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# SEDIMENT GRANULOMETRY AND ORGANIC MATTER CONTENT IN THE INTERTIDAL ZONE OF THE SUNGAI BRUNEI ESTUARINE SYSTEM, NORTHWEST COAST OF BORNEO

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**Abstract:** Most of the estuarine and ocean bottoms are covered with sediments making this the largest habitat on our planet. Grain size data of the estuarine sediments are of great importance in differentiating various depositional microenvironments and also useful for assessing the textural characteristics of the habitat in benthic ecological studies. Here we use grain size analysis of the intertidal surface sediments along the Brunei estuary (Borneo, South East Asia) and the result reveals the dominance of sand fractions, and the percentage of dominance follows the order of sand > clay > silt. The sand size fraction was higher at seaward stations, which were poor in organic matter (<4 %), in contrast to the low-energy landward stations, which comprised a higher proportion of fine-grained (clay and silt) sediments and were rich in organic matter (> 5%). This pattern suggests that the intertidal sediments of the estuary derive from a mixed origin, including continental/marine and terrestrial sources, which vary in degree along the estuarine gradient in relation to hydrodynamic wave/current energy (generally low to high in a seaward direction along the estuary). There was strong negative correlation between the sand fraction and the other sediment variables (silt, clay and organic matter), whereas a positive correlation was observed between organic matter and silt/clay. Univariate (ANOVA) and multivariate (PCA) techniques clearly showed significant spatial differences in the sediment variables among the stations investigated, confirming differential energy conditions at different locations. Cluster analysis and PCA helped to discriminate the station groups along the estuary according to their sediment textural properties. This study also revealed that sediment grain size is a key factor influencing the organic matter accumulation in surface sediments. The organic matter observed in different stations is quite in agreement with the widely accepted view of other researchers from the tropical region that fine grained sediments generally have higher amounts of organic matter than the coarse grained one. The high organic matter at landward stations was found to reflect natural (mangroves) and anthropogenic (pollution) organic input.

**Keywords**: grain size, sand, silt, clay, organic matter, Brunei estuary, Borneo

## 1. INTRODUCTION

Estuaries act as trap of sediments and nutrients that are carried from the land by rivers and from the ocean by tides (Day et al., 1989; Venkatramanan, et al., 2013; Czarnecki et al., 2014). As a result, estuarine sediments are relatively heterogeneous, comprising detritus, inorganic and organic particles and constituting a unique environment for organisms (Dyer et al., 2000; Bragadeeswaran et al., 2007). Sediment grain size is influenced by several physical, chemical and biological factors including tidal current, wave action, climatic condition, salinity fluctuation, bio-turbation and various anthropogenic activities (Gray & Elliott, 2009; Nayar et al., 2007; Venkatramanan et al., 2013). Sediment supplied to an estuarine area might follow a route whereby they are suspended and carried back and are eroded before they are finally deposited either permanently or for a certain period (Manning et al., 2010). Sediments are deposited during periods of near slack high tide when the turbulence disappears (Saad et al., 1999; Dyer et al., 2000; Manning et al., 2010). Generally, the faster the current, the greater the size of the sediment particles that a river can move. When the velocity of tidal current (flood or ebb) gradually slackens along the course of the estuary, fine particles of sediment drop out of the water column and settle on the bottom (Ralston et al., 2013).

