www.gondwanags.org.in
Research Article

ISSN : 2455-1953
JGSR
Journal of Geosciences Research
Vol. 10, No.1, January, 2025, pp. 36-43
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Spatial Distribution Analysis of Seasonal Variation in Salinity Stratification at Vembanad Estuary, Kerala, India

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Abstract

Estuaries are among the most important interconnections between land and sea. The restricted exchange between estuaries and the open sea allows rapid changes in salinity, temperature, nutrients, and sediment load. This study focuses on spatial and temporal variation of salinity stratification of Vembanad estuary, Kerala with reference to the seasonal variations and tidal effects. Water samples are taken from 20 locations along the Vembanad Estuary throughout the pre-monsoon, monsoon, and post-monsoon seasons for the year 2022. By application of stratification parameters, salinity stratification in the water column was determined. Linear regression analysis was applied to model the relationship between the salinity and distance from the estuary mouth. Spatial variations of salinity and temperatures maps were prepared using Arc GIS software. Based on the field analysis and statistical studies it was found that horizontal salinity structure of the estuary was inhomogeneous, such that the southern region was less saline than the northern region. The vertical profiles of salinity at the mouth region showed stratification, with a low saline water floating on the surface and high saline water at the bottom. These variations were influenced by the intrusion of up-welled waters from the Arabian Sea and by changes in the meteorology. Comparing the spring–neap salinity variation, it has been observed that, spring tide phase is more saline than neap tide.

Keywords: Vembanad Estuary, Salinity Stratification, Regression Analysis, GIS, Spring Tide

Introduction

Estuaries are dynamic aquatic environments where the ocean and river interact through the interchange of hydro-chemical sedimentological and biological features (Xiao *et al.*, 2019). It demonstrates significant fluctuations based on rainfall, tidal incursions, circulation patterns, rate of freshwater influx, and numerous abiotic and biotic processes of coastal settings (Nisha and Achyuthan, 2014). Cameron and Pritchard (1963) used the term "Estuarine Oceanography" to examine the quasi-dynamic equilibrium between seawater pressing inward and freshwater continually draining from the land into the estuary. Large amounts of suspended and dissolved inputs are discharged into estuaries from a variety of sources as runoff during the course of rivers (Jennerjahn *et al.*, 2004). The coastal oceanic phenomena have a significant impact on estuarine salinity because of the intrusion of sea water by the tidal effect. The Vembanad Estuary experiences mixed, semi-daily tides with two high and two low tides, higher high water (HHW), lower high water (LHW), higher low water (HLW), and lower low water (LLW) that differ noticeably in range and timing (Dietrich, 1963). Due to differences in surface elevations of water levels, the tides can also distinguish eight additional watermarks within a half lunar month; these are the highest higher high water (HHHW), lowest higher high water (LHHW), highest lower high water (HLHW), lowest lower high water (LLHW), highest higher low water (HHLW), lowest higher low water (LHLW), lowest higher low water (HHLW) and lowest lower low water (LLLW) (Qasim and Gopinathan, 1969). Similar to the tide action, the upwelling and down-welling of the sea water also significantly affect the change of several estuarine features especially salinity and temperature. Seasonally, the downward flow of nutrient components in upwelling regions is reversed, replenishing the surface waters with nutrients (Rixen, 2021).Undercurrents may accompany upwelling and transport mud deposits from deeper to shallower places (Gopinathan and Qasim, 1974). According to Sankaranarayanan and Qasim (1969), upwelling causes fish and prawns to relocate closer to the shore in order to avoid the oxygen deficient waters. From June to September, upwelling occurs in the coastal region of western India (Naqvi *et al.*, 2009). Along India's west coast, the monsoons produce a time-dependent wind stress that leads to the upwelling of highly salinized sea water and subsequent salinity changes (Sastry and d'Souza, 1972; Pankajakshan and Rama, 1987). The dynamic structure of the estuarine system is governed by the spatiotemporal fluctuations in salinity (Chevalier *et al.*, 2014). Estuaries can be categorised as highly stratified (salt wedge), strongly stratified (Fjords), weakly stratified (Partially mixed), laterally inhomogeneous or sectionally homogeneous (vertically mixed) in accordance with the

(Received : 09 August 2024 ; Revised Form Accepted : 10 December 2024)
https://doi.org/10.56153/g19088-024-0214-64

classification of Cameron and Pritchard (1963) based on water column stratification or salinity vertical structure. The intensity of stratification may be shown by vertical salinity variance. Total salinity variance can be decomposed into vertical and horizontal salinity variance, and vertical salinity variance can be used to represent the strength of stratification (Li *et al.*,, 2018). It would be worth-while to examine the predominance of lower frequencies in salinity and temperature as the estuarine conditions are closely related to the coastal dynamics and spectra. In estuarine waters, stratification plays a unique and fundamental part in altering estuarine charac-teristic. Thus, understanding the physical processes underlying salinity stratification is of great importance to estuarine science (Yang *et al*., 2022). This paper deals with the study related to spatial and temporal variation of salinity stratification of Vembanad Estuary related to the seasonal variations and tidal effects.

