RESEARCH ARTICLE

Coastal Ecology

Spatial distribution of heavy metals in surface sediments of the Kalametiya Lagoon in southern Sri Lanka: Insights into the pollution status and socio-economic interactions

KAS Kodikara[1*†], T Hoessein[2†], PMCS De Silva[3], P Ranasinghe[4], HPPS Somasiri[4], SK Madarasinghe[1], DUV Gunathilaka[1], D Ranawaka[1], M Danaee[5], J Andrieu[6] and F Dahdouh-Guebas[2,7]

[1] Department of Botany, Faculty of Science, University of Ruhuna, Matara, Sri Lanka.

[2] Ecology and Biodiversity, Laboratory of Plant Biology and Nature Management, Biology Department, Vrije Universiteit Brussel, Brussels, Belgium.

[3] Department of Zoology, Faculty of Science, University of Ruhuna, Matara, Sri Lanka.

[4] Herbal Technology Section, Industrial Technology Institute, Colombo 7, Sri Lanka.

[5] Department of Social and Preventive Medicine, Faculty of Medicine, University of Malaya, 50603 Kuala Lumpur, Malaysia.

[6] GEOSpatial Monitoring & Information Technology (GeoSMIT) department, French Institute of Pondicherry (IFP), Pondicherry, India.

[7] Laboratory of Systems Ecology and Resource Management, Département de Biologie des Organismes, Université Libre de Bruxelles, Brussels, Belgium.

Abstract: Heavy metal pollution has become a serious threat to coastal aquatic ecosystems. Therefore, this study, aimed to assess the spatial distribution of five selected heavy metals/metalloids, arsenic (As), cadmium (Cd), chromium (Cr), lead (Pb), and mercury (Hg), in surface sediment samples collected from the Kalametiya Lagoon in southern Sri Lanka. Sixteen (16) areas of the lagoon were sampled. The sediment samples were analysed for heavy metal content by using ICP-MS while the water samples were measured for salinity and pH. A questionnaire survey was conducted to investigate the possible sources of heavy metal pollution in the Lagoon. Water pH and salinity showed significant variations across the lagoon. The overall mean value of pH and salinity were 6.68 ± 0.17 and 2.9 ± 2.2 PSU, respectively. The spatial distribution of the heavy metals was not monotonous and showed a high spatial variation. The kernel density maps of the measured heavy metals demarcated several spatially different patches in the lagoon. The mean levels of As, Cd, Cr, Hg, and Pb were lower than the threshold effect level (TEL) although it was higher for Hg in the North inlet. Nevertheless, it was still lower than the potential effect level (PEL). Industrial sewage, river suspended sediments, and agrochemicals such as fertilizers and pesticides were identified as the possible sources for heavy metal loads. Accumulation of toxic heavy metals can be minimized by by-passing the freshwater inflow to the lagoon.

Keywords: Fertilizers, heavy metals, kernel density maps, pesticides, Sri Lanka.

INTRODUCTION

Coastal lagoons are highly productive ecosystems that provide numerous ecosystem goods and services many of which are important in terms of economic benefits. These include the provision of products for human use, efficient nutrient cycling, water regulation and flood protection, sediment trapping and water purification, lagoon fisheries, and ecotourism (Dahdouh-Guebas *et al.*, 2021). However, coastal lagoons have not escaped human pressure (Ofori *et al.*, 2021; 2022).

In this respect, heavy metal pollution in aquatic environments has evidently become a menace due to their high toxicity, low solubility, wide range of sources, and bioaccumulation behaviour (Yu *et al.*, 2008). Heavy metal pollution is also a matter of concern because it poses a high risk to aquatic organisms at different trophic levels owing to biomagnification through the food chain (Liu *et al.*, 2018). In recent decades, large amounts of

* Corresponding author (sunandaruh@gmail.com; https://orcid.org/0000-0002-2493-3580)
† First co-authors

agricultural, industrial and domestic pollutants, especially heavy metals, have accumulated in coastal aquatic ecosystems, such as lagoons and estuaries (Bandara *et al*., 2008; Wuana & Okieimen, 2011; Chandrajith *et al*., 2012; Sivanantha *et al*., 2016; Kodikara, 2021). Sediments at the bottom of the water body serve as an ideal material for monitoring of contaminants including heavy metals in aquatic ecosystems. They can also act as a sink and a transport agent for aquatic pollutants (Ulbrich *et al*., 1997). Therefore, determining the levels of heavy metals in aquatic sediments is imperative to identify sources of heavy metal pollution (Diop *et al*., 2014). Further, the spatial distribution of heavy metals in aquatic sediments can also provide valuable information regarding the impact of discharged waste on ecosystems and associated risks (Yan *et al*., 2010). This approach would assist effective management of polluted aquatic ecosystems and also serve to monitor such systems (Li *et al*., 2016).

Whereas several studies in Sri Lanka have been carried out to assess the heavy metal content in food crops, land sediments, atmospheric depositions, and drinking water (Herath *et al*., 2016; Subasinghe *et al*., 2016; Weerasundara *et al*., 2018; Kodikara *et al*., 2022). Heavy metal contents in coastal aquatic ecosystems and spatial distribution of heavy metals received less attention. Adhikaram *et al*. (2016) reported the distribution and contamination status of environmentally important elements including major heavy metals of superficial sediments in the Batticaloa Lagoon, which is situated in the northern part of the eastern coast of Sri Lanka; they concluded that discharges from agricultural channels and marine fluxes in the lagoon affects the spatial distribution of the measured elements. The Kalametiya Lagoon on the southern coast of Sri Lanka, on the other hand, has been subjected to extensive discussions as the Udawalawe irrigation scheme. This came into operation in 1967, and has severely affected the lagoon over the past decades (Dahdouh-Guebas *et al*., 2005a), and continues to do so today (Madarasinghe *et al*., 2020a). In the Udawalawe project, drainage canals with excess water from upstream paddy lands and other areas in the immediate neighbourhood including industrial, urban and domestic areas, are connected to natural tributaries discharging into the sea through the Kalametiya Lagoon. This has caused heavy silt and pollutant input and salinity reduction. Further to this, Jayatissa *et al*. (2002) and Dahdouh-Guebas *et al*. (2005a) have reported that socio-economic interactions with the lagoon have become nearly nil (i.e., drastic socioeconomic degradation) resulting from these hydrological alterations.

Taking these facts into account, this study aims to assess selected heavy metals/metalloids in the surface sediments in the Kalametiya Lagoon and their spatial distribution. The following research questions were addressed: a) what is the average content of the major heavy metals in the lagoon; b) what is the spatial distribution of HMs in the lagoon; and c) what are the possible sources of heavy metal pollution in the lagoon.