Tidal currents and surface waves play important roles in sediment dispersal and deposition in tide-dominated systems (Manning et al., 2010), but seasonal variation in discharge may be the most important factor in Southeast Asian estuaries, where monsoons prevail (Alongi, 1987). Salinity variation may cause fine particles to flocculate and settle as larger composite particles, and the circulation pattern in shallow areas may promote retention of the sediment load (Gray & Elliott, 2009; Manning et al., 2010). The resistance of cohesive mud deposits to resuspension is also a factor in holding sediments, once they have settled. Microorganisms are one of the major agents producing the organic matrix that binds sediment (DeFlaun & Mayer, 1983). Some burrowing benthic organisms (crabs, polychaetes, gastropods) in the mud increase water content in the sediments, and thereby decrease near surface sediment compaction, thus affecting the sediment textural composition (Davis, 1993). In contrast, tube-dwelling polychaetes (e.g., *Diopatra cuprea*) stabilize the bottom against erosion and also enhance sediment accumulation (Sarkar et al., 2005). Mangroves and sea grass in the intertidal area are effective traps for fine grained sediment in the estuaries. Anthropogenic sources often include disposal of channel dredged material, while waste product input from nearby towns may change the sediment composition and cause enrichment of organic matter (Robin et al., 2012). Sediment grain size analysis has a wide range of ecological and environmental implications. For example, sediment characteristics, mainly grain size, strongly influence the macrobenthos distribution (Alongi, 1990; Islam et al., 2011). Many investigators have shown higher densities, diversities and richness of macrobenthic species in finer particles (silt and clay), which are characterized by a relatively high organic matter fractions and low-hydrodynamic properties, conditions also favouring the nutrition and movement of infaunal organisms (Day et al., 1989; Alongi, 1990; Sarkar et al., 2005; Gray & Elliott, 2009; Hossain,2011). Spatial variation in sand, silt and clay ratio can therefore be useful to understanding and predicting faunistic distributions (Hossain, 2011; Anithamary et al., 2011).

Estuaries collect and transport natural weathering products as well as potentially harmful elements derived from anthropogenic sources. Fine-grained estuarine sediments are sinks for river borne heavy metals (Flemming et al., 1996) and are potential sources of bioavailable metals to benthic organisms leading to dispersal of metals through the aquatic food chain (Munksgaard & Parry, 2002). Hence, the study of the grain-size distribution in estuarine sediments is very important from the point of view of environmental pollution. The Sungai Brunei is facing pollution problems as it has received treated and untreated sewage, domestic wastes from water villages and drainage from the adjacent urban area (e.g., Bandar Seri Begawan, Beribi, Gadong and Kiulap) for decades, which potentially has had a deleterious effect on the water and sediment quality of the estuary (Hooi, 1987; Marshall et al., 2008). The mangrove forests of Brunei's estuaries, which are among the most pristine in Southeast Asia, are potentially under threat of ongoing deterioration of the estuarine water and sediment quality, consequently impacting the ecosystem in general.

A review of literature reveals that there exists a wealth of information with respect to grain-size distribution in South Asian tropical estuaries (Saad et al., 1999; Sarkar et al., 2005; Nayar et al., 2007; Prasad & Ramnathan, 2008; Hossain, 2011; Anithamary et al., 2011; Chen et al., 2012; Venkatramanan et al., 2013). However, little information is available for the textural composition of sediments of the estuaries of Borneo (the third largest island on the earth). Hence, the present study was conducted to present an analysis of intertidal sediments in terms of grain size and organic matter distribution along the Sungai Brunei estuary.

## 2. MATERIALS AND METHODS

### 2.1. Study site

Sungai Brunei estuary, facing the South China Sea, is a 15 km (approximately) long, mangrove-fringed estuary located in Brunei Darussalam, north-west coast of Borneo. The area is characterized by tropical climate with high annual rainfall (2300 mm), air temperature (28- 32°C) and humidity (70-98%) (Grealish & Fitzpatrick, 2013). Geologically, Brunei Darussalam is located within the Neogene Baram Delta Province (Back et al., 2008; Cullen, 2010) and the main prospective structure was deposited from the Middle Miocene (Fig. 1). The country can be divided into three delta systems (James, 1984; Sandal, 1996; Lambiase & Cullen, 2013): the Meligan Delta (the oldest, pre-Middle Miocene, situated in the uplifted and deeply eroded hinterland of onshore Sabah and Brunei), the Champion Delta (Late-Middle Miocene to Early Pliocene, in Brunei's present day onshore and eastern offshore areas) and the Baram Delta (the youngest Early Pliocene, in Brunei's western offshore area). The deltaic overburden on the undeformed fault blocks created some wide synclines (ridges). The sediments in the Baram Delta Province have been through diverse phases of reworking, which explain their generally high mineralogical maturity and a fine grained texture. The alluvial deposit, which mainly comprises inter-bedded sand stone, shale and clay materials, has mostly accumulated during and since the last post-glacial sea-level rise, some 5400 years ago (James, 1984; Hutchison, 2005; Peucker-Ehrenbrink & Miller, 2004). The Late Tertiary synclinal basins surround the coastal lowlands particularly in the Brunei Muara district (Back et al., 2008; Cullen, 2010).