Study Area

Vembanad Lake is the largest estuarine system and second-largest Ramsar site in the southwest coast of India (Fig. 1). The area spreads over Kottayam, Alappuzha and Ernakulam districts in Kerala, between Latitude 09°25′30″-10°10′30″N and Longitude 76°21′00″-76°31′30″E (Fig. 1). It lies parallel to the coastline with a maximum length of 96.5km and covers an area more than 2033.02km^2. The estuary opens into Arabian Sea at Cochin bar mouth. Due to the harsh monsoon and drought circumstances,

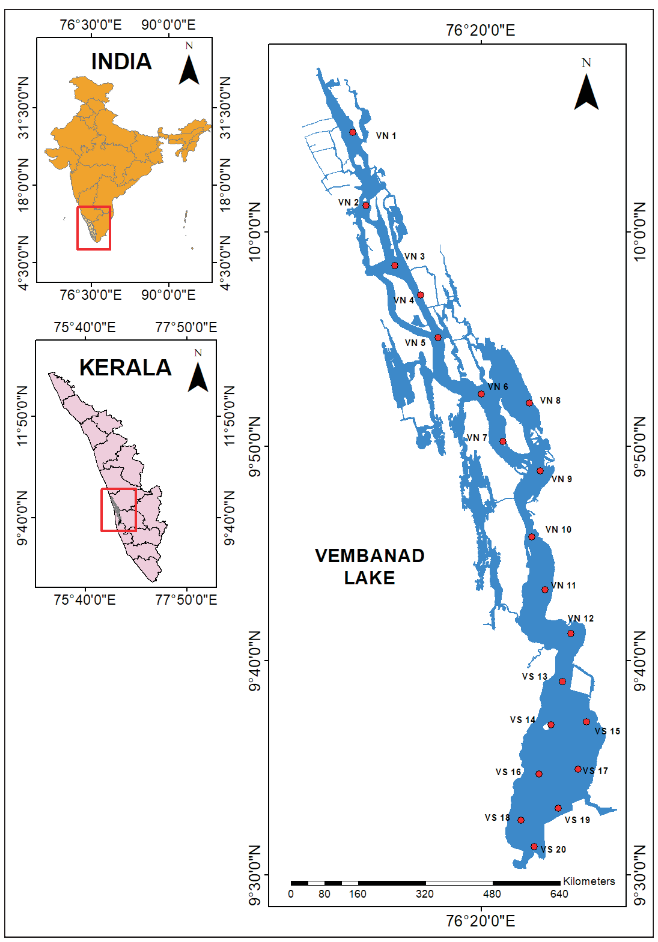

Fig.1. Location map of the study area

Vembanad Estuary is known to have wide salinity variations (Haridas *et al.,* 1973; Balakrishnan and Shynamma*,* 1976). The lake is separated into northern and southern portion by Thanneermukkom Bund-a manmade barrier to prevent the seeping of saline water by the tidal action. The lake's southern portion has fresh water, while the northern section possesses brackish water. Saraladevi (1986) observed a wide range of salinity fluctuation in this region due to the estuary's shallowness, monsoonal flow, and tidal pressure. The rivers which discharge fresh water into this lake are Periyar and Muvattupuzhaon the north and Manimala, Meenachil, Pamba and Achenkovil on the south.

Methodology

Samples are taken at 20 locations along the Vembanad Estuary throughout the pre-monsoon, monsoon, and post-monsoon seasons of the year 2022. On the basis of estuary's accessibility, the sampling sites were randomly selected. Using the surface grab sampling technique and Niskin water sampler, the water samples were taken at the surface and at a depth of 3 metres, respectively. The Hanna instrument- HI98319 Digital Salinity Tester, was used to monitor the salinity and temperature in the field in real-time. The salinity measurement unit displayed on parts per thousand (ppt) and the Automatic Temperature Compensation (ATC) displayed temperature in °C. Using ArcGIS software, the distribution patterns of the recorded temperature and salinity data were shown as vertical and spatial 2D maps. Utilising stratification parameters (ns), salinity stratification in the water column was determined (Eqn.1).

Stratification parameters (ns) = δS/S'm..................... (1)

Where, $\delta S = S_{bot} - S_{sur}$

S_{bot} and S_{sur} are the salinity concentrations in bottom and surface water, respectively.

S'm = ½ (Sbot + Ssur)

If ns = 0.1, the water column is well-mixed.

If ns = 0.1 to 1.0, the water column is somewhat mixed.

If ns > 1.0, there is considerable stratification caused by the salt wedge (Haralambidou *et al.*, 2010; Mahesh *et al.*, 2021).

The tide chart data of the study area during spring and neap tide were obtained from https://www.tide-forecast.com and rainfall data of the study area during pre-monsoon, monsoon and post monsoon seasons were acquired from Power Data Access Viewer by NASA POWER in order to conduct a comparative study of tides, rainfall and salinity of the estuary. A simple linear regression was applied to model the relationship between the salinity and distance from the estuary mouth.

