek and control area were estimated for these return periods and described in following paragraphs.

8.3.1 Studies for Flooding with Scenario-2 for 1 in 25 yrs RP

The studies were carried out to assess the impact of proposed development of port at Vadhavan on the flooding in control area by carrying out simulation for existing bathymetry condition as well as finalised Master Plan layout condition. The bathymetry for existing condition and finalised Master Plan layout of Port condition are shown in FIG.42.

The significant wave height for 1 in 25 yrs RP estimated from EVA is 5.54 m while rise in water level is 1.16m. The storm tides for 1 in 25 yrs RP mentioned in Table-IX to Table-XI were considered as boundary conditions along with flood hydrographs for Scenario-2 (mentioned under heading 4.9 on page no. 23) at various locations for 1in 25 yrs RP. These parameters along with intake/outfall discharges of Dahanu Thermal Power Plant were used for the studies.

The simulations for existing bathymetry condition as well as finalised Master Plan layout condition for Scenario-2 were carried out and the extent of flooding is determined in terms of ground level in meters w.r.t. CD of Dahanu up to which water is likely to spread. The data on likely spread of flood water was extracted from regions shown in FIG. 43(A).

The data extracted from model for existing & port conditions is represented in the form of bar charts and are shown in FIG. 47(A) & 47(B) respectively.

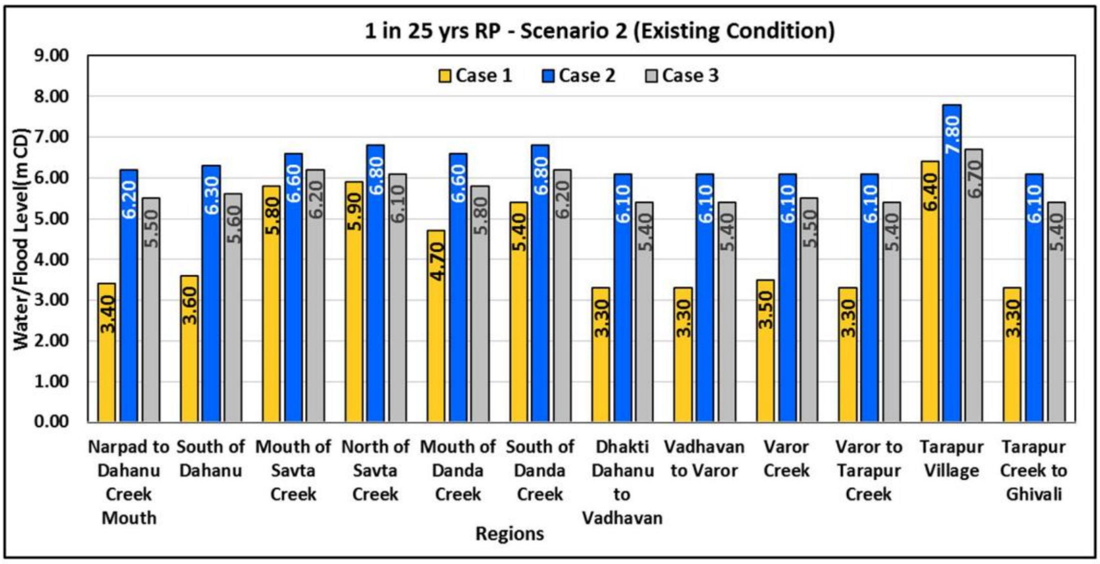


FIG.47(A) : Data on extent of flooding 1 in 25 yrs RP –Scenario 2 (Existing Condition)

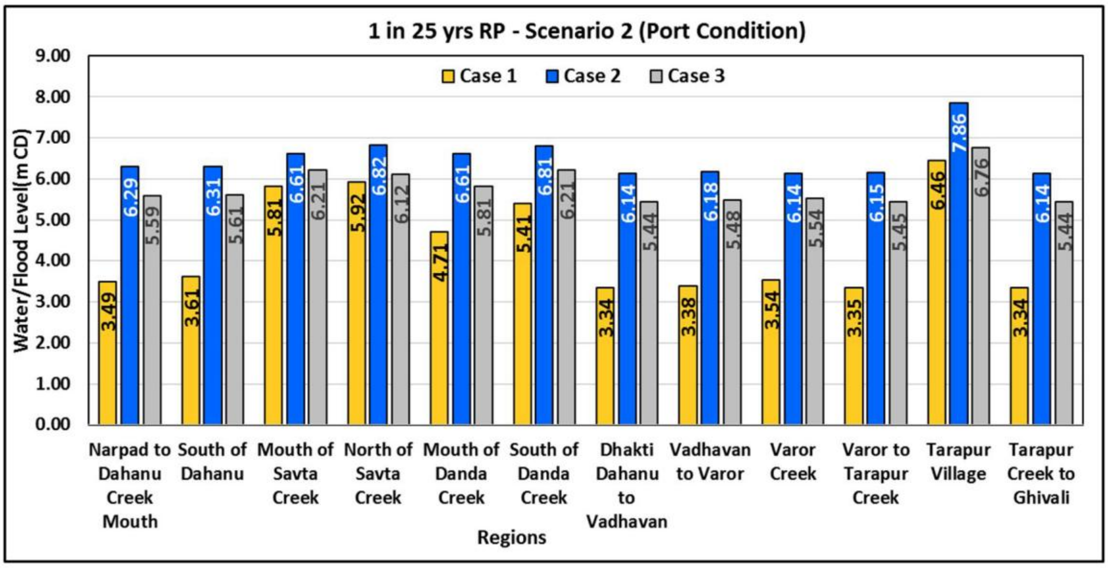


FIG.47(B) : Data on extent of flooding 1 in 25 yrs RP –Scenario 2 (Port Condition)

It can be inferred from above plots that there is no significant change in the extent of flooding due to development of port at Vadhavan in Dahanu creek and control area for 1 in 25 yrs RP (Scenario-2) condition. It is also observed that the extent of flooding inside the Dahanu and Tarapur creek area has increased marginally than that for the Scenario-1 due to the increase in runoff discharges in these creeks.