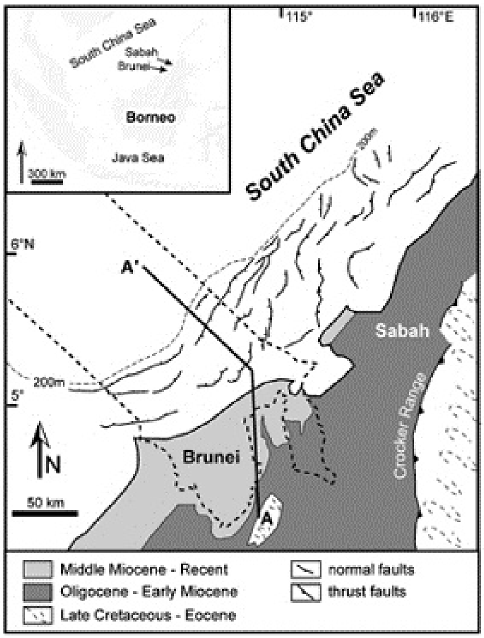


Figure 1. The geological map of Brunei Darussalam and NW Borneo (Source: Back et al., 2008).

Because of a different geological environment, important mineral deposits of Brunei Darussalam are oil, natural gas, peat and coal, construction sand, clay, white quartz and beach sand heavy minerals. The country is one of the largest oil and gas producers in the region. Peat swamps cover large parts of Brunei Darussalam, particularly in the western part of the country, beside the border with Sarawak (Back et al., 2008). Recently a diverse range of acid sulfate soils have also been reported from the country (Grealish & Fitzpatrick, 2013). Thin layers of heavy mineral sand have accumulated at favorable points along the beach from Tutong to Muara. The grey beach sands comprise mainly of zircon (75%), ilmenite, rutile and magnetite (around 10%), the remainder being mostly quartz and feldspar.

The water ways, Sg Brunei, Sg Damuan, Sg Kedayan and Sg Kianggeh carry sediment load from the catchment to the upper Sungai Brunei estuary, and the massive freshwater flux mainly from the Limbang and Temburong rivers carries high silt loads to the Inner Bay. Our study considers the Brunei estuarine system, including sites along the Sungai Brunei estuary and the Inner Brunei bay (Fig. 2). The estuary is partially stratified and tide dominated (mainly diurnal, tidal ranges: 2.0 to 0.9 m) draining into the Brunei Bay with a catchment area of 380 $km^2$ (Currie, 1979; Hooi, 1987). There is an established physicochemical gradient along the Brunei estuary, with salinity and pH respectively varying between 30 and 5 psu and 8 and 6.5 pH (Marshall et al., 2008).

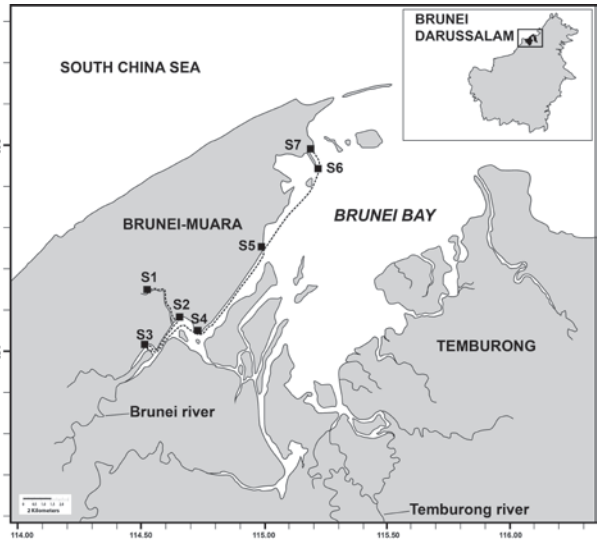


Figure 2. The location of the study sites (S1-S7) in the Brunei estuary.