Results

Salinity and Temperature distribution

Estuaries are gradual transition zones between rivers and coasts (Elliott and McLusky, 2002). In Vembanad Estuary due to the substantial rainfall and fresh water flow from rivers and other water channels, the surface salinity of the entire lake is significantly lower during the monsoon season (Jun-Sept) than in the pre-monsoon (Feb-May) and post-monsoon (Oct-Dec) seasons (Fig. 2). The Thannirmukkam barrage has a considerable influence on the salinity of the lake's southern half and prevents it from being as

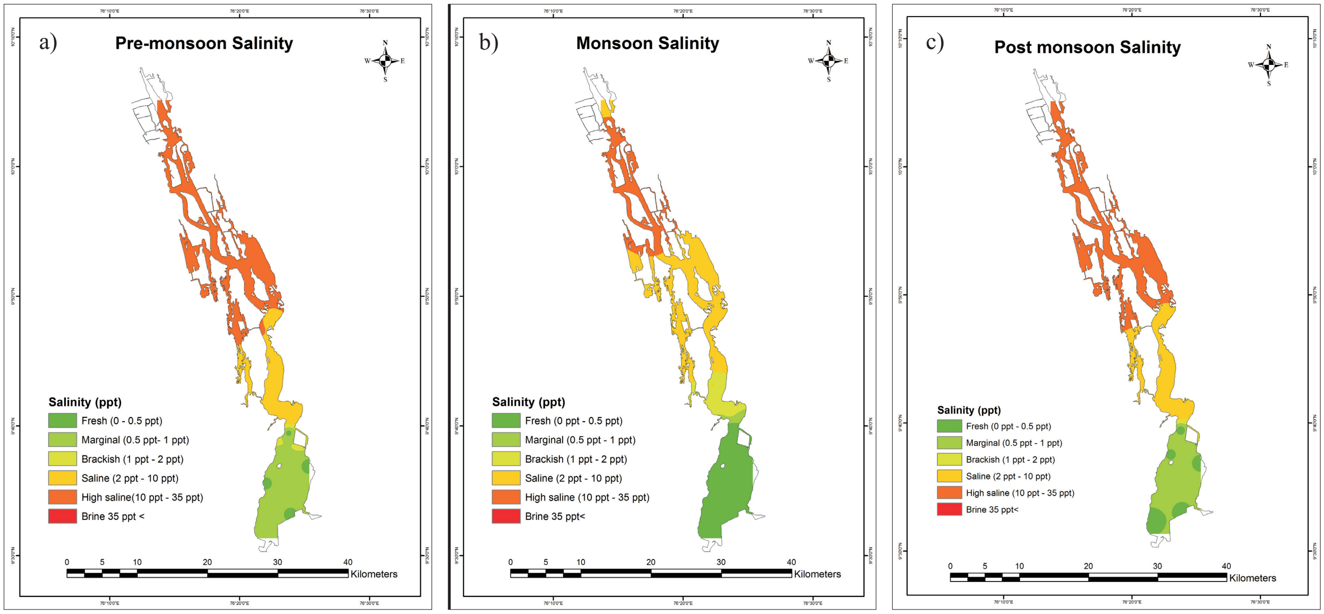

Fig.2. Spatial distribution of salinity in Vembanad lake during (a) pre-monsoon (b) monsoon (c) post-monsoon seasons

salinized as the northern part throughout the year. In comparison to the other sample locations, Location No. 3, the Cochin bar mouth at the lake's entry to the Arabian Sea, consistently shows a higher surface salinity content (25.9 ppt).

Both at the surface and at the bottom, salinity increased throughout the pre- and post-monsoon seasons, with the pre-monsoon season having the maximum salinity. However, in these seasons the vertical salinity variations were minimal. The vertical salinity distribution brought a dramatic shift with the beginning of the monsoon. Salinity levels on the surface were almost negligible during this period. But the bottom layers of water in the Lake often remain saltier than the surface. The monsoon might thus be predicted to have a significant halocline in the northern region of the lake, as it moved towards the upstream region, this halocline lost its vertical stratification (Table 1).

The seasonal variation in water temperature was shown to be substantial. The arrival of the monsoon season caused a significant shift in temperature distribution, comparable to salinity. The spread of surface temperature in the Vembanad Estuary is depicted in Figure 3. The result shows that the greatest surface temperature of 31.2°C occurred during the pre-monsoon season at Location No.5 in northern Vembanad. During peak monsoon, the minimum surface temperature was 26°C, at site no. 3, which is the outlet of Vembanad Lake to the Arabian Sea. The bottom temperature, on the other hand, varied more considerably with the seasons. During the peak of the monsoon, cooler water with a temperature of 23.6°C was recorded at site no.3, Cochin bar mouth. Following the monsoon, the temperature at the bottom gradually increased until the maximum 30.1°C was attained during the pre-monsoon (Table 2).

Table 1: Salinity (ppt) variation in Vembanad Lake during pre-monsoon, monsoon and post monsoon seasons.

Locations	Pre-monsoon		Monsoon		Post monsoon	
	Surface (–1m)	Bottom (–5m)	Surface (–1m)	Bottom (–5m)	Surface (–1m)	Bottom (–5m)
N. Lake 1	20.82	22.11	10.01	21.80	15.20	15.90
N. Lake 2	22.04	23.90	10.10	22.20	16.10	17.40
N. Lake 3	25.10	25.90	12.10	24.80	20.40	21.10
N. Lake 4	23.70	23.80	11.10	23.40	18.60	20.20
N. Lake 5	20.70	20.20	12.01	22.90	17.10	18.90
N. Lake 6	16.92	18.10	8.02	16.90	14.30	17.20
N. Lake 7	15.86	17.80	6.01	15.70	12.80	15.10
N. Lake 8	10.58	11.90	4.10	14.20	9.90	11.80
N. Lake 9	9.31	11.40	3.80	12.90	9.10	10.10
N. Lake 10	8.41	9.80	2.50	11.80	8.90	8.80
N. Lake 11	8.15	8.30	1.40	10.30	5.70	6.30
N. Lake 12	4.61	4.90	1.10	5.20	3.40	3.10
S. Lake 13	0.40	0.44	0.04	1.20	0.30	0.30
S. Lake 14	0.47	0.40	0.05	0.30	0.40	0.20
S. Lake 15	0.39	0.38	0.03	0.05	0.30	0.40
S. Lake 16	0.36	0.34	0.03	0.07	0.50	0.50
S. Lake 17	0.69	0.31	0.01	0.02	0.60	0.40
S. Lake 18	0.53	0.49	0.01	0.02	0.40	0.50
S. Lake 19	0.69	0.34	0.02	0.01	0.30	0.60
S. Lake 20	0.67	0.27	0.04	0.03	0.50	0.40

