

Chemical composition and possible sources of suspended particulate matter in the peripheral environments of Batticaloa lagoon, Sri Lanka

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HIGHLIGHTS

- Low correlation is noted among SPM and water physical properties in Batticaloa lagoon.
- SPM of lagoon peripherals originated from weathered sediments of the region.
- Biological activities are likely to explain the chemical compositional alterations.
- Trace metal concentrations pointed to a lower contaminated environment.

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ABSTRACT

Since coastal lagoons are mixing zones of fresh and saline water, suspended particulate matter (SPM) in different environments within a lagoon exhibits unique properties. Biogeochemical processes of different environments within a coastal lagoon are critically reviewed. In this study, the peripheral environment of Batticaloa lagoon which is a large, semi-enclosed, micro-tidal lagoon in the tectonically inactive tropical climatic zone of Sri Lanka was evaluated for its chemical composition of SPM in the post winter monsoonal season 2016. Further, it was compared with physical conditions of water and general surface sediment geochemistry. Overall physical parameters of the lagoon peripheral indicate low oxygenated brackish water with neutral pH. The concentration of SPM shows a weak correlation with the physical parameters of water. The peripheral environment of the lagoon has higher concentrations of Zn, Cu, Ni, MnO and P₂O₅ in SPM compared to the surface sediments. Previous studies have shown that these elements are rich in marine micro-organisms. Further, with respect to the statistical correlations, no evidence was found to prove the sorbing nature of iron and manganese coatings as described in other studies. Hence the results suggest that the tropical climates and allied organisms at the peripheral environment of the lagoon have improved the chemical composition of SPM with respect to that of lagoon surface. Environmental concerning elements indicate minor to moderate enrichments compared to upper continental crust with iron as the reference element in the Enrichment Factor calculation. Despite the size and micro-tidal effect of Batticaloa lagoon environment, the concentration of SPM does not vary throughout the entire study area except at the river discharging points.

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1. Introduction

Physical, chemical and biological characterization of a lagoon environment is very important to understand the nature of biogeochemical processes (Basaham, 2008; Magallanes-Ordóñez et al., 2015). The peripheral environment of a lagoon is the shallow mixing zone of the local and distant runoff with marine fluxes.

Hence it is susceptible to rapid physical, biological and chemical fluctuations compared to other internal environments of the lagoon. Accumulation of different organic and inorganic particles in this environment can be in the form of aqueous and/or solid phase as pore water, overlying water, solid sediments, suspended particulate matters (SPM) and biota (Eggleton and Thomas, 2004). Further, chemical contaminants, including heavy metals and other toxic elements can be dissolved in water or adsorbed on suspended and surface sediments in different proportions during the mixing of different water types (Namieśnik and Rabajczyk, 2010; Hartnett and Berry, 2012).

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SPM measures the chemical composition of organic and inorganic particulates (i.e. different types of particulate matter and their concentrations) with particle sizes greater than 0.45 μm , which are suspended in water (Turner and Millward, 2002). Chemical composition of SPM in coastal environments is primarily controlled by lithogenic, hydrogenic, biogenic and anthropogenic supplying factors (Turner and Millward, 2002; Eisma, 2012). Distribution of SPM within a water body of a lagoon is further controlled by physical properties and processes, such as temperature, tides, wind, sedimentation and re-suspension, chemical properties and processes such as pH, salinity, dissolution, adsorption and coagulation and biological processes (Cantwell et al., 2002; Siraswar and Nayak, 2013). The high sorptive nature in finer particle sizes of SPM is a primary factor in contaminant accumulation (Li et al., 2000; Fan et al., 2002). Many aquatic organisms feed on SPM and, therefore, have a significant ability to modify the physical, ecological and chemical characteristics of the aquatic environment (Turner and Millward, 2002; Twining et al., 2014).

Chemical composition of SPM in different coastal environments has been studied extensively to understand contamination caused by natural or anthropogenic disturbances (Price et al., 2005; Violintzis et al., 2009; Schubert et al., 2012; Beck et al., 2013; Helali et al., 2016). Lagoon–estuarine environments have also been studied for spatial and temporal distributions of contaminants and their possible sources (Vazquez et al., 1999; Zwolsman and Van Eck, 1999; Siraswar and Nayak, 2013; Meng et al., 2015). Further, SPM in lagoon environments has provided valuable information on changes to the surrounding environment (Miller and Cruise, 1995; Magallanes-Ordóñez et al., 2015). However, the scientific literature rarely addresses the chemical composition of SPM within different local environments of a lagoon (lagoon mouth, river inputs, mixing zones, etc.) and its relations to physical properties of water. Further, these local lagoon environments in tectonically inactive tropical monsoonal climatic zones have not been studied for the chemical composition of SPM in detail. These research findings will be helpful in characterization of biogeochemical processes of different environments within a lagoon.

This study focuses on using the chemical composition of SPM to understand some of the physical, geochemical and biological processes in a lagoon in tectonically inactive tropical monsoonal climatic zone during the post monsoon period. This research provides the results of a detail study of the peripheral environment of a large, semi-enclosed, micro-tidal lagoon in aforementioned climatic and tectonic settings of Sri Lanka on the following: (a) Chemical composition of SPM (b) Possible sources of SPM (c) Relationships between chemical composition of SPM and physical properties of water and (d) Relations in chemical composition of SPM and surface sediments.

2. Regional settings

Batticaloa is the largest lagoon in eastern Sri Lanka and is connected to the Bay of Bengal by a semi-enclosed narrow mouth (Fig. 1; latitude $7^{\circ}24'–7^{\circ}46'$ N and longitude $81^{\circ}35'–81^{\circ}49'$ E). The area surrounding the lagoon is topographically leveled with low surface undulations (Cooray, 1984). The average length, depth and surface area are 56 km, 4 m, and 168 km², respectively (Sugirtharan et al., 2015). Fresh water flows into the lagoon from two major stream channels that pass more than 10 km through paddy fields. The paddy fields are cultivated primarily during the seasons of Yala (May–August) and Maha (September–March). In addition, there are six tributaries at various landward points (Fig. 1). The eastern side of the lagoon is a barrier spit and is densely populated (Cooray and Katupotha, 1991). On the other hand, the western side is demarcated by paddy lands and is sparsely populated.