### 2.2. Sample collection and processing

Surface sediment samples were collected from seven stations along the length of the estuary between Sg. Damuan and the Pulau Bedukang, during July-August 2011. During each collection trip, three replicate samples were taken at each station from mid-intertidal area. The samples were excavated from an area of 25 cm X 25 cm using a spade (with depth penetration of 20 cm). Samples were kept in pre-labeled polyethylene bags and return to the laboratory for further analysis. For sediment texture analysis, the samples were dried at 100°C for 24h, powdered, and sieved through a 0.5mm sieve. Grain size was analyzed following a hydrometer method described by Bouyoucos, (1962). Organic matter was determined by loss on ignition (LOI) method in a Muffle furnace. The furnace was calibrated before every use with a reference digital thermometer that can measure at least 500°C. One standard soil of known LOI value was also run with the sample for checking the accuracy of the reading. Initially, wet samples held in porcelain crucibles were heated in an oven 100°C for 24h. Thereafter, the dried samples were passed through a 2mm sieve to remove large–sized organic and inorganic material. After sieving, a 100g dried sediment sample was weighed (accuracy ± 0.001 g), placed in crucible and heated in a Muffle furnace at a constant temperature of 500°C for at least 3 hours. Samples were removed from the furnace, cooled at room temperature and weighed. The difference in weight between the original and final weights gave the total organic matter content of the sample (Boyd, 1995). All determinations were in triplicate and the mean value was used to obtain representation of each parameter. The average grain size data were used to generate the map of the spatial distribution using Arc GIS 9.3.

### 2.3. Statistical analysis

Data for sediment particle size and organic matter were statistically compared among stations using a Kruskal–Wallis ANOVA test. Correlations between environmental parameters, such as sand, silt, clay and organic matter, were statistically tested using simple correlation matrix (r). Cluster analyses were performed on the sediment data using group-average-linkage with Euclidean distance as a similarity measure. The data were also ordinated using principal component analysis (PCA). All statistical analyses were performed by using the computer packages, PAST (Hammer et al., 2004) and PRIMER v.6 (Clarke & Warwick, 2001).

## 3. RESULTS AND DISCUSSION

Sediment texture, in terms of percentage of sand, silt and clay, varied from 61.28 – 90.48, 1.2- 9.4 and 6.72- 30.72 for these parameters, respectively, along the Brunei estuary (Table 1). A comparative account of grain size data in surface sediments from different estuarine environments is given in table 2. The percentages of sand and clay are higher in the present study compared to Limbang and Kemaman (Malaysia), Ponoggal estuary (Singapore) which might be attributed to its parent material. Cullen (2010) mentioned the coastal land of the catchment area of Brunei estuary composed of loose sand and clay contents. In contrast, Chen et al. (2012) showed highest percentage of silt in nearby Limbang estuary which was explained by the low energy environment and high fresh water flux carrying silt fractions from upriver to the estuary. The spatial distribution of sediment particles (Fig. 3.) shows higher silt and clay fractions at upstream stations, and lower at sea ward stations, in agreement with findings of studies in other Asian regions by Hossain (2011) and Bragadeeswaran et al., (2007).

Table 1. Distribution of sand, silt, clay and organic matter (OM) in the Brunei estuary

| Stations | Latitude (N) | Longitude (E) | % Sand | % Silt | % Clay | % OM |
|---|---|---|---|---|---|---|
| S1 | 04 $^0$53.933' | 114$^0$56.037 ' | 62.48 | 6.8 | 30.72 | 7.8±0.14 |
| S2 | 04$^0$53.200 ' | 114$^0$56.737 ' | 88.08 | 1.2 | 10.72 | 6.01±0.03 |
| S3 | 04$^0$52.086 ' | 114$^0$54.630 ' | 61.28 | 9.2 | 29.52 | 6.1±0.22 |
| S4 | 04$^0$52.379 ' | 114$^0$57.247 ' | 65.08 | 9.4 | 25.52 | 5.26±0.11 |
| S5 | 04$^0$55.666 ' | 115$^0$00.872 ' | 85.28 | 5.2 | 9.52 | 4.08±0.06 |
| S6 | 04$^0$59.335 ' | 115$^0$04.148 ' | 81.08 | 5.4 | 13.52 | 3.41±0.34 |
| S7 | 05$^0$00.025 ' | 115$^0$03.773 ' | 90.48 | 2.8 | 6.72 | 2.49±0.14 |
| Minimum | | | 61.28 | 1.2 | 6.72 | 2.49 |
| Maximum | | | 90.48 | 9.4 | 30.72 | 7.8 |
| Average | | | **76.25** | **5.71** | **18.03** | **5.02** |