Table 2: Temperature (°C) variation in Vembanad Lake during pre-monsoon, monsoon and post monsoon seasons.

Locations	Pre-monsoon		Monsoon		Post monsoon	
	Surface (–1m)	Bottom (–5m)	Surface (–1m)	Bottom (–5m)	Surface (–1m)	Bottom (–5m)
N. Lake 1	28.1	27.1	28	25.1	26.1	27.2
N. Lake 2	26.7	26	27.1	24	27	27.4
N.Lake 3	30.1	29.2	26	24.6	28.2	27.6
N. Lake 4	30.7	29.1	26.2	24.1	27.1	27
N. Lake 5	31.2	30.1	26.5	24	26.6	27
N. Lake 6	29.1	28.1	26.8	25.1	28.3	27.4
N. Lake 7	28.4	27	28	25	28.1	27.9
N. Lake 8	27.9	26.9	27.4	26	27.9	26.8
N. Lake 9	28	28	27.4	26.1	28.2	27.6
N. Lake 10	27.6	27.1	27.1	25.4	27.3	26.1
N. Lake 11	28.1	27	28	25.1	28.6	27.1
N. Lake 12	28.6	28.1	29	26.5	26.1	26.4
S. Lake 13	30.1	29.6	30.1	26.1	28.4	27.9
S. Lake 14	31	30.1	28	26.6	27.1	27
S. Lake 15	27.6	26.4	27.8	26	27.2	26.4
S. Lake 16	28.4	26.4	26.7	25.1	28.4	26.9
S. Lake 17	27.8	27.5	27	25.9	28.5	27.5
S. Lake 18	28.3	27	28	26.4	27.5	26.8
S. Lake 19	26.9	26	26.9	26	26.9	26.4
S. Lake 20	28.5	27.1	26.5	26	28.1	27.1

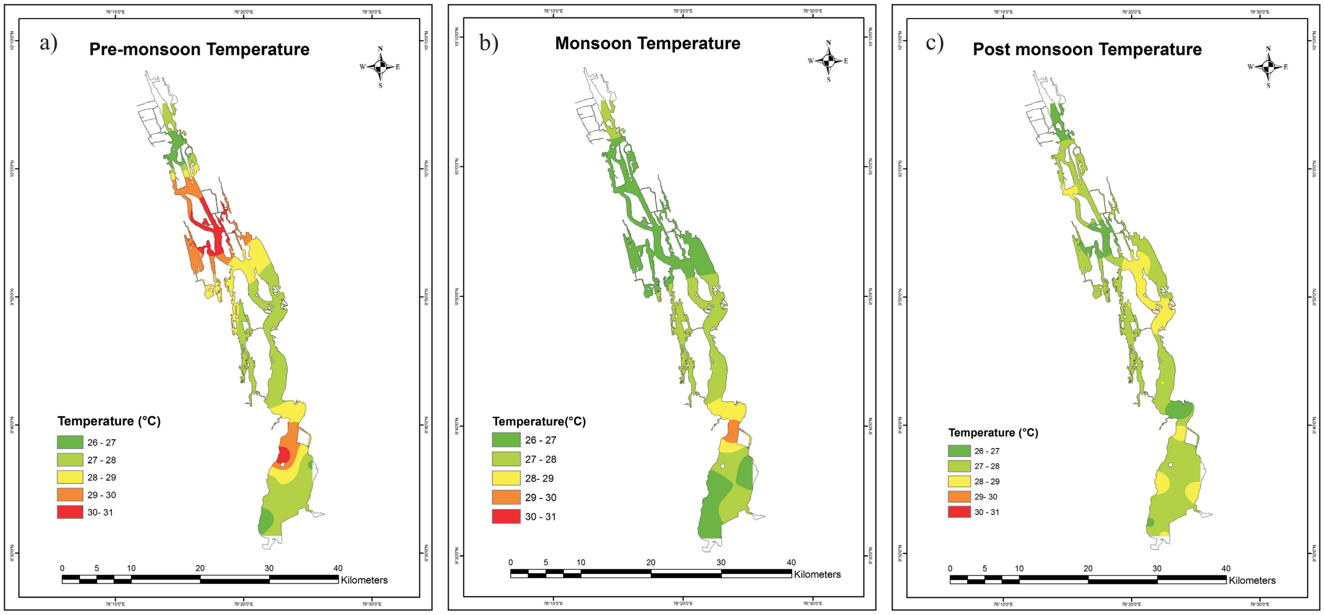

Fig.3. Spatial distribution of temperature in Vembanad lake during (a) pre-monsoon (b) monsoon (c) post-monsoon seasons

Salinity Stratification

Stratification is a key indicator of water quality because it represents the degree of vertical mixing in estuaries, lakes, and other wetlands. It has a significant impact on the chemistry of the sediment and can restrict the movement of dissolved gases such as oxygen through the water column (Kolb and Heineman, 1995). Salinity stratification in the water column was established using stratification parameters (ns).