The basement rocks of the lagoon consist of hornblende–biotite migmatite, granite gneiss, alkali feldspar migmatite, augen gneiss

and minor amphibolite layers with sedimentary enclaves (Fig. 1; Cooray, 1994; Kehelpannala, 2003; Kröner et al., 2012). Thin Quaternary sediments cover the basement rocks with weathered exposures observed in northern, middle and southern regions (Cooray and Katupotha, 1991).

The climate of the Batticaloa lagoon and surrounding area is typically dryer than other areas within the country. The average temperature ranges from 22 °C to 32 °C and the annual rainfall ranges between 1500 mm to 2000 mm with sunshine of 2500 h/annum and evaporation of 1400 mm/annum (Chandrapala and Wimalasuriya, 2003; Department of Meteorology, Sri Lanka, 2015). In general, the highest rainfall is recorded during November to February months due to the monsoons while the other months are dry. The average wind direction is north-east to south-west with a speed between 3–4 m/s. The humidity is above 75% throughout the year (Chandrapala and Wimalasuriya, 2003).

The tide ranges between 0.2–0.8 m (average value for 2014 and 2015, National Aquatic Resources, research and development Agency, Sri Lanka). Salinity ranges from 3.5–37.5 ppt (Sugirtharan et al., 2015). Freshwater circulation has been observed with prevailing monsoonal wind currents. The lagoon has a complex ecosystem with freshwater wetlands and marine habitats including sea grasses and mangroves (Kularatne, 2014). Therefore, the SPM of the lagoon is nourished from lithogenic, biogenic, hydrogenic and anthropogenic components.

3. Materials and methods

3.1. Sample collection and analysis

SPM sampling was carried out during the post-monsoon period in May 2016. The temperatures of the locations ranged from 26 to 33 °C with very low wind speed (<1 m/s) while sampling was carried out. A total of 34 locations were selected around the lagoon to cover both river input and lagoon output regions (Fig. 1). Sampling locations were carefully chosen based on similar hydrological conditions in general currents and wind speeds. Each sampling point was selected 50 cm below the water surface in places where water height was approximately 1 m. A total of 5 l samples were collected in pre-cleaned polypropylene containers. Physical parameters including pH, oxidation reduction potential (ORP), dissolved oxygen (DO), salinity and temperature were measured in the field using a portable Horiba D-73 combined instrument (Rikagaku kenkujo, Japan), which was calibrated for pH, DO and salinity by means of standard calibration procedure (Jayawardana et al., 2012). Average accuracy for pH, ORP, DO and salinity were ± 0.1 , ± 10 mV, ± 10 mg/L and $\pm 0.5\%$ respectively, with approximately 1–5% precision. Collected water samples were stored immediately in a cooling box with temperatures less than 4 °C for laboratory analyses.

The water samples were vacuum filtered using pre-weighed 0.45 μm Whatman quartz filters. Remaining sediments and Whatman quartz filters were oven dried at 60 °C. Concentration of SPM was calculated on a dry weight basis. The oven dried filters were sealed (air tight) and sent for chemical analysis. The samples were analyzed for 13 elements (As, Pb, Zn, Cu, Ni, Cr, V, Sr, Y, Nb, Zr, Th and Sc) and five oxides (TiO₂, Fe₂O₃, MnO, CaO, P₂O₅) using X-ray fluorescence spectrometry (Rigaku RIX 2000) at Shimane University, Japan. The element concentrations of SPM were determined directly from loaded quartz filters in to the Rigaku RIX-2000 spectrometer equipped with an Rh-anode tube. Average error for these elements is less than 10%.

