SEDIMENT AND PHYSICOCHEMICAL CHARACTERISTICS IN MADU-GANGA ESTUARY, SOUTHWEST SRI LANKA

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ABSTRACT

The tropical Madu-ganga Wetland is an important Ramsar Convention site on the southwest coast of Sri Lanka. This study aimed to evaluate spatial and temporal hydro-and sediment dynamics in Madu-ganga Estuary for developing future sustainable management strategies. In this study, physicochemical parameters such as conductivity, pH and turbidity were measured. Sediment samples were also collected for grain size and X-ray fluorescence spectrometer analysis. In addition, geophysical investigation was carried out using sub-bottom profiler. Conductivity and pH values suggest admixing of saline water from the ocean, and preferential intrusion of saline water when the estuary mouth is opened. The transparency of the water column has been significantly improved when the estuary mouth is opened due to well circulation of freshwater flux. The average phosphate values in water samples of the estuary mouth closed and opened periods are 0.37 ppm ± 0.12 and 0.39 ppm ± 0.13, respectively. In contrast, sediment samples show that phosphate values are progressively increased towards the upstream due to the supply of terrestrial nutrients. Geochemical and grain size relationships in sediment samples indicate a hydrodynamic separation of sands and muds and sorting or accumulation of heavy minerals in Madu-ganga Estuary. Three acoustic facies were identified based on the echogram records such as an opaque type (fresh bed rocks), a transparent type (weathered bed rocks) and a layered type sedimentary infill. The layered type facies can be characterized by a sequence of Quaternary sedimentary beds with no direct evidence for erosional surfaces.

Keywords: Tropical Estuary, Physicochemical properties, Seasonal variations, Sub-bottom profiler, Sri Lanka

INTRODUCTION

Madu-ganga Wetland is a small (about 60 km² watershed) and relatively shallow (maximum water depth about 3 m) brackish coastal aquatic system situated in the Galle District of Southern Province, Sri Lanka (Fig. 1a). This wetland has a significant ecological, biological and aesthetic value. For example, Madu-ganga Wetland consists of 303 species of plants and 248 species of vertebrate animals. Total plant species comprise 19 endemics and 8 nationally threatened species, while vertebrate animals comprise 20 endemics and 30 nationally threatened species (IUCN Sri Lanka, 2000). Local vegetation in Madu-ganga Wetland is dominated by mangrove swamps, and this is one of the last enduring tracts of pristine mangrove forests in Sri Lanka (Amarathunga et al., 2010). Therefore, Madu-ganga Wetland was declared
as Ramsar Convention site in 2003. Madu-ganga Wetland comprises a central basin, which is fed by tributary rivers and opens to the Indian Ocean by a narrow and short entrance channel (Fig. 1a). This wetland thus consists of several niches such as brackish to freshwater area (estuary), small islands and mangrove dominant forests. The present study is mainly focused to Madu-ganga Estuary. This tropical aquatic system in the wet zone of Sri Lanka (Fig. 1a) is strongly influenced by regional monsoon climate. The average annual temperature of the study area is around 27ºC, and the average annual precipitation is around 2500 mm.

The satellite images of the study area show periodic opening, semi-closed and closure nature in Madu-ganga Estuary (Fig. 1b). It can probably indicate deposition of sand under the influence of southwest (summer) and northeast (winter) monsoons by longshore currents. The seasonal changes (i.e., opened/closed nature) in the estuary mouth may probably influence the health of this ecosystem such as accumulation of pollutants/nutrients and variations in physicochemical parameters. Because of tropical

![Figure 1](image_url)

**Fig. 1.** (a) Map of Sri Lanka showing Madu-ganga Estuary and sampling locations and (b) satellite images show periodic geomorphological changes in Madu-ganga Estuary mouth.
Aquatic systems are one of the most threatened ecosystems due to their ecological sensitivity to anthropogenic activities and climate change (e.g. Mcgowan et al., 2005; Ratnayake et al., 2005; Satpathy et al., 2010; Jayasingha et al., 2011; Chandrajith et al., 2013). Consequently, the monitoring of seasonal hydro and sediment dynamics is an essential for future sustainable development of this tropical coastal wetland. Since the local communities in the study area greatly depend on ecological and socio-economic benefits in this wetland, including tourism, fishing/nursery areas for marine estuarine opportunists and traditional industries such as cinnamon processing.

In this study, an attempt is given to investigate seasonal variations of physicochemical properties, elemental abundances and grain size variations of surface sediments and echogram records in Madu-ganga Estuary. Therefore, this article particularly assistances to designing of environmental monitoring systems, natural resource management, pollution risk evaluations and creating baseline data for future decision making in tropical Madu-ganga Estuary.