Table 2. Sediment grain size (%) in different tropical estuaries

| Estuary | Sand | Silt | Clay | References |
|---|---|---|---|---|
| Tirumalairajanar, India | 68.76 - 98.21 | 1.34 -26.92 | 0.01- 4.32 | Venkatramanan et al., 2013 |
| Vellar and Coleroon, India | 71-89 | 11-25 | 0-4 | Prasad & Ramnathan, 2008 |
| Ponggol, Singapore | 13.4 – 39.3 | 41.6 – 60.7 | 19.2 – 25.9 | Nayar et al., 2007 |
| Kemaman, Malaysia | 25.22 | 56.96 | 17.82 | Saad et al., 1999 |
| Morgan, Australia | 31.6 -86.9 | 10.9 - 55.4 | 2.2 -12.3 | Alongi, 1987 |
| Punang River, Malysia | 75.51 | 9.63 | 4.86 | Chen, et al., 2012 |
| Limbang, Malaysia | 3.28 | 78.38 | 18.34 | Chen, et al., 2012 |
| Meghna, Bangladesh | 42.3-62.6 | 11.8-33.2 | 18.9-36.9 | Hossain, 2011 |
| Brunei Estuary, Brunei | 61.28 – 90.48 | 1.2- 9.4 | 6.72- 30.72 | Present study |

The sand particle fraction was dominant throughout the estuary (Fig. 4), and was opposite to the trend of silt and clay fractions, which were highest at landward stations (Fig. 3). The non-parametric Kruskal- Wallis ANOVA showed significant variation ($p< 0.05$) in the distribution among the seven stations (Table 3) of all sediment particles. This variation in the distributional pattern may be attributed to a number of factors like tidal current, wave energy, fresh water discharge, salinity intrusion and human activities. Particularly, low to moderate hydrodynamic energy and reduction in water movement in the inner stations, S1, S3 and S4 increased the deposition of fine grained sediment (see also Venkatramanan et al., 2013), and the prevalence of a high energy environment at seaward stations ( S5, S6 and S7) increased the deposition of sand size fractions. During high tide, the incoming tides bring marine sands into the lower estuarine stations potentially increasing the relative content of bottom sand. But the proportional amount of sand is also dependent on the strength of the hydrodynamic forces. Sediment weathering, erosion, suspension, transportation, deposition and permanent settlement in an estuarine system are nonetheless extremely complex. In the BES, these relate to urban development and use of the estuary (at especially Kg Ayer, Bandar Seri Begawan and Muara port), where water transport increases turbulence within major channels. However, studies have suggested that offshore sediment flux still may have a strong influence on sediment and hydrological phenomena of unstable estuarine channels, as do high river discharges (Chen et al., 2010).

The sediments were generally rich in organic matter (Table 1). This varied from 2.49 to 7.8%, was greatest at the landward stations, and decreased towards the sea (ANOVA $F_{6,1}=317.8$ ; $p<0.0001$; Fig. 2d). This finding concurs with the earlier report of Hooi (1987) that suggests an average organic matter value of 7% in the sediments of Brunei estuary.