MATERIALS AND METHODS

Study site

This study was conducted on the southern coast of Sri Lanka in 2020. The Kalametiya Lagoon was selected for the study based on the fact that this coastal lagoon is highly affected by the aforementioned Udawalawe irrigation scheme, which irrigates 32,000 ha of land, particularly paddy cultivations in the dry zone of southern Sri Lanka. In this scheme, drainage canals with excess water from the paddy lands are connected to the sea through the Kalametiya Lagoon (details are extensively discussed in Madarasinghe *et al*., 2020a). Furthermore, this may have caused deposition of loads of heavy metals in the lagoon. Therefore, this coastal ecosystem on the southern coast could be considered as a model site to study heavy metal pollution. The Kalametiya Lagoon (6° 04' 26"–6° 07'19" N and 80° 54' 43"–80° 57' 25" E), located in the dry zone (annual rainfall is < 1750 mm) about 65 km east from Matara (Figure 1), is the largest lagoon on the southern coast of Sri Lanka, having an area of approximately 4.8 km^2. Several canals, streams and reservoirs feed the Kalametiya Lagoon through Kuchchigal Ara, which is the main freshwater inflow to the lagoon. At present, the lagoon is dominated by *Sonneratia caseolaris* (low saline mangrove species) and marsh vegetation. A narrow canal, reinforced by a rocky dyke, has been constructed under the Udawalawa irrigation scheme as a pathway for continuous outflow from the lagoon to the sea. After construction of this reinforced outlet, the natural mouth of the lagoon has been closed almost permanently by the formation of a sand bar. Meteorological data (2019) obtained from Hambantota – the recording station nearest to the Kalametiya Lagoon – show that mean annual rainfall and monthly temperature for the area vary from 07-164 mm (January to December) and from 29.7–32.9 °C, respectively (Figure 1). The present study was performed in five areas ('sampling regions'), as shown in the map (Figure 2): Lagoon Outlet (A), Centre (B & F-

M), Narrow West Stream (C & N-P), Wide East Stream close to the inlet after paddy lands (D), and North Inlet (E).
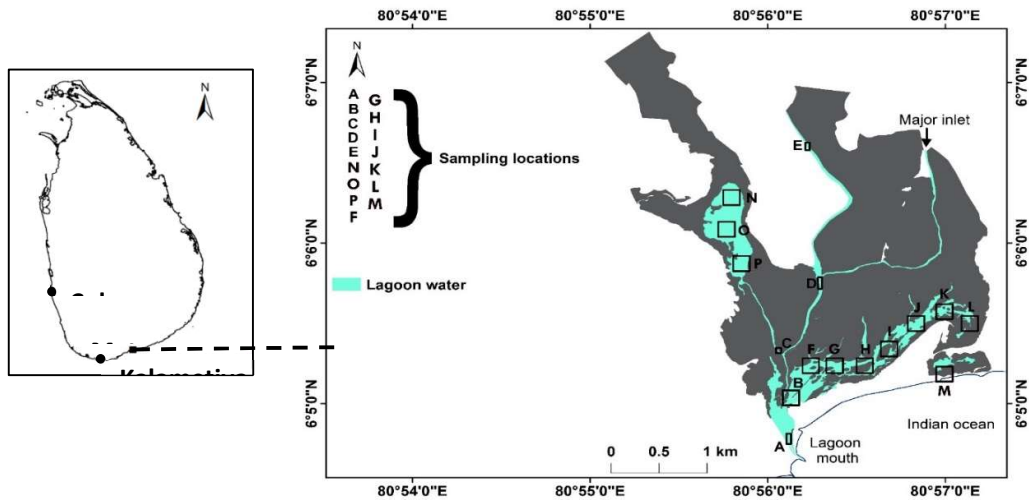
Figure 1: Map of Sri Lanka (left) and location of the Kalametiya Lagoon (right) on the southern coast of Sri Lanka, approximately 65 km to the east of Matara in the dry zone. Dark colour shows land area (silted landmass) while blue colour represents waterways.
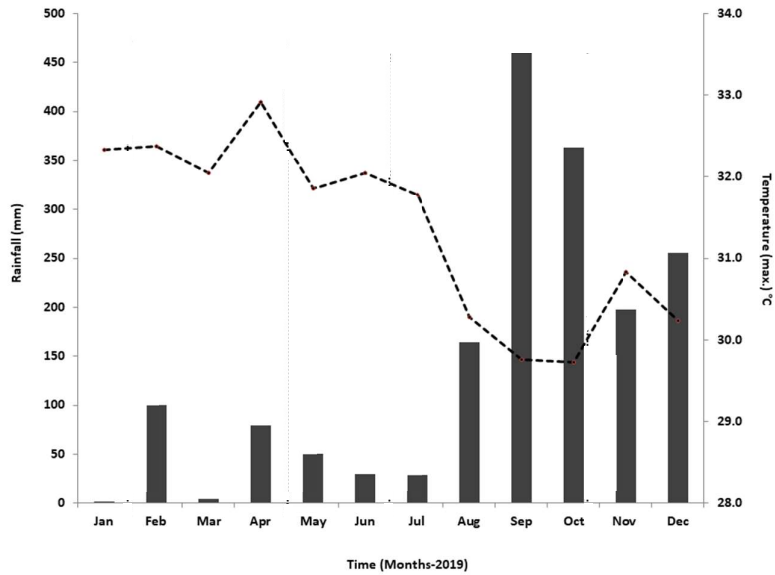
Figure 2: The graph shows the variation of rainfall (bar-graph) from January to December 2019 and the maximum temperature (line-graph) (weather station: Hambantota). Sediment and water sampling was done from February to April-2019, while the questionnaire survey was performed during July to October 2019.

Water and sediment sampling

Sediment sampling was conducted from February to mid-March in 2019, and water sampling in April-2019 (Figure 2). Water and sediment samples were collected from the five major sampling regions (sampling points A-P) shown in the map. Water sampling was done at the sub water layers (20–80 cm) with the help of a Ruttner

sampler (HYDRO-BIOS, PMMA Water Sampler, China), and water samples were taken at the middle water. In total, 84 water samples were collected covering the major sampling regions (Lagoon Outlet: n = 12; Centre: n = 36; Narrow West Stream: n = 12; Wide East Stream: n = 12, North Inlet: n = 12), and stored in the laboratory under cool conditions (at 4 °C temperature). The pH and salinity were measured by using a pH meter (STRATER300, OHAUS, USA) and refractometer (ATAGOS/Mill-E, Japan), respectively. Sediment sampling was also carried out in the major sampling areas at a depth of 0–10 cm by using a bottom dredge sampler (Ponar grab, WILDCO, New York, USA). In total, 60 sediment samples (Lagoon Outlet: n = 10; Centre: n = 26; Narrow West Stream: n = 12; Wide East Stream: n = 06; North Inlet: n = 06) were collected, placed in labelled plastic bags, and stored under cool conditions until analysis.