8.3.2 Studies for Flooding with Scenario-2 for 1 in 50 yrs RP

The studies were carried out to assess the impact of proposed development of port at Vadhavan on the flooding in control area by carrying out simulation for existing bathymetry condition as well as finalised Master Plan layout (FIG.42) condition for 1 in 50 yrs RP (Scenario-2).

The significant wave height for 1 in 50 yrs RP estimated from EVA is 6.50 m, while rise in water level is 1.6 m. The storm tides for 1 in 50 yrs RP mentioned in Table-IX to Table-XI were considered as boundary conditions along with flood hydrographs for Scenario-

2 (mentioned under heading 4.9 on page no. 23) at various locations for 1in 50 yrs RP. These parameters along with intake/outfall discharges of Dahanu Thermal Power Plant were used for the studies.

The model studies were carried out for existing bathymetry condition as well as finalised Master Plan layout condition for Scenario-2 and the extent of flooding is determined in terms of ground level in meters w.r.t. CD of Dahanu up to which water is likely to spread. The data on likely spread of flood water was extracted from regions shown in FIG. 43(A).

The data extracted from model for existing & port conditions is represented in the form of bar charts and are shown in FIG. 48(A) & 48(B) respectively.

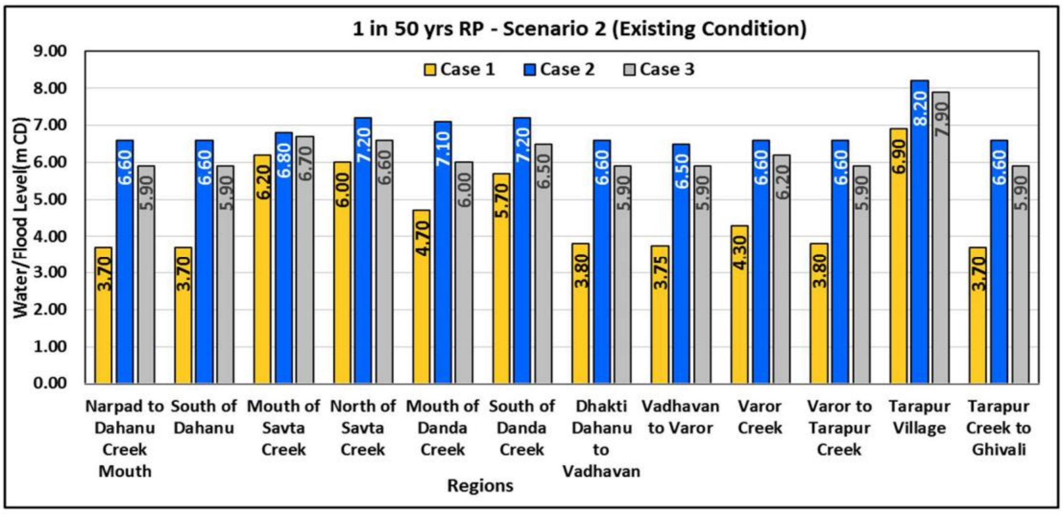


FIG.48(A) : Data on extent of flooding 1 in 50 yrs RP –Scenario 2 (Existing Condition)

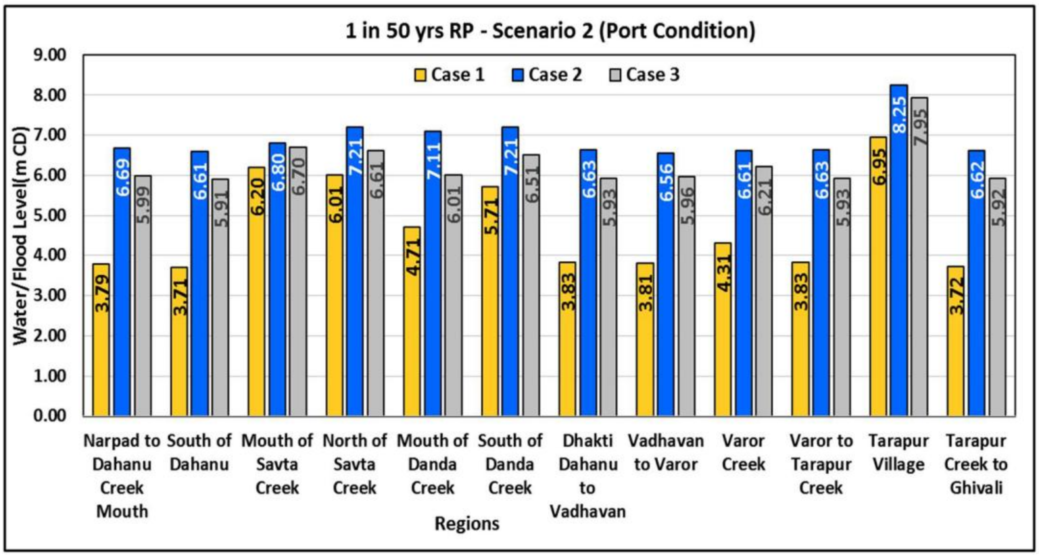


FIG.48(B) : Data on extent of flooding 1 in 50 yrs RP –Scenario 2 (Port Condition)

It is observed that the runoff discharges contribute significantly in flooding inside the Dahanu & Tarapur creek area only and not along the open coast. The extent of flooding inside the Dahanu & Tarapur creeks is observed to be increased in Scenario-2 than that in Scenario-1 due to increase in runoff discharges. The above plots indicate that there is practically no change in the extent of flooding due to development of port at Vadhavan in Dahanu creek and control area for 1 in 50 yrs RP (Scenario-2) condition.

8.3.3 Studies for Flooding with Scenario-2 for 1 in 100 yrs RP

The studies were carried out to assess the impact of proposed development of port at Vadhavan on the flooding in control area by carrying out simulation for existing bathymetry condition as well as finalised Master Plan layout (FIG.42) condition for 1 in 100 yrs RP (Scenario-2).

The significant wave height for 1 in 100 yrs RP estimated from EVA is 7.46 m while rise in water level is 2.1 m. The storm tides for 1 in 100 yrs RP mentioned in Table-IX to Table-XI were considered as boundary conditions along with flood hydrographs for Scenario-2 (mentioned under heading 4.9 on page no. 23) at various locations for 1in 100 yrs RP. These parameters along with intake/outfall discharges of Dahanu Thermal Power Plant were used for the studies.

