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# Sand dynamics as a tool for coastal erosion management: A case study in Darwin Harbour, Northern Territory, Australia

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## Abstract

Darwin Harbour, Northern Territory, Australia, is a semi diurnal macro-tidal embayment that is situated in a cyclone prone area. The tidal variations range up to 8 m with a mean tidal range of 3.7 m. The coastal area consists of mangrove fringes, sandy beaches, tidal flats, rocky shore platforms and coastal cliffs. The main morphological changes are movement of the sandbars and erosion of beaches and coastal cliffs. Sea level rise due to climate change and more intense cyclones and storm surges may exacerbate these processes with detrimental impacts on the coast and the adjacent city, particularly when occurring at high tide. To assist with coastal erosion management, a greater understanding of morphological changes is required. A two-dimensional depth averaged finite-element hydrodynamic model (RMA-2), coupled with a sediment transport model (RMA-11) from Resource Modelling Associates, have been used to deduce the sources and spatial patterns of sand erosion and deposition in the harbour. Geochemical analysis is also used to characterize the sand source(s). This paper presents hydrodynamic simulations focusing on culturally and recreationally significant beaches in Fannie Bay. Simulations indicate that the Cullen Bay sandbar is an indirect sand source replenishing Fannie Bay beaches. Respective geochemical results also show similar Rare Earth Element contents of the sand in the area. Considering the fast pace of development in and around Darwin Harbour, this study is essential in providing a fundamental understanding of coastal processes and to assist coastal and shoreline management in a tropical estuary.

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## 1. Introduction

Sand dynamics play an important role in decision making of coastal protection management, which primarily focuses on the management of coastal erosion and accretion. Within this, a range of complex processes needs to be investigated, including sediment motion due to sea hydrodynamics, the impact of human activities along the coast, in the river catchments and offshore, across a range of both spatial and temporal scales. Understanding the key processes of coastal dynamics and how the coast functions, on both spatial and temporal scales, is essential for managing coastal erosion.

Physical processes such as tides, waves, currents and winds shape the coastline while coastal geology determines the origin, structure and characteristics of the sediments that make up the coastal region. Interaction between local coastal geology and coastal processes results in regional variations of coastlines that might be short-term, seasonal or long-term. To understand the relationships between coastal processes and shoreline morphology, it is necessary to identify the sediment sources, transport pathways, the typical shoreline form, coastal processes, and the extent of modification [1].

Coastal erosion indicates an imbalance in the sediment supply and removal in the sediment budget, which contains the sources, the transport pathways and the sinks of the sediment. The sediment budget information, which can be used to predict morphological changes over time, is usually obtained from the sediment dynamics in a theoretically confined coastal area called a sediment/littoral cell. The boundaries of a littoral cell can be marked by several features such as headlands, submarine canyons, or river mouths [2]. Therefore, in order to assess sandy beach erosion problems in a certain coastal area, a sand movement dynamics study is significantly important.

Beaches are unconsolidated deposits of sand and gravel on the shoreline [3]. These sediments can be of terrestrial origin delivered to the coast by river, eroded from coastal landforms, or marine sediment that has been reworked from offshore deposits onto the coast. Due to the variability of sediment supply, most beaches show changes in plan and in profile, rapidly over periods of a few hours or days, or slowly over several decades or centuries. A stretch of sandy beach is said to be in a dynamic equilibrium when the beach sand that eroded during a storm season, accumulated at the nearshore areas and replenishes the beach in calmer periods [4]. Human induced activities, such as catchment modification or improper planning of coastal protection structures, may influence the sediment dynamics and result in beach erosion or unwanted beach accretion.

The sources of coastal sediment can be traced using petrological and mineralogical methods to determine the sediment provenance. Elements most suitable for provenance analysis are, amongst others, rare earth elements (REE), Thorium (Th), and Scandium (Sc), because of their stability when subjected to secondary processes such as diagenesis, metamorphism and heavy mineral fractionation [5]. Among these elements, REE are excellent provenance/petrogenic indicators due to the suitable chemical fractionation results and their consistent behaviour during weathering [6].