The high percentage of organic matter in the inner estuary is probably owing to litter fall from mangroves, domestic sewage from water villages and the city, Bandar Seri Begawan (BSB). High organic matter accumulation may also result from a low decomposition rate, consistent with anaerobic metabolic processes (Day et al., 1989; Islam et al., 2011; Robin et al., 2012). Correlation analysis showed that variables such as sand, silt, clay and organic matter were significantly associated. While there was a strong negative correlation ($p < 0.05$) between the sand fraction and other sediment variables (silt, clay and organic matter), there was a positive correlation between organic matter and silt/clay. The distribution of organic matter followed the sediment types in the Brunei estuary. The high percentage of organic matter in the inner stations is associated with a high percentage of fine-grained particles at these stations, which have a greater surface area and consequently greater power to retain organic matter (Day et al., 1989; Flemming et al., 1996; Venkatramanan et al., 2013).

Table 3. Results of Kruskal-Wallis ANOVA test comparing the sediment textural properties among the stations in the Brunei Estuary.

| | df | $\chi^2$ | p |
|---|---|---|---|
| % Sand | 6 | 16.74 | <0.05 |
| % Silt | 6 | 15.58 | <0.05 |
| % Clay | 6 | 16.34 | <0.05 |
| % OM | 6 | 19.32 | <0.01 |

Table 4. Correlation coefficient (r) values of sediment properties among seven stations

| | % Sand | % Silt | % Clay | % OM |
|---|---|---|---|---|
| % Sand | 1 | | | |
| % Silt | -0.89** | 1 | | |
| % Clay | -0.99*** | 0.82* | 1 | |
| % OM | -0.69 | 0.35 | 0.78* | 1 |

* p<0.05, ** p<0.01, *** p<0.001

Table 5. Results of the first two principal component axes in PCA analysis

| | PC1 | PC2 |
|---|---|---|
| Eigen Values | 3.24 | 0.71 |
| % Variation | 81.0 | 17.8 |
| Cumulative % Variation | 81.0 | 98.8 |

The unstable sandy bottom at lower stations (S5, S6 and S7) has a lower organic matter. A similar observation was made by Badarudeen et al., (1996), and Robin et al. (2012) from other tropical estuaries, India. It is likely that fine grain sediment, containing a greater percentage of clay, is associated with greater organic content (Gray & Elliott, 2009).

A Cluster analysis (CA) with Euclidean distances as a similarity measure and a Principal component analysis (PCA) biplot revealed grouping of stations. The dendogram shows that stations 1, 3 and 4 correspond with the upward section clustered in one group (Fig. 5).

Stations 2, 5, 6 and 7 form another group comprising the estuarine and seaward zones of the system. Despite being an upward station, station 2 clustered with group 2, due to the high percentage of sand. Comparisons of the results obtained by the above two methods indicate that several stations may cluster with different groups.

