What controls the flushing efficiency and particle transport pathways in a tropical estuary? Cochin estuary, southwest coast of India

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Abstract: Estuaries with poor flushing and longer residence time retain the effluents and pollutants, ultimately resulting in eutrophication, declining in biodiversity and, finally deterioration of water quality. Cochin Estuary (CE), southwest coast of India is under the threat of nutrient enrichment by the anthropogenic interventions and terrestrial inputs through the land runoff. The present study used the FVCOM hydrodynamic model coupled with a Lagrangian particle module (passive) to estimate the residence time and to delineate site-specific transport pathways in the CE. Moreover, understanding the back and forth movements and residence time of particles was elucidated using metrics such as path length, net displacement, tortuosity and time to flushed out from the system. Spatio-temporal patterns of the particle distribution in the CE showed a similar trend during monsoon and post-monsoon with an average residence time of 25 and 30 days respectively. During the low river discharge period (pre-monsoon), flood-ebb velocities resulteda minimum net transport of the water and longer residence time of 90 days compared to that of high discharge period (monsoon). During the pre-monsoon, particle released at the southern upstream (station 15) traversed a pathlength of 350 km in 90 days before flushed out through Fortkochi inlet, where the axial distance was only 35 km. This indicates that the retention capacity of pollutants within the system is very high and can adversely affect the water quality of the ecosystem. However, path length (120 km) and residence time (7.5 days) of CE considerably reduced during high discharge period. Thus the reduced path length and residence time can effectively transport the pollutants reaching to the system and restore the healthy ecosystem. This is a pioneer attempt to estimate the flushing characteristics and residence time of the CE by integrating the hydrodynamics and Lagrangian particle tracking module of FVCOM. This information is vital for the sustainable management of the sensitive ecosystems.

Keywords: Cochin Estuary, FVCOM, Lagrangian trajectory, Residence time, Pollution dispersion

1. Introduction

The estuarine environment is one of the most exclusive productive systems on the Earth, supporting unique communities of species specially adapted for life in a highly changing environment. Many industries and human settlements in and around the estuaries are draining large amount of effluent discharges[1]. Similarly, anthropogenic interventions create disturbances and pressure on the system that result in eutrophication of water bodies and declining of biodiversity. The self-purification capacity of the estuarine system strongly depends on its hydrodynamic conditions such as tides, currents and freshwater influx. Estuaries with poor flushing
and longer residence time tend to retain nutrients within the system leading to high primary productivity rates [2]. In contrast, well-flushed estuaries are more resilient to nutrient loading due to reduced residence time and greater exchange with less impacted coastal waters. The rate of exchange is generally determined by three-time scales, viz flushing time, age of water, and residence time [3]. 1) Flushing time is the time required to replace the existing freshwater in the estuary at a rate equal to the river discharge. The flushing time characteristics can be computed in two ways viz classical approach of the tidal prism and freshwater fraction method. 2) Age of the estuarine water body, which represents the time taken for a dissolved or suspended material at any location to be transported from its source to its current location [4]. 3) Estuarine residence time can be defined as average time interval of the water parcel needs to cover its path through the estuary. It is a major driver of eutrophication and water quality[5], which results in the impairment of the ecological function of estuaries in terms of biodiversity, habitat quality, and trophic structure. The calculation of residence time for particles in natural reservoirs was described by Bolin and Rodhe 1973 and further the concept was extended and modified for coastal sea applications [7,8].

About 70% of chemical industries of Kerala state (India) are located in the Ernakulam district dotted along the banks of the rivers Periyar and Chitrapuruzha(Figure. 1). The northern part of the CE (Angamali to Kochi region) is highly overwhelmed with >50 large and medium industries and 2500 small scale industries. This estuary receives high concentrations of industrial effluents of \(10^4 \times 10^5\) m\(^3\) per day and untreated domestic wastewater about \(0.26 \times 10^5\) m\(^3\) per day [9]. Cumulative daily freshwater intake of the industries located in the Edayar to Eloor region is \(1.8 \times 10^5\) m\(^3\) and discharge 75% of this intake water to the river as effluent water. The major types of these industries are fertilizers, pesticides, chemicals, and allied industries, petroleum refining and heavy metal processing, radioactive mineral processing, rubber processing units, animal bone processing units, battery manufacturers, acid manufacturers, pigment and latex producers etc. High concentrations of Fe, Mn, Zn, Cu, Cd, Pd, Cr, Co and Ni in the surficial sediments of the estuary were reported in northern parts of the estuary [10–13]. On the other hand, houseboat tourism (houseboats-604, private motorboats-308 and speed boats-33) discharges wastewater of 0.23 million litter per day and unaccountable quantity of oil spillage that inversely affect the estuarine environment [14]. A recent study by Sruthy and Ramasamy (2017) reported evidence of microplastics (96-496 particles m\(^{-2}\)) in the sediment, which has not only direct impact on the aquatic environment and habitats but also set off cascade perturbations to the entire food web. Since large freshwater influx contributed by prolonged monsoon enhances the complexity of residence time and it is very relevant to identify the retaining capacity of the CE. Thus, anthropogenic and terrestrial inputs adversely affect the health of the estuarine ecosystem, which needs immediate attention by addressing the transport process of the pollutant in detail.

Sustainable management of any ecosystem strongly depends on dilution, dispersion and transport dynamics of the waste that received from various point and non-point sources. Proper understanding of pollutant transport in the CE became very important because it holds 24th place in the critically polluted areas of the India [16]. Nearly 1.6 million peoples [17] live on the banks of the CE in 38 local government bodies (3 municipalities and Cochin Corporation) that spread across three districts (Ernakulam, Kottayam and Alappuzha). Domestic sewage from the urban areas of Alappuzha and Kochi is about 2550 million litter per day. Indiscriminate application of pesticides, industrial effluents and lack of adequate sanitation facilities during the closure period of the Thanneermukkom barrier aggravated the water pollution. According to Remani et al. 2010, sewage waste will double (~428 million litter per day) from the present value (~227.2 million litter per day) by the year 2034 considering the projected population of Ernakulam, Alappuzha and Kottayam district. Over the years CE has been subjected to heavy eutrophication and resulted in the deterioration of the water quality, but systematic approach to understand the spatial and temporal variation of the circulation and residence time is still lacking. Previous efforts focused on estimating the flushing characteristics of the CE using the tidal prism method and flushing time by estuarine volume and freshwater fraction methods. These methods have limitations in the systems like CE, as owing to the highly complex hydrodynamic conditions [19,20]. Field experiments to address the
residence time are expensive and required vast human resources; hence it is highly appropriate to use a 3D hydrodynamic model. The results provide an insight to understand (physical characteristics) the deposition of sediments, debris, pollutants etc., and thereby elucidate the origin, path and fate of the water parcel in time. This study offers one possible way to address the flushing efficiency of the CE in terms of residence time.