The model studies were carried out for existing bathymetry condition as well as finalised Master Plan layout condition for Scenario-2 and the extent of flooding is determined in terms of ground level in meters w.r.t. CD of Dahanu up to which water is likely to spread. The data on likely spread of flood water was extracted from regions shown in FIG. 43(A).

The data extracted from model for existing & port conditions is represented in the form of bar charts and are shown in FIG. 49(A) & 49(B) respectively.

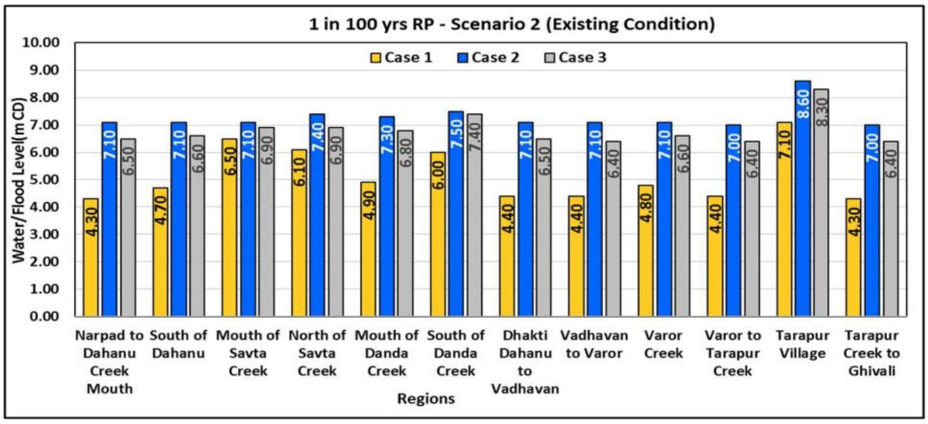


FIG.49(A) : Data on extent of flooding 1 in 100 yrs RP –Scenario 2 (Existing Condition)

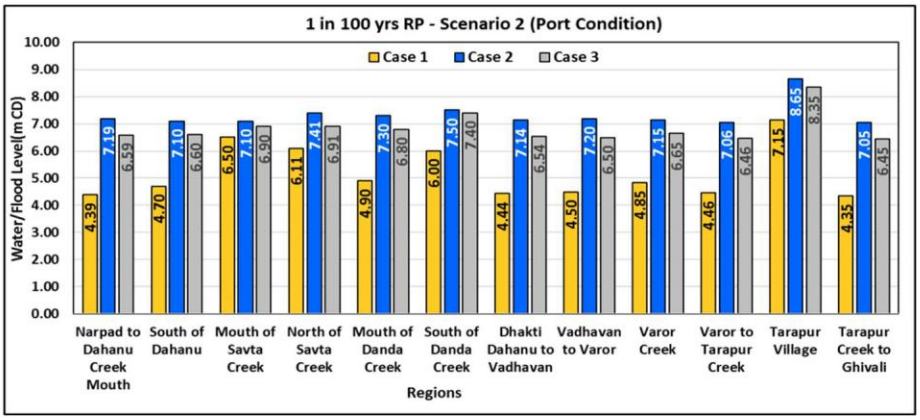


FIG.49(B) : Data on extent of flooding 1 in 100 yrs RP –Scenario 2 (Port Condition)

The above plots indicate that due to the development of port at Vadhavan there is insignificant / no variation in the extent of flooding in Dahanu creek and control area for 1 in 100 yrs RP (Scenario-2) condition. It is also observed that due to increase in runoff discharges in Scenario-2, the extent of flooding inside the Dahanu & Tarapur creeks is increased than that in Scenario-1.

Note: The studies are carried out and reported based on the data provided by JN Port for oceanographic parameters, bathymetry, topography of the area, Dahanu Thermal Power Plant data, bridge details etc. for the studies. The model studies were carried out considering Scenario-1 (Flooding due to cyclonic storms + rainfall (occurred during such stormy conditions only)) & Scenario-2 (Flooding due to cyclonic storms + rainfall (considering past 50 years of rainfall data)). It is observed from FIG.17 that the storms which are of significance for Vadhavan area have occurred in the months of May & June and September to November i.e. mostly during pre & post monsoon seasons. Thus, the probability of considering past 50 years of rainfall data and its simultaneous occurrence with rise in water level due to storm (SS) considered in Scenario-2 is very less as compared with Scenario-1. It is observed that the Case-1 mentioned under Joint Probability Analysis (Heading 7, Page 39) prevails at site however considering the fact that some of the storms which has occurred in the past considered for analysis indicate that 'SS' has also occurred during nearest high waters (within 6 hrs) and as such studies for the same (storm surge during high tide), Case-2 & 3 were also considered for the studies. However, based on the past fifty years (1970 – 2020) of cyclonic storm data, the occurrence of Case-2, Case-3 & Scenario-2 is rare in nature.

9. CONCLUSIONS

1. The bathymetry data at proposed Vadhavan port site (Year 2017), Dahanu creek area (Year 2021) supplied by JN port as well as for the region of Arabian sea from Kerala up to Gujarat with seaside depth up to 4600 m and up to West Coast of India is taken from GEBCO-2021 & MIKE C-map database and was used for the regional model domain. The topographic data with 10 m grid interval of Dahanu creek & nearby region within control area (10 km radius from headland at Vadhavan) from HTL up to +10 m CD contour carried out by JN Port was also used to reproduce the topography of the region.
2. The oceanographic data collected at the proposed port location at Vadhavan on various parameters such as tide, current, waves, bed samples etc. during January-February 2017 (non-monsoon) as well as September–October 2020 (monsoon) indicate that the tides are semi-diurnal in nature with diurnal inequality. The maximum tidal range during non-monsoon season is about 5.87 m during spring tide and it is 2.1 m during neap tide; while during monsoon season, it is about 6.0 m during spring

tide and 1.14 m during neap tide. This indicates that the proposed project is in macro tidal region.