**MATERIAL AND METHODS**

**WATER SAMPLES**

Physicochemical parameters were measured at 18 locations in Madu-ganga Estuary, covering southwest and northeast monsoons, and opened/closed estuary conditions. In detail, the first field visit (in September, 2016) covers southwest monsoon and closed estuary condition. The second (in November, 2016) and third (in January, 2017) field visits were carried out during the periods having opened estuary mouth. In addition, the second and third field visits cover second inter-monsoon and northeast monsoon periods, respectively. Vertical water quality profiles of these stations were obtained at surface and bottom levels. Surface water samples were directly collected in pre-cleaned polythene bottles, and bottom samples were collected using a Ruttner water sampler. Sample bottles were stored in a cooling box and transported to the oceanography laboratory at University of Moratuwa, Sri Lanka. Conductivity of water samples was measured by conductivity meter (HACH HQd Portable Meter). pH measurements were obtained by pH meter (HACH SCNSION1) having a resolution of 0.01. Turbidity of water samples was obtained by turbidity meter (TB300IR) having a resolution of 0.01 NTU. Dissolved nutrient such as phosphate was estimated for selected water samples by following standard colorimetry method of UV-visible spectrophotometer (thermo scientific GENESYS 10S).

**SEDIMENT SAMPLES**

**GRAIN SIZE ANALYSIS**

Surface sediment samples (L1 to L18) were collected using an Ekman-Barge type grab sampler during the first field visit (Fig. 1a). About 5g of an oven-dried sample was weighed and put into beakers. Sediment samples were treated with an excess amount of H2O2 for several days (at least seven days) to completely remove organic matter. Then the samples were sieved through 1 mm mesh and undersize particles were fed to the HMK-CD2 laser particle analyzer at University of Moratuwa, Sri Lanka.

**P2O5 ANALYSIS**

The air-dried surface samples were crushed in a Tema mill. After that, each sample was sieved through 106 micron sieve. For the digestion, 2 ml of 1M HNO3 and 6 ml of 1M HCl were added to about 1g of sieved sediment samples. The solution was diluted up to 50 ml, and then phosphate was estimated by following standard colorimetry method of UV-visible spectrophotometer (thermo scientific GENESYS 10S).

**X-RAY FLUORESCENCE SPECTROMETER ANALYSIS**

The crushed powders (<63 μm) were mounted on the sample stage using double tapes. Elemental compositions were measured for eight different places of the particular sample using HORIBA scientific XGT- 5200 X-ray analytical microscope with X-ray tube of 50 kV at Sri Lanka Institute of Nano Technology (SLINTEC) laboratory. The element percentage values were calculated by the machine itself relative to the total detected elements present in each spot. Therefore, the total detected elements percentage values were added up to 100%, and the average value of each element was calculated for the particular sample.
GEOPHYSICAL INVESTIGATION

Bathy 2010PC™ CHIRP sub-bottom profiler (frequency 3.5 kHz) and bathymetric echo sounder (frequency 210 kHz) surveys were carried out to generate about 400 m in length hydro-acoustic data close to Madu-ganga Estuary mouth (Fig. 1a). The transducer was hanged vertically (0° angle) as a stable platform and below the water surface on the side of a small boat. The average speed of the boat was almost constant (less than about 2 m s⁻¹) and the navigational data were recorded using a differential global positioning system (GPS) receiver. The data processing and interpretation were carried out at the oceanography laboratory, University of Moratuwa, Sri Lanka.

RESULTS AND DISCUSSION

PHYSICOCHEMICAL PARAMETERS

pH values show no conspicuous variation (range from 6.9 to 8.2, average = 7.6 ± 0.2) with the sampling locations and periods (Fig. 2). It may be followed by low terrestrial drainage and/or the extensive buffering capacity of seawater that results in the change of pH values within a narrow range (Riley and Chester, 1971; Satpathy et al., 2010). The oceanic pH values are slightly basic (around 8.1) including in the Indian Ocean (e.g. Wootton et al., 2008; Lauvset et al., 2015). In this study, pH values show good positive correlation (R = 0.65) with conductivity by Y = 0.015X + 7.33 (Fig. 3). Therefore, the alkalinity of Madu-ganga Estuary is mainly controlled by seawater invasion. The observed conductivity values range from 2.7 to 43.0 mS/cm (average = 18.9 mS/cm ± 10.2). The conductivity can be identified as an indicator for salinity or the total amount of salt content in water (e.g. Morrison et al., 2001; Ratnayake et al., 2013). Therefore, conductivity variations should indicate salinity gradient along this coastal aquatic system (Fig. 2). As expected, the conductivity values of Madu-ganga Estuary were decreased from the estuary mouth to upstream due to dilution of seawater intrusion along the freshwater stream (Fig. 2). In addition, the conductivity values of Madu-ganga Estuary were increased with depth during the second (in November) and third (in January) field visits (Fig. 2), suggesting that increment of density stratification during the periods of low freshwater input. However, location-wise conductivity gradient and drastic spatial variation cannot be observed during the first field visit (in September, Fig. 2), may be due to higher precipitation during the subsequent months of southwest monsoon and minor seawater invasion during the periods having closed estuary mouth.

