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Spatial and temporal variation of salinity stratification in a tropical estuary

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Longitudinal and vertical distribution of salinity field in the Vellar River Estuary (VRE) was investigated across the lower, mid and upper estuarine zone, monthly from January to December 2011. The hydrological survey of VRE revealed shallow bathymetry with a complex topography and a mean tidal amplitude of around 0.9 to 1 m. The depth-averaged tidal velocity had a magnitude that was observed with a maximum value of 0.56 m/s at the estuarine mouth and was indirectly proportional to the increasing distance from the mouth. The wind speed fluctuated from 1 to 4.1 km h^{-1} with a mean of 2.5±0.82 km h^{-1}. The temperature ranged from 25.32 °C to 32.93 °C with a mean of 28.89±2.26 °C while salinity varied between 0 to 34 psu with a mean of 13±12.77 psu and negatively correlated with rainfall (r = -0.69; p = 0.04). A higher stratification number, *i.e.* $n_s \sim 1$ at the lower estuarine zone indicated the formation of the salt wedge in the monsoon while during the rest of the year the estuarine water column was observed to be homogeneous. Wave height, tide and currents were estimated through 2D hydrodynamic models and they were significantly correlated with *in-situ* data. Recorded seasonal variation in salinity stratification of VRE from the present work reflected on shaping the primary governing factors on estuarine circulation at spatial and temporal scales.

[**Keywords**: Estuary, Portonovo, Regression, Salinity stratification, Tidal current, Vellar river estuary]

Introduction

The estuarine ecosystem is biologically very productive in nature. One of the fundamental reasons for an estuary to be defined as an ecotone is because of its salinity gradient. The spatio-temporal variations in salinity govern the dynamic structure of estuarine ecology[1]. Estuaries play a vital part in transporting dissolved nutrients and suspended particles to the coastal water and in fostering the regional biodiversity[2-4]. VRE is a transitional zone between a riverine and marine environment; possesses a complex ecosystem with a dynamic combination of physico-chemical and biological characteristics. VRE and its adjoining brackish water system serve as nursery grounds for several juveniles[5-8] and provide a very hospitable environment to primary[9,10], secondary[11] and tertiary producers for breeding purposes[12-14]. Despite the importance of VRE, sufficient spatial and temporal resolution to examine the longitudinal and vertical distribution of salinity fields are meagre except for the survey conducted by Dyer & Ramamoorthy[15] wherein, the salinity structure and water circulation of this estuary were investigated over a short period. In addition, irregular bathymetric conditions and topography in the shallow estuary, further complexes the hydrodynamic behavior[16]. Therefore, understanding of physical processes of an estuary is essential for assessing its ecosystem function. In this regard, the following three objectives were aimed: 1) To assess the longitudinal and vertical distribution of the salinity field, 2) To understand the influence of tidal currents on the salinity stratification, and 3) To model the relationship between saline intrusion and the distance from the estuarine mouth for surface and subsurface water.

Materials and Methods

Study area

VRE is located at Portonovo (11°29'33" N; 79°46'21" E) along the southeast coast of India (Fig. 1). The Vellar River geographically starts from the Shervaroyan hills and meanders about a distance of 480 km forming an estuarine ecosystem (VRE) before the confluence with the Bay of Bengal (BoB). VRE's width ranges from 500 m to 1 km with a maximum depth of 6 m[(ref. 8)]. The area of the estuarine