Acid digestion of sediment samples for heavy metal analysis

The sediment samples were digested and analysed for the selected heavy metals i.e., arsenic (As), cadmium (Cd), chromium (Cr), lead (Pb), and mercury (Hg) following the methodology described by Wathsara *et al.* (2020), with minor modifications. Approximately 0.5 g of finely powdered dried sediment sample was weighed using an electronic balance (KERNTM KB2000-2N) into an easy prep high-pressure microwave vessel, and approximately 10 mL of nitric acid was added, and the microwave digestion programme of the microwave digester (CEM MARS5, USA) was run to digest all samples. The digested samples were filtered with No.542 Whatman filter paper, washed with deionized water to a volume of 25 mL, and the metal ion content of the samples was determined by inductively coupled plasma mass spectrometry (ICP- MS, Agilent 700, USA).

Questionnaire survey

A questionnaire survey was conducted to obtain an overall view of the current human activities that led deposition of heavy metals in the lagoon, and their life experience related to lagoon pollution (mainly unsuitability of lagoon water). A standardized questionnaire (open-ended) was designed to evaluate the socio-economic status of the Kalametiya Lagoon using a preliminary field survey and interviews. The key stakeholders were identified through a combination of methods: expert knowledge elicitation and preliminary field survey. The snowball sampling technique (Atkinson & Flint, 2001) was used to identify further resource persons from whom more information could be collected. A face-to-face interview was carried out as a two-way interaction between respondent and interviewer (Kelley *et al.*, 2003). In total, 45 people (single person from a given family) including five community leaders, were interviewed individually in the survey.

Data analyses and kernel density mapping

Heavy metal content and physicochemical parameters were treated as continuous variables, and descriptive statistics were studied along with data distribution patterns. Parametric assumptions were verified for normality of the data by the Shapiro-test, and homogeneity of variances by the Levene's test. As all conditions were met for the dependent variables at a 95% confidence level, one-way ANOVA was performed to determine the level of significance of heavy metal distribution among the sampling regions. Similarly, the level of significance was tested for physicochemical parameters among the sampling regions using one-way ANOVA. The Pearson correlation test was performed to study correlation between physicochemical parameters of lagoon water and the heavy metal content. All statistical analyses were performed using R-3.2.2 statistical software. Kernel density maps were prepared using the heavy metal contents obtained from 60 sediment samples representing the total spatiality of the lagoon. The maps were processed on ArcMap v. 10.6.

RESULTS AND DISCUSSION

Physicochemical parameters

The results of the physicochemical parameters of water samples from the five regions (A-E) in Kalametiya Lagoon are presented in Table 1. The pH ranged from 6.58 to 6.92 with an overall mean value of 6.68 ± 0.17. Water acidity varied in different regions of the lagoon and water collected near the North Inlet showed the highest acidity. The water samples collected from B (Centre), D (Wide East Stream), and E (North Inlet) showed significantly higher ($p < 0.05$) water acidity than those collected from A (Outlet) and C (Narrow West Stream). Similarly, the

level of salinity also showed some variations across the lagoon. The highest salinity (i.e., 5.1 ± 0.06 PSU) was recorded near region A (Outlet) while the lowest (i.e., 1.1 ± 0.25 PSU) was recorded for water near region E (North Inlet). The overall mean salinity of the lagoon for the studied period was 2.9 ± 2.2 PSU. A significantly higher salinity ($p < 0.05$) was recorded in region A (Outlet) than in region E (North Inlet). The level of salinity in regions B (Centre), D (Wide East Stream), and C (Narrow West Stream) was significantly higher ($p < 0.05$) than in region E (North Inlet) while significantly lower than ($p < 0.05$) in region A (Outlet).

Table 1: Descriptive details of heavy metal content (mg/kg) in surface sediments of the study area. Values are mean ± SD.

Sites	As (mg/kg)	Cd (mg/kg)	Cr (mg/kg)	Hg (mg/kg)	Pb (mg/kg)	pH	Salinity (PSU)
Outlet (A)	0.104 ± 0.003	0.007 ± 0.001	2.635 ± 0.617	0.002 ± 0.001	0.347 ± 0.076	6.85 ± 0.07	5.1 ± 0.06
Centre (B)	0.137 ± 0.012	0.014 ± 0.005	2.723 ± 0.723	0.004 ± 0.002	0.411 ± 0.191	6.61 ± 0.03	2.4 ± 0.04
Narrow west stream (C)	0.112 ± 0.018	0.016 ± 0.002	2.926 ± 1.081	0.002 ± 0.001	0.315 ± 0.071	6.73 ± 0.02	2.7 ± 0.05
Wide east stream (D)	0.082 ± 0.022	0.004 ± 0.003	1.253 ± 0.437	0.003 ± 0.001	0.137 ± 0.045	6.60 ± 0.05	3.1 ± 0.04
North inlet (E)	0.075 ± 0.036	0.004 ± 0.003	1.849 ± 1.323	0.425 ± 0.134	0.235 ± 0.160	6.62 ± 0.04	1.1 ± 0.25
Threshold effect level (TEL)[i]	7.420	0.680	52.30	0.130	30.200		
Probable effect level (PEL) [i]	41.600	4.200	160.400	0.700	112.200		
Effect range low (ER-L) [ii]	8.200	1.200	81.000	0.150	46.700		
Effect range medium (ER-M)[ii]	70.000	9.600	370.000	0.170	218.000		

TEL: threshold effect level, represents the concentration below which adverse biological effects are rarely expected to occur; PEL: probable effect level (PEL), defines the level above which adverse effects are expected to occur frequently; ER-L: effect range-low, is interpreted with a rare biological effect; ER-M: effect range-medium, indicates frequent biological effects. i) Threshold effect level or probable effect level for marine and estuarine sediments (Long *et al.*, 1995). ii) Sediment quality guidelines for metals in the freshwater ecosystem (Macdonald *et al.*, 2000)