2. Materials and Methods

The Finite Volume Community Ocean Model (FVCOM, v. 4.1) was used in the present study. It is an unstructured grid, finite-volume, free surface, three-dimensional primitive equation coastal ocean model that solves the momentum, continuity, temperature, salinity, and density equations [21] CE is directly connected to the Arabian Sea through two inlets (Figure. 1), one at Fortkochi (450m wide, depth >15m) and other at Munambam (250 m wide, depth >7m). The tide is mixed semidiurnal in nature with a range of 1 m that progressively decreases to the upstream [22–24]. CE is aligned parallel to the Arabian Sea over 96 km from Munambam to Alappuzha. The system receives a high amount of freshwater discharge (22 x 10^6 m^3/yr.) annually from seven major rivers (Figures. 2 and 3) with peak discharge during the summer monsoon [23]. Hence, the proper estimation of surface water elevation (m) at the ocean boundary as well as at the confluence of each river to the model domain are of prime importance to the hydrodynamic modelling. Surface water elevations at each hour were calculated at the two open ocean boundaries using 25 tidal constituents. These tidal constituents were derived from the one-year tide data at Munambam and Fortkochi (Ocean/Open Boundaries) using Tidal Analysis Software Kit 2000 developed at Proudman Oceanographic Laboratory in the United Kingdom. The daily river discharge data was forced to the model domain from the river gauge stations (sourced from the Central Water Commission - CWC, Government of India). The model domain consist of unstructured triangular grids with resolution ranging from 10 to 600 meter and contains 15479nodes and22520elements (Figure. 1). The uniform sigma-coordinate system was applied with 10 levels for vertical grid resolution (see supplementary figure. S1). The base map was digitized using LISS-III and the corresponding grid was generated with Gmsh (version 2.5) developed by Geuzaine and Remacle 2009. The bathymetry data for the model was derived from digitizing Inland water Authority Plan Chart-2006 (IWAI, NW-3) using QGIS (see supplementary figure. S2). The bottom roughness parameter was set to 0.035 with minimum value 0.015 for the model drag co-efficient with initial conditions provided by the simulation from the previous year and produced an hourly output of three-dimensional currents, temperature, turbulent diffusivity, and 2-D water level fluctuations. During the pre-monsoon period (January- April), the tidal propagation was obstructed due to the closure of Thanneermukkom barrage to prevent salt intrusion towards the upper reaches of the CE. Hence the pre-monsoon simulations incorporated the feature of artificial barrage in the model domain and it created the stagnant waterbodies at upper reaches of CE. FVCOM model simulations were performed during the period of 2009-2015 for validating with available seasonal hydrographic datasets.
Figure 1. CE is situated in the state of Kerala (red filled circle in the in sitemap), southwest coast of India. This satellite (Landsat-8) image shows the model domain with the unstructured grid (yellow), and the major stations are numbered (1-19) on this map. An artificial barrage was constructed to prevent salt intrusion during the pre-monsoon period are marked by red line in this map.
Figure 2. Study region (red box) encompassing the Digital Elevation Model map (Shuttle Radar Topography Mission-90 m resolution) and Central Water Commission river gauge stations (red dots).

Figure 3. Daily climatological river discharges of the seven rivers at CE. Discharge data sourced from Central Water Commission, Government of India (2000-2016)

2.1. In-situ observations
One month-long time-series observations of water level and currents were conducted in the CE during low (22/2/2010 00:00 hrs-22/3/2010 08:00 hrs) and highriver discharge periods (24/07/2010 00:00 hrs-21/08/2010 00:00 hrs). Water levels were recorded from seven different locations (Figure 4) with 10-minute interval using Seabird SBE-26 plus water level recorder having an accuracy of 0.1% of full-scale (Strain Gauge Pressure). Acoustic Doppler current meters (Aanderaa RCM-9) were used to record speed (accuracy of ±0.15 cm s⁻¹) and direction (accuracy of ±2°) with 10-minute interval from four stations (Figure 4). Daily surface salinity (0.4m below surface) monitoring was carried out using SBE 19 plus CTD (conductivity ± 0.001 S/m) at Vypin and Bolgatty (Figure 4) covering a period from 1/06/2013 to 31/05/2014 between 10.30 am and 11.30 pm respectively. Water samples (0.4m below surface) were collected from four locations simultaneously at 11.00 am on a daily basis (Elloor, Arookutty, Thanneermukkom and Alappuzha) during the year 2014 by involving public participation and samples were analysed in the laboratory using Eutech salinity probe. In addition to those observations, we also conducted an in-situ salinity profiling survey (Figure 4) in August 2013 (high discharge period) and March 2015 (low discharge period) using CTD-SBE19 Plus at 16 locations (from station 7 to 19). The corresponding data was extracted from the model output and validated with in-situ observations.

Table 1. Seasonal hydrographic data collected at different stations of CE during the period of 2010-2015

| In-situ Observation Dates       | Tide      | Currents         | Surface Salinity (0.4m below the surface) | Salinity profiles |
|---------------------------------|-----------|------------------|------------------------------------------|-------------------|
| 22nd February - 22nd March 2010| 3, 5, 7, 12,15 &bottom),17 | 3,7(surface) | 6,8,9,12,17,19 |
| 25th July – 21st August 2010    | 3, 4, 7, 12,15,17 | 3,7(surface), 12, 17 | Between |
| 21st July 2013- 25th December 2014 | Between 7 and 19 | Between |
| 12th -21st August 2013          | Between 7 and 19 | 6,8,9,12,17,19 |
| 24th -27th March 2015           | Between 7 and 19 | Between |

2.2. Validation of the model

The reliability of the model was expressed using the Taylor diagram (plotrix package in R) and Index of agreement (d). Willmott 1981 proposed a new approach in model skill Index of agreement (d), which can be defined as

\[
d = 1 - \frac{\sum_{i=1}^{N} (P_i - O_i)^2}{\sum_{i=1}^{N} \left| P_i - \bar{O} \right|^2}
\]

where \(P\) and \(O\) represent the predicted model and observed values respectively. \(\bar{O}\) is time mean of \(O\), and \(N\) is the size of the data set. Perfect agreement between model results and observations yields a skill value of one and complete disagreement gives a skill value of zero.
2.1.1. Tide