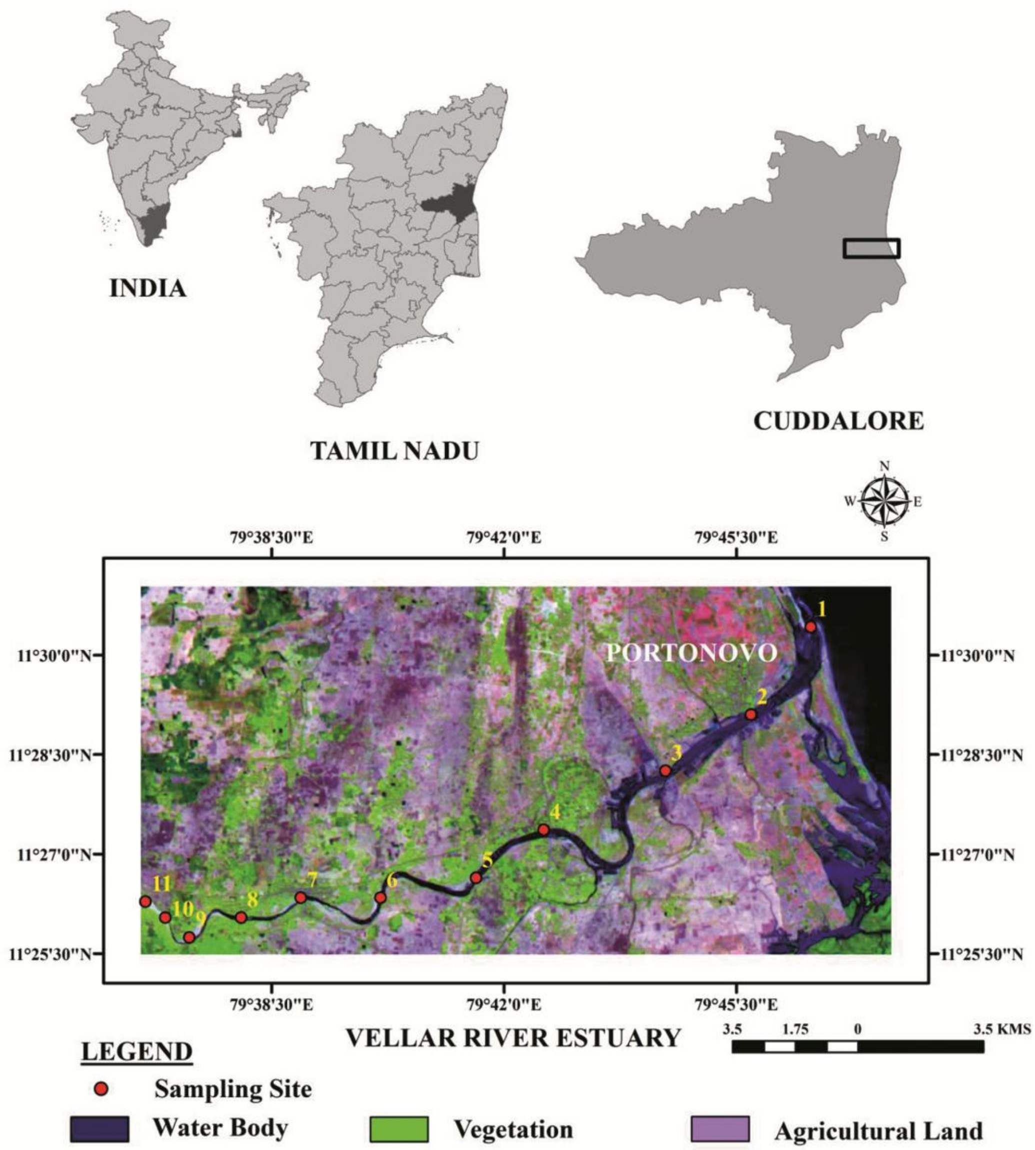

Fig. 1 — Map representing the study area with sampling sites

alone is about 4 sq.km[17] and classified as an open type bar-built estuary[15]. The tidal range varies from 0.2 m to 0.8 m[(ref. 18)]. Owing to the regional atmospheric forcing and precipitation, the Gregorian calendar year is categorized into four contrasting seasons, *i.e.* Monsoon (October to December), Post-monsoon (January to March), Summer (April to June) and Pre-monsoon (July to September). The average annual rainfall is about 1250 mm and most of the rainfall occurs during monsoon[8].

Sampling design

The virtual instantaneous depiction of salinity stratifications was obtained by surveying VRE during spring tidal phases at 11 sites every month from January to December 2011. The sites were chosen considering the accessibility and geomorphological similarity of the estuary. Water samples were collected from surface to subsurface (3 m) at an interval of 1 m in polypropylene bottles using the surface grab sampling method and Niskin water sampler, respectively. The salinity was measured in real-time on the field with the help of a refractometer (ATAGO S/Mill-E, ±0.2 %), whilst the water temperature was recorded using a multisystem digital thermometer (accuracy ±0.1 °C). Rainfall and wind data were acquired from the automatic weather station (AWS), Centre of Advanced Studies in Marine Biology, Annamalai University, located 150 m from the estuary. The coordinates of the sampling sites were recorded using the Global Positioning System (JUNO, SB model). A cloud-free Linear Imaging Self Scanning (LISS III, Res. 23.5 m) data of the IRS-P6 satellite was downloaded for the preparation of a base map by demarcating the periphery of the Vellar estuary. Furthermore, for an easy interpretation of data, all the eleven sites were grouped into 4 zones based on the distance *i.e*. Zone I (sites 1 – 3): completely inundated by neritic water; Zone II (sites 4 – 5) and Zone III (sites 6 – 8): moderately mixed with freshwater; and Zone IV (sites 9 – 11): entirely covered by freshwater.

Bathymetry survey and processing

The bathymetry of VRE was surveyed in June 2011 with a single beam echo-sounder (Model: ODOM Hydrotrac) which was connected to a Differential Global Positioning System (DGPS- Trimble) and a laptop computer system in a small fishing boat along with a heave sensor. The grid spacing of 30 m was configured in both X and Y directions. The transducer sends water depth soundings every 100 milliseconds with an accuracy of 0.1 m. The latitude and longitude of measured points were acquired from a DGPS, which were connected to the transducer. The echo-sounder system was calibrated before the survey by conducting a bar check. The transducer sent the sound waves that spread inside the conical volumetric surface to the estuarine floor and the return sound signal was recorded. As a result, the arrival time (t) of the sound signal is calculated electronically. The survey soundings were incorporated into Hypac software to produce the survey chart. The data were recorded digitally and stored on a computer for further processing. Although the echo-sounder provided essential hydrographic information during survey operations, tidal corrections were made in the observed depths and reduced to chart datum. Time, water depth and DGPS positions were noted in a text file on the computer while data records were converted into latitude, longitude, and average elevation. VRE bathymetry along with C-MAP data was used to generate a mesh which was fed into the MIKE 21 software for the 2D hydrodynamic flow model.

Tide and currents

Time series tide and current data were collected for 45 days from 4th August to 17th September 2011. Two tide gauges (Valeport Limited, UK) and current meters (Aanderaa RCM 9) were deployed near the mouth (at site 1, 6.2 m depth) and upstream of the VRE (at site 3, 6.5 m depth). The frequency of tide gauges was 25 GHz (accuracy ±10 mm) with a sampling interval of 10 ms. The measured water level elevation was processed for harmonic analysis using MIKE 21 software to calculate the tidal constituents' amplitudes and phases[19], following the IOS method as described by Godin[20] and Foreman[21]. The significance of diurnal and semidiurnal constituents differs with geographical position. Estuarine environments are classified based on four major tidal constituents as expressed by the tide form number (F),

$$F = (K_1+O_1)/(M_2+S_2)$$

i.e. the ratio between the sum of two major diurnal (K_1 and O_1) and semi-diurnal (M_2 and S_2) constituents, respectively[22], *i.e*., when, $F < 0.25$ - Semi-diurnal tide; $0.25 < F < 3$ - Mixed tide; $F > 3$ - Diurnal tide.

Current velocity was calculated using Recording Current Meters (Aanderaa RCM 9) with 2 MHz frequency and measurement level ranges from 0 to 3 m s^{-1} with 0.003 cm s^{-1} resolution and ±0.015 cm s^{-1} accuracy. MIKE 21 post-processing software was used for modelling the wave height and current velocity during the pre-monsoon season.

Hydrodynamic model

The integrated modelling system (Hydrodynamic and Spectral Wave Models) was performed and simulated for the monsoon and pre-monsoon seasons with a finer resolution bathymetry. The hydrodynamic model of the MIKE 21 Flow module was performed to analyse the flow dynamics and nearshore circulation in the river mouth and coastal region of the study area. This is two-dimensional modelling for different applications within the ocean and coastal environment with the provision of flexible mesh. The spectral wave numerical model is a third-generation based spectral wind-wave numerical model to simulate the growth, decay, and transformation of local wind-induced waves and swells in the offshore and nearshore coastal region. It is framed with fully spectral and directional decoupled parametric numerical formulations. The initial and lateral model boundary conditions provided in the model setup, are given in the following section. The boundary conditions such as wave radiation, water level, wind and current in the offshore and nearshore region are configured in the model. The bottom friction or resistance type in the model is provided as a manning number with the constant value of 32.