According to the stratification parameters (ns), the northern part of the lake exhibits weakly stratified/partially mixed conditions during pre-monsoon season. The ns value ranges from 0.1 to 1.0. Conversely, the southern region displays a well-mixed/vertically mixed condition with a ns value less than 0.1.The majority of the sample from the northern and southern portions of the lake showed weak stratification during the monsoon season. (Fig. 4).The central region of the lake, spanning from locations 8 to 13, exhibits a strongly stratified/least mixed condition during the monsoon season, with a ns value greater than 1.0. The southernmost points of the lake, locations 19 and 20, display vertically mixed/well mixed condition with ns value less than 0.1.The post-monsoon season has weak stratification conditions in most sites, while well mixed conditions are seen in locations 10, 12, 14, 17, and 20 (Table 3).

Salinity vs Tides

Estuarine processes such as water mixing, temperature changes and salinity gradients are all interrelated (Gutierrez *et al.,*

Table 3: Stratification parameters (ns) in Vembanad water columnduring pre-monsoon, monsoon and post monsoon seasons.

Locations	Pre-monsoon			Monsoon			Post monsoon		
	δS = Sbot – Ssur	S'm = ½ (Sbot + Ssur)	ns = δS/S'm	δS = Sbot – Ssur	S'm = ½ (Sbot + Ssur)	ns = δS/S'm	δS = Sbot – Ssur	S'm = ½ (Sbot + Ssur)	ns = δS/S'm
N. Lake 1	1.29	21.47	0.06	11.79	15.91	0.74	0.70	15.55	0.05
N. Lake 2	1.86	22.97	0.08	12.10	16.15	0.75	1.30	16.75	0.08
N.Lake 3	0.80	25.50	0.03	12.70	18.45	0.69	0.70	20.75	0.03
N.Lake 4	0.10	23.75	0.00	12.30	17.25	0.71	1.60	19.40	0.08
N. Lake 5	-0.50	20.45	-0.02	10.89	17.46	0.62	1.80	18.00	0.10
N. Lake 6	1.18	17.51	0.07	8.88	12.46	0.71	2.90	15.75	0.18
N. Lake 7	1.94	16.83	0.12	9.69	10.86	0.89	2.30	13.95	0.16
N. Lake8	1.32	11.24	0.12	10.10	9.15	1.10	1.90	10.85	0.18
N. Lake 9	2.09	10.36	0.20	9.10	8.35	1.09	1.00	9.60	0.10
N. Lake 10	1.39	9.11	0.15	9.30	7.15	1.30	-0.10	8.85	-0.01
N. Lake 11	0.15	8.23	0.02	8.90	5.85	1.52	0.60	6.00	0.10
N. Lake 12	0.29	4.76	0.06	4.10	3.15	1.30	-0.30	3.25	-0.09
S. Lake 13	0.04	0.42	0.10	1.16	0.62	1.87	0.00	0.30	0.00
S. Lake 14	-0.07	0.44	-0.16	0.25	0.18	1.43	-0.20	0.30	-0.67
S. Lake 15	-0.01	0.39	-0.03	0.02	0.04	0.50	0.10	0.35	0.29
S. Lake 16	-0.02	0.35	-0.06	0.04	0.05	0.80	0.00	0.50	0.00
S. Lake 17	-0.38	0.50	-0.76	0.01	0.02	0.67	-0.20	0.50	-0.40
S. Lake 18	-0.04	0.51	-0.08	0.01	0.02	0.67	0.10	0.45	0.22
S. Lake 19	-0.35	0.52	-0.68	-0.01	0.02	-0.67	0.30	0.45	0.67
S. Lake 20	-0.40	0.47	-0.85	-0.01	0.04	-0.29	-0.10	0.45	-0.22
	Well mixed/Vertically mixed (<0.1)			Weakly stratified/Partially mixed (0.1-1.0)			Strongly stratified/Least mixed (>1.0)		