The assessment of the model performance begins with analyzing the tidal variations in surface water elevations with respect to in-situ measurements. The spring – neap variability of the CE and
associated water level changes were able to predict precisely using FVCOM model (refer supplementary figures. S3 and S4). The model performance was assessed qualitatively using agreement of index and correlation. The surface water elevation at all stations was well captured with an average agreement of index of 0.96 and a correlation coefficient of 0.92 (Table 2). The maximum amplitude was noticed in the Fortkochi (0.63 m in pre-monsoon) and followed by Munambam (0.54 m in pre-monsoon) in the northern arm. The tidal dampening was high in the southern arm (station 7-17) compared to the northern arm (station 3-7). This can be attributed to the frictional dissipation and partly due to the presence of shallow and wide water bodies in the southern upstream. Among these locations, Fortkochi and Munambam have the best fit to the observed value with an agreement of index and correlation coefficient of 0.99. Most of the stations exhibited ≥ 90% of correlation during pre-monsoon and monsoon except at Thanneermukkom (station 17), where the index of agreement was 0.86 and the correlation coefficient of 0.75.

Taylor diagram provided a graphical summary of how accurately simulated the surface water elevation to the observation. In the Figure. 5, the similarity between the observation and modelled elevation were quantified in terms of correlation, centered root mean square differences and the amplitude variations. Simulated elevations that agreed well with observations and lied nearest to the ‘observed’ on the x-axis. These predicted elevations at seven locations showed good correlation and low RMS errors during both the seasons. However, the predicted elevations during pre-monsoon are comparatively close to the observed point on the x-axis than that of monsoon. The lowest correlation was observed at the stations Thanneermukkom (station 17) and Makayikadavu (station 15), which were located above the upstream regions of the CE.

Figure 5. Normalized Taylor diagram for the statistical significance of the surface water elevation of the model during the a) pre-monsoon (2010) and b) monsoon (2010).

Table 2. Showed the index value and correlations of the predicted/simulated time series surface water elevations at seven locations in CE during pre-monsoon (2010) and monsoon (2010).

| Stations         | Index of agreement | Correlation coefficient |
|------------------|--------------------|-------------------------|
|                  | Pre Monsoon       | Monsoon | Pre Monsoon | Monsoon |
| Munambam         | 0.99               | 0.99     | 0.99         | 0.99     |
| Cherai           | NM                 | 0.95     | NM           | 0.98     |
| Nedungad         | 0.94               | NM       | 0.94         | NM       |
| Fort Kochi       | 0.98               | 0.99     | 0.97         | 0.99     |
| Arookutty        | 0.95               | 0.98     | 0.93         | 0.97     |
| Makayikadavu     | 0.96               | 0.91     | 0.94         | 0.85     |
| Thanneermukkom   | NM                 | 0.86     | NM           | 0.75     |

* NM = No Measurements
2.1.2. Currents

Currents in the CE were dominated by the tidal signals and the model was able to capture the diurnal inequality and spring-neap variability. Time series of along channel and across channel velocities are shown in the supplementary figures (S5 and S6). The phase of the along and across channel velocity of the model is exactly similar to that of the observed ones. The maximum flow velocity noticed in the Fortkochi and Munambam was 1 m/s and 0.7 m/s respectively (Supplementary S7 and S8). Comparison between the model and observed velocities (along and across channel velocity) at four stations showed a good agreement of index for the predicted velocities with an average of 0.80 and the correlation of 0.78 (Figures 6 and 7, Table 3) during the pre-monsoon and monsoon. Bi-directional flow noticed at Fort Kochi inlet during the flood period (surface layer flow towards the sea while bottom layer to the lake) was captured by the model, where the index of agreement with the observed data at surface and bottom was 0.81 and 0.76 respectively (Table 3). Majority of the stations exhibit ≥ 70% of correlation in velocity during pre-monsoon and monsoon expect at Thanneermukkom. During pre-monsoon, Thanneermukkom region experiences low correlation and index of agreement (0.6) with minimum flow velocity (< 0.1 m/s) due to the closure of Thanneermukkom barrage (Supplementary S8b).

![Figure 6](image_url)

**Figure 6.** Normalized Taylor diagram for the statistical significance of along channel velocity of the model during the a) pre-monsoon (2010) and b) monsoon (2010).

![Figure 7](image_url)

**Figure 7.** Normalized Taylor diagram for the statistical significance of across channel velocity of the model during the a) pre-monsoon (2010) and b) monsoon (2010).
Table 3: Showed the index value for the model and correlations of the time series currents (U and V Components) at four locations in VL during pre-monsoon (2010) and monsoon (2010).

| Stations          | Velocity Components | Index of agreement | Correlation coefficient |
|-------------------|---------------------|--------------------|-------------------------|
|                   |                     | Pre Monsoon        | Monsoon                 | Pre Monsoon | Monsoon |
| Munambam          | along               | 0.93               | 0.71                    | 0.92        | 0.62    |
|                   | across              | 0.84               | 0.81                    | 0.92        | 0.64    |
| Fort Kochi (Surface) | along         | 0.76               | 0.87                    | 0.74        | 0.77    |
|                   | across              | 0.69               | 0.70                    | 0.67        | 0.69    |
| Fort Kochi (Bottom) | along         | 0.81               | NM                      | 0.80        | NM      |
|                   | across              | 0.76               | NM                      | 0.72        | NM      |
| Arookutty         | along               | NM                 | 0.94                    | NM          | 0.91    |
|                   | across              | NM                 | 0.95                    | NM          | 0.90    |
| Thanneermukkom    | along               | 0.60               | 0.86                    | 0.61        | 0.91    |
|                   | across              | 0.61               | 0.80                    | 0.62        | 0.87    |

* NM = No Measurements

2.1.3. Salinity

Salinity distributions reflect the combined results of all processes, including density circulation and gravitational circulation. During the simulation period, the FVCOM model were able to capture seasonal variation of the surface salinity (0.4m depth) pattern with respect to the freshwater influx (supplementary figure. S7). The large longitudinal salinity gradients were noticed and ranged from 0 psu (Eloor, Arookutty, Thanneermukkom and Alappuzha) to 35 psu (Vypin and Bolgatty). Taylor diagram drawn for six locations showed (Figure. 8 and Table 4) an average value of correlation is 0.87 and the index of the agreement as 0.9 during 2013-2014. Majority of the stations were showed similarity to the observed salinity in the Normalized Taylor diagram. However, the maximum RMSE at Eloor with correlation of 0.8, while the stations at Vypin & Alappuzha were underestimated the standard deviation for the model. Vertical salinity section (Figure. 9) comparison during the high river discharge period (August 2013), the model clearly predicted the salinity with higher thickness of the low dense water. Similarly during low discharge period (March 2015) the model was able to predict the maximum salt intrusion (Figure. 10) southern upstream of CE (Thanneermukkom) which maintains the homogeneity of the water column (well mixed).
Figure 8. Normalized Taylor diagram for the statistical significance of the surface salinity at 6 locations during 2013-2014.