Model inputs		Description/ Input data
Bathymetry	:	C-MAP (90 m) and field surveyed bathymetry data
Wind fields	:	Interim wind – ECMWF Data (12.5 km resolution)
Tide	:	Mike 21 Global tidal data
Sediment	:	Field collected samples Mike 21 generated Global sediment tables
Lateral boundary condition	:	In-situ wave measurement (Wave Rider Buoy) In-situ current measurement (RCM)
Time Step	:	60 Seconds
Critical Courant–Friedrichs–Lewy (CFL) number	:	0.8
Time Integration & Space discretization	:	Fast Algorithm, Low order
Eddy	:	Smagorinsky formulation (0.28)
Resistance	:	Manning Number (32)
Formulation for Bed load and Suspended Load	:	Engelun Hansen
Porosity value	:	0.4
Grain diameter (d_{50}) size	:	0.2

In order to comprehend the flow dynamics and circulation features, the comprehensive 2-dimensional hydrodynamic modelling was simulated with flexible mesh. The finer and coarser element meshes were performed for nearshore and offshore regions, respectively for the better simulations of coastal processes. Bathymetry was imported into the model using the field surveyed datasets and the data extracted from the C-map. The domain bathymetry was created using the optimum interpolated methods with a negligible noise level. The model validation was extensively carried out using observational data.

Salinity stratification

The measured salinity values are used to depict the 2D maps of stratification to show the variability of salinity concentration horizontally and vertically in the VRE using the SURFER Golden Software with a kriging interpolation algorithm. Salinity stratification in the water column was calculated using stratification parameters (n_s),

$$n_s = \delta S/S'_m$$

Where, $\delta S = S_{bot} - S_{sur}$, $S'_m = ½ (S_{bot} + S_{sur})$; S_{bot} and S_{sur} are salinity concentrations in bottom and surface water, respectively. If $n_s < 0.1$, refers to well-mixed water column, when $0.1 < n_s < 1.0$ means, water column partially mixed, while $n_s > 1.0$ refers to strong stratification due to salt wedge[23]. The salt-wedge intrusion distance (L30 km) is the length from the mouth to the upstream of the estuary where 30 psu isohaline from the seaward boundary was observed[24].

Statistical analysis

Prior to statistical analysis, salinity and rainfall values are grouped based on sites and seasons. The correlation between salinity and rainfall was deduced by evaluating Pearson's correlation coefficient. Further, the significance of salinity and rainfall on the spatiotemporal scale was estimated by analyzing their variance using a One-way ANOVA statistical tool with a confidence interval of 95 % ($\alpha = 0.05$; 2-tailed). The modelled wave height, water level elevation and current speed are validated with measured data using some standard statistical methods such as Root Mean Squared Error (RMSE) and Mean Absolute Error (MAE). RMSE and MAE are the common tools used to characterize the error[25].

$$\text{MAE} = \frac{\sum [\text{xi} - \text{yi}]}{\text{n}}$$

$$\text{RMSE} = \sqrt{\frac{\Sigma(\text{xi} - \text{yi})^2}{\text{n}}}$$

Where, x_i is the modelled value, y_i is the measured value and n is the sample size.

A simple linear regression was applied to model the salinity using measured salinity values and distance from the estuary mouth. Prior, salinity values were grouped based on depth such as for surface (0 – 1 m) and subsurface waters (1 – 3 m) in order to get the accurate values of salinity from the model. The statistical analysis was carried out using SPSS 17 software package.

Results

Rainfall and wind speed

The Vellar coastal plain experienced its heaviest rainfall during monsoon with maximum precipitation of 4699 mm in November 2011 with a mean of 1249.5±1509.3 mm. The rainfall was significant among the season ($F = 10.72$; $p = 0.004$) and inversely proportional with salinity ($r = -0.69$; $p = 0.04$). The wind speed ranged from 1 km h^{-1} (October 2011) to 4.1 km h^{-1} (December 2011) with a mean of 2.5±0.82 km h^{-1} (Fig. 2).

Tidal variability

Variation in tidal water level is a function of time owing to its dependency on the ebb and flood of the tide. The bathymetric data revealed the shallow nature of the estuary where a significant portion of the estuary depth was less than 3 m (Fig. 3). Time series tide data revealed a semi-diurnal tidal pattern comprising two high and low tides with almost equal heights each day with a maximum elevation of water level of 1.13 m at site 1 on 31.08.2011 and a minimum of 0.57 m at site 3 on 01.09.2011. The mean tidal amplitude during the study period on the Vellar river estuary is around 0.9 m to 1 m. The influencing factors that govern the tidal patterns by functioning at varying periods are known as ‘tidal constituents’. The most important constituents are the positions of the moon and the sun relative to the earth, the earth’s rotation, the moon’s altitude above the earth’s equator and the bathymetry of the VRE. The four major constituents derived by the harmonic analysis performed on the tidal variability data revealed that (M2, S2, K1 and O1) are the most important tidal constituents. The change in the amplitudes pertaining to the change in phases of these constituents is specified in Table 1. M2 (Principal lunar semi-diurnal) constituent was observed with the highest amplitude in the order of 0.247 m and 0.249 m, followed by S2 (0.121 m and 0.123 m), K1 (0.066 m and 0.065 m) and O1 (0.018 m and 0.021 m) at sites 1 and 3, respectively. The phases of tidal constituents were 308 for M2, 359 for S2, 28 for K1 and 348 for O1 at site 3.