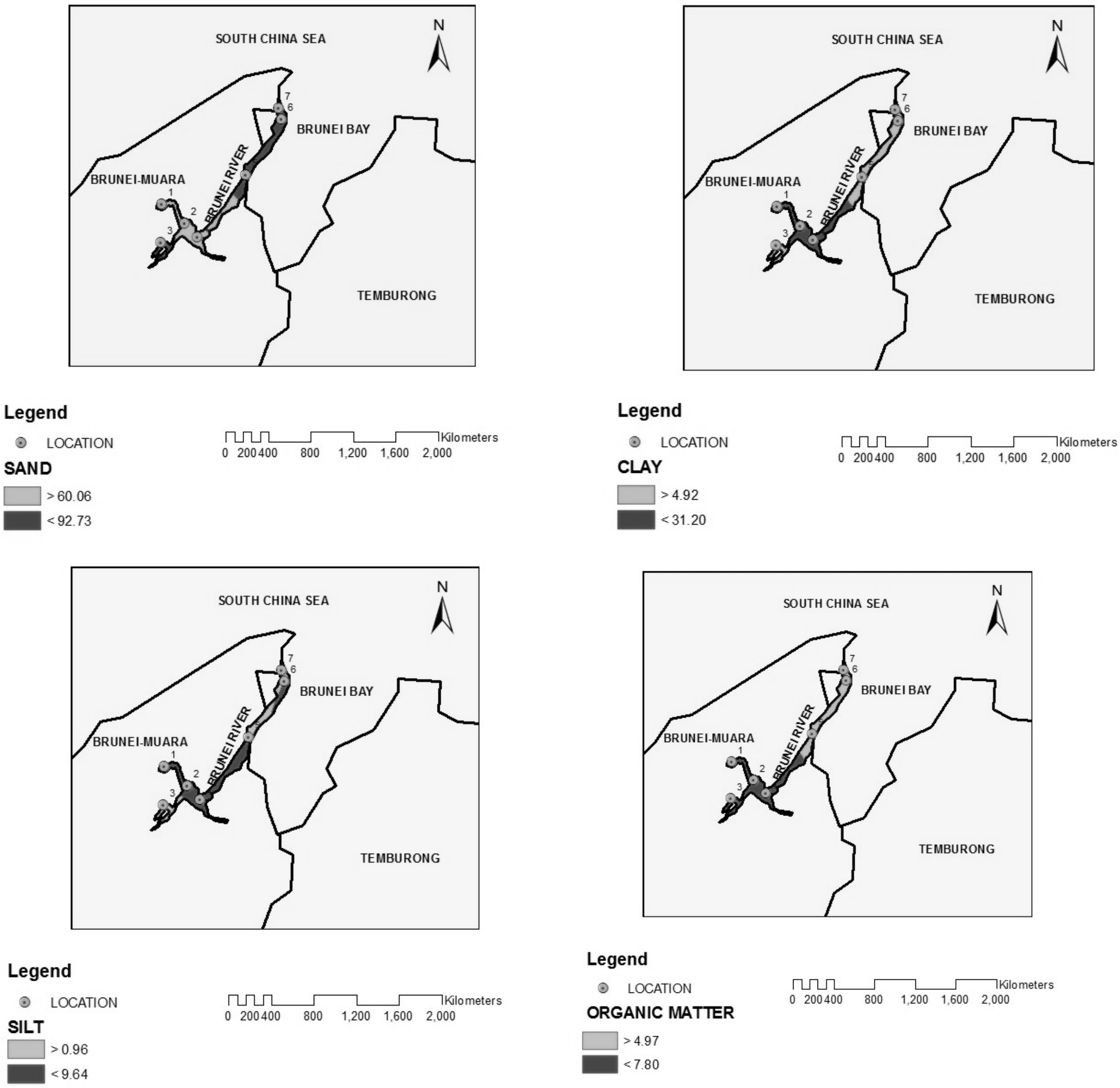


Figure 3. Spatial distribution of percentage of sand, silt, clay and organic matter in the Brunei river estuary.

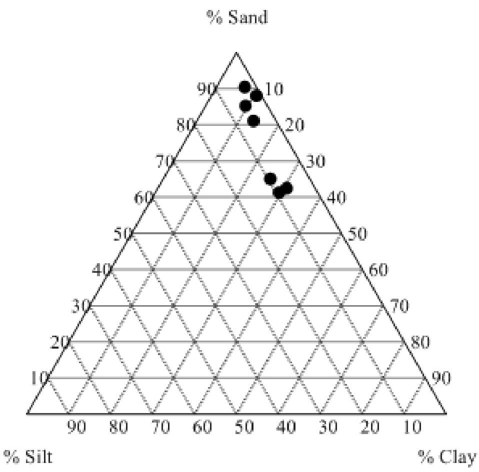


Figure 4. Ternary plot for sediment grain size analysis. The figure shows the dominance of sand fractions in the estuary.

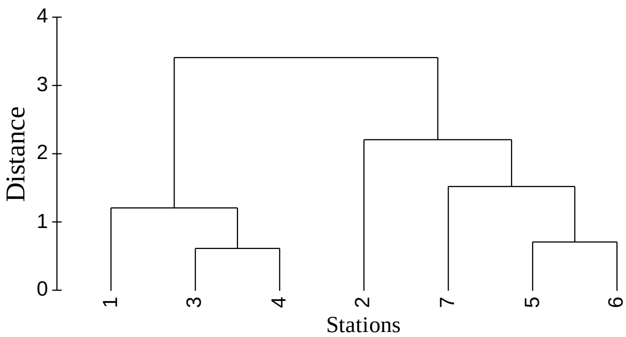


Fig. 5. Dendogram of sediment properties for seven stations. Based on Euclidean distance and average value of three replicates of sand (%), silt (%), clay (%) and organic matter (%). Data were square-root transformed. 1-7 indicates the sampling stations.