3. The information on current strength measured at mid-depth in the port area during non-monsoon season reveal that the maximum strength of the current is about 1.25 m/s during spring tide while it is about 0.50 m/s during neap tide. The current direction w.r.t. north varies between 3° – 23° during flood tide, while it is about 204° – 215° during ebb tide. Similarly, during monsoon season, the maximum strength of the current is about 1.4 m/s during spring tide while it is about 0.4 m/s during neap tide. The current direction w.r.t. north varies between 16° – 23° during flood tide, while it is about 203° – 210° during ebb tide. The information on wave data indicate that the maximum significant wave height (Hs) is 1.19 m during non-monsoon season and the waves mainly approaches from N-W quadrant while for monsoon season the maximum significant wave height (Hs) is 2.3 m and the waves approaches from SW-WNW quadrant. (Ref. CWPRS TR. No. 5968 November 2021). The analyses of the bed samples indicate that the material is Clayey Silt with average D_{50} = 0.011 mm.
4. The wave data (height, direction & period) obtained from Indian National Centre for Ocean Information Services (INCOIS) and supplied by JN Port at three locations viz. SW01 for period of 15th -26th May 2001; at CB03 for the period 1st -15th June 2012 and Versova wave rider buoy for the period 1st – 10th December 2017 was used for the calibration of regional model for waves during cyclonic conditions. Similarly, the wind data (speed & direction) was also obtained from INCOIS at two locations viz. SW01 (Lat. 20.89°N; Long. 71.5°E) for period of 15th - 26th May 2001 and at CB03 (Lat. 20.27802°N; Long. 71.87767°E) for the period 1st - 15th June 2012 was used for the calibration of regional model for wind conditions.
5. Based on the past 50 years (1970-2020) of cyclonic data, out of total 125 storms in the Arabian Sea, 44 cyclonic events are of significance to the proposed port development at Vadhavan and as such are considered for the studies. The information on storm track, central pressure as well as maximum sustained wind speed etc. for the cyclonic storms available with Indian Meteorological Department (IMD) along with Joint Typhoon Warning Centre (JTWC) best track information as well as from the ECMWF database is used to simulate the cyclonic storm events.
6. The estimation of flood hydrographs was carried by HMET Division of CWPRS (CWPRS TR. No. 5985 of January 2022) at six locations (FIG.21) for 25 years, 50 years & 100 years return period by considering two scenarios viz. (i) Flooding due to cyclonic storms + rainfall (occurred during storm conditions only) and (ii) Flooding due to cyclonic storms + rainfall (considering past 50 years of rainfall data). These flood hydrographs are used to simulate runoff discharges in the control area considered in the model domain.

7. The tidal hydrodynamic simulation of regional model developed for Arabian sea region is carried out by considering TPXO tides as boundary conditions and the results reveals that for the existing bathymetry condition, tide measured at Dahanu and observed in model compares reasonably well and is 90% in agreement.
8. The wind data considered for simulation of cyclonic events and measured at “SW01” near Diu, Gujarat indicates that both are reasonably in agreement with each other. Thus wind data considered for model properly simulates wind field (FIG. 28) thereby simulates the reliable wind field.
9. The cyclonic storm events for the year 2001 & 2017 simulating cyclonic wind field for wave propagation studies reveal that the wave data extracted from regional model at “SW01” & Versova Buoy locations compare well with that measured (FIG.29(A) & 29(B)). Also rise in water level observed during cyclonic event in model is 2.1 m and is in good agreement with that observed at site i.e. 2.0 m. Thus, it can be inferred that the cyclonic storm model is reasonably well calibrated with respect to water level, wind field, significant wave heights & direction as well in the area under consideration. The data on rise in water level and significant wave height is extracted in the model domain of local model of Vadhavan port (Vadhavan port & control area) for all 44 cyclonic stormy events.
10. The prediction of extreme value of significant wave height (Hs) and rise in water level (SS) based on analysis of cyclonic events is carried out by censoring the data based on Peak over threshold (POT) method and fitting data set to various distribution functions viz. FT-I, FT-II, Weibull for various shape parameters (k) and it reveals that for rise in water level (FT-II, k=2.5) distribution gives highest co-relation co-efficient and the predicted rise in water level (Table-VIII) will be 1.16 m, 1.6 m & 2.1 m for 1 in 25 yrs, 1 in 50 yrs & 1 in 100 yrs return periods respectively; while the extreme value of significant wave height happens to give best fit (FT-I) type of distribution function and significant wave height (Hs) predicted (Table-VII) are as 5.54 m, 6.50 m & 7.46 m for 1 in 25 yrs, 1 in 50 yrs & 1 in 100yrs return periods respectively due to cyclonic storms.
11. The determination of storm tidal level to simulate simultaneous occurrence of tide level along-with rise in water level (SS) plays a crucial role in determining the flood level under combined effect of hydrographs from riverine areas, significant wave heights from seaside and storm tidal level. In such cases, problem is multivariate in nature. However, in present case the effect of hydrographs on flood levels on open coast is not significant in macro tidal region under consideration and thus Joint probability analysis of rise in water level (storm surge) and tide is carried for three cases viz.

   1) The occurrence of maximum rise in water level(SS) and corresponding tidal level

2) The occurrence of maximum rise in water level and the maximum high tide in proximity of the occurrence of maximum rise in water level(SS) and
3) The occurrence of maximum rise in water level(SS) and the second-high tide in proximity of the occurrence of maximum rise in water level.

The case-2 and case-3 are considered in view of the fact that out of total 44 cyclonic events, during 22 cyclones it has been found that maximum rise in water level had occurred in proximity of maximum high tide or of second high tide. Considering the above facts, the studies carried out for simultaneous occurrence of maximum rise in water level and high tide provides maximum extent of flooding as a conservative approach. The studies carried out reveal that for Case-1, storm tidal levels (Table-IX) will be 3.18 m, 3.63 m, 4.20 m while for Case-2 (Table-X) as 5.81 m, 6.26 m, 6.80 m and for Case-3 (Table-XI) they are 5.35 m, 5.80 m, 6.31 m for 1 in 25 yrs, 1 in 50 yrs & 1 in 100yrs return periods respectively.