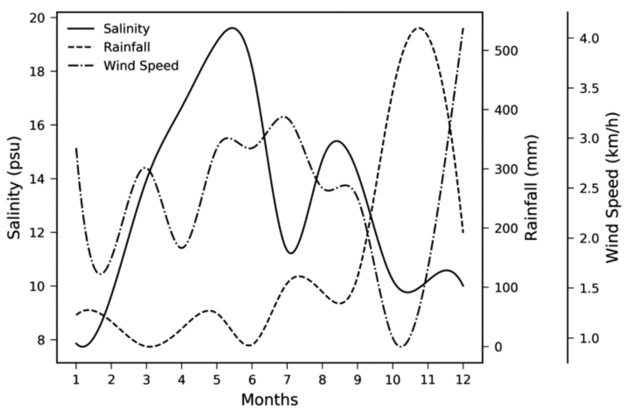

Fig. 2 — Line plots showing the monthly average of salinity concentration, rainfall intensity and wind speed observed during 2011

Temperature and salinity distribution

The water temperature ranged from 25.32 °C (site 10, November 2011) to 32.93 °C (site 11, May 2011) with a mean of 28.89±2.26 °C. Variation in the water

Table 1 — Tidal constituents observed in the estuary

Sl. No.	Tidal constituents	Site 1 (at lower estuary)		Site 3 (at central estuary)	
		Amplitude (m)	Phase (deg)	Amplitude (m)	Phase (deg)
1	Z0	0.065	0	0.661	0
2	MSF	0.019	272.79	0.052	264
3	O1	0.018	312.04	0.021	348.38
4	K1	0.066	7.50	0.065	28
5	M2	0.247	265.31	0.249	308.50
6	S2	0.121	316.48	0.123	359.89
7	M3	0.007	116.90	0.007	157.30
8	SK3	0.004	197.89	0.002	251.03
9	M4	0.012	99.76	0.013	196.80
10	MS4	0.009	135.53	0.011	221.02
11	S4	0.003	191.80	0.004	320.17
12	2MK5	0.003	117.47	0.001	205.50
13	2SK5	0.002	114.93	0.001	245.15
14	M6	0.003	21.95	0.005	200.43
15	2MS6	0.004	135.97	0.005	263.11
16	2SM6	0.001	292.03	0.001	218.20
17	3MK7	0.002	319.48	0.001	238.79
18	M8	0.001	197.34	0.002	63.81

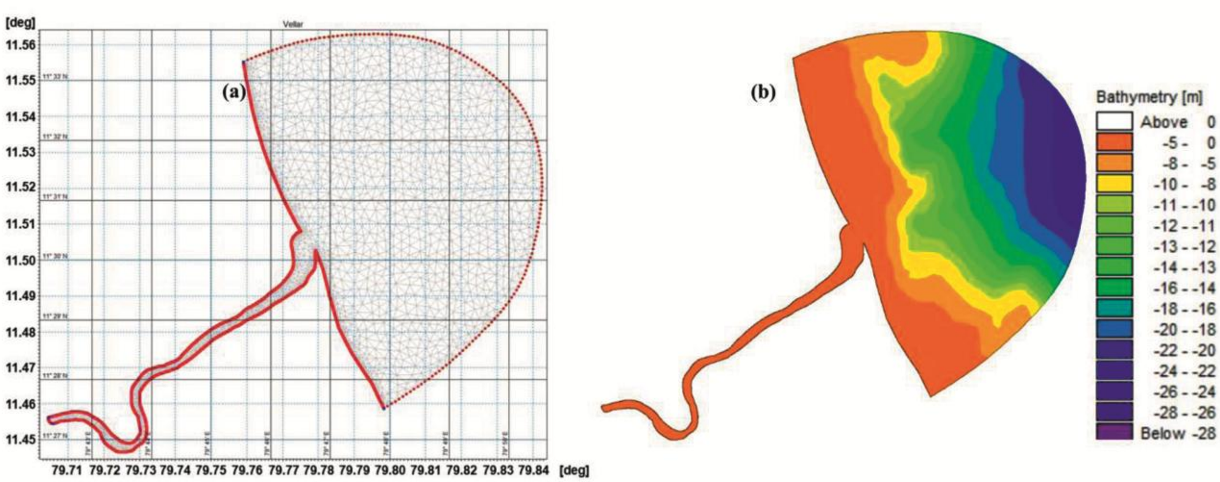

Fig. 3 — Map showing mesh (a) created and bathymetry (b) of the estuary

temperature was found to be statistically significant among the seasons (*F* = 0.116; $p < 0.0001$). Salinity ranged between 0 to 34 psu with the mean of 13±12.77 psu with significant variation amongst the sites (*F* = 5.72; $p < 0.0001$) and seasons (*F* = 5.42; $p = 0.003$) and its spatial and temporal distribution are given in Table 2. It has been observed that there is a regular decrease in the depth-averaged salinity values and it is indirectly proportional to the increasing distance from the estuarine mouth.

Concerning the longitudinal distribution of salinity, the zonation of VRE may be classified into three categories, *i.e.*, stratified water, mixed water and freshwater. Zone I (downstream) exhibited a higher salinity gradient (10 – 34 psu) during most of the season in a year, therefore, may be classified as "stratified" water. Zone II and III (midstream) were recorded to be predominantly inundated by freshwater which influences high salinity variability in space and time, with salinity varying between 0 – 29 psu and 0 – 27 psu during monsoon and post-monsoon, respectively. However, a lessor amount of salinity variation was observed during the rest of the year, *i.e.*, during summer and pre-monsoon the salinity varied between 14 – 31 psu and 6 – 26 psu at Zone II respectively while it was 0 – 8 psu at Zone III, which makes brackish to freshwater or vice-versa as a result Zone II and III may be classified as "well-mixed water". Upper estuarine zone (zone IV) is marked with prominent inundation of freshwater from the Vellar river throughout the year (0 psu) and negligible tidal influence may be classified as freshwater.