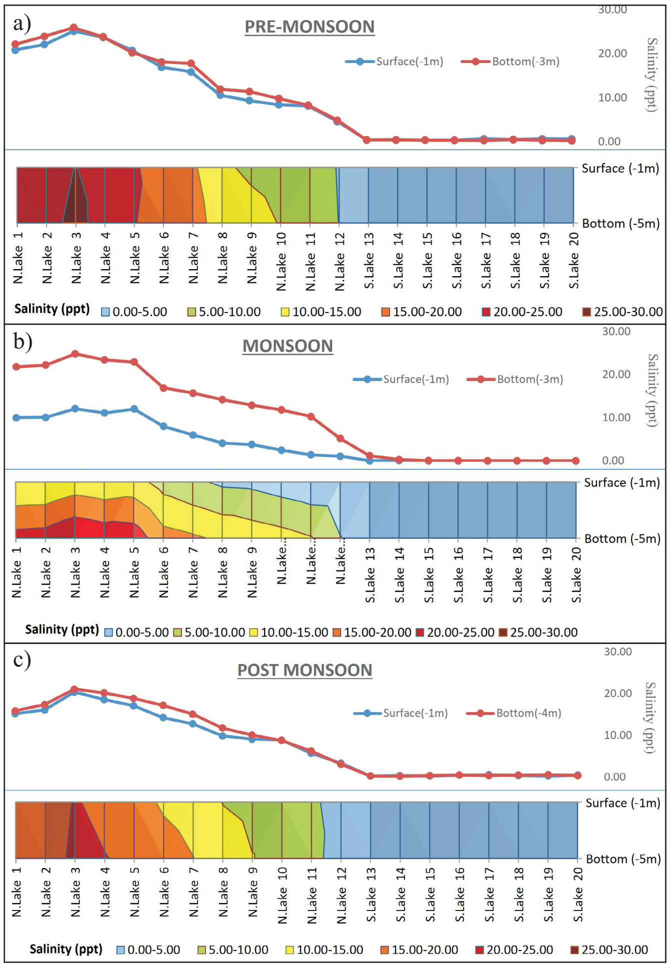

Fig.4. Vertical distribution of salinity in Vembanad lake during (a) pre-monsoon (b) monsoon (c) post-monsoon seasons

2018). The tidal effect has a significant impact on the estuary's temperature, salinity, and other characteristics. Salinity variations often follow the tidal pattern. Salinity rises with the high tide and falls during the low tide. The magnitude of variation and tidal range gradually decrease as one advances farther away from the bar mouth and into the upper portions of the estuary. As a result, the northern part of the lake experiences more of the tidal influence than the southern part. Additionally, the Thanneermukkom Bund's operation aids in keeping seawater from seeping into the lake's southern region.

According to the current study it is found that the flooding and ebbing of spring tide last longer than those of neap tide. The salinity is highest at the bottom during spring-high and lowest at the surface during neap-low. This discovery is congruent with the outcome of Jomon and Kurup (1989) investigation in the same area. During the spring tide the estuary exhibit high saline vertically homogeneous condition similar to the marine environment. According to Prandle (2004) the absence of a vertical salinity gradient at spring tide indicates the predominance of a well-mixed condition, which is enhanced by strong tidal currents. While in low tide phase it shows slightly stratified behaviour. Thus, depending on changes in the tidal cycle, the estuary might range from being well-mixed to partially mixed nature. In comparison to spring tide, neap tide results in less tidal forcing. In this situation, the bottom becomes more salty but fresh water from upstream discharge still predominates in the surface waters (Table 4).

The estuary experiences high salinity at the bottom and very low salinity at the surface during the monsoon season due to the massive amounts of freshwater that enter the area. At both the surface and bottom levels during these months, the salinity fluctuations caused by the tides are particularly noticeable. Fresh water near the surface is more or less unaltered since water mixing is prevented. Freshwater flow to the estuary decreased during the months leading up to and following the monsoon, therefore the vertical salinity gradients are less obvious. Since the entire water column becomes well mixed, the variations in salinity at the surface and bottom were essentially identical. However, during these seasons, the estuary's overall salinity increased during high tide and reduced at low tide (Fig. 5). As more freshwater from the rivers enters the estuary at the end of the ebb, the salinity at the surface layers decreases. After the flood, the water undergoes mixing, resulting in a reduction in the vertical salinity gradient.

Salinity vs Rainfall

In estuaries rainfall causes various environmental fluctuations, such as salinity, temperature and can affect distribution patterns and stratification of the entire system. This study reveals that rainfall is inversely related to salinity of Vembanad Estuary (Fig.6). In 2022, estuary experienced its heaviest rainfall during monsoon with maximum precipitation of 439.3 mm, resulting the

Table 4: Salinity Stratification inVembanad Estuary according to the Tidal phases during pre-monsoon, monsoon and post monsoon seasons.

Tide		Tidal height	Tidal Coefficient	Surface salinity (0 - 1m)	Bottom salinity (1-5m)	δS = Sbot - Ssur	S'm = ½ (Sbot + Ssur)	Stratification parameters (ns)	Type of Estuary
Spring Tide (2022 March 3)	HT	1.1 m	Very high	29.1	29.6	0.5	29.35	0.02	Well mixed
	LT	-0.5 m		20.6	21	0.4	20.8	0.02	Well mixed
Neap Tide (2022 March 10)	HT	0.9 m	Low	27.2	28.1	0.9	27.65	0.03	Well mixed
	LT	-0.7 m		19	26	7	22.5	0.3	Weakly stratified
Spring Tide (2022 June 14)	HT	1.0 m	Very high	9.3	30.02	20.72	19.66	1.1	Strongly stratified
	LT	-0.6 m		8.2	29.1	20.9	18.65	1.1	Strongly stratified
Neap Tide (2022 June 22)	HT	0.9 m	Average	8.7	24.02	15.32	16.36	0.9	Weakly stratified
	LT	-0.5 m		7.4	20.1	12.7	13.75	0.9	Weakly stratified
Spring Tide (December 23)	HT	1.2 m	Very high	25.9	27.6	1.7	26.75	0.06	Well mixed
	LT	-0.7 m		20.1	21.1	1	20.6	0.05	Well mixed
Neap Tide (December 16)	HT	1.0 m	Low	24	25.1	1.1	24.55	0.04	Well mixed
	LT	0.6 m		18.6	19.1	0.5	18.85	0.03	Well mixed