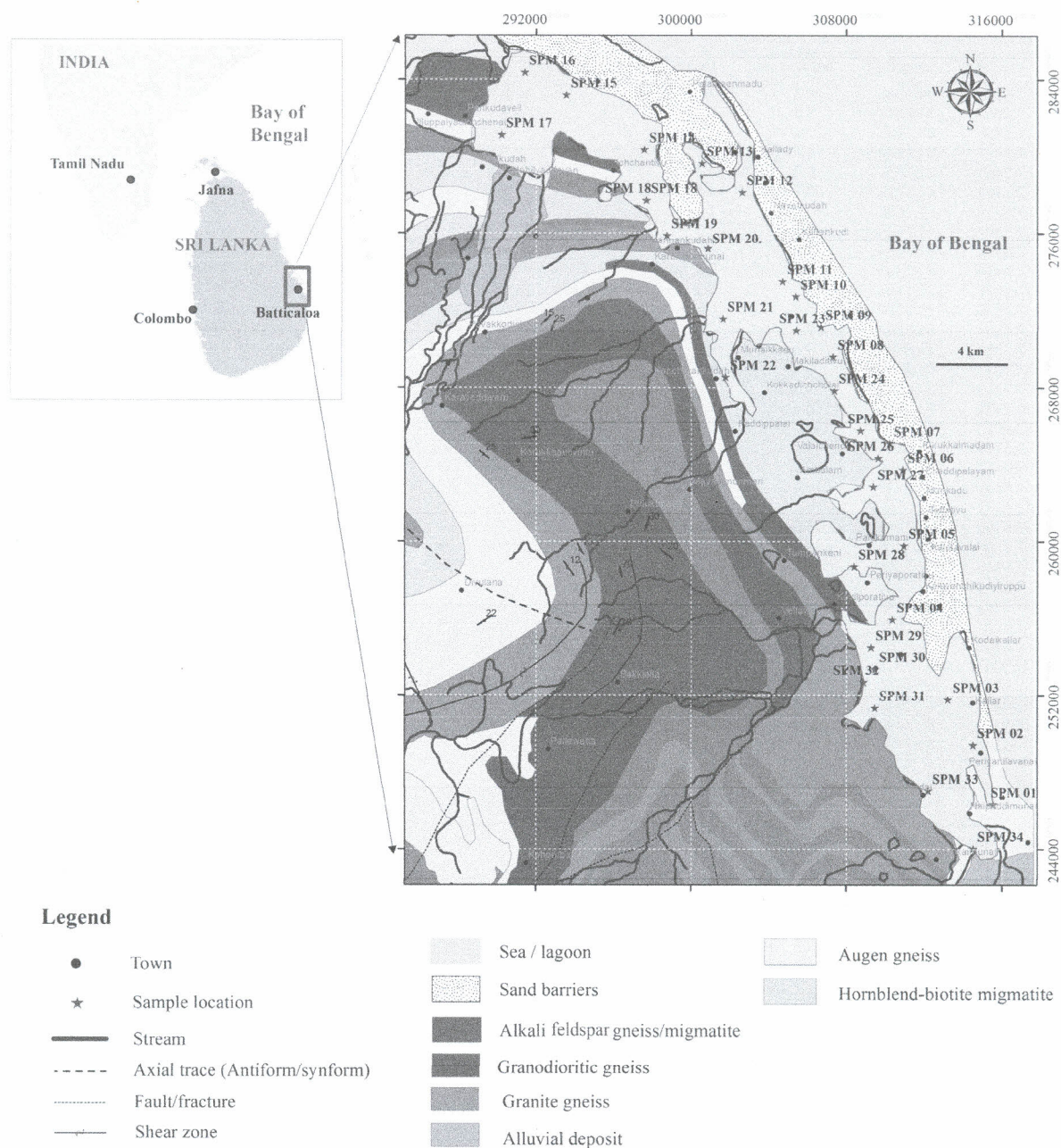


Fig. 1. Simplified geological map and sampling locations of the Batticaloa lagoon.

3.2. Enrichment factor

SPM metal enrichment was calculated using an Enrichment Factor (EF) (Lin et al., 2012). Fe was selected as the standardized element to calculate the EF out of the number of conservative elements (Fe, Al, Mn) that were used (Aprile and Bouvy, 2008; Martins et al., 2012; Uduma and Awagu, 2013). Fe has been used as the normalization metal to assess the contamination status of SPM in coastal environments (Balls, 1986; Carvalho et al., 2005; Acevedo-Figueroa et al., 2006). The EF was calculated using the following expression:

$$EF = \frac{[X/Fe]_{\text{Sample}}}{[X/Fe]_{\text{UCC}}}$$

where, X and Fe are the element concentration and iron concentration in each sample and Upper Continental Crust (UCC), respectively. The average UCC values were used, as described in Taylor and McLennan (1985). The EF values were interpreted according to Birch (2003) where $EF < 1$ represents no enrichment, $1 \leq EF < 3$ represents minor enrichment, $3 \leq EF < 5$ represents moderate enrichment, $5 \leq EF < 10$ represents moderately severe enrichment, $10 \leq EF < 25$ represents severe enrichment, $25 \leq EF < 50$ represents very severe enrichment and > 50 represents extremely severe enrichment.

3.3. Statistical analysis

Elemental correlations were examined using the Spearman rank correlation via SPSS 16 software. Spearman correlation matrix

Table 1

Physical parameters of water in SPM sampling locations and concentration of SPM, Batticaloa lagoon.

Sample	Latitude	Longitude	Salinity (‰)	Dissolved Oxygen (mg/L)	pH	Water temperature (°C)	ORP(mV)	SPM (mg/L)	Remarks
SPM01	7.4394	81.7938	0.1	1.6	6.9	33	13.1	678	Coastal side
SPM02	7.4660	81.8052	2.0	0.7	7.1	33	40.1	24	Coastal side
SPM03	7.4858	81.7965	2.7	2.1	6.9	33	13.4	24	Coastal side
SPM04	7.5271	81.7799	2.7	0.5	6.9	34	12.8	42	Coastal side
SPM05	7.5468	81.7750	0.3	0.4	7.5	33	201.0	28	Coastal side
SPM06	7.5768	81.7729	0.7	1.1	7.4	32	402.0	36	Coastal side
SPM07	7.5874	81.7680	1.3	1.3	7.3	33	480.0	70	Coastal side
SPM08	7.6302	81.7498	6.3	2.2	7.7	33	553.0	14	Coastal side
SPM09	7.6397	81.7439	6.8	3.1	7.2	35	593.0	6	Coastal side
SPM10	7.6658	81.7249	19.0	0.8	7.9	36	510.6	12	Coastal side
SPM11	7.6788	81.7193	19.6	1.2	7.2	34	547.8	76	Coastal side
SPM12	7.7099	81.7070	28.8	0.8	7.6	34	590.5	2	Coastal side
SPM13	7.7281	81.6804	22.1	0.9	7.6	35	148.0	24	Coastal side
SPM14	7.7387	81.6565	8.1	0.6	7.8	33	220.0	26	Land side
SPM15	7.7631	81.6172	6.1	0.5	7.3	32	440.0	98	Land side
SPM16	7.7709	81.6009	5.4	2.0	7.4	34	532.0	45	River discharge
SPM17	7.7371	81.5776	18.4	0.9	7.3	35	−53.6	138	River discharge
SPM18	7.6973	81.6537	11.7	0.7	7.7	34	−24.6	32	Land side
SPM19	7.6774	81.6664	15.5	0.7	8.5	36	−83.0	27	River discharge
SPM20	7.6671	81.6890	18.9	0.9	8.1	33	−17.2	52	Land side
SPM21	7.6409	81.6848	16.6	0.8	7.5	33	−24.7	166	River discharge
SPM22	7.6182	81.6938	16.1	2.7	7.4	35	−101.2	144	River discharge
SPM23	7.6365	81.7251	13.9	3.2	7.1	34	−23.1	146	Land side
SPM24	7.6199	81.7406	6.2	7.7	7.5	36	−70.0	68	Land side
SPM25	7.5919	81.7464	1.5	2.0	7.2	35	−104.2	20	Land side
SPM26	7.5848	81.7601	1.4	1.2	6.9	34	−141.4	20	Land side
SPM27	7.5708	81.7585	0.3	1.2	6.7	33	25.0	28	Land side
SPM28	7.5337	81.7627	0.2	0.6	7.1	34	184.1	28	Land side
SPM29	7.5136	81.7793	0.1	1.0	7.1	34	−1123.0	34	River discharge
SPM30	7.5066	81.7573	0.3	0.8	6.8	35	408.2	658	River discharge
SPM31	7.4861	81.7651	0.2	0.9	7.0	33	115.3	68	Land side
SPM32	7.5067	81.7513	0.5	0.9	7.1	34	−220.2	344	Land side
SPM33	7.4431	81.7793	0.2	1.0	7.0	33	−77.8	40	Land side
SPM34	7.4246	81.7902	0.1	1.1	7.0	33	7.1	30	River discharge
Min			0.1	0.4	6.7	32	−1123.0	2	
Max			28.8	7.7	8.5	36	593.0	678	
Average			7.5	1.4	7.3	34	116.9	96	