Hydrodynamic characteristics

The tides and the back and forth flow of tidal currents are being one of the most prominent features of estuaries, predominantly governing the mixing of water. The maximum wave height at VRE was 0.8 m at the estuarine mouth while the wave period varied between 2 to 8 sec (Fig. 4). The current speed varied

Table 2 — Descriptive statistics of salinity concentrations (psu) in the estuary

Seasons	Tides	Zone I		Zone II		Zone III		Zone IV	
		Range	Mean (± SD)	Range	Mean (± SD)	Range	Mean (± SD)	Range	Mean (± SD)
Post-monsoon	HT	8 - 34	24.5 (8.3)	0 - 27	14.7 (9.7)	0	0	0	0
	LT	8 - 33	24.2 (7)	2 - 25	14.5 (6.6)	0	0	0	0
Summer	HT	29 -34	32.4 (1.5)	20 - 31	26.3 (3.4)	0 - 21	11.7 (8.4)	0 - 8	0.8 (2.2)
	LT	21 - 34	30.4 (3.5)	14 - 30	23.8 (4.3)	0 - 20	10.3 (7.6)	0	0
Pre-monsoon	HT	25 - 31	29.1 (1.7)	8 - 26	19 (5.2)	0 - 15	2.8 (5.1)	0	0
	LT	22 - 33	28.1 (2.8)	6 - 26	18.5 (6)	0 - 14	2.6 (4.8)	0	0
Monsoon	HT	14 - 32	24.4 (5.1)	0 - 27	9.7 (9.4)	0	0	0	0
	LT	11 - 32	23.7 (7)	10 - 29	17 (5.8)	0	0	0	0

HT - High tide, LT - Low tide

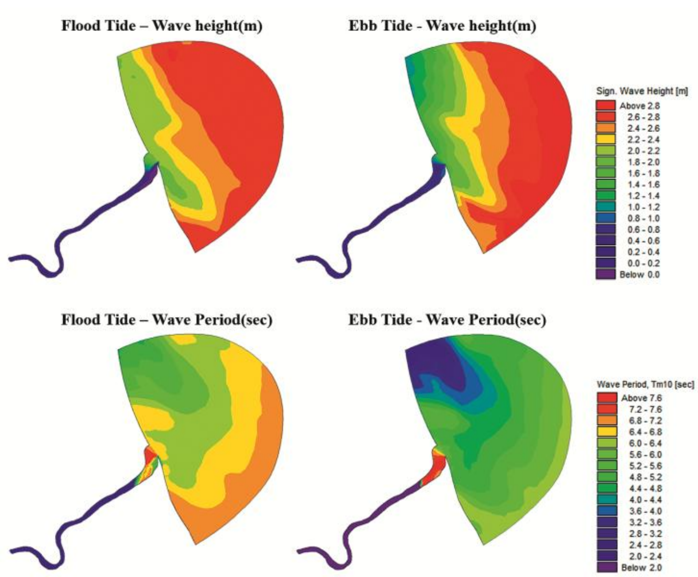

Fig. 4 — Wave height and period due to flood and ebb tides during pre-monsoon season

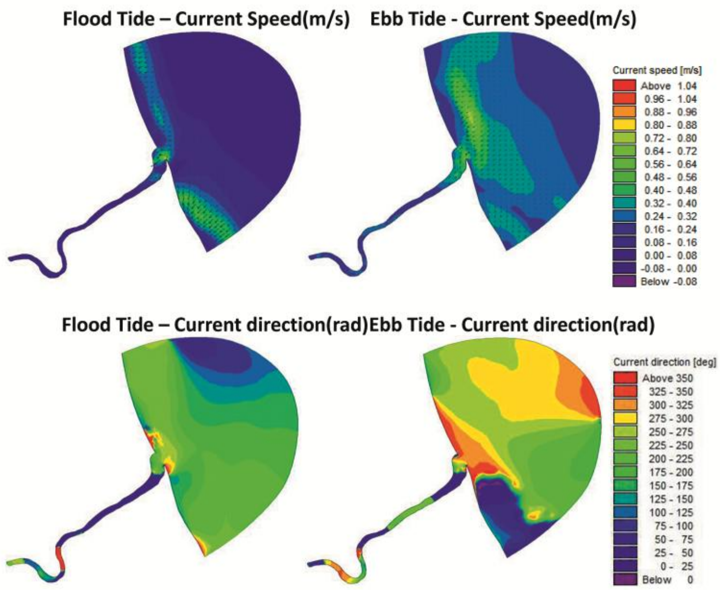

Fig. 5 — Current speed and direction due to flood and ebb tides during pre-monsoon season

from 0.003 to 0.563 m s^{-1} with a mean of 0.151 ± 0.11 m s^{-1} and the water moves towards 215º - 280º during flood tide. Similarly, the water in the ebb moves to 35º - 50º at site 1 while at site 3 current speed was minimum and varied from 0.01 to 0.16 m s^{-1} (0.035±0.02 m s^{-1}) (Fig. 5). The model results were validated with field measured values. Figure 6 reveals the validation of water level elevation and current speed parameters. The modelled and observed water level elevation and current speed data were validated and the R^2 value of the water level (m) and current speed (m/s) are 0.81 and 0.78, respectively. Statistical analysis, such as Correlation Coefficient (r), Root Mean Square Error (RMSE) and Mean Absolute Error (MAE) were analyzed for the modelled wave height (r = 0.85; *RMSE* = 0.20; *MAE* = 0.17), water level variation (r = 0.81; *RMSE* = 0.12; *MAE* = 0.10) and currents speed (r = 0.89; *RMSE* = 0.22; *MAE* = 0.20) with *in-situ* data and results were statistically significant.

Stratification parameters

At the lower estuarine zone, salinity stratification was observed to be distinct during the initial phase of post-monsoon ($0.95 \le n_s \le 1.03$) which gradually reduced towards the mid and end-phase of this season. Significantly weaker ($n_s < 0.1$) stratification was recorded throughout summer and pre-monsoon season, which with the onset of monsoon became stronger and distinct ($0.21 \le n_s \le 0.95$) during both tidal phases (Table 3). Concerning the definite salinity gradient during monsoon at the lower estuarine zone, salt wedge formation was witnessed (Figs. 7 & 8).

Mid-estuarine zone revealed remarkable distinct salinity stratification during post-monsoon and monsoon ($n_s > 1.0$) with weaker stratification during the rest of the seasons ($n_s < 0.1$) (Table 3). Whereas, irrespective of the season, the upper estuarine zone exhibited predominantly weaker salinity stratification ($n_s < 0.1$). The salt-wedge intrusion length (L30) was observed to be maximum (10 km) during March and June. Regression analysis revealed a strong inter-correlation between the salinity of the estuary and the distance from the mouth. The maximum regression coefficient was 0.92 and 0.88 for surface and subsurface water, respectively in the pre-monsoon period and the relationship was statistically significant ($p < 0.05$, $\alpha = 0.05$) (Table 4).