The study area, Darwin Harbour, is located in the Northern Territory, Australia. It has high tropical marine biota diversity and is socially and culturally significant to the local community. It is a large embayment covering the area from Charles Point in the west to Gunn Point in the east. A macro-tidal estuary, it drains the Blackmore, Darwin, Elizabeth and Howard Rivers. The semi-diurnal tides record the highest astronomical tide at 8 m [7] with the mean spring and neap tide variations around 6 and 3 metres respectively [8]. At spring tides, the peak tidal flux through the heads of the harbour is approximately $1{,}2 \times 10^5$ $m^3s^{-1}$ and over a spring tide period, up to $1 \times 10^9$ $m^3$ water can pass through this area [8]. Regardless of the large flux of water in peak spring tidal periods, Darwin Harbour has a water residence time of at least 20 days in the dry season and has a possible tendency to trap sediment [7]. The complex bathymetry and tidal currents in the harbour create a complex circulation near headlands and in embayments, which possibly regulate sand bank formation in the area.

Presently there are no defined sediment/littoral cells in Darwin Harbour, therefore this study was carried out within certain noticeable coastal features in the area. Two prominent headlands of the harbour, i.e. Charles Point in the west and Lee Point in the east were selected as the boundaries of the study area (Fig. 1).

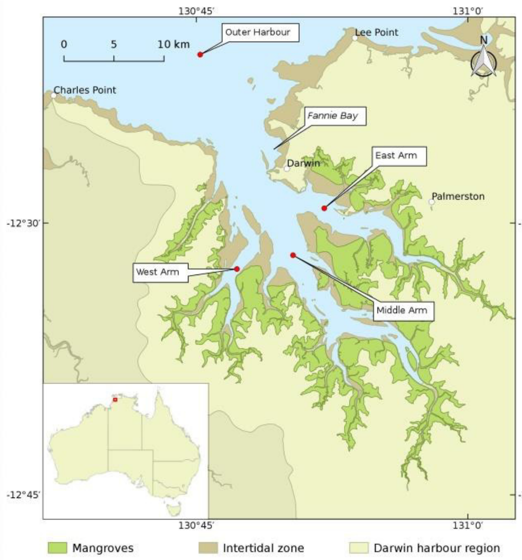

Fig. 1. Darwin Harbour, the study area

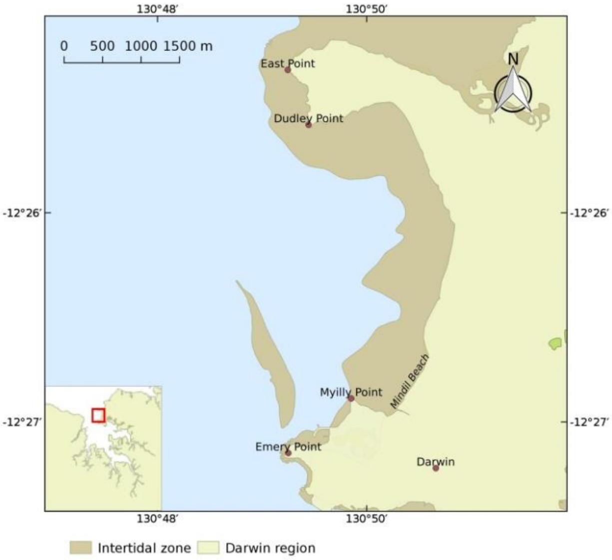

Fig. 2. Fannie Bay area

The northern coastline of Darwin Harbour consists of coastal cliffs and cliff scree slopes. The bottom sediment of Darwin Harbour is spatially distributed by tidal currents and deposition affected by the bathymetry. The main channel within the harbour and its arms is composed of bed sediments of coarse sand and gravel, fringed successively by fine sand and extensive intertidal and subtidal mud flats in the more sheltered parts of the harbour [7].