ORP: oxidation reduction potential, SPM: suspended particulate matter.

is a nonparametric correlation analysis that evaluates the relationship between two independent variables of raw data (Corder and Foreman, 2014). In general, the trace element data of the study area are not normally distributed and does not indicate linear relationships among them. Therefore, Spearman correlation matrix was calculated and *p* values <0.05 were considered significant. In addition, Principal Component Analysis (PCA) was performed on the elemental concentration data of SPM. According to Woods et al. (2012), this is a more reliable statistical analysis when interpreting the source of the heavy metals in estuarine sediments.

4. Results and discussion

4.1. Physical parameters of water

Table 1 provides the physical parameters and the concentration of SPM of the sampling locations in the Batticaloa lagoon. The peripheral water temperature values indicate high temperature tropical lagoon conditions (Sujitha et al., 2017). The pH values fall in a narrow range between 6.7 and 8.5 which coincides with the pH of freshwater aquatic life (6.5–9.0) as determined by the United States Environmental Protection Agency (USEPA, 1999). ORP values are negative in samples collected near river discharges while positive near the seaside. Presence of mangroves and other biotic sources, such as organic matter found at the bottom of the lagoon, suggests variations in ORP values in peripheral environments. Salinity variation of the different lagoon environments is similar to other lagoons found elsewhere (Garrido et al., 2016; Taylor et al., 2016). Lagoon DO values indicate the low oxygenated nature of lagoon peripherals. This suggests that majority of the

lagoon peripheral area is under 'severe hypoxia' (<4 mg/l), with a few locations characterized as 'minimum acceptable level' (<2 mg/l) for estuarine waters (Windsor, 1985). It is possible that lower levels of DO are due to lack of water circulation in the shallow lagoon peripherals which are covered by land morphologies.

4.2. SPM

The overall SPM concentration of the lagoon ranges from 2 mg/l to 678 mg/l with an average of 96 mg/l (Table 1). In general, the concentration of SPM is lower at the surface and increases towards the bottom of the water column (Garzanti et al., 2011; Siraswar and Nayak, 2013; Helali et al., 2016). The data of this study represent the center of the selected water column and, hence, may represent average conditions. The spatial variation of SPM concentration from fresh water discharge zones towards the mouth of the lagoon suggests water mixing and particle settling in stratified water as shown by Karageorgis et al., 2014 (Table 1, Fig. 1).

The total elemental concentrations in the SPM show low variability (Table 2). Environmental concerning elements (As, Pb, Zn, Ni, Cu and Cr) exhibit average concentrations below 90.8 ppm. The Fe₂O₃ (8.93 mg/kg) concentration is significantly high compared to other oxides which range from 0.23 to 1.22 mg/kg.

4.3. Enrichment factor of SPM

Elemental enrichments in SPM indicate minor to moderate enrichment of Mn and minor enrichment of As and Cr (Fig. 2).

Table 2
Geochemistry of SPM in Batticaloa lagoon.