Discussion

In tropical countries, precipitation in the form of rainfall is a seasonal phenomenon which significantly influences the hydrographic properties of an estuary. The maximum rainfall during monsoon is attributed to the effect of the north-east monsoon. The longitudinal and vertical distribution of salinity in the estuary exhibited a clear seasonal pattern. In the present study, salinity value was mainly considered for describing stratification as salinity plays a pivotal role in the stratification of water due to its wide range in comparison to temperature[26].

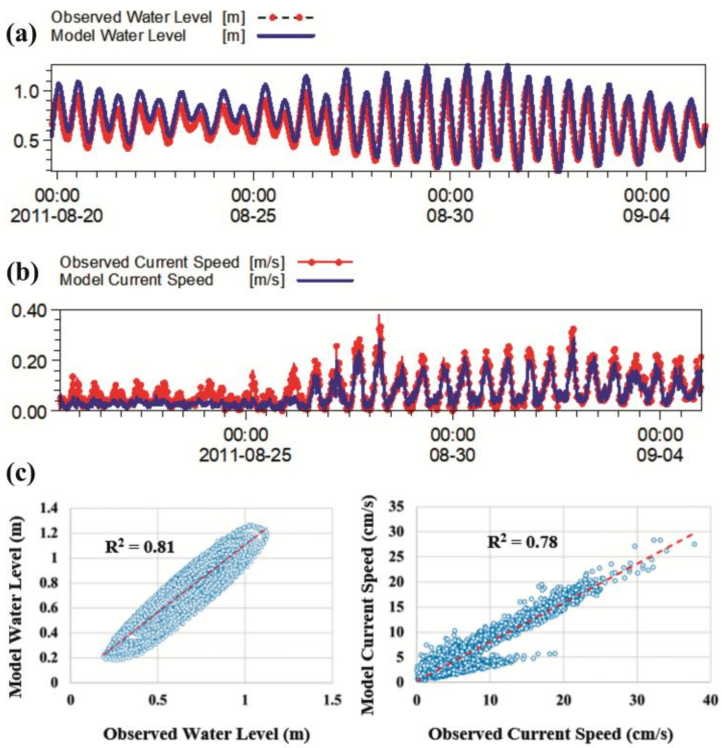

Fig. 6 — Validation of the model with measured values (a) water level, (b) current, (c) linear regression plots for water level and current, respectively

Table 3 — Spatial and temporal variation of salinity stratification parameter (n_s)

Months	Tides	Zone I		Zone II		Zone III		Zone IV	
		Range	Mean (± SD)	Range	Mean (± SD)	Range	Mean (± SD)	Range	Mean (± SD)
January	HT	0.95 - 1.03	0.99 (0.04)	1.14 - 1.33	1.24 (0.13)	0	0	0	0
	LT	0.18 - 1.03	0.71 (0.46)	1.20 - 1.56	1.38 (0.25)	0	0	0	0
February	HT	0.03 - 0.70	0.40 (0.34)	0.42 - 1.13	0.78 (0.5)	0	0	0	0
	LT	0.22 - 0.29	0.25 (0.03)	0.48 - 1	0.74 (0.37)	0	0	0	0
March	HT	0.03 - 0.11	0.07 (0.04)	0.08 - 0.14	0.11 (0.04)	0	0	0	0
	LT	0.03 - 0.07	0.04 (0.02)	0.22 - 0.27	0.25 (0.04)	0	0	0	0
April	HT	0 - 0.06	0.03 (0.03)	0.03 - 0.07	0.05 (0.03)	0 - 0.21	0.07 (0.12)	0	0
	LT	0.03 - 0.06	0.04 (0.02)	0.42 - 0.49	0.45 (0.05)	0 - 0.48	0.16 (0.28)	0	0
May	HT	0 - 0.03	0.01 (0.02)	0.04 - 0.07	0.05 (0.03)	0.12 - 0.32	0.20 (0.11)	0 - 0.67	0.22 (0.34)
	LT	0.19 - 0.44	0.33 (0.13)	0.07 - 0.13	0.10 (0.04)	0.16 - 0.50	0.31 (0.17)	0	0
June	HT	0.06 - 0.06	0.06 (0)	0.09 - 0.1	0.09 (0.01)	0 - 0.29	0.15 (0.14)	0	0
	LT	0 - 0.06	0.04 (0.04)	0.14 - 0.17	0.15 (0.02)	0 - 0.37	0.20 (0.19)	0	0
July	HT	0 - 0.07	0.03 (0.03)	0.13 - 0.4	0.26 (0.19)	0	0	0	0
	LT	0.04 - 0.09	0.06 (0.03)	0.13 - 0.5	0.32 (0.26)	0	0	0	0
August	HT	0.03 - 0.08	0.06 (0.02)	0.04 - 0.1	0.07 (0.04)	0 - 0.31	0.10 (0.18)	0	0
	LT	0.06 - 0.14	0.10 (0.04)	0.16 - 0.21	0.19 (0.04)	0 - 0.33	0.11 (0.19)	0	0
September	HT	0.03 - 0.04	0.03 (0)	0.04 - 0.11	0.07 (0.04)	0 - 0.29	0.10 (0.16)	0	0
	LT	0.04 - 0.10	0.07 (0.03)	0.04 - 0.23	0.14 (0.14)	0 - 0.44	0.15 (0.26)	0	0
October	HT	0.25 - 0.70	0.47 (0.23)	0.92 - 1.16	1.04 (0.17)	0	0	0	0
	LT	0.38 - 0.95	0.74 (0.31)	0.53 - 0.9	0.72 (0.26)	0	0	0	0
November	HT	0.21 - 0.35	0.29 (0.07)	0 - 0.86	0.43 (0.61)	0	0	0	0
	LT	0.42 - 0.61	0.51 (0.1)	0.40 - 0.47	0.44 (0.05)	0	0	0	0
December	HT	0.22 - 0.36	0.29 (0.07)	0 - 1.03	0.52 (0.73)	0	0	0	0
	LT	0.38 - 0.53	0.44 (0.08)	0.46 - 0.57	0.52 (0.08)	0	0	0	0