Table 4. Shows the index value and correlations of the predicted/simulated daily surface salinity at six locations in CE during 2013-2014.

| Stations     | Index of agreement | Correlation coefficient |
|--------------|--------------------|-------------------------|
| Vypin        | 0.94               | 0.91                    |
| Bolgatty     | 0.94               | 0.88                    |
| Eloor        | 0.70               | 0.53                    |
| Arookutty    | 0.96               | 0.98                    |
| Alappuzha    | 0.88               | 0.96                    |
Figure 9. Validation of vertical salinity at CE during the period of 12th - 21st August 2013 (a- observation and b- model)

Figure 10. Validation of vertical salinity at CE during the period of 24th - 27th March 2015 (a- observation and b- model)
2.3. Lagrangian Particle Tracking Model

The Lagrangian particle-tracking technique has been widely used to estimate the transport time scales in number of water bodies with varying complex dynamics and geometries. This technique was used to study larval transport in the Gulf of Maine [27,28] and applied in the Great Lakes[29]. In the present study, Finite Volume Community Ocean Model (FVCOM) coupled with Lagrangian particle module was used to estimate the residence time and the site-specific transport trajectory of CE. Model simulations were performed for three distinct seasons pre-monsoon (January–March), monsoon (June–August) and post-monsoon (October–December) according to the river discharge(Figure. 4). For model simulation, we used climatological river discharge of seven rivers, which generated from daily river discharge data sets spanning from 2000 to2016 obtained from the Central Water Commission (CWC), Government of India. We confined our discussion only to the major scenarios such as high discharge (monsoon) and low discharge period (pre-monsoon; closure period of barrage at Thanneermukkom). In order to understand the water transport trajectories, 2584 particles were evenly distributed in the CE with a spatial resolution 300 m. These particles were defined as neutrally buoyant, passive in nature and released at the surface layer (sigma layer=1), which was tracked until they flushed out from the system. The objective of this study is to qualitative and quantitative estimation of flushing characteristics and residence time of the estuarine system and hence the transient waters were not considered. The distribution of these particles were analysed for 60-90 days during each season and its positions were recorded at 1-hour interval. The flushing through both inlets in the CE was quantified by the percentage of particles transported out of the system. The residence time (days) for each particle was calculated as the time period at which particle resided in the CE. The mean residence time of the estuary was estimated by the e-folding time, which is the time taken to decrease the particles to 1/e (37%, e folding) from the initial particle numbers. This can be calculated by applying ensemble averaging individual particle’s residence time in the domain after release [30].

$$T_{rc} = \frac{1}{R} \sum_{j=1}^{N} \sum_{i=1}^{N} (t_{ij})_{ij}$$ where

$T_{rc}$ is the mean residence time based on the ensemble averaging, $R$ is the total number of release, $N$ is the total number of particles, and $(t_{ij})_{ij}$ is the residence time for the $i^{th}$ particle in $j^{th}$ release.

Back and forth movement of the particle released in the model domain can be estimated using metrics such as the path length, net displacement and tortuosity or relative meandering of the particle path. Tortuosity ($\tau$) can be described as the ratio between the net displacement and path length that subtracted from unity. Such that a straight line of transport would have a value of 0 and a looped transport would have a value of 1.

$$\tau = 1 - \frac{d}{L}$$

The average path length ($L$) was calculated as the average of the total absolute distance travelled by a particle at each time step in all of the releases and given by

$$L = \frac{1}{R} \sum_{j=1}^{N} \sum_{i=1}^{N} \sqrt{(x_{j}^{i+1} - x_{j}^{i})^2 + (y_{j}^{i+1} - y_{j}^{i})^2}$$

where $L$ is the average path length, $m$ is the total number of time steps; $x$ and $y$ are the coordinates of a particle at a given time step.

To elucidate the major dynamics that control the flushing efficiency of the CE, we conducted two types of control run viz. Case1: river ON and tide OFF condition and Case2: river OFF and tide ON condition. In both cases, trajectory of the released particles were identified to estimate residence time, path length, net displacement and tortuosity.

3. Results and discussion

3.1. Spatial distribution of the particles during the monsoon period
Uniformly distributed particles (first time step-100%) and its temporal evolution according to the prevailing dynamics during the summer monsoon period were given in the Figures 11 and 12. Fifty percentage of the particles were quickly flushed out (Figure. 11) from the system (fast flushing phase); thereafter particle trajectory becomes steady (slow flushing phase). Particles left the CE within the e-folding time revealed that majority (90% of the e-fold time) of the particles were flushed through Fortkochi inlet (station 7) and remaining through Munambam inlet (station 3). Particle resided at a radial distance of 8 km from the both inlets were completely flushed out within one day. The region between station 3 and 12 (Figure. 12) showed a residence time of 5 days except at Nedungad (station 5). This region exhibited astagnant nature during the initial 20 days. Due to the recurring tidal excursion the particles in the region moved towards south (station 3) and flushed out within 5 days. This region (station 5) is identified as a null zone by Ramamirtham and Muthusamy (1986); Balachandran et al. (2005), which was well established with our studies. The fast flushing phase is termed as 50% of initial particle flushed out of the system with in 15 days. Towards southern part of the CE navigational channel is maintained at western bank and hence faster movement was noticed compared with eastern bank. The faster movements of the particles were observed at station 13 (residence time – 6 days) compared to the station 17 (residence time – 17 days) is mainly attributed to the immense discharge from the Muvattupuzhariver (station 14). The average residence time of the CE in the monsoon period is 25 days, in which 67% of the initial particles were flushed out from the domain.

Tortuosity gives an idea about the meandering path of the water parcel travelled by the effect of freshwater discharge and tidal activity. When tortuosity is >0.6 it implies that the average path length is approximately 2.5 times larger than the actual distance [30]. The minimum tortuosity 0.3 was noticed at station 2, 3 (Figure. 13c) and maximum (>0.8) at station 5. Particles released at station 17 took 17.5 days to flushed out from the CE by which it travelled a path length of 264 km (actual axial distance of 48 km) under high discharge and tidal dynamics (Figure. 13a and 13b).