12. The local model developed for Vadhavan area for the oceanographic data provided reveal that for the prevailing existing bathymetry condition, tide measured at the mouth of Dahanu creek and observed in model compares well and is 95% in agreement. Similarly, current strength & direction are also in good agreement with that observed at site both for non-monsoon as well as monsoon season. Thus mathematical model is reasonably well calibrated for the prevailing hydrodynamic flow conditions at the proposed port location for the tide and current data provided by JN Port for non-monsoon and monsoon seasons.
13. The simulations are carried out using local model to assess the flooding in Dahanu creek & control area due to cyclonic storm events with the storm tides (Maximum rise in water level + estimated tidal level) as boundary conditions along with runoff discharges at various locations viz. “A”, “B”, “C”, “D” and “E”, “F” for all three cases (Case-1, Case-2, Case-3) with two scenarios Scenario-1 & Scenario-2 each for 1 in 25 yrs, 1 in 50 yrs & 1 in 100yrs return periods, reveal that the flood levels on the open coast are mainly governed by tides/waves while that inside the Dahanu & Tarapur creek area are governed by the combined effect of tides & runoff discharges due to rainfall/runoff. However, the effect of runoff discharges is significant than that of the tides inside the creeks and thus the extent of flooding is more due to Scenario-2 discharges than that due to the Scenario-1.
14. The model studies for all combinations/cases reveal that there is practically no variation (less than 15 cm) in extent of flooding / water levels within control area (10 km radius from headland at Vadhavan) due to proposed development of port at Vadhavan (about 6 km offshore of headland at Vadhavan) as compared to the extent of flooding observed for the existing condition (without port).

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Annexure-A

Results of distribution fitting to Wave height data using method of least squares

m	H_s	FT-I		FT-II(k=10)		Weibull (k=1.4)		Weibull (k=2)		FT-II (k= 2.5)		FT-II (k= 3.33)		FT-II (k= 5)		Weibull (k= 0.75)		Weibull (k= 1)	
	$x_{(m)}$	$\hat{F}_{(m)}$	$y_{(m)}$	$\hat{F}_{(m)}$	$y_{(m)}$	$\hat{F}_{(m)}$	$y_{(m)}$	$\hat{F}_{(m)}$	$y_{(m)}$	$\hat{F}_{(m)}$	$y_{(m)}$	$\hat{F}_{(m)}$	$y_{(m)}$	$\hat{F}_{(m)}$	$y_{(m)}$	$\hat{F}_{(m)}$	$y_{(m)}$	$\hat{F}_{(m)}$	$y_{(m)}$
1	6.90	0.987	4.360	0.988	5.618	0.987	2.859	0.986	2.071	0.992	14.731	0.991	10.281	0.990	7.463	0.989	7.455	0.988	4.429
2	6.50	0.965	3.324	0.966	3.991	0.965	2.367	0.964	1.821	0.969	7.512	0.968	6.000	0.967	4.858	0.967	5.107	0.966	3.369
3	5.67	0.942	2.817	0.943	3.282	0.942	2.112	0.941	1.683	0.947	5.486	0.945	4.581	0.944	3.858	0.944	4.104	0.943	2.866
4	4.75	0.919	2.475	0.920	2.828	0.920	1.935	0.919	1.584	0.924	4.397	0.923	3.770	0.922	3.253	0.922	3.475	0.921	2.533
5	4.10	0.897	2.216	0.898	2.495	0.897	1.798	0.896	1.505	0.901	3.683	0.900	3.218	0.899	2.825	0.899	3.024	0.898	2.283
6	4.00	0.874	2.005	0.875	2.232	0.874	1.685	0.874	1.438	0.879	3.164	0.877	2.804	0.876	2.496	0.877	2.676	0.876	2.084
7	3.65	0.851	1.827	0.852	2.014	0.852	1.588	0.851	1.380	0.856	2.762	0.855	2.477	0.854	2.229	0.854	2.394	0.853	1.918
8	3.60	0.829	1.672	0.830	1.828	0.829	1.503	0.828	1.328	0.833	2.437	0.832	2.208	0.831	2.005	0.832	2.159	0.831	1.775
9	3.10	0.806	1.534	0.807	1.665	0.807	1.427	0.806	1.280	0.811	2.166	0.809	1.980	0.808	1.813	0.809	1.959	0.808	1.650
10	3.03	0.783	1.410	0.784	1.521	0.784	1.358	0.783	1.237	0.788	1.936	0.787	1.782	0.786	1.644	0.787	1.786	0.786	1.539
11	3.00	0.761	1.296	0.762	1.390	0.762	1.294	0.761	1.196	0.765	1.735	0.764	1.609	0.763	1.494	0.764	1.633	0.763	1.440
12	2.96	0.738	1.191	0.739	1.271	0.739	1.235	0.738	1.158	0.742	1.559	0.741	1.454	0.740	1.358	0.742	1.497	0.740	1.349
13	2.90	0.715	1.094	0.716	1.161	0.717	1.181	0.716	1.122	0.720	1.401	0.719	1.314	0.718	1.234	0.719	1.375	0.718	1.266
14	2.70	0.693	1.002	0.694	1.058	0.694	1.129	0.693	1.087	0.697	1.258	0.696	1.186	0.695	1.120	0.697	1.265	0.695	1.189
15	2.69	0.670	0.915	0.671	0.963	0.672	1.080	0.671	1.054	0.674	1.129	0.673	1.069	0.672	1.014	0.674	1.165	0.673	1.118
16	2.64	0.647	0.833	0.648	0.872	0.649	1.034	0.648	1.022	0.652	1.010	0.651	0.961	0.650	0.915	0.652	1.074	0.650	1.051
17	2.56	0.625	0.754	0.626	0.787	0.627	0.990	0.626	0.991	0.629	0.900	0.628	0.860	0.627	0.822	0.629	0.989	0.628	0.989
Parameter A		**1.3703**		1.0434		2.6070		4.4298		0.3668		0.5437		0.7689		0.7798		1.4449	
Parameter B		**1.3323**		1.6620		-0.2663		-2.1732		2.5732		2.2879		1.9815		1.8301		1.0171	
Correlation		**0.9808**		0.9763		0.9811		0.9777		0.9165		0.9453		0.9649		0.9724		0.9806	
MIR		**0.5948**		0.6789		0.6550		0.8376		1.5191		1.1771		0.8762		0.7625		0.6061	