HT - High tide, LT - Low tide

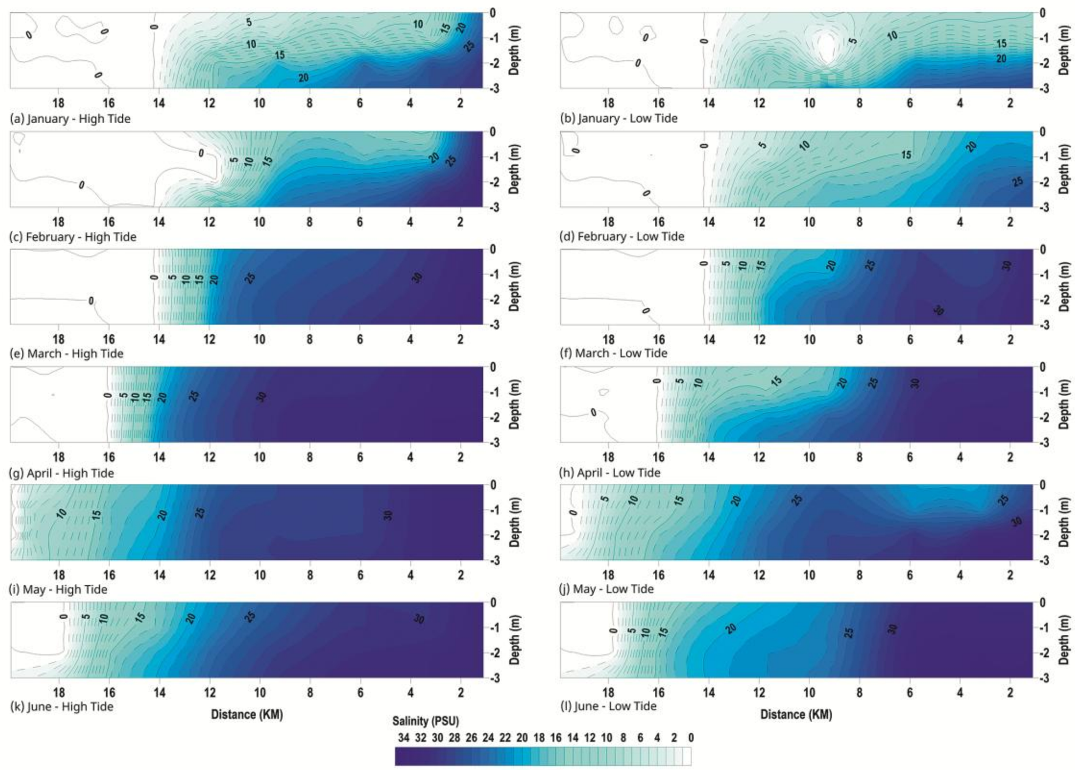

Fig. 7 — Vertical and horizontal profile of salinity distribution during the flood (high) and ebb (low) tides from January to June 2011

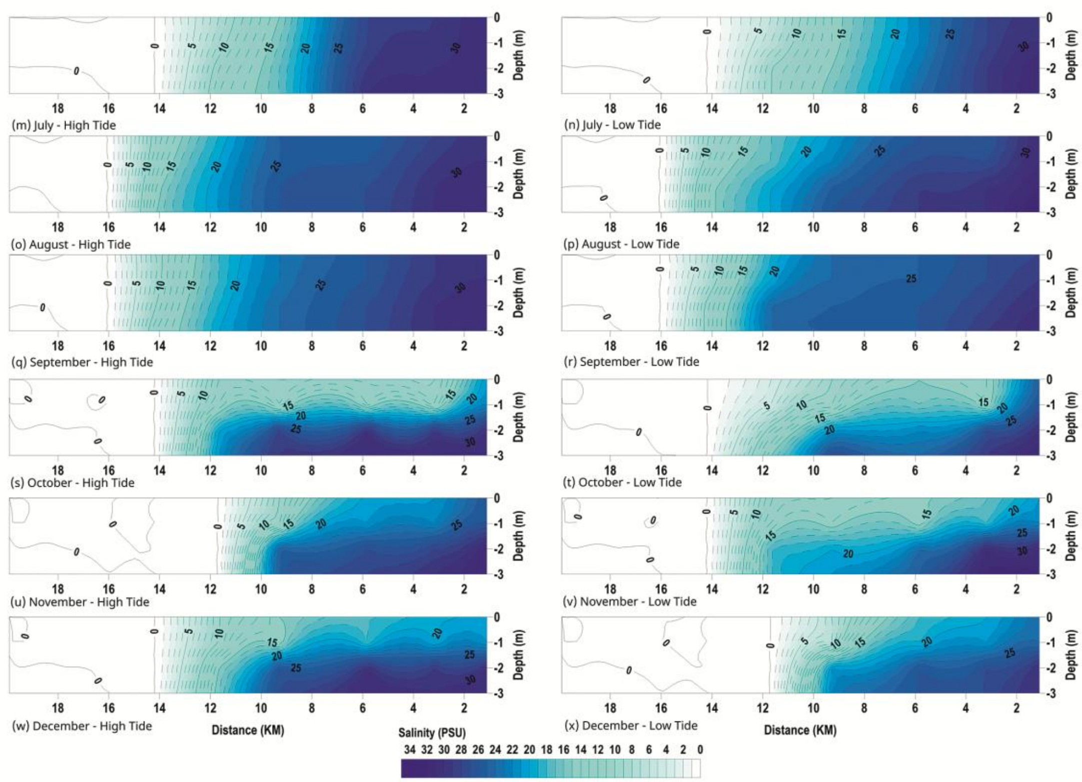

Fig. 8 — Vertical and horizontal profile of salinity distribution during the flood (high) and ebb (low) tides from July to December 2011

Table 4 — Regression equation between salinity and distance from the shore

SEASONS	SURFACE (0 – 1 m)		SUBSURFACE (1 – 3 m)	
	Equation	R^2 ($n = 132$)	Equation	R^2 ($n = 102$)
Post-monsoon	Y = -1.382X + 25.02	0.71	Y= -1.947X + 34.57	0.84
Summer	Y= -1.846X + 38.31	0.87	Y= -1.775X + 40.26	0.81
Pre-monsoon	Y= -1.81X + 34.07	0.92	Y= -1.95X + 36.55	0.88
Monsoon	Y= -1.248X + 22.47	0.87	Y= -2.056X + 36.07	0.85