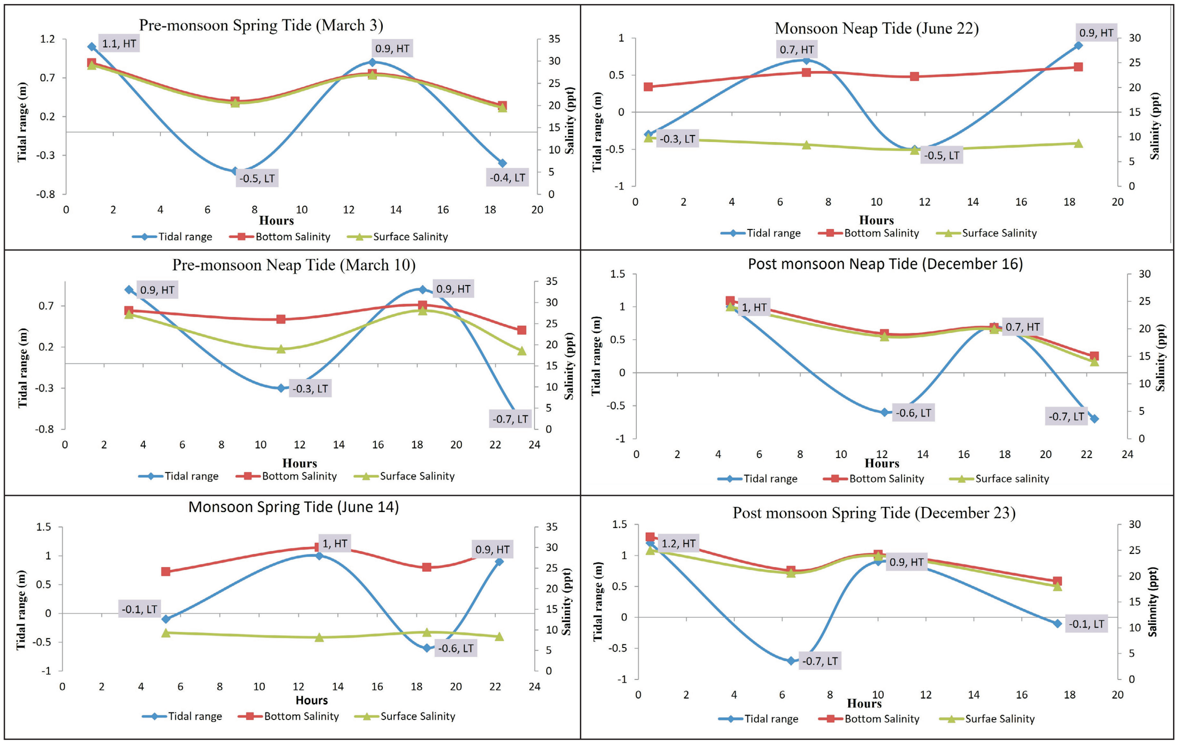

Fig.5. Graphical representation of Salinity Stratification in Vembanad estuary according to the Tidal phases during pre-monsoon, monsoon and post monsoon seasons

reduction of salinity into 15.1 ppt. Heavy rains and high river discharge dilute the salinity of seawater in the estuary during this season. Pre-monsoon season sees an average salinity of 29.2 ppt and 80.5 mm of precipitation in the study area. The salinity and rainfall in the post-monsoon period are 23.3 ppt and 50.8 mm, respectively. It is evident from this study that the local rainfall has a significant impact on the salinity fluctuation of Vembanad Lake.

Salinity vs Distance

Regression analysis is a set of statistical techniques used for the estimation of associations between two variables. R^2 is a statistic used in regression analysis that provides information about how well a model fits the data. In scientific studies, the R-squared may need to be above 0.95 for a regression model to be considered credible (Menard, 2000). In this study, regression analysis found a substantial negative linear relationship between estuary salinity and distance from the bar mouth (Fig.7). Salinity is highest at the estuary's mouth and gets down as one proceeds upstream. Both in pre and post monsoon surface water has a maximum regression coefficient (R^2) of 0.96. During the monsoon season, the maximal regression coefficient for subsurface water is 0.97 (Table 5).

In pre-monsoon (February to May) and post monsoon (October to January) seasons the fresh water flow through South Indian rivers that join the Vembanad Lake diminishes and resulted in a gradual increase in the salinity both in the surface and bottom layer and consequently the estuaries become well mixed type. In Southwest monsoon season (June to September) estuaries along the south west coast of India are influenced by the large fresh water influx from the rivers due to heavy rain fall. During this season, the salt-water intrusion will be limited to a short distance in the estuary from mouth and generates a sharp decline in surface salinity of lake water. However, during the monsoon season, the southerly winds cause the upwelling of deep, cool, and saline sea water in the west coast of India. The up-welled saline water causes greater salinity and low temperature in the bottom layer of the lake (Ramamirtham *et al.*, 1987) and consequently the estuaries become partially mixed type in monsoon season. A few attempts have been undertaken in recent years to correlate the monsoon effect with the observed salinity fluctuations of Vembanad Estuary. According to

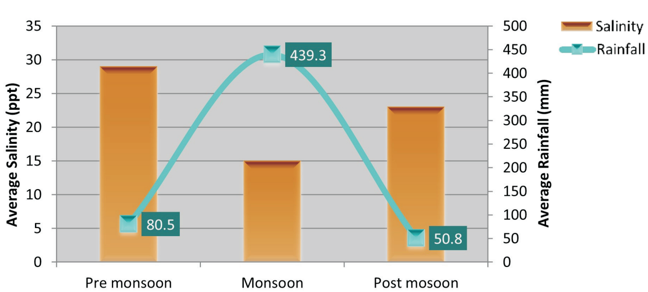

Fig.6. Average salinity and rainfall data in Vembanad lake during pre-monsoon, monsoon and post monsoon seasons

Table 5: Regression equation between salinity and distance from the bar mouthof Vembanad Estuary.