Sample	Concentration														wt%				
	ppm														TiO ₂	Fe ₂ O ₃	MnO	CaO	P ₂ O ₅
	As	Pb	Zn	Cu	Ni	Cr	V	Sr	Y	Nb	Zr	Th	Sc						
SPM01	3	21	106	36	30	87	200	124	48	12	377	19	14	1.17	10.12	0.33	1.40	0.41	
SPM02	2	11	48	27	50	68	100	5	5	3	16	2	9	1.30	13.04	0.86	0.91	0.25	
SPM03	2	11	69	28	83	90	137	7	6	3	22	3	13	0.80	6.19	0.15	1.27	0.17	
SPM05	3	12	109	30	36	98	238	15	13	5	21	5	21	1.44	9.95	0.25	1.10	0.15	
SPM06	3	11	87	29	36	87	196	11	11	4	17	5	19	1.35	9.62	0.08	1.61	0.14	
SPM07	4	15	143	24	74	122	249	23	13	4	24	6	17	0.84	7.61	0.14	2.13	0.28	
SPM16	3	11	65	31	35	61	141	14	8	2	27	3	14	1.22	11.43	1.35	1.29	0.25	
SPM21	4	17	69	18	20	70	124	94	19	5	165	7	9	1.51	10.20	0.46	0.89	0.22	
SPM25	2	12	63	26	34	44	96	15	7	3	38	1	11	1.60	13.01	0.51	1.03	0.18	
SPM28	2	12	95	28	38	95	232	9	9	4	18	4	20	1.53	11.80	0.49	0.91	0.22	
SPM29	3	13	102	29	34	102	255	14	13	5	34	5	18	1.66	12.09	0.55	1.01	0.22	
SPM30	3	24	112	25	29	85	224	119	63	20	360	24	15	0.84	4.47	0.32	1.00	0.20	
SPM31	4	17	126	29	95	97	250	38	23	7	82	10	19	1.40	9.02	0.59	0.81	0.20	
SPM32	3	19	89	25	32	106	235	204	40	12	300	17	19	1.05	5.02	0.27	0.91	0.27	
SPM33	4	22	89	24	25	75	152	96	15	4	170	6	11	0.73	3.96	0.58	0.84	0.31	
SPM34	4	13	85	23	47	85	207	14	10	4	63	4	14	1.08	6.00	0.19	1.44	0.21	
Min	2	11	48	18	20	44	96	5	5	2	16	1	9	0.73	3.96	0.08	0.81	0.14	
Max	4	24	143	36	95	122	255	204	63	20	377	24	21	1.66	13.04	1.35	2.13	0.41	
Average	3	15	91	27	44	86	190	50	19	6	108	8	15	1.22	8.97	0.44	1.16	0.23	

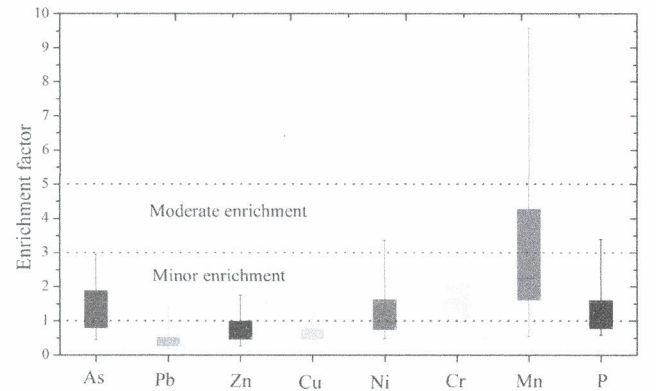


Fig. 2. Enrichment factors for elements of environmental concern in SPM of peripherals of Batticaloa lagoon.

Enrichment of environmental concerning elements in SPM indicates an unpolluted to moderately polluted environment for the Batticaloa lagoon peripherals.

4.4. Correlation of concentration of SPM and chemical elements

The Spearman correlation matrix indicates a grouped cluster of elements As, Pb, Sr, Y, Nb, Zr and Th (Cluster 1; Table 3). Another cluster of metals (Zn, Cr, V and Sc) is highlighted in the correlation matrix (Cluster 2). Zn of Cluster 2 indicates a high positive correlation between Cluster 1 elements. Concentrations of SPM indicate a very high positive correlation between Sr, Y and Th with high correlations between As, Pb, Nb and Zr. Hence, SPM has a good positive correlation with Cluster 1 elements.

The loading plot of the PCA after varimax rotation is shown in Fig. 3. First two components were selected which describe over 61.42% of the total variance. Principle Component 1 (PC1) accounted for 40.92% of the total variance indicating high loadings for Zr, Y, Th, Nb, Sr, Pb and SPM. The elements of above category are associated with heavy minerals which are commonly found on eastern coastal areas of Sri Lanka. This suggests that the inorganic portion of the composition of SPM is derived from the weathering products of associated rocks of eastern coast.

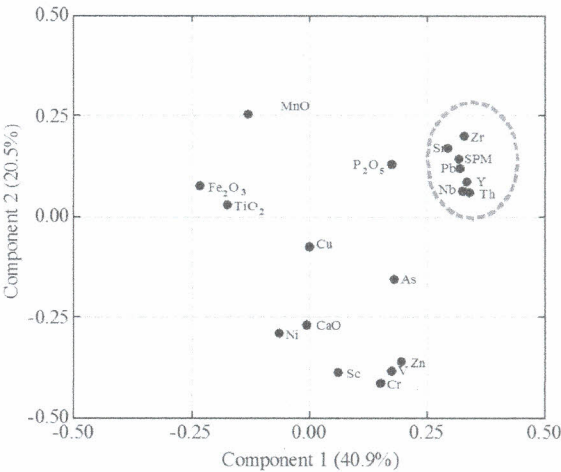


Fig. 3. Principal component loading plot of first two PCs for elements and concentration of SPM of the Batticaloa lagoon, Sri Lanka.

4.5. Relationship of SPM and physical parameters

Salinity, pH, temperature and ORP show weak negative correlations with SPM concentration ($r_s = -0.26$) and DO shows a weak positive correlation ($r_s = 0.10$). The negative correlation between SPM concentration and physical parameters suggests mixing and dilution of local discharges with sea water near lagoon margins. SPM in fresh water is deposited in early stages of a lagoon environment due to sea water–fresh water mixing regions (Zhang et al., 1998; Karageorgis et al., 2014). In some instances, salt induced flocculation of finer particles is a reason for particle settling (Thill et al., 2001). The other possibility is dilution of fresh water with particle depleted sea water. In contrast, the lower values and linearity of the correlation between salinity and SPM concentration can also be affected by the biogenic components and mineral grains observed in other studies due to flood periods (Bainbridge et al., 2012). In general, streams have high DO concentrations when enough time has passed to allow natural replenishment from the atmosphere (Ecker, 1975). However, fresh water discharge zones and high wave energy environments have comparatively high DO concentrations (>2 mg/L) showing positive correlations with SPM concentrations

Table 3

Spearman correlation matrix for SPM concentration, trace elements and major oxides.