Figure 11. The residence time of CE during the monsoon season was calculated by varying resolution of the initially distributed particles. The particles are initially realised with the resolution of 300 m X 300 m (2584 particles) over the model domain. N(0) is the initial number of particles in the domain and N(t) is the number of particles at time t. The percentage of particles initially reduced from 100% to 50% in the model domain is considered as fast flushing phase, followed by slow flushing phase.
3.2. Spatial distribution of the particles during the pre-monsoon period (Barrage closure period at Thanneermukkom)

The particles movement were negligible at south of the Thanneermukkom barrage (station 17) due to the closure of the barrage during this period. Low river discharge and overwhelming tidal dynamics significantly altered the flushing dynamics of the CE. Only 30% of the particles released in the CE were flushed out from the...
system (Figures 14 and 15). Particles at 8 km radial distance from the both inlets were completely flushed out within one day, whereas the region between station 3 and 12 (Figure. 15c) took 20 days for complete flushing except for a small region at station 5. However, these particles exhibited an oscillating nature within a limited distance to the upstream and downstream of the estuary depending upon the tidal phase. Artificial barrage at station 17 practically cut off the freshwater supply from the southern rivers Achankovil, Pampa, Meenachil and Manimala, consequently limit the particle displacement. There is a distinct lateral variation in the speed of the particles (eastern and western banks of the southern CE) could be attributed to the deep and shallow regions. The results showed that downstream transport of particles were much faster along the western bank, where the deeper channel is maintained. Particles at north of the artificial barrage (station 17) were more or less stagnant presumably due to the prevailing standing waves. During the pre-monsoon, particles at station 15 traversed 350 km (Figure. 16) in 90 days (residence time) before flush out through Fortkochi inlet whereas during monsoon it flushed out within 17 days. Longer residence time noticed during the pre-monsoon is conducive for pollutant retention and eventual degradation of the ecosystem.

![Figure 14](image)

**Figure 14.** The residence time of CE during the pre-monsoon season was calculated by varying resolution of the initially distributed particles. Red and Blue lines indicate the disintegration of evenly distributed particles with the resolution of 300 m x 300 m and 500 m x 500 m respectively. N (0) is the initial number of particles in the domain and N(t) is the number of particles at time t. Fast and slow decay phase are not present in this simulation. The particles are oscillating within model domain due to the overwhelming of tidal interaction over the relatively lower discharge period.
3.3. Comparison with worldwide studies on residence time

Data collected from the 39 estuaries in the world has been compared with river discharge, tidal length and residence time of the CE (Figure 17). Drastic variation in the river discharge was noticed among these estuaries that varied from 0 to $>10000 \text{ m}^3/\text{s}$. These estuaries were categorised according to tidal amplitude such as micro (0 m to 2 m), meso (2 m to 4 m) and macro ($>4 \text{ m}$). Tidal length varied from 5 km to $>300 \text{ km}$ and residence
timespanned from 0 to 250 days. Normally estuaries with longer (smaller) tidal length having longer (smaller) residence time, but this residence time can be modified according to their river discharge. Estuaries like Chesapeake Bay, N. San Francisco Bay, Delaware, Hudson, and Godavari are belonging to microtidal group with an average freshwater influx > 300 m³/s. Generally, microtidal estuaries exhibited longer residence time unless and until a high discharge that are comparable with the estuarine volume. Figure 17 inferred that micro-tidal estuaries showed longer residence time compared to meso and macrotidal estuaries. However, the river discharge of these estuaries is higher than that of micro and meso tidal estuaries, which may not be sufficient to flush out the estuarine waters against tidal forcing. Hence, longer residence time can be attributed to the geometry (area and depth) and the ratio of freshwater volume to the total volume of the estuary. Among the microtidal estuaries, tidal length of N. San Francisco Bay, Delaware, Hudson, Potmac and Hooghly estuaries are approximately twice that found in the Cochin estuary (47 km), on the contrary residence time of these estuaries are significantly lesser than CE (90 days). This could be attributed to the meandering of the CE and dual opening to the Arabian Sea.

3.4. Pollution transport mechanism with special emphasis to the Tortuosity and Residence time

Spatio-temporal variations of the particle during its transport from source to flushing point undergoes various processes like diffusion, dispersion, settling or resuspension. These processes are linked with tortuosity and can be a proxy to the active and passive nature of the system. Irrespective of the season, estuarine regions near to the inlets (≤ 8 km) were found to be fast flushing zones (<1 day) with an average tortuosity of 0.3. Even though large freshwater influx received by the CE during the monsoon, residence time (Table 5) showed significant spatial variations from 2.5 to 25 days. Congruently a drastic increase in the tortuosity and residence time (Table 5) was noticed from monsoon to pre-monsoon in the CE except 8 km near to the inlet.
regions. The residence time of station 1 was increased from 4 days in monsoon (path length of 20 km) to 23 days (path length of 70 km) in pre-monsoon. Owing to the opposing tidal force from both the inlets, the particle displacement at station 5 was negligibly small during monsoon and pre-monsoon though it registered a high tortuosity (2.07). Particles released in this region retained for a longer period covering pre-monsoon and monsoon with a path length of 43-45 km. This could be due to the opposing tidal propagation through this region from the two inlets. Stagnant nature of this region were noticed earlier by Balachandran et al. (2005 and 2006) as high accumulation of pollutants in water column and sediment throughout the season. Studies by Kumar et al. (2011); Anas et al. (2015); Sheeba et al. (2017) revealed that the contamination of heavy metal concentration in water was higher during the pre-monsoon than monsoon at station 1. Tortuosity values were high during pre-monsoon, which supports the process of precipitation, co-precipitation and flocculation of metals [10,11,13,48]. The maximum path length of 350 km (10-fold longer than the actual axial distance from the inlet) observed at station 15 (Figures. 16a, 16b and 19h) during the pre-monsoon could be attributed to amplification of tidal currents due to funnelling effect which favoured the retention capacity of pollutants or holding degraded water in the system for long time. However, during monsoon this region exhibited a reduced path length of 120 km (Figures. 13a, 13b, and 18h) (3-fold longer than the actual axial distance from the inlet) and shorter residence time (7.5 days). In general, upstream of the CE exhibited longer residence time during the pre-monsoon (180 flood-ebb cycles) and minimum during monsoon (50 flood-ebb cycles), which was well justified with tortuosity values (Table 5).