Darwin city is located only a few metres above sea level and some coastal cliffs have suffered lateral erosion of 1.9 – 17.3 m over a 28 year period, with an average shoreline recession of 0.2-0.4 m $y^{-1}$ or 30 cm $y^{-1}$ [9]. The eastern beaches have experienced beach erosion and vegetation loss, as well as damage to public and private infrastructure. Beach erosion and profile changes indicated that Darwin coastlines between Emery Point and Lee Point experienced seasonal changes in both climatic and oceanographic events [10].

Despite potential impacts, there have been no interactive sand dynamics studies conducted to cover the whole Darwin Harbour area. While recent hydrodynamic modeling covers the entire estuary region, the beach erosion and profile change studies were only carried out for particular areas of the harbour and mostly in an ad-hoc manner. Furthermore, the studies so far have not specifically intended to infer the sources and pathways of sand in Darwin Harbour. Sand bars remain as permanent features of the harbour despite being dredged, while shorelines and dunes are eroding. In order to mitigate coastal erosion and to study the implications of human-induced activities in Darwin Harbour, Williams et al [7] highlighted the importance of the link between hydrodynamics and sediment dynamics of Darwin Harbour. Therefore, the aim of this study was to provide an analysis of sand dynamics and provenance in Darwin Harbour thus providing a fundamental understanding of beach processes. This in turn will assist the broader coastal and shoreline management measures with regards to tropical, macro-tidal estuaries. In this study, hydrodynamics modelling was carried out on the whole study area, while the sand transport study was focused on the Fannie Bay area, where cliff erosion (East Point) and beach erosion (Mindil Beach) are occurring (Fig. 2).

## 2. Methods

The hydrodynamics of the study area was simulated using RMA-2, a 2D depth-averaged hydrodynamic modelling software package from Resource Modelling Associates [11]. The simulation was carried out using the calibrated and validated Darwin Harbour model mesh created by the Australian Institute of Marine Science (AIMS) based on 2012 bathymetry. A 2D modelling approach is valid for Darwin Harbour hydrodynamic simulation as numerous surveys of tidal currents profiling by AIMS has shown that the vertical profile of currents are of similar magnitude and direction during the tidal cycle. Furthermore, the computation of bed shear gives similar values compared to a 3D model. The model mesh comprises of 9,669 elements and 20,089 nodes. The cell sizes range from 20 m$^2$ at the wharf area to 3,000 m$^2$ at the offshore boundary. The mesh was divided into three element types, each assigned with different bed roughness in Manning's 'n' values, i.e.: 1) Submerged/water area, 'n' = 0.030; 2) Mangrove area, 'n' = 0.100; and 3) Intertidal area, 'n' = 0.025. The model was run for a 12-month period, from May 2012 to April 2013, covering both the dry and the wet seasons. Tide forces and river inflow were used to run the model with a 15-minute time step.

The RMA-2 hydrodynamic output was then input to RMA-11 [12] to simulate fine and medium sand transport. Simulations were run using the sand transport potential method based on Van Rijn's 1984 computation. This method is most appropriate for sand with diameter > 0.100 mm (fine sand size and greater). The size distribution of sand used in the simulations was determined from terrestrial and marine samples from the study area. Sub samples were also taken for geochemical analysis.

In order to infer the sand transport pathways from Fannie Bay area, a one metre sand bed thickness was applied on the intertidal area of Fannie Bay and run for 12 months. No other part of the harbour was assigned any sand substrate, so that the sand from the Fannie Bay intertidal area is the only source for any deposition occurring in the simulation area.

Another simulation was investigating the Cullen Bay sandbar, which is assumed to be the sand sink from the Fannie Bay area. A one metre sand bed thickness was applied to the sandbar and a 12-month simulation was run. No other part of the harbour was assigned any sand bed, so that the sand from the Cullen Bay sandbar is the only source for any deposition occurring in the area.

The sediment transport pathways were also inferred using the REE composition of the sand samples. The light- and heavy-REE composition and its chondrite normalized values were determined using a semi-quantitative ICP-MS method.