Annexure-B

Results of distribution fitting to rise in water level (SS) data using method of least squares

m	$x_{(m)}$	FT-I		FT-II(k=10)		Weibull (k=1.4)		Weibull (k=2)		FT-II (k=2.5)		FT-II (k= 3.33)		FT-II (k= 5)		Weibull (k= 0.75)		Weibull (k=1)	
		$\hat{F}_{(m)}$	$y_{(m)}$	$\hat{F}_{(m)}$	$y_{(m)}$	$\hat{F}_{(m)}$	$y_{(m)}$	$\hat{F}_{(m)}$	$y_{(m)}$	$\hat{F}_{(m)}$	$y_{(m)}$	$\hat{F}_{(m)}$	$y_{(m)}$	$\hat{F}_{(m)}$	$y_{(m)}$	$\hat{F}_{(m)}$	$y_{(m)}$	$\hat{F}_{(m)}$	$y_{(m)}$
1	2.32	0.987	4.360	0.988	5.618	0.987	2.859	0.986	2.071	0.992	14.731	0.991	10.281	0.990	7.463	0.989	7.455	0.988	4.429
2	1.92	0.965	3.324	0.966	3.991	0.965	2.367	0.964	1.821	0.969	7.512	0.968	6.000	0.967	4.858	0.967	5.107	0.966	3.369
3	0.85	0.942	2.817	0.943	3.282	0.942	2.112	0.941	1.683	0.947	5.486	0.945	4.581	0.944	3.858	0.944	4.104	0.943	2.866
4	0.79	0.919	2.475	0.920	2.828	0.920	1.935	0.919	1.584	0.924	4.397	0.923	3.770	0.922	3.253	0.922	3.475	0.921	2.533
5	0.67	0.897	2.216	0.898	2.495	0.897	1.798	0.896	1.505	0.901	3.683	0.900	3.218	0.899	2.825	0.899	3.024	0.898	2.283
6	0.61	0.874	2.005	0.875	2.232	0.874	1.685	0.874	1.438	0.879	3.164	0.877	2.804	0.876	2.496	0.877	2.676	0.876	2.084
7	0.6	0.851	1.827	0.852	2.014	0.852	1.588	0.851	1.380	0.856	2.762	0.855	2.477	0.854	2.229	0.854	2.394	0.853	1.918
8	0.6	0.829	1.672	0.830	1.828	0.829	1.503	0.828	1.328	0.833	2.437	0.832	2.208	0.831	2.005	0.832	2.159	0.831	1.775
9	0.57	0.806	1.534	0.807	1.665	0.807	1.427	0.806	1.280	0.811	2.166	0.809	1.980	0.808	1.813	0.809	1.959	0.808	1.650
10	0.54	0.783	1.410	0.784	1.521	0.784	1.358	0.783	1.237	0.788	1.936	0.787	1.782	0.786	1.644	0.787	1.786	0.786	1.539
11	0.51	0.761	1.296	0.762	1.390	0.762	1.294	0.761	1.196	0.765	1.735	0.764	1.609	0.763	1.494	0.764	1.633	0.763	1.440
12	0.5	0.738	1.191	0.739	1.271	0.739	1.235	0.738	1.158	0.742	1.559	0.741	1.454	0.740	1.358	0.742	1.497	0.740	1.349
13	0.47	0.715	1.094	0.716	1.161	0.717	1.181	0.716	1.122	0.720	1.401	0.719	1.314	0.718	1.234	0.719	1.375	0.718	1.266
14	0.47	0.693	1.002	0.694	1.058	0.694	1.129	0.693	1.087	0.697	1.258	0.696	1.186	0.695	1.120	0.697	1.265	0.695	1.189
15	0.42	0.670	0.915	0.671	0.963	0.672	1.080	0.671	1.054	0.674	1.129	0.673	1.069	0.672	1.014	0.674	1.165	0.673	1.118
16	0.41	0.647	0.833	0.648	0.872	0.649	1.034	0.648	1.022	0.652	1.010	0.651	0.961	0.650	0.915	0.652	1.074	0.650	1.051
17	0.4	0.625	0.754	0.626	0.787	0.627	0.990	0.626	0.991	0.629	0.900	0.628	0.860	0.627	0.822	0.629	0.989	0.628	0.989
18	0.39	0.602	0.678	0.603	0.706	0.604	0.947	0.603	0.961	0.606	0.798	0.605	0.765	0.604	0.735	0.607	0.912	0.605	0.930
19	0.34	0.579	0.605	0.580	0.628	0.582	0.906	0.581	0.932	0.584	0.702	0.583	0.676	0.581	0.651	0.584	0.840	0.583	0.875
Parameter A		0.476		0.377		0.889		1.462		**0.149**		0.213		0.289		0.290		0.514	
Parameter B		-0.098		-0.015		-0.626		-1.208		**0.242**		0.156		0.069		0.019		-0.232	
Correlation		0.911		0.931		0.899		0.878		**0.957**		0.956		0.946		0.944		0.923	
MIR		2.902		2.081		3.769		4.978		**0.803**		0.979		1.389		1.608		2.544	

Annexure-C

Estimation of joint probability:

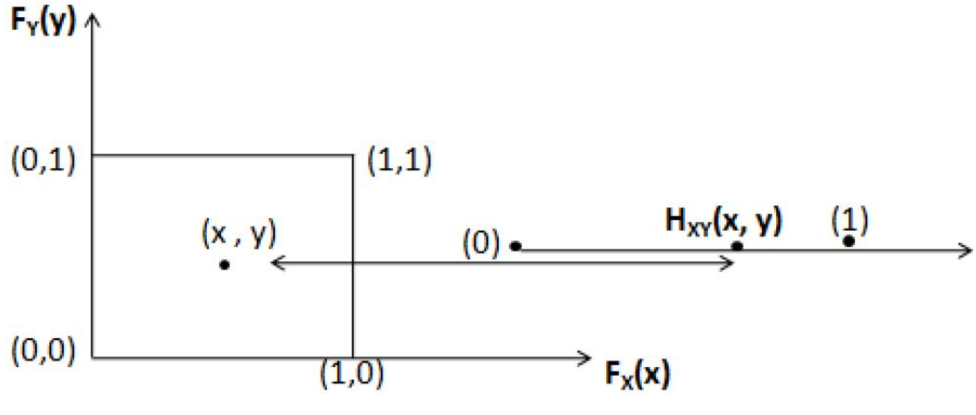
The estimation of joint probability was carried out using Copula distribution function. Copula is a kind of distribution functions which have been emerged as a powerful approach in obtaining a joint cumulative distribution function (CDF) F(x,y) for the random variables X & Y which has marginal distributions as u=FX(x) and v=FY(y). As per Sklar's theorem a copula function C can be described as C(u,v)=C(FX(x),FY(y)). Three widely used Archimedean Copulas such as Gumbel, Frank and Clayton which are considered to solve probabilistic problems in civil engineering especially in the water resource sector. The definitions for one parameter Copulas and the probability of are given below.