During the closure period of Thanneermukkom barrage (pre-monsoon), barrage prevents natural flushing and enhance tidal amplification [49,50] resulting in a negligible displacement (Figure. 15b, 15c and 15d) due to the generation of the standing wave. This could modify the prevailing dynamics and result a stagnant water body about 8 km north of the barrage with tortuosity of 0.7. While south of the barrage exhibited with least path length, tortuosity and longer residence time due to the interruption of the natural ebb-flood flow (Figure. 19i). Negligible flushing with shorter path length and a heavy load of pollutants such as pesticides, fertilizers etc., to this region from the paddy field promotes the proliferation of weeds and water hyacinths. Annually, 1,80,000 tourist visits the southern estuary [51] and many of them utilize houseboats (~604 houseboats) for recreational purpose, that increase dumping of effluents, oil and solid waste to the system. These activities can enhance accumulation of pollutants/material to the sediment layers due to the stagnant nature of the water body during the barrage closure period. A serious concern is needed to prevent the accumulation of pollutants in the vicinities of Thanneermukkom Barrage. The study highlighted a drastic drop in the flushing efficiency with a larger path length during the low discharge period to increased flushing nature by high riverine influx during the monsoon season. Longer residence time noticed in the CE during pre-monsoon could be due to the generation of higher tidal harmonics, geomorphologic alteration, increased residual circulations and reduced river discharge. These factors resulted an oscillating water body and enhance accumulation of pollutant in the estuarine environment. These finding underlines ameliorative management of wastewater discharge from the point and non-point sources to the CE. Estuarine livelihoods, such as agriculture, fishing, transport and tourism, are likely to be enhanced by a more rational and optimum utilization by the integral knowledge of site-specific transport trajectory and residence time.

Table 5. Comparison of residence time, path length, tortuosity at various location in monsoon and pre-monsoon period

| Sl. No | Locations | Residence time Monsoon | Pre-monsoon | Path length Monsoon | Pre-monsoon | Tortuosity Monsoon | Pre-monsoon | Flushing inlet |
|-------|-----------|------------------------|-------------|---------------------|-------------|--------------------|-------------|---------------|
| a     | Cheria    | 2.6                    | 10          | 20                  | 30          | 0.4                | 0.5         | Munambam      |
| b     | Nedungad  | 25                     | 90          | 45                  | 43          | 0.7                | 0.73        | Munambam      |
| c     | Periyar   | 4                      | 23          | 20                  | 70          | 0.34               | 0.76        | Fortkochi     |
| d     | Thevara   | 4                      | 15          | 22                  | 52          | 0.53               | 0.75        | Fortkochi     |
| e     | Arookutty | 5                      | 20          | 50                  | 74          | 0.55               | 0.63        | Fortkochi     |
| f     | Murinjapuzha | 6.6                | 90          | 90                  | 130         | 0.57               | 0.75        | Fortkochi     |
| g     | Makayilkadavu | 7.5               | 90          | 120                 | 350         | 0.68               | 0.89        | Fortkochi     |
| h     | Thanneermukkom | 17.5             | 90          | 130                 | 63          | 0.70               | 0.72        | Fortkochi     |
| i     | Alappuzha | 21                     | 90          | 160                 | 3           | 0.70               | 0.03        | Fortkochi     |
Figure 18. Particle trajectories in nine locations during the monsoon period. Red (1)-Yellow (2)-Green (3)-Cyan (4)-Blue (5)-Magenta (6) lines indicate the path of the particles at each location.
Figure 19. Particle trajectories in nine locations during pre-monsoon period. Red (1)-Yellow (2)-Green (3)-Cyan (4)-Blue (5)-Magenta (6) lines indicate the path of the particles at each location.
3.4. Controlling factors determining the flushing characteristics of the CE

3.4.1 Case.1: Particles released in the model domain with river ON and tide OFF condition

The estuarine region showed a unidirectional flow, so that particles near to the inlet flushed out first and farthest at last within 22 days, which was 3 days earlier than the actual monsoon simulation. Back and forth movement of these particles was not evident, which corresponds same path length and net displacement of the particles and hence minimum tortuosity for the river ON and tide OFF simulation. The maximum path length of 70 km (Case 1) was noticed in southern upstream of the CE, which was twofold lower than path length in actual monsoon simulation (160 km). This experiment confirms that the particles were flushing with least path length and comparable residence time to that noticed during monsoon simulation.

**Figure 20.** Displacement, path length and tortuosity of the CE during the control run simulation with Case.1 (river ON and tide OFF condition).
3.4.1 Case.2: Particles released in the model domain with river OFF and tide ON condition

The average residence time of this simulation was almost comparable to that of pre-monsoon simulation (90 days), where < 30 % of the particles only flushed from the system. Strong back and forth movement of these particles were noticed with the larger path length and high tortuosity in the river ON and tide OFF simulation. The flushing efficiency of CE was significantly reduced during the actual pre-monsoon simulation, which was clearly reproduced in this experiment. This experiment also confirms the least flushing nature of the CE with larger path length, high tortuosity and longer residence time and almost corresponds to the pre-monsoon simulation.

Figure 21. Displacement, path length and tortuosity of the CE during the control run simulation with Case.2 (river OFF and tide ON condition).

4. Conclusions

A thorough understanding of the pollution transport and dispersal mechanism in the estuaries are highly essential for its sustainable management. Cochin city is one of the densely populated regions in India, where most of the industries in the state are co-located. Hence an understanding of the hydrodynamic behavior, it’s mixing and flushing time scale is highly essential to the legislation of policymakers to implement sustainable management of the estuary. Hydrodynamic model (FVCOM) coupled with particle tracking module was used to study the pollution transport trajectories and its residence time with respect to seasonal river discharge. Spatio-temporal patterns of the particle distribution in the CE showed similar trend during monsoon and post-monsoon with an average residence time of 25 and 30 days respectively. The longer residence time of 90 days were noticed during the pre-monsoon could be attributed to low river discharge and tidal incursion to the upstream regions resulted in a limited transport. This augments the retention capacity of pollutants in the system for a long time with longer path length and high tortuosity. Shorter path length, tortuosity and shorter residence during the monsoon, significantly modified the flushing efficiency of the CE. Irrespective to the season, estuarine regions nearer to the inlets Fortkochi and Munambam found to be fast flushing zones with minimum tortuosity. Slow flushing zones were demarcated at Nedungad (all seasons) and Thanneermukkom (pre-monsoon). The sluggish movement noticed in the Nedungad region was due to the opposing tidal forces entering from two inlets, whereas during
the closure of Thanneermukkom barrage, tidal wave reflect from the barrage results a standing wave.