Turbidity in the estuarine is an important to monitor water quality, primary productivity, fate of pollutants, fish migration and dredging operations (e.g. Rao et al., 2011). Turbidity was higher during the first field visit (range from 4.05 to 18.85 NTU, average = 9.16 NTU ± 3.41, under closed estuary condition) compared to second field visit (range from 1.88 to 6.93 NTU, average = 4.04 NTU ± 1.41, under opened estuary condition) (Fig. 4). Turbidity depends on concentration and size of suspended and dissolved particulate matter in the water column (La Fond, 1954; Rao et al., 2011). In addition, the secchi depth was reduced during the first field visit (average = 0.5 m ± 0.1) compared to the second field visit (average = 1.0 m ± 0.1) (Fig. 5). Therefore, the transparency of water is very low under closed estuary condition.

Concentration of dissolved phosphate in water samples range from 0.17 to 0.67 ppm (average = 0.37 ppm ± 0.12) during the first field visit (under closed estuary condition), and from 0.20 to 0.65 ppm (average = 0.39 ppm ± 0.13) during the second field visit (under opened estuary condition).

Fig. 2. Surface and bottom conductivity and pH changes in Madu-ganga Estuary.
condition) (Fig. 6). Therefore, no significant variation of phosphate concentration can be observed in closed and opened conditions of the estuary mouth. However, phosphate concentration of Madu-ganga Estuary stands higher than the recommended value of 0.025 ppm for controlling algae growth in lakes/reservoirs, according to the United States Environmental Protection Agency criteria (USEPA, 1986). In addition, phosphate can be identified as the most important and limiting inorganic nutrient in tropical coastal ecosystems for algae growth (Cole and Sanford, 1989; Satpathy et al., 2010). Therefore, dissolved nutrient rich water in Madu-ganga Estuary can probably suggest (i) favorably conditions for algae growth and (ii) influxes of nutrient to freshwater sources from agricultural/domestic areas by erosion of sediments.

The variations of elemental abundances versus average grain size in surface sediments of Madu-ganga Estuary are shown in Fig. 8. Si contents range from 9.7 to 76.7 wt%. As expected, Si shows a positive correlation with average grain size (Fig. 8a). Therefore, Si contents of surface sediment samples are mainly controlled by coarse-grained quartzose or quartzofeldspathic sediments (e.g. Roser, 2000; Hossain et al., 2010). Al mainly resides in the fine-grained aluminous clay fraction. Al contents range from 0.7 to 9.1 wt%, and it shows a negative correlation with average grain size of varying strength (Fig. 8b). Therefore, Al and Si variations in surface sediments clearly indicate a hydrodynamic separation of mud and sand dominant sediments.

Both S and Fe are negatively correlated with average grain size variation of surface sediments (Fig. 8c, d). In general, tropical wetlands provide favorable conditions for the burial of organic carbon and formation of pyrite sulfur in oxygen-poor to anoxic fine-grained sediments. In detail, sulfate reduction leads to the formation of hydrogen sulfide that further reacts with reactive iron to precipitate iron sulfides such as mainly pyrite (FeS$_2$) during early diagenesis. Sedimentary pyrite can also be reacted with organic matter to form organic sulfur compounds at the second stage in fine-grained sediments (Berner, 1982, 1984, 1985; Berner and Raiswell, 1984; Sampei et al., 1997; Ratnayake and Sampei, 2015).

**SURFACE SEDIMENTS**

Fig. 7 shows the distribution of P$_2$O$_5$ concentration in surface sediments of Madu-ganga Estuary. P$_2$O$_5$ contents range from 0.14 to 0.60 ppm with an average of 0.34 ppm ± 0.16. The most noticeable variation is the higher content of P$_2$O$_5$ after L11 sampling location (Fig. 7). The spatial variation of P$_2$O$_5$ content suggests enhancement of nutrients towards the upstream (in the basin part) of the estuary (Fig. 1a), may be due to agricultural and/or domestic practices (e.g. Jayasingha et al., 2011; Chandrajith et al., 2013).