Spatial distribution of heavy metals

The analytical results of the heavy metals are presented in Table 1. The overall mean levels of heavy metals in descending order were Cr > Pb > As > Hg > Cd. The ranges (mg/kg) recorded for the heavy metals were 1.253–2.926 for Cr, 0.137–0.411 for Pb, 0.137–0.075 for As, 0.002–0.425 for Hg, and 0.004–0.016 for Cd. Further, according to the kernel maps (Figure 3), the following descending order was observed: A (Outlet): Cr > Pb > As > Cd > Hg; B (Centre): Cr > Pb > As > Cd > Hg; C (Narrow West Stream): Cr > Pb > As > Cd > Hg; D (Wide East Stream): Cr > Pb > As > Cd > Hg and E (North Inlet): Cr > Hg > Pb > As > Cd. The spatial distribution of the heavy metals was not monotonic and showed a considerable spatial variation. The kernel density maps based on the heavy metal levels indicated that A to E have different compositions (Figure 3). The distribution maps of Cr and Pb indicated significantly higher concentrations ($p < 0.05$) in A (Outlet), B (Centre), C (Narrow West Stream) and E (North Inlet) compared to D (Wide East Stream). The levels of As and Cd were significantly higher ($p < 0.05$) in B (Centre). The distribution of Hg was comparatively higher in E (North Inlet) than other areas.

The recorded heavy metal levels further showed that the mean levels of As, Cd, Cr, Hg, and Pb were lower than the threshold effect level (TEL). The TEL is the contaminant level below which harmful effects on organisms are not expected (MacDonald *et al.*, 2000; EC, 2018) while it was higher for Hg in E (North Inlet) (Table 1). However, it was still lower than the probable effect level (PEL) [*PEL is the contaminant level above which harmful effects on organisms are expected* ((MacDonald *et al.*, 2000; EC, 2018)]. Similarly, none of the heavy metal exceeded the effect range low (ER-L) [*ER-L is interpreted with a rare biological effect (*Long *et al.*, 2015] and effect range medium (ER-M) [*ER-M indicates frequent biological effects* (Long *et al.*, 2015)]. According to the results of the correlation analysis, Cr (r= 0.56) and Pb (r=0.45) showed a positive correlation with water pH while Hg (r= -0.53) had a negative correlation with salinity. The rest of the heavy metals did not show any correlation with water pH and salinity.
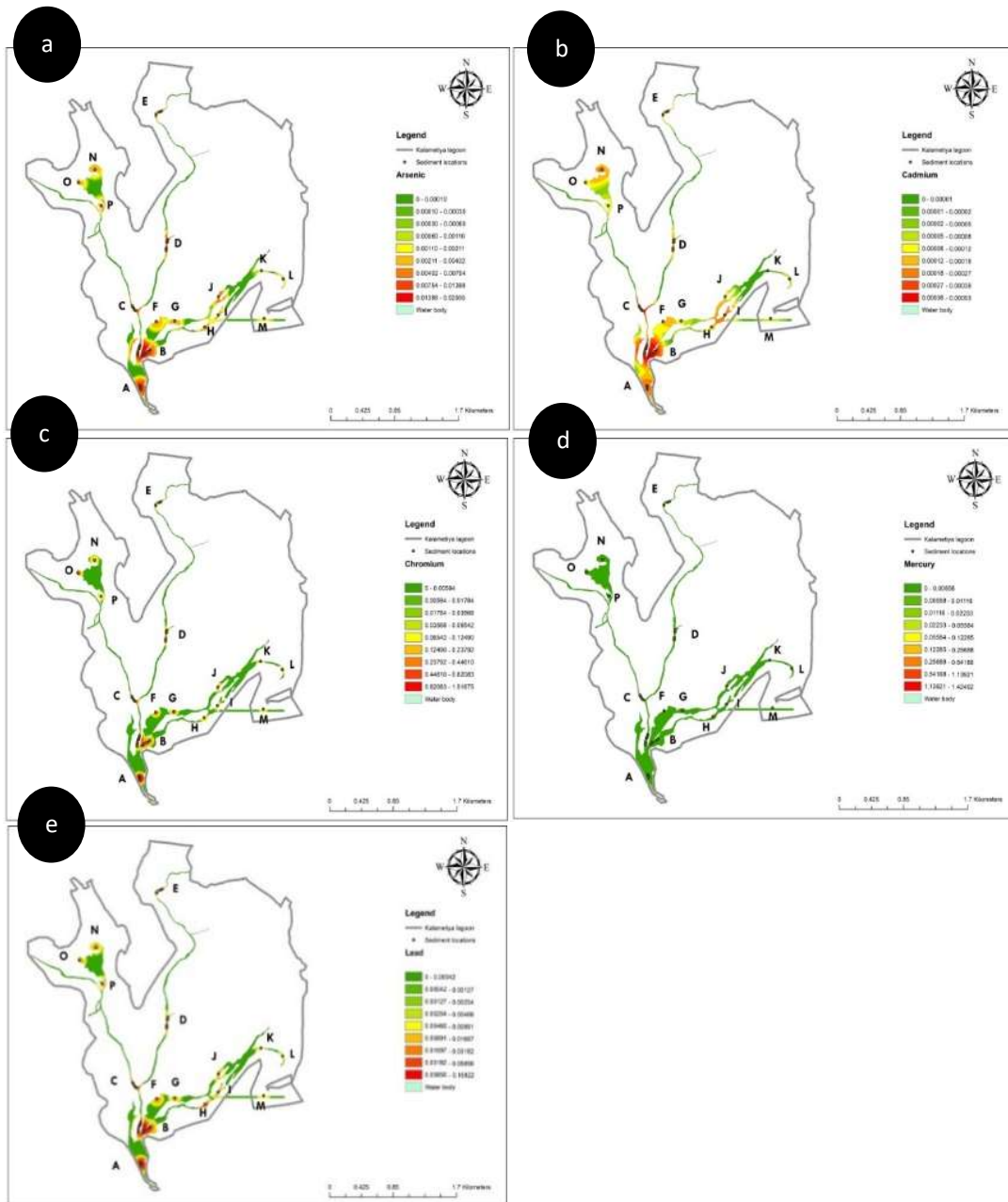
Figure 3: Kernel density maps (a-e) reflect spatial distribution of the studied heavy metals; a) As; b) Cd; c) Cr; d) Hg; e) Pb. Ranges of heavy metal contents are given in the map legends. Major sampling regions of the lagoon are A: Outlet; B: Centre; C: Narrow West Stream; D: Wide East Stream; E: North Inlet