The experiments carried out tide OFF and river ON (Case 1) is almost similar to the monsoon condition of the CE, while tide ON and river OFF (Case 2) was typically simulate pre-monsoon scenario. This confirms that seasonal forcing has significant influence on the flushing characteristics and residence time of the CE. Thus, major factor that controls the flushing characteristics and residence time of Cochin estuary is river discharge during monsoon while that of pre-monsoon is driven by tidal dynamics and geomorphological settings. Since CE experiences untreated pollution stress from all directions, stringent measures must be adopted before any catastrophic events affect this estuary. These results emphasis the need for the proper treatment of pollutants before they released into the estuary especially during the pre-monsoon period due to the longer residence time. This will be crucial information for multiple stakeholders in planning and adaptive management of developmental activities in the CE that supports a healthy, sustainable estuarine environment.

**Supplementary Materials:** The following are available online at www.mdpi.com/xxx/s1, Video S1: Particle tracking animation during the monsoon and pre-monsoon, Video S2: An animation of salinity changes with respect to ebb-flood periods during high discharge period and supplementary figures. S1 to S8

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**References**

1. Liu, W.X.; Li, X.D.; Shen, Z.G.; Wang, D.C.; Wai, O.W.H.; Li, Y.S. Multivariate statistical study of heavy metal enrichment in sediments of the Pearl River Estuary. *Environ. Pollut.* **2003**, *121*, 377–388.

2. Lancelot, C.; Billen, G. Activity of heterotrophic bacteria and its coupling to primary production during the spring phytoplankton bloom in the southern bight of the North Sea. *Limnol. Oceanogr.* **1984**, *29*, 721–730.

3. Monsen, N.E.; Cloern, J.E.; Lucas, L. V; Monismith, S.G. A comment on the use of flushing time, residence time, and age as transport time scales. *Limnol. Oceanogr.* **2002**, *47*, 1545–1553.

4. Delhez, E.J.M.; Campin, J.-M.; Hirst, A.C.; Deleersnijder, E. Toward a general theory of the age in ocean modelling. *Ocean Model.* **1999**, *1*, 17–27.

5. González, F.U.T.; Herrera-Silveira, J.A.; Aguirre-Macedo, M.L. Water quality variability and eutrophic trends in karstic tropical coastal lagoons of the Yucatán Peninsula. *Estuar. Coast. Shelf Sci.* **2008**, *76*, 418–430.

6. Bolin, B.; Rodhe, H. A note on the concepts of age distribution and transit time in natural reservoirs.
Tellus 1973, 25, 58–62.

7. Takeoka, H. Fundamental concepts of exchange and transport time scales in a coastal sea. Cont. Shelf Res. 1984, 3, 311–326.

8. Zimmerman, J.T.F. Mixing and flushing of tidal embayments in the western Dutch Wadden Sea part I: Distribution of salinity and calculation of mixing time scales. Netherlands J. Sea Res. 1976, 10, 149–191.

9. CPCB Pollution potential of industries in coastal areas of India. Coastal Pollution Control Series: Central Pollution Control Board Report; 1996;

10. Nair, S.M.; Balchand, A.N. Phosphate-Phosphorus (Ad-)Sorption Characteristics of Sediments from a Very High Productive Coastal Zone. Toxicol. Environ. Chem. 1993.

11. Martin, G.D.; George, R.; Shaiju, P.; Muraleedharan, K.R.; Nair, S.M.; Chandramohanakumar, N. Toxic metals enrichment in the surficial sediments of a eutrophic tropical estuary (Cochin Backwaters, Southwest Coast of India). Sci. World J. 2012, 2012.

12. Nair, M.P.; Sujatha, C.H. Environmental geochemistry of core sediment in the Cochin Estuary (CE), India. Res. J. Chem. Sci. 2013, 3, 65–69.

13. Balachandran, K.; Raj, C.M.L.; Nair, M.; Joseph, T.; Sheeba, P.; Venugopal, P. Heavy metal accumulation in a flow restricted, tropical estuary. Estuar. Coast. Shelf Sci. 2005, 65, 361–370.

14. Narayanan, N.C.; Venot, J.-P. Drivers of change in fragile environments: Challenges to governance in Indian wetlands. In Proceedings of the Natural Resources Forum; 2009; Vol. 33, pp. 320–333.

15. Sruthy, S.; Ramasamy, E.V. Microplastic pollution in Vembanad Lake, Kerala, India: the first report of microplastics in lake and estuarine sediments in India. Environ. Pollut. 2017, 222, 315–322.

16. KPCB Kerala state pollution control board action plan for greater Kochi area; 2010;

17. Rajan, P.D.; Purushothaman, S.; Krishnan, Siddhartha, M.C., Kiran, D., Deepak, T.D.; J. Strengthening Communities and Institutions for Sustainable Management of Vembanad Backwaters, Kerala. In Proceedings of the Taal 2007: The 12th World Lake Conference; 2008; pp. 1158–1163.

18. Remani, K.N.; Jayakumar, P.; Jalaja, T.K. Environmental Problems and Management Aspects of Vembanad Kol Wetlands in South West Coast of India. Nature, Environ. Pollut. Technol. 2010, 9, 247–254.

19. Lallu, K.R.; Fausia, K.H.; Vinita, J.; Balachandran, K.K.; Naveen Kumar, K.R.; Rehitha, T. V. Transport of dissolved nutrients and chlorophyll a in a tropical estuary, southwest coast of India. Environ. Monit. Assess. 2014.

20. Janardanan, V.; Amaravayal, S.; Revichandran, C.; Manoj, N.T.; Muraleedharan, K.R.; Jacob, B. Salinity Response to Seasonal Runoff in a Complex Estuarine System (Cochin Estuary, West Coast of India). J. Coast. Res. 2015, 314.
21. Chen, C.; Liu, H.; Beardsley, R.C. An unstructured grid, finite-volume, three-dimensional, primitive equations ocean model: application to coastal ocean and estuaries. *J. Atmos. Ocean Technol.* **2003**, *20*, 159–186.

22. Srinivas, K.; Revichandran, C.; Thottam, T.J.; Maheswaran, P.A.; Mohamed Ashraf, T.T.; Murukes, N. Currents in the Cochin estuarine system [southwest coast of India] during March 2000. *Indian J. Mar. Sci.* **2003**, *32*, 123–132.

23. Revichandran, C.; Srinivas, K.; Muraleedhharan, K.R.; Rafeeq, M.; Amaravayal, S.; Vijayakumar, K.; Jayalalshmy, K. V. Environmental set-up and tidal propagation in a tropical estuary with dual connection to the sea (SW Coast of India). *Environ. Earth Sci.* **2012**, *66*, 1031–1042.

24. Shivaprasad, A.; Vinita, J.; Revichandran, C.; Manoj, N.T.; Jayalakshmy, K. V; Muraleedhharan, K.R. Ambiguities in the classification of Cochin estuary, West coast of India. *Hydrol. Earth Syst. Sci. Discuss.* **2013**, *3595–3628*.