## 3. Results and Discussion

### *3.1. Sand distribution from the Fannie Bay intertidal area*

Simulations showed that there was no extensive erosion occurring in the Fannie Bay intertidal area. Only the northern intertidal area was significantly eroded, i.e. up to 103 mm of the initial sand bed thickness was eroded at the end of the 12-month simulation period, while the southern part lost less than 9 mm (Table 1, Figs. 3-4). In contrast to erosion, the middle intertidal area experienced deposition (Fig. 5), indicating lower current velocities in the area.

While the bed change trends were similar, the simulation showed that the medium and the fine sand distributed differently from the Fannie Bay intertidal area. The medium sand underwent higher erosion at its initial position and was not distributed widely compared to the fine sand, indicating normal behaviour of sand in water. Given similar hydraulic conditions, greater sand size with the same physical properties tends to be readily deposited back from suspension around its initial position while the finer sand will be distributed further and deposited away from its original position. Hence, while the erosion rate of the medium sand in the source area was higher compared to the fine sand, its deposition rate was lower in the sink area (Fig. 5). Nonetheless, in spite of the sand sizes, the simulations showed that the sand pathways from the Fannie Bay intertidal area were mostly westward and that sand was deposited in the submerged and the sandbar areas. If the area is not exposed to extreme events or substantial human intervention, altering the beach dynamic equilibrium, the submerged and the sandbar areas will continue serving as sand sources for Fannie Bay beaches.

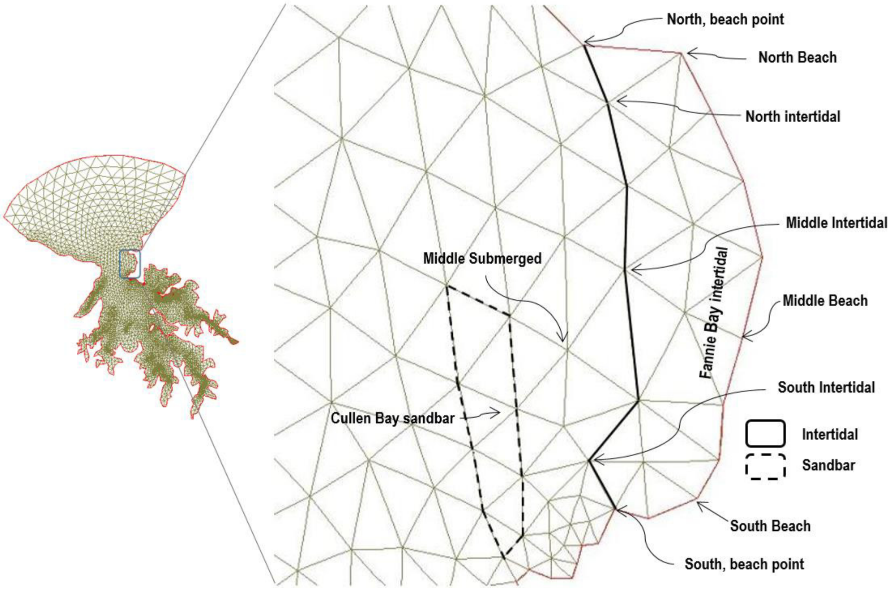

Fig. 3. Fannie Bay sand transport simulation locations

Table 1. Sand bed thickness changes at Fannie Bay

| Location | Initial sand bed thickness (mm) | Sand bed thickness changes after 12 month simulation (mm) | |
|---|---|---|---|
| | | Fine sand | Medium sand |
| North, beach point | 1.000.00 | -79.39 | -103.02 |
| North Intertidal | 1,000.00 | -56.45 | -74.43 |
| South Intertidal | 1,000.00 | -1.95 | -8.88 |
| South, beach point | 1,000.00 | -0.54 | -2.35 |
| Beach | 1,000.00 | 2.78 | 2.54 |
| Middle Intertidal | 0.00 | 23.97 | 27.44 |
| Middle Submerged | 0.00 | 67.04 | 60.29 |
| Cullen Bay sandbar | 0.00 | 425.08 | 211.34 |