	SPM	As	Pb	Zn	Cu	Ni	Cr	V	Sr	Y	Nb	Zr	Th	Sc	TiO ₂	Fe ₂ O ₃	MnO	CaO	P ₂ O ₅
SPM	1.00																		
As	0.74	1.00																	
Pb	0.71	0.65	1.00																
Zn	0.52	0.51	0.59	1.00															
Cu	−0.07	−0.42	−0.39	0.09	1.00														
Ni	−0.48	−0.19	−0.52	0.05	0.22	1.00													
Cr	0.22	0.18	0.21	0.71	0.15	0.32	1.00												
V	0.33	0.32	0.34	0.84	0.16	0.22	0.86	1.00											
Sr	0.80	0.65	0.89	0.49	−0.24	−0.59	0.14	0.25	1.00										
Y	0.86	0.67	0.87	0.70	−0.10	−0.51	0.35	0.48	0.90	1.00									
Nb	0.73	0.50	0.81	0.75	−0.03	−0.41	0.50	0.58	0.80	0.95	1.00								
Zr	0.72	0.58	0.89	0.29	−0.27	−0.63	−0.06	0.11	0.88	0.77	0.65	1.00							
Th	0.88	0.69	0.87	0.70	−0.14	−0.45	0.41	0.49	0.83	0.97	0.93	0.75	1.00						
Sc	0.09	0.01	−0.02	0.63	0.40	0.32	0.75	0.82	0.02	0.26	0.37	−0.20	0.22	1.00					
TiO ₂	−0.33	−0.35	−0.34	−0.11	0.29	−0.01	−0.05	0.07	−0.31	−0.20	−0.06	−0.30	−0.29	0.20	1.00				
Fe ₂ O ₃	−0.44	−0.57	−0.59	−0.40	0.38	0.10	−0.29	−0.26	−0.53	−0.52	−0.41	−0.48	−0.57	−0.15	0.80	1.00			
MnO	−0.08	−0.20	−0.05	−0.25	0.14	−0.15	−0.46	−0.19	−0.06	−0.13	−0.21	0.10	−0.17	−0.27	0.31	0.46	1.00		
CaO	−0.05	−0.02	−0.33	0.01	0.28	0.25	0.11	0.01	−0.22	−0.25	−0.24	−0.27	−0.24	0.09	−0.17	−0.01	−0.61	1.00	
P ₂ O ₅	0.48	0.32	0.37	0.10	−0.18	−0.31	0.00	0.04	0.40	0.25	0.11	0.40	0.30	−0.28	−0.33	−0.05	0.34	−0.13	1.00

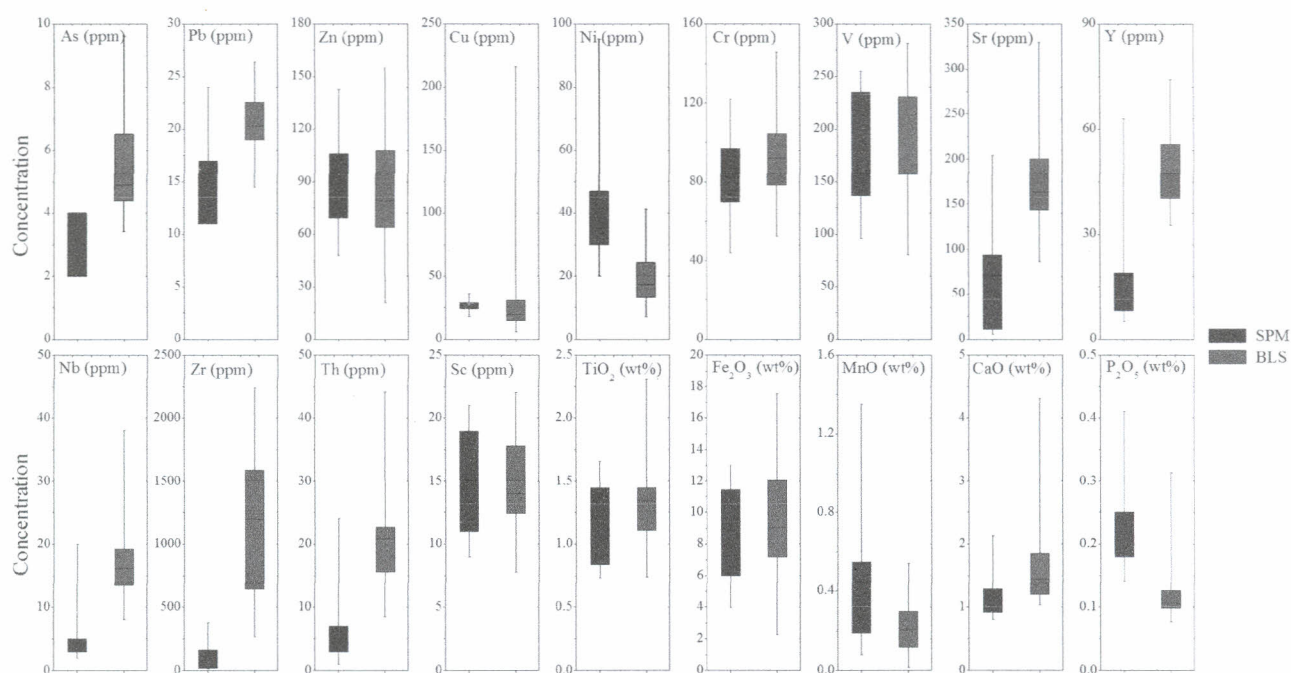


Fig. 4. Concentration of elements and oxides in SPM and surface sediments of Batticaloa lagoon (SPM is suspended particulate matters and BLS is surface sediments).

(Table 1). The slight negative correlations of pH ($r^2 = -0.15$) also might be due to mixing processes of fresh and saline waters.