Questionnaire survey

There were 65% male and 35% female respondents. According to the questionnaire survey, 32% of the respondents engaged in lagoon fishery for their daily subsistence; of these 16% were farmers and the rest (52%) involved in various occupations. Moreover, 53% of the farmers claimed that they had been using fertilizers such as urea, potash, rock dust fertilizer, and general fertilizers for their paddy lands to provide nitrogen (N), phosphorus (P), and potassium (K) requirements. In addition, 21% of interviewees stated that they had not used fertilizers and the rest (26%) did not clearly answer the question. Dwellers in the area mentioned the benefits that they obtained from the lagoon during 2000–2019; 79% said that the local people largely engaged in fishing in the

past, but now many of them are working in the bird sanctuary in the lagoon as tourist guides. In addition, 90% of the respondents mentioned the changes that had taken place during the past two decades: a) decrease in bird diversity and density; b) increase in mangroves and *Typha* (water sedge) plants; c) decrease in water salinity and lagoon depth; d) increase in freshwater fish species with shallow water column; and e) heavy sedimentation with the onset of the Udawalawe irrigation project. Of the respondents, 75% pointed out that the lagoon water has become unsuitable for use and hence was not using for drinking and bathing purposes. Furthermore, the respondents remarked on the managerial actions that would have been taken to conserve the Kalametiya Lagoon. The suggestions included: a) removal of excess sedimentation; b) removal of aquatic invasive plants; c) widening of the lagoon outlet; d) planting of fibrous rooted plants along the main freshwater channel that can trap excess sediments brought by freshwater; e) strengthening institutional coordination – both government and non-governmental institutions.

Discussion

The Udawalawe irrigation project, which came into operation in 1967, has caused the release of excess freshwater into the Kalametiya Lagoon through Kuchchigal Ara (Dahdouh-Guebas *et al.*, 2005a; Madarasinghe *et al.*, 2020a) resulting in desalination. In addition, due to the fact that the natural sand bar is not seasonally opened, as a result of continuous outflow of lagoon water through the man-made canal supported by the dyke constructed during the irrigation project, the ebb-flow system of the lagoon has been disturbed. Therefore, the tidal effect has become minimal (Madarasinghe *et al.*, 2020) [Sri Lanka, anyway has a microtidal system (Kodikara *et al.*, 2017a)]. This scenario has eventually caused a reduction of the overall mean salinity level of the lagoon. In contrast, during the dry season, seawater intrusion becomes prominent and leads to an increase in the lagoon salinity. Owing to this fact, a spatial disparity in salinity distribution could be observed with the highest salinity at the lagoon outlet and the lowest at the inlet, particularly in the dry season. It is evident that the lagoon ecology and biology are affected with such salinity reduction (Madarasinghe *et al.*, 2020b), and salinity further plays a crucial role since increased salinity results in increasing heavy metal bioavailability (Hou *et al.*, 2013). In term of water pH, Ramanathan *et al.* (2005) recommended an optimum pH range of 6.8 – 8.7 for proper function of a lagoon and the mean value in this study for water pH was lower than that of the prescribed range (dry season). This directly indicates a deterioration of water quality of the Kalametiya Lagoon. In addition to pH and salinity, it is recommended to check the dissolved oxygen, total suspended materials, redox potential, and organic matter content, which may be useful in figuring out a holistic picture of the lagoon (Lawson, 2011).

Heavy metals have recently gained worldwide attention due to their high toxicity, environmental persistence, and accumulation in the environment and organisms (Zhang *et al.*, 2014). Heavy metal levels are mainly attributed to lithogenic and anthropogenic inputs (Kabata-Pendias & Mukherjee, 2007). Two major causes are discussed for Cr enrichment in the lagoon. It is apparent that sediments are brought to the lagoon with excess freshwater and that heavy sedimentation taking place due to excess freshwater inflow to the lagoon, may have caused the addition of Cr into the lagoon. There is evidence which reflects that the lithogenic components, produced from the weathering of bedrocks and soils (Yunginger *et al.*, 2018), in the upper areas are transported by water, which then settles at the bottom of the downstream water bodies (Tamuntuan *et al.*, 2015). Cromium, in many cases, is controlled by bedrock influence (Sun *et al.*, 2013) and the other probable source of Cr may be phosphate fertilizers used in agricultural fields in the area (Dissanayaka & Chandrajith, 2009). There is a high likelihood of phosphate being solubilized from phosphate fertilizers when excess freshwater flows through the agricultural lands, situated at the upstream areas whereas extensive paddy cultivation may occur in downstream areas in the area of interest. In addition, Dissanayaka & Chandrajith (2009) reported that the phosphate fertilizers used in Sri Lanka contain not only Cr, but also high amounts of other heavy metals such as Ni, and Pb. Furthermore, Zn, Cu, Cd, Pb, and As, have also been identified as widely found heavy metals in agricultural fertilizers, pesticides and fungicides (Gimeno-Garci'a *et al.*, 1996; Kelepeitzis, 2014). Therefore, As, Cd and Pb could be linked with agricultural fertilizers, being used in the area. Although Adikaram *et al.* (2016) reported that most marine algae produce organo-arsenic compounds, for example in the Batticaloa Lagoon, it is unlikely to be applicable to the Kalametiya Lagoon since material exchange is minimal at the lagoon outlet (Madarasinghe *et al.*, 2020a). When Hg is considered, this could be due to higher input from domestic sewage and hospital effluents (Wang *et al.*, 2017). Moreover, metal processing, stainless steel welding, chromate production, tannery facilities and ferrochrome and chrome pigment production could largely contribute to heavy metal release (ATSDR, 2012; Jayawardana *et al.*, 2014). (During the initial site visit, we observed homemade paint shops, metal processing and stainless steel

welding). It is well-known that the pH of water directly influences the heavy metal concentrations by altering bio-availability and toxicity. Metals such as Cr and Pb had a significant correlation with water pH and are recorded to increase detrimental environmental effects with increasing acidity (DWAF, 1996). It has been found that pH governs the methylation of elements such as Pb and Hg (van Loon, 1982) that was best reflected by significant correlation shown for Hg in this study. In general, higher water acidity (low pH) causes higher heavy metal availability in water and the opposite was obtained in our study. That could be linked with the continuous flow of freshwater into the lagoon through which heavy metals are unremittingly brought in. However, it is recommended to re-conduct the research covering both rainy and dry seasons and that will help to provide a holistic view of the levels of heavy metals in the sediments.