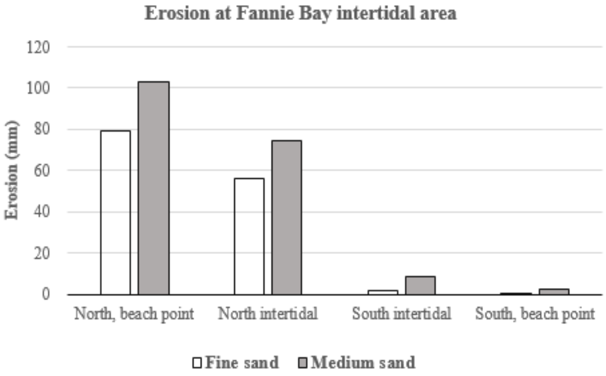

Fig. 4. Erosion at Fannie Bay intertidal area

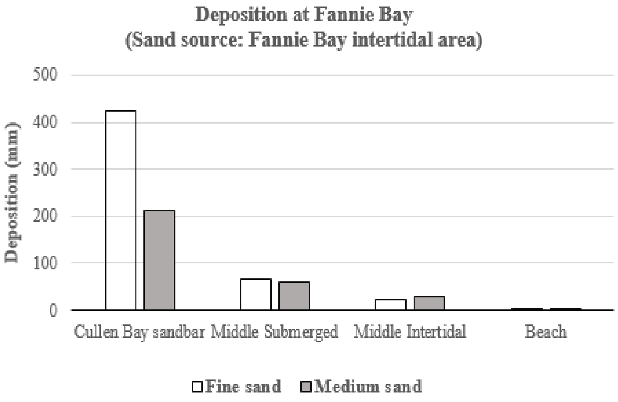

Fig. 5. Deposition at Fannie Bay Intertidal area

### *3.2. Sand distribution from Cullen Bay sandbar*

Both erosion and deposition occurred to the initial 1 metre sand bed thickness on the Cullen Bay sandbar. Fig. 6 shows the locations of the erosion (non-circled) and deposition (circled) points in the sand bar. The contrasting bed changes occurred on both sides of the sandbar with the east side eroded less compared to the west side (Table 2). The northern and the southern tips of the sandbar were completely eroded at the end of the simulation period, indicating strong eddies in the area and higher current velocities in the central harbour area compared to the Fannie Bay area.

Unlike the pathways from the intertidal area, the medium sand from the Cullen Bay sandbar was distributed and deposited at higher rates compared to the fine sand (Table 3, Fig. 7), suggesting vigorous water circulations in the area. The strong eddies, not only reworked the sand bed, but also redeposited the medium sand at its initial position and transported it to the adjacent areas. The fine sand, on the other hand, stayed in suspension longer and distributed to a wider area of the harbour. However, regardless of the sand sizes, the simulations showed that sand from Cullen Bay sandbar is distributed to the Fannie Bay area (Fig.7). The sand was mostly deposited in the submerged area and to a lesser extent to the intertidal and the beach area, suggesting that the sandbar provides a sand source to replenish the Fannie Bay beach area, albeit indirectly.

Table 2. Sand bed thickness changes at Cullen Bay sandbar

| Location | Initial sand bed thickness (mm) | Sand bed thickness changes after a 12-month simulation (mm) | |
|---|---|---|---|
| | | Fine sand | Medium sand |
| 410 | 1,000.00 | -715.95 | -999.97 |
| 426 | 1,000.00 | 9.83 | -165.90 |
| 443 | 1,000.00 | 560.17 | 595.34 |
| 461 | 1,000.00 | 335.78 | 170.60 |
| 482 | 1,000.00 | -1,000.00 | -999.96 |
| 409 | 1,000.00 | 197.16 | 112.07 |
| 425 | 1,000.00 | 69.15 | 3.54 |
| 442 | 1,000.00 | -324.71 | -574.81 |
| 460 | 1,000.00 | -353.26 | -745.04 |