4.6. Geochemical relationship between SPM and surface sediments

The elemental and oxide concentrations of SPM show higher concentrations of Zn, Cu, Ni, MnO and P_2O_5 than the surface sediments of the Batticaloa lagoon determined by Adikaram et al. (2016a, b) (Fig. 4). High concentrations of Zn and Cu have also been observed in SPM with compared to surface sediments in the Thermaikos Gulf in Northwestern Aegean Sea which were interpreted as both natural and anthropogenic origin (Price et al., 2005). In addition, similar concentrations of Cr, V, Sc, TiO_2 and Fe_2O_3 were observed in both surface sediments and SPM.

Typically, Fe and Mn are considered as common elements in estuarine environments (Zwolsman and Van Eck, 1999). In this case, MnO indicate higher concentrations in SPM than surface sediments while Fe_2O_3 indicate similar values in both SPM and surface sediments (Fig. 5). The continental crust of the study area (Vijayan Complex) consists of I-type granitoid gneiss, migmatite, minor metasedimentary enclaves and calcsilicate rocks including augen gneiss and hornblende-biotite bearing augen gneiss (Kröner et al., 2012). Hence, the Fe–Mn biotites of the area suggest being the major source of MnO and Fe_2O_3 contents in surface sediments and SPM. Further, Fe_2O_3 and MnO indicate a good correlation in surface sediments while the concentrations show scattered correlation in SPM (Fig. 5). This deficiency in correlation implies a biogenic origin for MnO.

Zwolsman (1994) shows that lower oxidation and precipitation rates of Mn in water compared to Fe. This interpretation can also be considered for higher concentrations of MnO in SPM relative to Fe_2O_3 . In addition, the peripheral environment of the lagoon has high bioturbation processes increasing the re-suspension of bottom sediments. Re-suspension ability of Mn is higher than that of Fe due to its high mobility in suboxic/anoxic conditions (Skei and Melsom, 1982; Salomons and Förstner, 1984; Calvert and Pedersen, 1993). Hence, higher concentrations of MnO could be observed in SPM in peripheral lagoon environments.

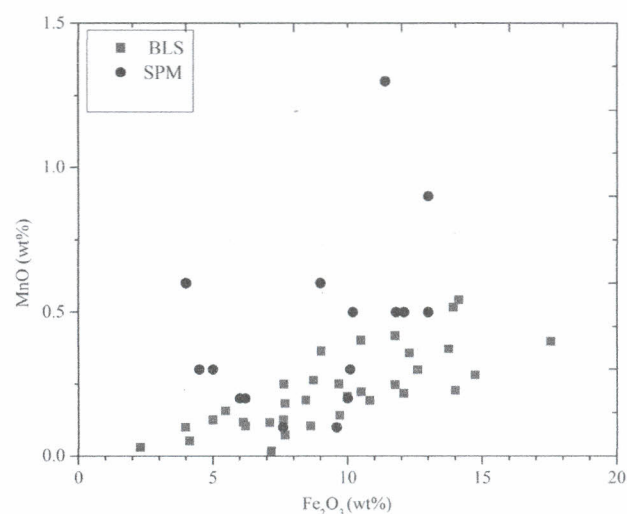


Fig. 5. Correlation between Fe_2O_3 and MnO in SPM and surface sediments of Batticaloa lagoon.

Organic matter and hydrous oxides of Fe and Mn in aquatic particles play a major role in sorption of trace metals (Balls, 1986; Turner et al., 2004). Therefore, SPM trace metal (Cu, Zn and Ni) enrichment, as compared to surface sediments, were considered with respect to Fe_2O_3 and MnO (Fig. 6). Trace metals have a good correlation with Fe_2O_3 and MnO in surface sediments while they display a scattered correlation with SPM. This scattered nature of SPM for these heavy metals can be considered as an indication of biogenic occurrences.

Schoer et al. (1983) and Turner et al. (1991) show that most of the trace metals change their concentrations in sea water with changes of salinity in coastal environments. However, the salinity variation at the peripheral region of the Batticaloa lagoon is not