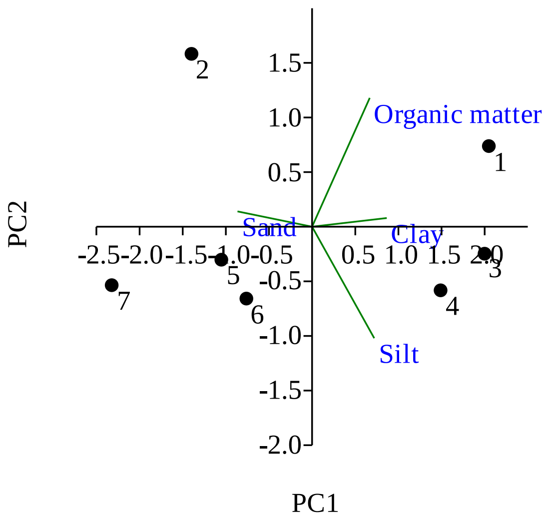


Figure 6. PCA ordination of sediment properties for the study locations. Data were square-root transformed and normalized. 1-7 indicates the sampling stations.

The stations in group 1 were strongly influenced by freshwater influx whereas those in group 2 were more influenced by sea water. Station 2 and 4 receives maximum urban sewage from the most point sources, the country's biggest sewage plant (Pintu Malim) and the traditional water village 'Kg Ayer'. The higher energy station 2 (Bandar) is prone to more erosion and resuspesion of sediments due to very strong current flowing in from Sg. Kianggeh and Kedayan rivers and boat movement, and thus revealed a higher percentage of sand and low amount of silt and clay. In contrast, the sediment bed of station 4 is less prone to resuspensions and represents higher amount of clay. The overall hydrodynamic condition in the estuary reflects a higher energy environment.

PCA biplot of sediment data shows stations 1, 3, 4 are to the left and 2, 5, 6, 7 to the right, which is similar to the dendogram groupings (Fig. 6). The first three components explain about 99 % of the variation.

Principal component 1 shows 81 % of the variation with positive loadings of sand and negative loadings of silt, clay and organic matter. Component 2 reveals 17 % of the variation with high negative loadings of organic matter and positive loadings of silt.

## 4. CONCLUSIONS

Based on this study, it can be concluded that the sand fractions were dominant throughout the Brunei estuary. Silt and clay fractions were higher in the inner than lower estuary. The organic matter was comparatively higher in this estuary than other estuary elsewhere, and associated with different size fractions of the sediment. The study further shows that sediment organic matter tends to associate closely with the finer fractions (silt and clay) of sediments. However, intensive sediment exchange occurs in the inner estuary due to the sand–silt–clay mixing, which is controlled by the bidirectional tidal flows. The overall hydrodynamic condition in the Brunei estuary reflects a higher energy environment.

This base line granulometric study of Brunei estuary will be very useful for future studies pertaining to the assessment and monitoring of the estuary and specially to predict the possible ecological changes in the estuary. Many studies (Padmalal et al., 1997; Preda & Cox, 2002; Lakhan et al., 2003; Zhou et al., 2004; Silva et al., 2014) have shown that the heavy metal concentration is controlled mainly by the textural composition of the sample i.e., fine grained sediment register higher concentrations of trace metals than that in sand-dominant sediments. This fact has wide ranging implications from the environmental perspective as these contaminants get dispersed and find their way into the trophic system. So the granulometric partitioning studies will help to explain the enrichment of heavy metals (e.g., Al, Co, Zn, Cu, Pb) in the estuaries (Padmalal et al., 1997; Lakhan et al., 2003; Zhou et al., 2004; Silva et al., 2014). Furthermore, relatively higher concentrations of organic carbon in the sediments can be traced to historical and present day anthropogenic activities in the estuary. This study further presents useful information for ongoing ecological investigation of this estuary, which is important in supporting a productive artisanal fishery and aquaculture industry though is under increasing threat from regional urban development (Marshall et al., 2008).


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