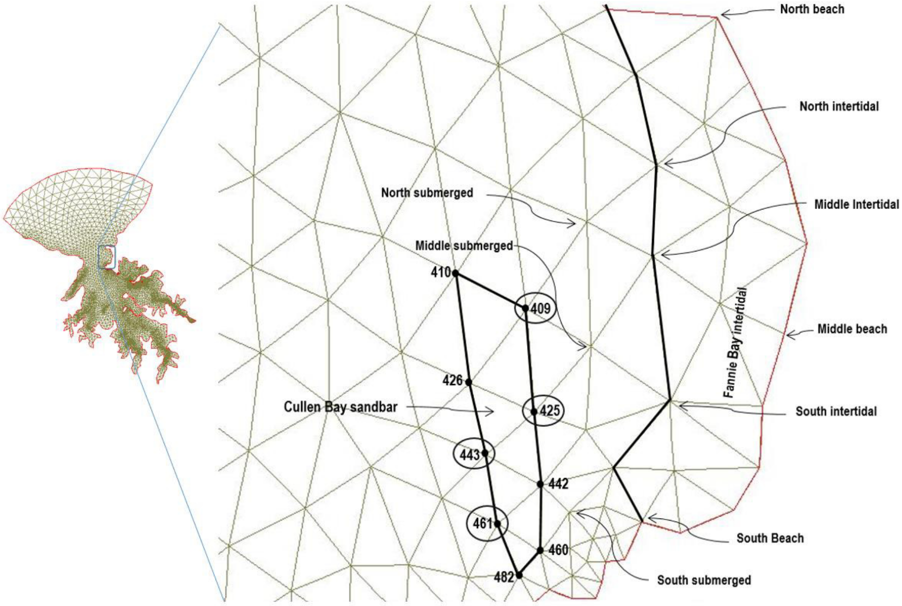

Fig. 6. Node locations at Cullen Bay sandbar

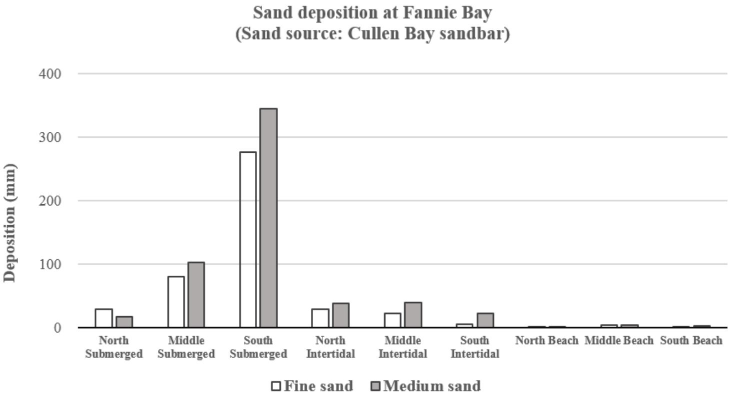

Fig. 7. Sand deposition at Fannie Bay (Sand source: Cullen Bay sandbar)

Table 3. Sand deposition at Fannie Bay (Sand source: Cullen Bay sandbar)

| Location | Initial sand bed thickness (mm) | Sand bed thickness changes after 12 month simulation (mm) | |
|---|---|---|---|
| | | Fine sand | Medium sand |
| North Submerged | 0.00 | 29.35 | 17.43 |
| Middle Submerged | 0.00 | 79.86 | 102.67 |
| South Submerged | 0.00 | 276.50 | 345.42 |
| North Intertidal | 0.00 | 28.31 | 37.60 |
| Middle Intertidal | 0.00 | 22.68 | 40.10 |
| South Intertidal | 0.00 | 5.34 | 22.67 |
| North Beach | 0.00 | 0.60 | 0.61 |
| Middle Beach | 0.00 | 3.28 | 3.57 |
| South Beach | 0.00 | 1.54 | 2.72 |

### *3.3. The provenance of sand in Fannie Bay*

Based on sedimentary compositions (Figs. 8 and 9), sand in the Fannie Bay area appears not to be derived from within the Darwin Harbour catchment. The contrasting REE composition of river sediment entering Darwin Harbour and sediment in the Fannie Bay area supports a predominantly marine source of the latter. This complements the modelling results and a previous study conducted in Darwin Harbour [13]. An additional source may be the erosion and the hydraulic sorting of coastal cliff materials (e.g. the East Point cliffs) but this could not be ascertained from REE data only.