Copula	$C_\theta(u,v)$	Parameter
Gumbel	$C(u,v)=\exp\{-[(-\ln u)^\theta+(-\ln v)^\theta]^{1/\theta}\}$	$\theta\in[1,\infty)$
Frank	$C(u,v)=-\frac{1}{\theta}\ln[1+\frac{(e^{-\theta u}-1)(e^{-\theta v}-1)}{e^{-\theta}-1}]$	$\theta\in R\backslash\{0\}$
Clayton	$C(u,v)=(u^{-\theta}+v^{-\theta}-1)^{-1/\theta}$	$\theta\in(0,\infty)$

Expressions of one parameter Copula

Wherein θ is the dependence parameter for the two random variables and its estimation can be made either based on the number of count of concordant and discordant pair of dataset or from the operator of the copula.

If $F_X(x)$ & $F_Y(y)$ are the marginal distribution of two random variables then for each pair (x,y) will lead to a point in the unit square I [0,1] X I [0,1]. This ordered pair in turn corresponds to a number H(x, y) in [0,1]. This correspondence is indeed a function which is called Copula C.



Pictorial representation of Copula distribution function

Domain of C=S1 x S2 wherein S1 & S2 are the subset of I containing 0 & 1 i.e. I=[0,1]; for every u in S1 & v in S2 , C(u,1)=u & C(1,v)=v (u and v are the value of the marginal distribution function for any point)

Selection of Best fitted Copula is obtained by estimating the error (E) between the parametric K(z) estimate and non-parametric estimate. Where, Parametric estimate

$$K(z) = z - \frac{\phi(z)}{\phi'(z)}$$

$\varphi(z)$ is the operator for the copula. The non-parametric estimate Kn(z) can be computed as follows:

$$K_n(z) = \frac{\text{Number of } (x_j, y_j) \text{ such that } x_j < x_i \text{ and } y_j < y_i}{(N-1)}$$

The error (E) between the parametric and non-parametric estimate is estimated as follows:

$$E = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(K_z - K_n(z))^2}$$

In the present study, the selected random variables for the four scenarios are tide data and rise in water level. The expressions for marginal distribution functions (F) for the random variables for Gumbel, Weibull and FT type-II distributions are as follow:

$$F(X;k,\alpha,\beta) = \left\{ e^{-\left[1-k\left(\frac{x-\beta}{\alpha}\right)\right]^{\frac{1}{k}}} \; for\; k \neq 0 \right\}$$

$$F(X;k,\alpha,\beta) = \left\{ e^{-e^{-\left(\frac{(x-\beta)}{\alpha}\right)}} \; for\; k = 0 \right\}$$

The shape (k), scale (α), and location (β) parameters are estimated by using probability weighted method/maximum likely hood estimators. After having the information about the marginal distributions of the individual variables (H & Z) and their copula; the probability of exceeding the value of h and z together i.e. P((H>h)∩(Z>z)) and its return period T can be computed as follows:

$$P\cap(h,z) = P((H>h)\cap(Z>z)) = 1 - F_h(h) - F_z(z) + F(h,z)$$

$$T = \frac{1}{P}$$

Annexure-D

Photographs captured during Site Visit to Vadhavan Area from 18.05.2022 to 20.05.2022

Photo 1 : View of Upstream of Tarapur Creek from Road Bridge at Tarapur Village (During High Tide)

Photo 2 : View of Upstream of Tarapur Creek from Road Bridge at Tarapur Village (During Low Tide)