It is commonly observed that, except Hg, the rest of the heavy metals are largely accumulated at the Centre and Outlet of the lagoon. Higher accumulation of heavy metals at these regions is due to poor ebb-flow system of the lagoon, which was most likely enhanced by the construction of the artificial dyke, and the natural sand barrier, which obstructed the water outflow. In general, the mosaic distribution of heavy metals in the Kalametiya Lagoon could be due to the limited circulation taking place inside the lagoon (Dahdouh-Guebas *et al*., 2005b; Madarasinghe *et al*., 2020a). Furthermore, the increasing trend of heavy metals in the lagoon from the Inlet (E) to the Outlet (A) might be due to the sediment accumulation pattern from upstream to downstream of the lagoon (Dahdouh-Guebas *et al*., 2005b). Although the sediment undergoes resuspension, redox reactions and biodegradation, could considerably change the affinity of the sediment, which is considered to be the deposition compartment of the marine environment. The distribution and accumulation of heavy metals depend on the grain size. Therefore, a grain size analysis of the lagoon would provide useful information on this aspect (ElNemr *et al*., 2007).

When the current pollution status is considered, the Kalametiya Lagoon is not critical since the heavy metal contents does not exceed the TEL and PEL. In Sri Lanka, a few studies have focused on heavy metal pollution in several water bodies and lagoons including Kumbichchankulama, Alankulama, and Thuruwila, in the dry zone (Bandara *et al*., 2008; Chandrajith *et al*., 2012), and the Negombo Lagoon (Sivanantha *et al*., 2016). According to their results, the Negombo Lagoon showed the highest content of heavy metals in the published data of Sri Lanka, for example As: 9.89 mg/kg; Cd: 2.63 mg/Kg; Cr: 26.1 mg/kg; and Pb: 20.26 mg/kg (sediments). In the other water bodies, Cd content was greater than 2.18 mg/kg (sediments). Thus, the pollution level of the Kalametiya Lagoon is far below the aforementioned values in the other water bodies in the country. Since an excess freshwater flow continues, higher levels of pollution can be expected soon. On the other hand, survey data clearly reflect that socio-economic interactions have become minimal and less than 5% of the dwellers now depend on lagoon fisheries. Further, the dwellers have indirectly experienced water quality changes including toxicity (sudden fish death, skin irritation). As a result, most dwellers are reluctant to use lagoon water for their daily use. However, such livelihood transformations are not uncommon in Sri Lanka as well as in other parts of the world (Schernewski *et al*., 2018; Okello *et al*., 2019; Madarasinghe *et al*., 2020a, 2020b;).

To minimize the impact of heavy metal pollution at this stage, it is recommended to implement eco-sustainable remedies such as construction of a separate canal to dispose excess water coming from the Udawalawe irrigation project, introduction of a cascade system to freshwater canals before entering in to the lagoon to minimize sediment loading, periodic removal of accumulated sediments manually, and the use of phytoremediation techniques.

CONCLUSION

The Kalametiya Lagoon in southern Sri Lanka contains heavy metals such as As, Cd, Cr, Hg, and Pb. The levels recorded in descending order were Cr > Pb > As > Hg > Cd. The spatial distribution of the heavy metals was not monotonic and showed considerable spatial variation. According to the kernel maps for the regions, A (Outlet), B (Centre), C (Narrow West Stream) and D (Wide East Stream) recorded heavy metal levels in the descending order: Cr > Pb > As > Cd > Hg; this was different from E (North Inlet): Cr > Hg > Pb > As > Cd. The mean levels of As, Cd, Cr, Hg, and Pb were lower than that of Threshold Effect Level (TEL) and Potential Effect Level (PEL). Similarly, none of the studied heavy metals/metalloids exceeded the Effect Range Low (ER-L) and the Effect Range Medium (ER-M). The highest levels of Cr recorded could be due to natural weathering. Therefore, the

Kalametiya Lagoon is not at risk from heavy metal pollution at present. However, there is a possibility of these levels increasing in the future with continuous freshwater input to the Kalametiya Lagoon.

Acknowledgement

REFERENCES

Adikaram M., Pitawala A., Ishiga H. & Jayawardana D. (2016). Spatial distribution, enrichment, and source of environmentally important elements in Batticaloa lagoon, Sri Lanka. *Environmental Science and Pollution Research* **24**: 2089–2099.
  DOI: https://doi.org/10.1007/s11356-016-7973-6

Agency for Toxic Substances and Disease Registry (ATSDR) (2012). *Toxicological Profile for Chromium*. Agency for Toxic Substances and Disease Registry, Department of Health and Human Services, Public Health Service, Atlanta, USA.

Atkinson R. & Flint J. (2001). Accessing hidden and hard-to-reach populations: Snowball research strategies. *Social Research Update* **33**(1): 1–4.

Bambaradeniya C.N.B. (2004). Freshwater wetlands in Sri Lanka: Their conservation significance and current status. *Proceedings of the National Symposium on Wetland Conservation and Management*, pp. 19–24.
  DOI: https://doi.org/10.1007/s10653-007-9129-6

Bandara J.M.R.S., Senevirathna D.M.A.N., Dasanayake D.M.R.S.B., Herath V., Bandara J.M.R. P., Abeysekara T. & Rajapaksha K.H. (2008). Chronic renal failure among farm families in cascade irrigation systems in Sri Lanka associated with elevated dietary cadmium levels in rice and freshwater fish (Tilapia). *Environmental Geochemistry and Health* **30**(5): 465–478.

Chandrajith R., Ariyaratna T. & Dissanayake C. (2012). The status of cadmium in the geo-environment of Sri Lanka. *Ceylon Journal of Science (Physical Sciences)* **16**: 47–53.

Dahdouh-Guebas F., Jayatissa L.P., Di Nitto D., Bosire J.O., Lo Seen D. & Koedam N. (2005a). How effective were mangoves as a defence against the recent tsunami? *Current Biology* **15**(12): R443–R447.
  DOI: https://doi.org/10.1016/j.cub.2005.06.008

Dahdouh-Guebas F. *et al*. (17 authors) (2021). Reconciling nature, people and policy in the mangrove socialecological system through the adaptive cycle heuristic. *Estuarine, Coastal and Shelf Science* **248**: 106942.
  DOI: https://doi.org/10.1016/j.ecss.2020.106942

Department of Water Affairs and Forestry (DWAF) (1996). *South African Water Quality Guidelines, Domestic Use*. volume 1, 2nd edition. Department of Water Affairs and Forestry, Pretoria, South Africa.