Seasons	Surface		Bottom	
	Equation	R^2	Equation	R^2
Pre-monsoon	y = -0.5652x + 25.108	0.96	y = -0.5894x + 26.38	0.97
Monsoon	y = -0.287x + 12.079	0.93	y = -0.5646x + 25.934	0.95
Post monsoon	y = -0.4443x + 20.115	0.96	y = -0.4821x + 21.647	0.96

x = Distance of the site from the shoreline(kms);
y = Salinity concentration (ppt)

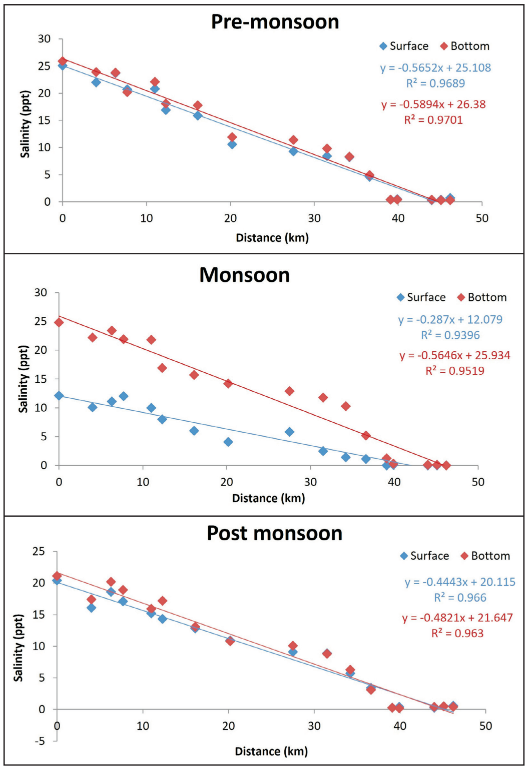

Fig.7. Linear regression analysis between salinity and distance from the bar mouth of Vembanad estuary

Ramamirtham and Jayaraman (1963), between June and September the flood waters from the rivers predominated at the surface while the up-welled water with low temperature and high salinity, extended along the bottom of the estuary and maintained a vertical temperature and salinity gradient. This vertical gradient, however, was to disappear during post monsoon period. The results of this study are in line with what other researchers have observed in this estuary and other estuaries along the south-west coast of India. The salinity fluctuations in the estuaries corresponding to tidal variations were marginally significant in most of the coastal areas (Capstick, 1957; Vasisht, 1965). In the Korapuzha estuary, Rao and George (1959) noted a change in the salinity brought on by the tides. Similarly, while comparing the high and low tide water levels in the Vellur Estuary, Rangarajan (1958) found that salinity varied significantly. Regarding the Vembanad Estuary freshwater is discharged from the estuary into the sea during low tide, and seawater seeps deeply into the estuary at high tide. However, during periods of monsoon months, due to heavy rainfall the conditions change slightly. More freshwater accumulates in the estuary with a constant river flow. As a result, during high tide, when sea water rushes into the estuary, more freshwater from the top layer escapes into the sea, creating a salt wedge condition by leaving a tongue of sea water at the bottom and freshwater at the top. In general, the salinity distribution pattern seen in the current study in the Vembanad Estuary has a similar pattern to that seen in past reports for the same season.

Conclusions

In this study, fluctuations in the salinity stratification of Vembanad Estuary, Kerala, is examined. Here we have analysed the longitudinal and vertical mixing of salinity on a seasonal scale under the influence of distance from estuary, rainfall, fresh water influx, flood–ebb and spring–neap tide. Based on the field analysis and statistical studies it can be conclude that horizontal salinity structure of the estuary was inhomogeneous, where the southern region was less saline than the northern portion of the lake with estuarine mouth. The vertical profiles of salinity at the mouth region showed stratification, with a low saline water floating on the surface and high saline water at the bottom. This structure was varied during monsoon season with the inundation of freshwater from the six inlet rivers, including land runoffs and strong tidal forcing, the northern estuarine zone leads to the formation of the salt wedge; however, in the pre and post monsoon seasons due to a drastic reduction in freshwater influx the estuarine water column homogenizes resulting in weaker salinity stratification. The temporal and spatial variations of salinity fluctuations are remarkable along the entire estuarine system. These variations were influenced by the intrusion of up-welled waters from the Arabian Sea and by changes in the meteorology. Comparing the spring–neap salinity variation, it has been observed that, spring tide phase is more saline than neap tide.

Authors' Contributions

AMJ: Sample Collection, Writing-Original Draft, Software, Resources, Methodology, Investigation, Formal Analysis, Data Curation. **MSG:** Review and Editing, Interpretation and Data Analysis**,** Visualization, Validation.

Conflict of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The authors are sincerely thanking our Head of Department, Department of Geology, University of Madras for providing lab facilities to carry out this work. The authors also thankful to the anonymous referees for correct the manuscript.

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