25. Guzain, C.; Remacle, J.-F. Gmsh: A 3-D finite element mesh generator with built-in pre-and post-processing facilities. *Int. J. Numer. Methods Eng.* **2009**, *79*, 1309–1331.

26. Willmott, C.J. On the validation of models. *Phys. Geogr.* **1981**, *2*, 184–194.

27. Churchill, J.H.; Runge, J.; Chen, C. Processes controlling retention of spring-spawned Atlantic cod (Gadus morhua) in the western Gulf of Maine and their relationship to an index of recruitment success. *Fish. Oceanogr.* **2011**, *20*, 32–46.

28. Huret, M.; Runge, J.A.; Chen, C.; Cowles, G.; Xu, Q.; Pringle, J.M. Dispersal modeling of fish early life stages: sensitivity with application to Atlantic cod in the western Gulf of Maine. *Mar. Ecol. Prog. Ser.* **2007**, *347*, 261–274.

29. Anderson, E.J.; Phanikumar, M.S. Surface storage dynamics in large rivers: Comparing three-dimensional particle transport, one-dimensional fractional derivative, and multirate transient storage models. *Water Resour. Res.* **2011**, *47*.

30. Defne, Z.; Ganju, N.K. Quantifying the residence time and flushing characteristics of a shallow, back-barrier estuary: Application of hydrodynamic and particle tracking models. *Estuaries and Coasts* **2015**, *38*, 1719–1734.

31. Ramamirtham, C.P.; Muthusamy, S. Estuarine oceanography of the Vembanad lake Part II: the region between Cochin and Azhikode. *Indian J. Fish.* **1986**, *33*, 218–224.

32. Du, J.; Shen, J. Water residence time in Chesapeake Bay for 1980–2012. *J. Mar. Syst.* **2016**, *164*, 101–111.

33. Uncles, R.J.; Stephens, J.A.; Smith, R.E. The dependence of estuarine turbidity on tidal intrusion length, tidal range and residence time. *Cont. Shelf Res.* **2002**, *22*, 1835–1856.

34. Marsan, D.; Rigaud, S.; Church, T. Natural radionuclides 210Po and 210Pb in the Delaware and Chesapeake Estuaries: modeling scavenging rates and residence times. *J. Environ. Radioact.* **2014**, *138*,
447–455.

35. Zhang, W.G.; Wilkin, J.L.; Schofield, O.M.E. Simulation of water age and residence time in New York Bight. *J. Phys. Oceanogr.* 2010, 40, 965–982.

36. Mahanty, M.M.; Mohanty, P.K.; Pattanaik, A.K.; Panda, U.S.; Pradhan, S.; Samal, R.N. Hydrodynamics, temperature/salinity variability and residence time in the Chilika lagoon during dry and wet period: Measurement and modeling. *Cont. Shelf Res.* 2016, 125, 28–43.

37. Samanta, S.; Dalai, T.K.; Pattanaik, J.K.; Rai, S.K.; Mazumdar, A. Dissolved inorganic carbon (DIC) and its δ13C in the Ganga (Hooghly) River estuary, India: Evidence of DIC generation via organic carbon degradation and carbonate dissolution. *Geochim. Cosmochim. Acta* 2015, 165, 226–248.

38. Sridevi, B.; Sarma, V.; Murty, T.V.R.; Sadhuram, Y.; Reddy, N.P.C.; Vijayakumar, K.; Raju, N.S.N.; Kumar, C.H.J.; Raju, Y.S.N.; Luis, R.; et al. Variability in stratification and flushing times of the Gautami–Godavari estuary, India. *J. Earth Syst. Sci.* 2015, 124, 993–1003.

39. Arneson, R.J. Seasonal variations in tidal dynamics, water quality, and sediments in the Coos Bay estuary. 1975.

40. Choi, B. Pollution and tidal flushing predictions for Oregon’s estuaries. 1975.

41. Wang, C.-F.; Hsu, M.-H.; Kuo, A.Y. Residence time of the Danshuei River estuary, Taiwan. *Estuar. Coast. Shelf Sci.* 2004, 60, 381–393.

42. Jiang, C.; Liu, Y.; Long, Y.; Wu, C. Estimation of Residence Time and Transport Trajectory in Tieshangang Bay, China. *Water* 2017, 9, 321.

43. Wang, Y.; Shen, J.; He, Q.; Zhu, L.; Zhang, D. Seasonal variations of transport time of freshwater exchanges between Changjiang Estuary and its adjacent regions. *Estuar. Coast. Shelf Sci.* 2015, 157, 109–119.

44. Grabemann, I.; Kühle, H.; Kunze, B.; Müller, A. Studies on transport times and water quality in the Weser estuary (Germany). *Coast. Estuar. Stud.* 1996, 291–301.

45. Kumar, A.A.; Dipu, S.; Sobha, V. Seasonal variation of heavy metals in cochin estuary and adjoining Periyar and Muvattupuzha rivers, Kerala, India. *Glob. J. Environ. Res.* 2011, 5, 15–20.

46. Anas, A.; Jasmin, C.; Sheeba, V.A.; Gireeshkumar, T.R.; Nair, S. Heavy metals pollution influence the community structure of Cyanobacteria in nutrient rich tropical estuary. 2015.

47. Sheeba, V.A.; Abdulaziz, A.; Gireeshkumar, T.R.; Ram, A.; Rakesh, P.S.; Jasmin, C.; Parameswaran, P.S. Role of heavy metals in structuring the microbial community associated with particulate matter in a tropical estuary. *Environ. Pollut.* 2017, 231, 589–600.

48. Nair, S.M.; Balchand, A.N.; Nambisan, P.N.K. Metal concentrations in recently deposited sediments of Cochin backwaters, India. *Sci. Total Environ.* 1990, 97, 507–524.
49. Kumar, P.K.D.; Srinivas, K.; Muraleedharan, K.R.; Thottam, T.J. Observed mixed standing-wave signatures in Cochin Estuary on the southwest coast of India. J. Coast. Res. 2009, 1106–1113.

50. Shivaprasad, A.; Vinita, J.; Revichandran, C.; Manoj, N.T.; Srinivas, K.; Reny, P.D.; Ashwini, R.; Muraleedharan, K.R. Influence of Saltwater Barrage on Tides, Salinity, and Chlorophyll a in Cochin Estuary, India. J. Coast. Res. 2013, 292.

51. Chandy, J.; Raghunathan, R. Impact of Back Water Tourism in Kerala. Int. J. Adv. Eng. Res. Dev. 2017, 4, 227–232.

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