Diop C., Dewaele D., Diop M., Toure A., Cabral M., Cazier F., Fall M., Diouf A. & Ouddane B. (2014). Assessment of contamination, distribution and chemical speciation of trace metals in water column in the Dakar coast and the Saint Louis estuary from Senegal, West Africa. *Marine Pollution Bulletin* **86**(1–2): 539–546.
  DOI: https://doi.org/10.1016/j.marpolbul.2014.06.051

Dissanayaka C.B. & Chandrajith R. (2009). Phosphate mineral fertilizers, trace metals and human health. *Journal of the National Science Foundation of Sri Lanka* **37**(3): 153–165.
  DOI: https://doi.org/10.4038/jnsfsr.v37i3.1219

ElNemr A.H., El Sikaily A. & Khaled A. (2007). Total and leachable heavy metals in muddy and sandy sediments of Egyptian coast along Mediterranean Sea. *Journal of Coastal Shelf Science* **129**: 151–168.
  DOI: https://doi.org/10.1007/s10661-006-9349-8

EC (European Commission) (2018). *European Technical Guidance Document (TGD) for Deriving Environmental Quality Standards No. 27, Common Implementation Strategy for the Water Framework Directive* (2000/60/EC). Guidance Document No. 27, Technical Guidance for Deriving Environmental Quality Standards; Technical Report-2011-055. Office for Official Publications in the European Communities, Brussels, Belgium.

Gimeno-Garci'a E., Andreu V. & Boluda R. (1996). Heavy metals incidence in the application of inorganic fertilizers and pesticides to rice farming soils. *Environmental Pollution* **92**: 19–25.
  DOI: https://doi.org/10.1016/0269-7491(95)00090-9

Herath D., Pitawala A. & Gunatilake J. (2016). Heavy metals in road deposited sediments and road dusts of Colombo Capital, Sri Lanka. *Journal of the National Science Foundation of Sri Lanka* **44**(2): 193–202.
  DOI: https://doi.org/10.4038/jnsfsr.v44i2.8000

Hou D., He J., Lu¨ C., Ren L., Fan Q., Wang J. & Xie Z. (2013). Distribution characteristics and potential ecological risk assessment of heavy metals (Cu, Pb, Zn, Cd) in water and sediments from Lake Dalinouer, China. *Ecotoxicology and Environmental Safety* **93**: 135–144.
  DOI: https://doi.org/10.1016/j.ecoenv.2013.03.012

Jayatissa L.P., Guero M.C., Hettiarachchi S. & Koedam N. (2002). Changes in vegetation cover and socio-economic transitions in a coastal lagoon (Kalametiya, Sri Lanka), as observed by teledetection and ground truthing, can be attributed to an upstream irrigation scheme. *Environment, Development and Sustainability* **4**(2): 167–183.
DOI: https://doi.org/10.1023/A:1020831416827

Jayawardana D.T., Pitawala H.M.T.G.A. & Ishiga H. (2014). Assessment of soil geochemistry around some selected agricultural sites of Sri Lanka. *Environmental Earth Sciences* **71**(9): 4097–4106.
DOI: https://doi.org/10.1007/s12665-013-2798-9

Kabata-Pendias A. & Mukherjee A. B. (2007). *Trace Elements from Soil to Human*. Springer, Berlin, Germany.
DOI: https://doi.org/10.1007/978-3-540-32714-1

Kelepertzis E. (2014). Accumulation of heavy metals in agricultural soils of Mediterranean: insights from Argolida basin, Peloponnese, Greece. *Geoderma* **221–222**: 82–90.
DOI: https://doi.org/10.1016/j.geoderma.2014.01.007

Kelley K., Clark B., Brown V. & Sitzia J. (2003). Good practice in the conduct and reporting of survey research. *International Journal for Quality in Health Care* **15**(3): 261–266.
DOI: https://doi.org/10.1093/intqhc/mzg031

Kodikara K.A.S. (2021). Phytoremediation capacity of aquatic floating plants; *Salvinia molesta* and *Eichhornia crassipes* in desalinated Kalametiya Lagoon, southern coast of Sri Lanka. *WILDLANKA* **9**(1): 150–59.

Kodikara K.A.S., Lewandowski S., De Silva P.M.C.S., Gunarathna S.D., Madarasinghe S.K., Ranasinghe P., Jayatissa L.P.R., Dahdouh-Guebas F. (2022). Heavy metal pollution in selected upland tributaries of Sri Lanka: comprehension towards the localization of sources of pollution. *Journal of Water and Health* **20**(3): 505–517.
DOI: https://doi.org/10.2166/wh.2022.250

Lawson E.O. (2011). Physico-chemical parameters and heavy metal contents of water from the mangrove swamps of Lagos Lagoon, Lagos, Nigeria. *Advances in Biological Research* **5**(1): 08–21.

Li R., Chai M. & Qiu G. Y. (2016). Distribution, fraction, and ecological assessment of heavy metals in sediment-plant system in Mangrove Forest, South China Sea. *PLoS One* **11**(1): e0147308.
DOI: https://doi.org/10.1371/journal.pone.0147308

Liu Y., Liu G., Yuan Z., Liu H. & Lam P. K. (2018). Heavy metals (As, Hg and V) and stable isotope ratios (d13C and d15N) in fish from Yellow River Estuary, China. *Science of the Total Environment* **613**: 462–471.
DOI: https://doi.org/10.1016/j.scitotenv.2017.09.088

MacDonald D.D., Ingersoll C.G. & Berger T.A. (2000). Development and evaluation of consensus-based sediment quality guidelines for freshwater ecosystems. *Archives of Environmental Contamination and Toxicology* **39**: 20–31.
DOI: https://doi.org/10.1007/s002440010075

Madarasinghe S.K., Yapa K.K.A.S., Satyanarayana B., Udayakantha P.M.P., Kodikara S. & Jayatissa L.P. (2020a). Inland irrigation project causes disappearance of coastal lagoon: the trajectory of Kalametiya Lagoon, Sri Lanka from 1956 to 2016. *Coastal Management* **48**(3): 188–209.
DOI: https://doi.org/10.1080/08920753.2020.1747914

Madarasinghe S.K. *et al*. (11 authors) (2020b). Retrospective study on changes in Dondra lagoon (2006–2017) resulting from tsunami impact and post-tsunami development. *Journal of Coastal Conservation* **24**(5): 1–11.
DOI: https://doi.org/10.1007/s11852-020-00777-1

McCartney M., Rebelo L.M., Senaratna Sellamuttu S. & De Silva S. (2010). Wetlands, agriculture and poverty reduction. *IWMI Research Report*, pp. 137–139. International Water Management Institute (IWMI), Colombo, Sri Lanka.
DOI: https://doi.org/10.5337/2010.230

Ofori S.A., Arachchilage S.K., Jayatissa L.P., Madarasinghe S.K., Gunathilaka U.V., Wijesundara I.T.D. (2021). Shrimp farming, a major threat to mangrove and lagoon ecosystem in the Pambala-Chilaw lagoon complex, Sri Lanka. In: *Book of Abstracts—VLIZ Marine Science Day, VLIZ Special Publication 85,* (eds. J. Mees & J. Seys), pp. 129. *Vlaams Instituut Voor de zee—Flanders Marine Institute* (VLIZ) Oostende, Belgium.