![Fig. 3. Relationship between pH and conductivity in water samples.](image)

![Fig. 4. Box plot for average turbidity during the estuary mouth opened and closed periods. Vertical lines indicate the range. Boxes indicate 25% and 75% quartiles. The median is given in horizontal](image)
In this study, a considerable positive correlation exists between Ti and average grain size variation of surface sediments (Fig. 8e). It is probably associated with mixing of heavy minerals (e.g. ilmenite and rutile) rich beach sand along Madu-ganga Estuary. In contrast, CaO shows no consistent pattern with average grain size variation (Fig. 8f), which may be associated with a biogenic components such as carbonate shells or organisms (e.g. Jayawardana et al., 2012).

**HYDRO-ACOUSTIC DATA ACQUISITION**

Fig. 9 shows the occurrences of the different acoustic facies along the survey lines at Madu-ganga Estuary mouth. Sub-bottom profiling provides continuous information along the surveying line with much greater resolution within its depth of optimum penetration (up to ~20 m). The sub-bottom profiler data were classified into three acoustic facies based on the pattern and shape of the reflectors (Fig. 9). It includes an opaque type (O-type), a transparent type (T-type) and a layered type (L-type) sequences.

The O-type acoustic facies is highly reflective (Fig. 9). This bottom facies is located about 10 m in depth from the estuary floor (Fig. 9). The O-type facies can generally correspond to fresh bed rocks/beach rocks below the soft

**Fig. 5.** Relationship between pH and conductivity in water samples.

**Fig. 6.** Box plot for P<sub>2</sub>O<sub>5</sub> concentration in water samples during the estuary mouth opened and closed periods. Vertical lines indicate the range, excluding outliers (dark circle). Boxes indicate 25% and 75% quartiles. The median is given in horizontal bar.

**Fig. 7.** P<sub>2</sub>O<sub>5</sub> concentration of surface sediment samples in Madu-ganga Estuary.
type and T-type facies boundary cannot be distinguished clearly based on the sub-bottom profiler data, may be due to the gradual transition from fresh to weathered bed rocks.

The L-type facies can probably indicate mixed fluvial deposits with interlayered marine based sand deposits. These facies are located parallel to both the estuary floor and topography of the acoustic basement (Fig. 9). Therefore, it can probably indicate absent of local erosion or seismic activities over geological time (e.g. García-García et al., 2004; Dove et al., 2014; Nakamura et al., 2016). The thickness of each sedimentary layer is almost constant along the survey line (Fig. 9), suggesting that homogeneous sediment distribution.

About fifteen major sedimentary layers can be recognized by multiple reflectors (Fig. 9) that are generally related to different beam amplitude. The sharp boundaries can probably show interface of different lithological units. The thickness of total sedimentary succession in Madu-ganga Estuary is about 7 m (Fig. 9).

In summary, sedimentary succession in Madu-ganga Estuary can be probably developed since middle Holocene highstands based on regional sequence stratigraphy and geomorphological frameworks of the west to southwest coasts in Sri Lanka (Katupotha and Fujiwara, 1988; Ratnayake et al., 2017). In detail, many of former drainage basins have changed into semi-closed and closed coastal aquatic systems such

Fig. 8. Selected major elements percentages versus average grain size variation diagrams for Madu-ganga Estuary surface sediment samples.
as lagoons, lakes and swamps with respect to middle Holocene sea-level changes (Katupotha, 1988a, 1988b; Weerakkody, 1992; Ratnayake, 2016).

CONCLUSIONS

The present multi-proxy investigation considered physicochemical properties and sediment dynamics in Madu-ganga Estuary. The temporal physicochemical properties of Madu-ganga Estuary can be most easily explained considering geomorphological changes of opened/closed estuary conditions. The study area can be recognized as the mixing zone of saline water and freshwater. The mixing pattern can be influenced by precipitation and geomorphological changes of the estuary mouth.

Turbulent condition (i.e., increase turbidity and decrease secchi depth) can be expected during the closed estuary period. The observed geomorphological characteristics have no direct influence to change dissolved phosphate concentration in the water column. However, the high concentration of phosphate was found in sediment samples from the upstream part of the estuary. Si and Al variations with respect to average grain size indicate hydrodynamic separation (detrital sorting trends) of sands and muds during deposition. Ti variation in Madu-ganga Estuary indicates the accumulation of heavy minerals from beach sand sources. Our geophysical investigation distinguished three acoustic facies of an opaque type (fresh bed rocks, depth >10 m from the estuary floor), a transparent type (weathered bed rocks, depth 7-10 m from the estuary floor), and layered type (unconsolidated sediments, depth 0-7 m from the estuary floor).

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![Characteristic echogram shows acoustic facies in Madu-ganga Estuary. Black lines represent facies boundaries.](image-url)
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