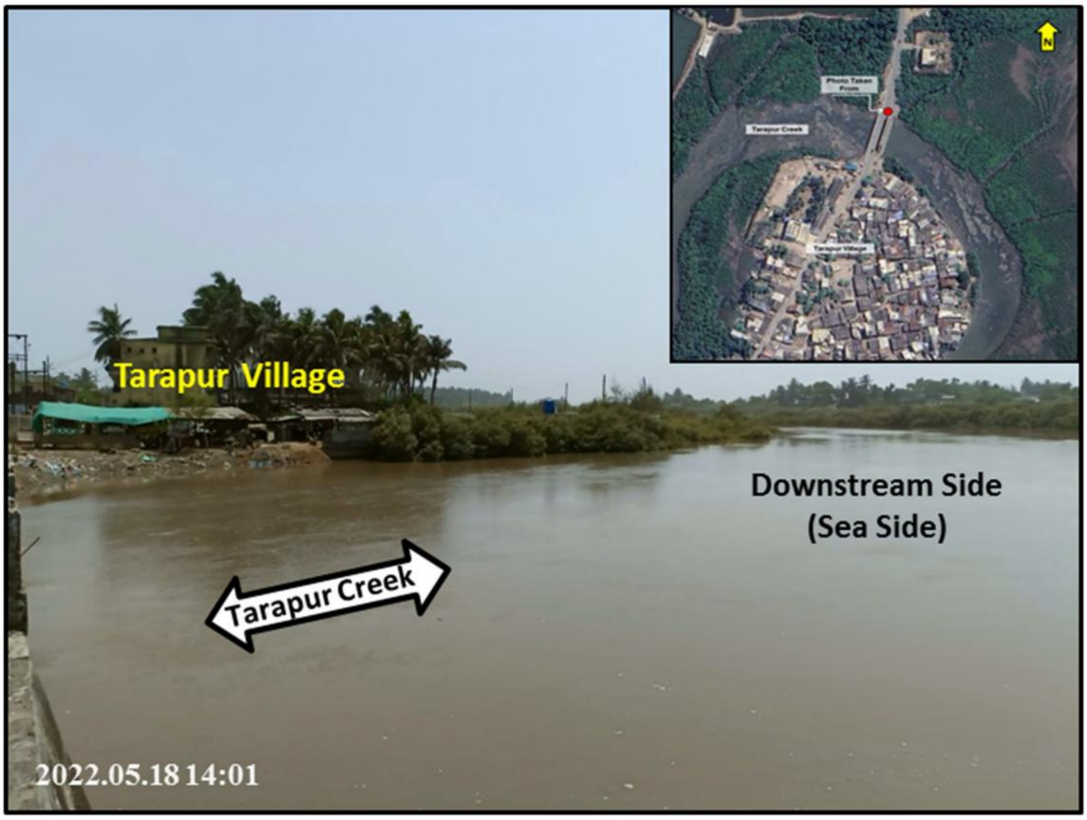


Photo 3 : View of Downstream of Tarapur Creek from Road Bridge at Tarapur Village (During High Tide)

Photo 4 : View of Downstream of Tarapur Creek from Road Bridge at Tarapur Village (During Low Tide)

Photo 5 : View of Downstream of Dahanu Creek from Dahanu Road Bridge (During High Tide)

Photo 6 : Zoomed View of Downstream of Dahanu Creek from Dahanu Road Bridge (During High Tide)

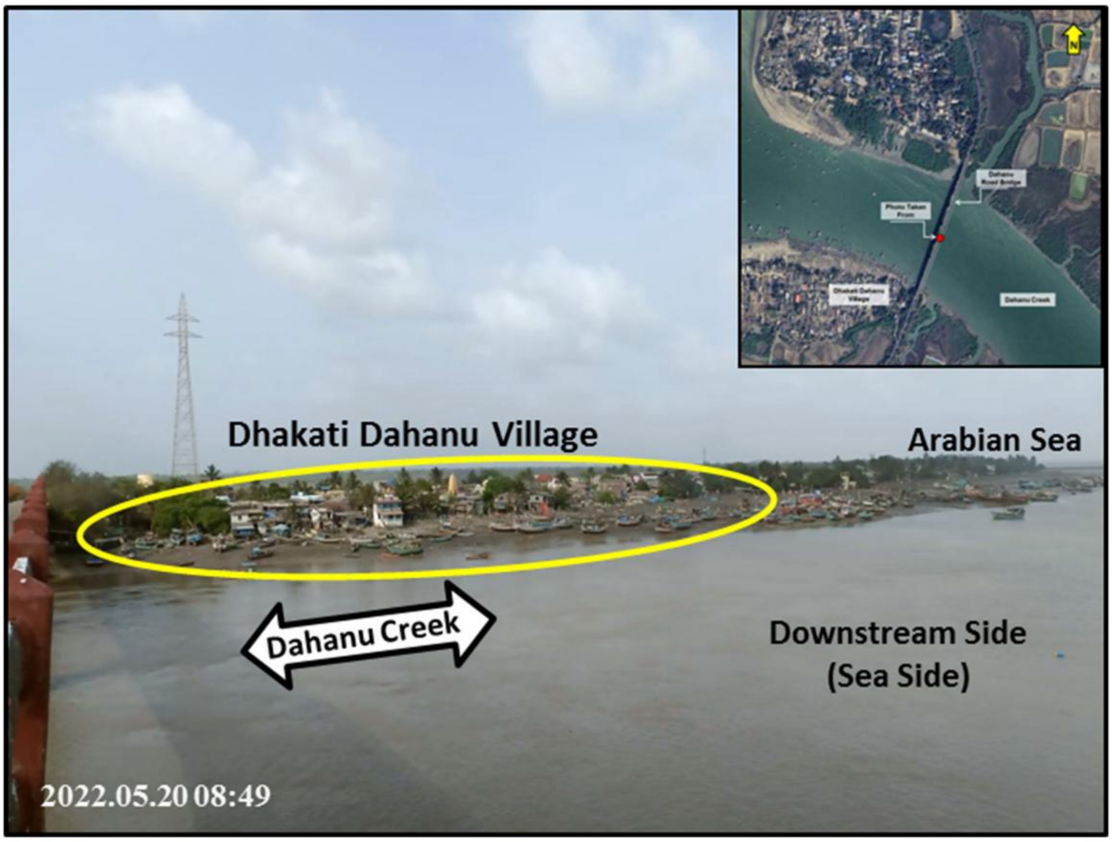


Photo 7 : View of Downstream of Dahanu Creek from Dahanu Road Bridge (During Low Tide)

Photo 8 : Zoomed View of Downstream of Dahanu Creek from Dahanu Road Bridge (During Low Tide)

Photo 9 : View of Upstream of Dahanu Creek (Dahanu Village side) from Dahanu Road Bridge (During High Tide)

Photo 10 : View of Dahanu Thermal Power Plant in Dahanu Creek from Dahanu Road Bridge (During High Tide)

Photo 11 : View of Upstream of Dahanu Creek (Dhumket Village side) from Dahanu Road Bridge (During High Tide)

Photo 12 : View of Vadhavan Headland (During Low Tide)

VISION

To be a world-class centre of excellence in hydraulic engineering research and allied areas; which is responsive to changing global scenario, and need for sustaining and enhancing excellence in providing technological solutions for optimal and safe design of water resources structures

MISSION

- To meet the country's need for basic & applied research in water resources, power sector and coastal engineering with world-class standards
- To develop competence in deployment of latest technologies by networking with the top institutions globally, to meet the future needs for development of water resources projects in the country effectively
- To disseminate information, build skills and knowledge for capacity-building and mass awareness for optimization of available water resources

MAJOR FUNCTIONS

- Undertaking specific research studies relating to development of water resources, power and coastal projects
- Consultancy and advisory services to Central and State Governments, private sector and other countries
- Disseminating research findings and promoting/assisting research activities in other organizations concerned with water resources projects
- Contributions to Bureau of Indian Standards and International Standards Organization
- Carrying out basic and applied research to support the specific studies
- Contribution towards advancements in technology through participation in various committees at National and State Levels

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