Ofori S.A., Kodikara K.A.S., Jayatissa, L.P., Gunathilaka U.V., Wijesundara I., Mafaziya Nijamdeen T.W.G.F., Dahdouh-Guebas F. (2022). Spatial dynamics of pollution in a tropical lagoon ecosystem and its social-ecological impacts. *Water Air Soil Pollution* **233**: 266.
DOI: https://doi.org/10.1007/s11270-022-05729-z

Okello J.A., Alati V., Kodikara S., Kairo J.G., Dahdouh-Guebas F. & Koedam N. (2019). The status of Mtwapa Creek mangroves as perceived by the local communities. *WIO Journal of Marine Science* **18**(1): 67–81.
DOI: https://doi.org/10.4314/wiojms.v18i1.7

Ramanathan N.P., Padmavathy T., Francis S., Athithian & Selvaranjitham N. (2005). *Manual on Polyculture of Tiger Shrimp and Carps in Freshwater*, pp. 1–161. Tamil Nadu Veterinary and Animal Sciences University, Fisheries College and Research Institute, Thothukudi, India.

Schernewski G., Baltranaite E., Katarzyte M., Balciunas A., Cerkasova N. & Mezine J. (2018). Establishing new bathing sites at the Curonian Lagoon coast: An ecological-social-economic assessment. *Journal of Coastal Conservation* **23**: 899–911.
DOI: https://doi.org/10.1007/s11852-017-0587-4

Sivanantha N., Wijesinghe M.R. & Wijesekara R.D. (2016). Distribution of five toxic heavy metals in biotic and abiotic constituents of the Negombo Lagoon, Sri Lanka. *Sri Lankan Journal of Biology* **1**(1): 1–14.

DOI: https://doi.org/10.4038/sljb.v1i1.1

Subasinghe S., Estoque R.C. & Murayama Y. (2016). Spatiotemporal analysis of urban growth using GIS and remote sensing: A case study of the Colombo Metropolitan Area, Sri Lanka. *International Journal of Geo-Information* **5**: 197.
DOI: https://doi.org/10.3390/ijgi5110197

Sun C., Liu J., Wang Y., Sun L. & Yu H. (2013). Multivariate and geostatistical analyses of thespatial distribution and sources of heavy metals in agricultural soil in Dehui, Northeast China. *Chemosphere* **92**: 517–523.
DOI: https://doi.org/10.1016/j.chemosphere.2013.02.063

Tamuntuan G., Bijaksana S., King J., Russell J., Fauzi U., Maryunani K., Aufa N. & Safiuddin L.O. (2015). Variation of magnetic properties in sediments from Lake Towuti, Indonesia, and its paleoclimate significance. *Palaeogeography Palaeoclimatology Palaeoecology* **420**: 163–172.
DOI: https://doi.org/10.1016/j.palaeo.2014.12.008

Ulbrich K., Marsula R., Jeltsch F., Hofmann H. & Wissel C. (1997). Modelling the ecological impact of contaminated river sediments on wetlands. *Ecological Modelling* **94**(2–3): 221–230.
DOI: https://doi.org/10.1016/S0304-3800(96)00023-3

United Nations Educational, Scientific and Cultural Organization (UNESCO) (1971). *Convention on Wetlands of International Importance especially as Waterfowl Habitat, Ramsar Iran-1971.* Available at https://www.ramsar.org/sites/default/files/documents/library/sitelist.pdf RamsarWeb, Accessed 1 September 2021.

Van Loon J.C. (1982). *Chemical Analysis of Inorganic Constituent of Water*. CRC Press, Boca Raton, Florida, USA.

Wang L., Ji B., Hu Y., Liu R. & Sun W. (2017). A review on in situ phytoremediation of mine tailings. *Chemosphere* **184**: 594–600.
DOI: https://doi.org/10.1016/j.chemosphere.2017.06.025

Wathsara H.P.T., Weeratunge H.D., Mubarak M.N.A., Godakumbura P.I. & Ranasinghe P. (2020). *In vitro* antioxidant and antidiabetic potentials of *Syzygium caryophyllatum* L. Alston. *Evidence-Based Complementary and Alternative Medicine* **2020**: 1–15.
DOI: https://doi.org/10.1155/2020/9529042

Weerasundara L., Magana-Arachchi D.N., Ziyath A.M., Goonetilleke A. & Vithanage M. (2018). Health risk assessment of heavy metals in atmospheric deposition in a congested city environment in a developing country: Kandy City, Sri Lanka. *Journal of Environmental Management* **220**: 198–206.
DOI: https://doi.org/10.1016/j.jenvman.2018.04.036

Wuana R.A. & Okieimen F.E. (2011). Heavy metals in contaminated soils: a review of sources, chemistry, risks and best available strategies for remediation. *ISRN Ecology* **2011**: 402–647.
DOI: https://doi.org/10.5402/2011/402647

Yan C., Li Q., Zhang X. & Li G. (2010). Mobility and ecological risk assessment of heavy metals in surface sediments of Xiamen Bay and its adjacent areas, China. *Environmental Earth Sciences* **60**(7): 1469–1479.
DOI: https://doi.org/10.1007/s12665-009-0282-3

Yu R.L., Yuan X., Zhao Y.H., Hu G.R. & Tu X.L. (2008). Heavy metal pollution in intertidal sediments from Quanzhou Bay, China. *Journal of Environmental Science* **20**: 664–669.
DOI: https://doi.org/10.1016/S1001-0742(08)62110-5

Yunginger R., Bijaksana S., Dahrin D., Zulaikah S., Hafidz A., Kirana K.H., Sudarningsih S., Mariyanto M. & Fajar S.J. (2018). Lithogenic and anthropogenic components in surface sediments from Lake Limboto as shown by magnetic mineral characteristics, trace metals, and REE geochemistry. *Geosciences* **8**(4): 116.
DOI: https://doi.org/10.3390/geosciences8040116

Zhang C., Yu Z.G., Zeng G.M., Jiang M., Yang Z.Z., Cui F., Zhu M.Y., Shen L.Q. & Hu L. (2014). Effects of sediment geochemical properties on heavy metal bioavailability. *Environment International* **73**: 270−281.
DOI: https://doi.org/10.1016/j.envint.2014.08.010