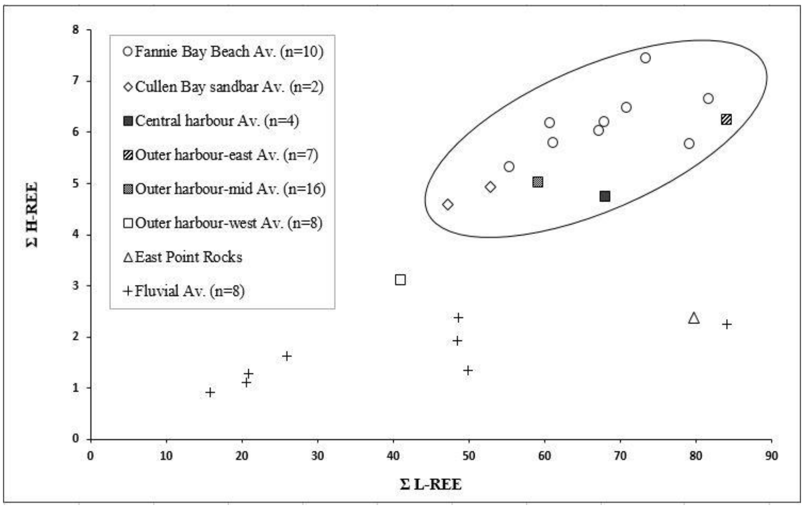

Fig. 8. Light versus Heavy REE

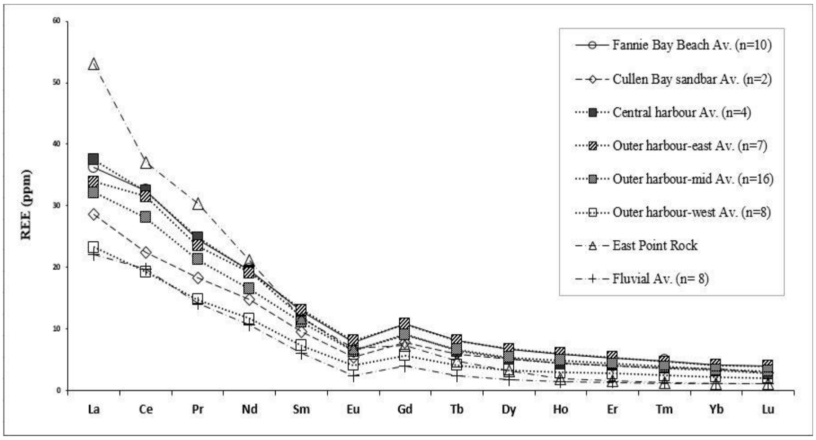

Fig. 9. Average chondrite-normalized REE concentrations

## 4. Conclusion

Two-dimensional hydrodynamic and sand transport simulations showed that fine and medium sand in the Fannie Bay intertidal area are not extensively eroded. Only the north part was substantially eroded after a 12-month simulation period, while the middle part experienced deposition, suggesting different current velocities in the area. The fine and medium sand from the intertidal area of Fannie Bay in Darwin Harbour is mostly distributed locally and replenishes the adjacent beaches and sandbar.

Hydrodynamic and sand transport analysis indicate that the Cullen Bay sandbar is an indirect sand source replenishing Fannie Bay beaches. The sand from the sandbar is temporarily deposited in the submerged and the intertidal areas, and replenishes the Fannie Bay beaches. A parallel geochemical study using Rare Earth Element analysis indicates a relationship between sand from the Fannie Bay intertidal area and the Cullen Bay sandbar, supporting the modelling analysis. Further research is necessary to determine the main sand source for Cullen Bay sandbar, as it is evident that the sandbar is an important feature to consider in decision making of coastal erosion management in Darwin Harbour, particularly for the Fannie Bay area.

## Acknowledgement

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