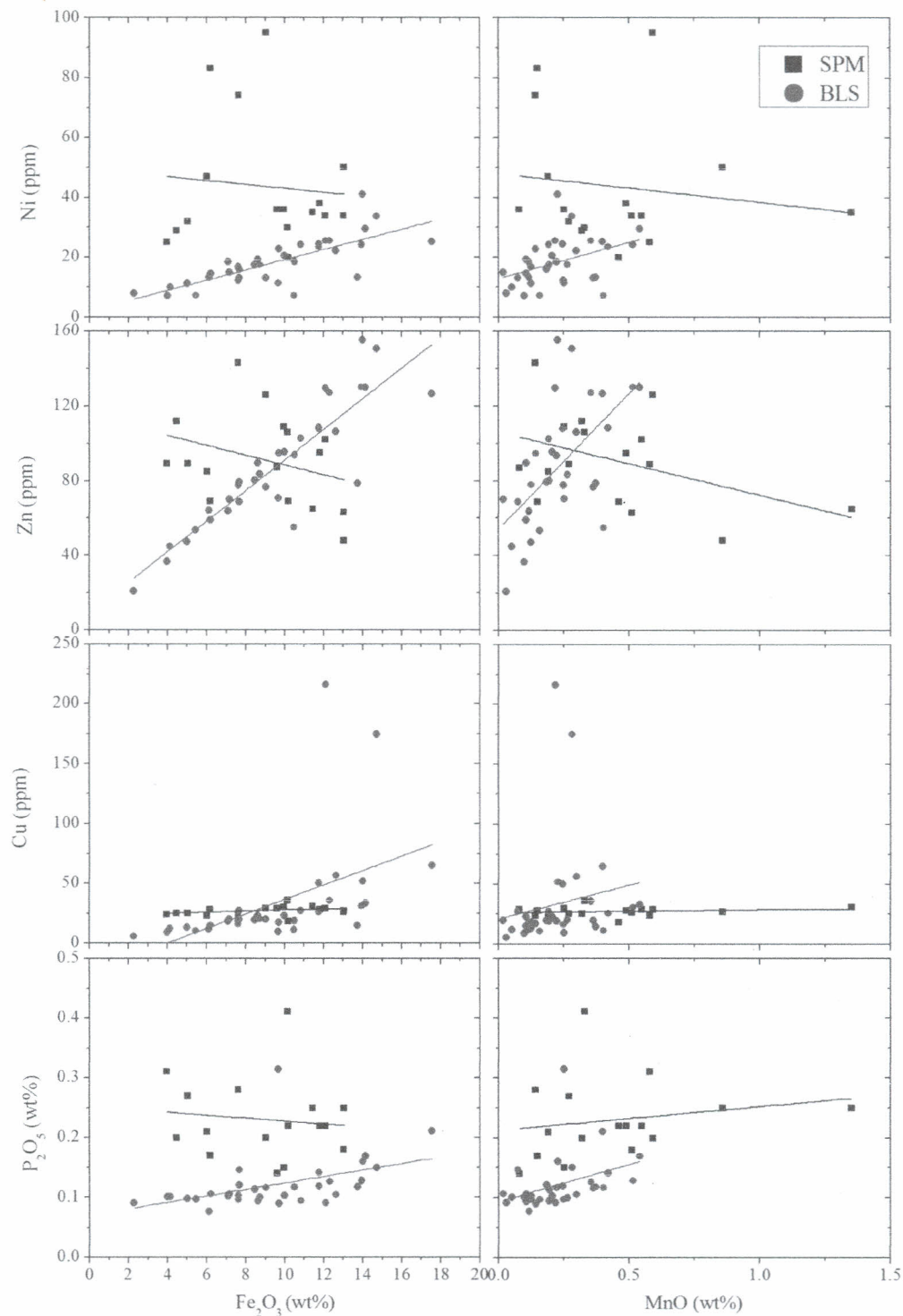


Fig. 6. Correlation between elements rich in SPM and oxides (Fe_2O_3 and MnO).

significant. The trace metal composition of marine phytoplankton suggests the metal enrichment in peripheral environments of Batticaloa lagoon. Twining and Baines (2013) and Twining et al. (2014) reported that the marine phytoplankton have high abundance of Fe and Zn followed by Mn, Ni and Cu. These results are matched with the present location. The elemental concentration is also dependent on the taxa of plankton (Twining and Baines,

2013). For example, a good source of Ni in coastal environments comes from diatoms (Böning et al., 2015). Hydroxides and oxides of Fe and Mn are considered as extracellular inorganic particles of phytoplankton (Ho et al., 2003). The higher MnO concentrations compared to Fe_2O_3 suggests a different type phytoplankton species present in the lagoon environment, such as coccolithophores as described by Ho et al. (2003).

The relationship of P_2O_5 with Fe_2O_3 in SPM of Batticaloa lagoon sediments is scattered while that of surface sediments indicate a linear correlation (Fig. 6). Phosphorus appears in coastal water bodies from both inorganic and organic sources (Meng et al., 2015). Detrital phosphorus (apatite) is the main source of inorganic phosphorus, which is derived from weathering of igneous or metamorphic carbonates. Hence, concentration of inorganic phosphorus in the lagoon sediments is expected to be low due to the rock assemblages of Eastern coastal areas. Hydroxides and oxides of Fe have the strongest absorption capacity for phosphate (Hingston et al., 1974; Khalid et al., 1977). Further, the concentration of inorganic phosphorus is decreasing with decreasing particle grain size, especially silt fraction (Zhu et al., 2013). Previous studies show that phosphorus can originate from biogenic activities with other elements such as N, Ba, Si and Ca (Zwolsman and Van Eck, 1999; Price et al., 2005; Violintzis et al., 2009). Most biogenic phosphorus is derived from biogenic apatite, $CaCO_3$ bound organic phosphorus and refractory organic phosphorus (Zhang et al., 2004). The concentration of CaO in the SPM of Batticaloa lagoon sediments is relatively low compared to the surface sediments. The concentration of CaO in the SPM of Batticaloa lagoon sediments is relatively low compared to surface sediments. This suggests that P_2O_5 has an organic origin by the decay of tissues of sea grasses and detritus of mangrove which are widely found near the peripheral areas of the lagoon similar to observations of Koch et al. (2001). Also, the weak positive correlation between P_2O_5 and MnO in SPM implies that both oxides have an effect from biogenic components.

5. Conclusion

Chemical composition of SPM and the physical parameters of the peripheral region of the Batticaloa lagoon were determined to understand its possible sources of SPM and its relation to physical properties and processes of water and chemical composition of surface sediments of the lagoon. Batticaloa lagoon is a semi-enclosed, micro-tidal lagoon in the tropical climatic zone of Sri Lanka.

Overall physical parameters of the lagoon periphery indicate low oxygenated brackish water and neutral pH conditions. The concentration of SPM shows a weak correlation with the physical parameters of water. Present day sedimentation of this environment is chemically unpolluted. The peripheral environment of the lagoon has higher concentrations of Zn, Cu, Ni, MnO and P_2O_5 in SPM compared to the surface sediments. Further, no evidence was found to prove the sorbing nature of iron and manganese coatings as described elsewhere. This suggests that the dilution of weathered bedrock materials in water and allied organisms at the peripheral environment of the lagoon control the chemical composition of SPM. Despite the size and micro-tidal effect of this lagoon environment, the concentration of SPM does not vary throughout the entire study area except at the river discharging points. This work presents the present day sedimentation processes of the periphery of a tropical lagoon and the results will be compared with the other internal environments of the lagoon in the future.

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