Y = Salinity concentration (psu); X = Distance of the sites from the shoreline (kms)

From the observed tidal data, the mean tidal amplitude during the study period in the Vellar river estuary is around 0.9 m to 1 m with a moderate tidal current velocity downstream of the estuary. The shallow and complex topography of the estuary leads to frictional losses over a small spatial scale resulting in a gradual decrease in the velocity of tidal currents with increasing distance from the mouth towards upstream. It indicates that the tidal currents were comparatively weak at the mid-estuarine zone and gradually diminished near the upper estuarine zone. In addition, the form number 0.23 deduced based on *in-situ* observation verified the tidal pattern to be semi-diurnal at this coast. The hydrodynamic model was performed and revealed that the correlation coefficients (r) for the wave height, water level variation and currents parameters between observed and modelled values were well-matched and statistically significant ($p < 0.001$). An important point to note here is that the tidal currents were moderate in the lower estuarine region while it was weak or absent in the mid and upper estuarine zone, respectively.

Owing to the precipitation being at its peak through the initial phase of monsoon, *i.e.* during October, a simultaneous heavy influx of freshwater from the Vellar river and strong tidal forcing at the shore confines the intrusion of sea water up to the lower estuarine zone as evident through the higher stratification number ($n_s \sim 1$). Freshwater being lower in density floats over sea water, creating a prominent and distinct vertical stratification at the lower estuarine zone with weaker longitudinal salinity stratification. This phenomenon leads to the formation of the salt wedge at a lower estuarine zone of VRE. The conspicuous salt wedge formation that occurs every monsoon due to the interaction between river flow and tidal currents is remarkable. The wind velocity, though maximum in December, exhibited a negligible effect on the salt wedge and the force exerted by the wind was proven to be inefficient in mixing the entire water column of the estuary. The salt wedge influences the hydrographic properties of an estuary[23] by affecting the substantial distribution of not only nutrients but also diminishing dissolved oxygen and inducing a turbidity maximum[26]. The mid-estuarine zone was relatively stratified whereas, the heavy inflow of the freshwater coupled with a negligible effect of tidal forcing the upper estuarine zone was completely inundated with the freshwater resembling it to be a freshwater ecosystem.

In the initial stage of post-monsoon, the salt wedge was noticeable during both flood and ebb-tidal phases. However, over a course of time, the decrease in precipitation reduced the inflow of freshwater, gradually diminishing the vertical salinity stratification ($n_s < 0.1$). By the end of the post-monsoon, *i.e.* during March, the formation of longitudinal salinity stratification gradually began from the mouth of the estuary and due to negligible riverine freshwater input, the longitudinal stratification distinctly extended up to the mid-estuarine zone during summer. The longitudinal salinity distribution governs the density-driven or residual circulation thereby, influencing the estuarine flushing and circulation of nutrients[27,28]. Interestingly, the vertical salinity stratification was weak. In other words, the water column in the estuary was almost patchy vertically, perhaps by astronomical tide forcing, reducing the stratification number to less than 0.1. The decreased river flow allowed the salt-wedge intrusion length (L30) to migrate up in the estuary covering a distance of a maximum of 10 km from the estuarine mouth during March and June.

Although the estuary received a riverine freshwater inflow from south-west monsoon showers, the distinct longitudinal stratification as observed during summer, remained unvaried with stratification number less than 0.1, patchy water column and negligible vertical stratification. Therefore, the cycle of salinity stratification varied from the formation of prominent vertical salinity stratification during monsoon and post-monsoon, and longitudinal stratification during summer and pre-monsoon and the pattern continued.

Further, it is of utmost importance to mention that the extent of salinity stratification is strongly influenced by complex interactions among the factors such as freshwater influx, spatial variation in water depth, the speed of tidal currents, stability of surface heating and the effects of wind mixing[29-31].

VRE system is a cyclone-prone area, in such case, this extreme event would significantly influence the hydrodynamics and salinity of the estuary, which consecutively could affect the physio-chemical properties of the estuary[32]. The present results are in agreement with earlier reports from Vellar estuary[15,33] and Cochin estuary[34,35]. In general, seasonal variation of river inflow coupled with tidal currents strongly influences the longitudinal and vertical distribution of salinity in the estuarine system. This study further deduced the regression coefficient between salinity and the distance of sites from the mouth. Considering the R^2 values, seasonal variation for both surface and subsurface water is statistically significant, implying the significance of bathymetry and spatial variation in the stratification process[36].

Conclusion

Vellar river estuary is a shallow and microtidal estuary with complex bathymetry. With the inundation of freshwater from the Vellar river, including land runoffs during monsoon coupled with strong tidal forcing, the lower estuarine zone leads to the formation of the salt wedge; however, in the summer season due to a drastic reduction in freshwater influx the estuarine water column homogenizes resulting in weaker salinity stratification. Moreover, owing to the lesser flow of the freshwater, the upstream salt-wedge intrusion length (L30) migrates up to 10 km from the mouth leading to prominent seasonal changes in the physical, chemical and biological properties of the VRE. Between these two seasons, *i.e*. monsoon and summer a transition phase occurs, wherein, the salinity gradient of the estuary is moderate. Though salinity stratification is subjected to seasonal variation, depth-averaged salinity is inversely correlated to the upstream distance from the mouth. The findings discussed herein serves as the preliminary work to understand the longitudinal and vertical mixing of salinity field on a seasonal scale under the influence of a fresh water influx, tide and wind. However, further investigation is necessary on the spring-neap cycle to clearly understand the dynamics of salinity stratification.

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Conflict of Interest

The authors hereby declare that they don't have any known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Author Contributions

RM: Conceptualization, investigation, methodology, formal analysis, software, data curation, writing – original draft, writing – review & editing, visualization. MM & KR: Investigation, formal analysis, visualization. RV: Investigation, visualization. SMSS, KG & TPSJ: Visualization. AS: Conceptualization, methodology, resources, supervision. TB: Resources, supervision.

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