

Understanding coastal processes to assist with coastal erosion management in Darwin Harbour, Northern Territory, Australia

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Abstract. Sand transport pathways in Darwin Harbour, Northern Territory, Australia, are being investigated to assist with coastal management. Coastal erosion, which threatens public and private infrastructure, is one of the major problems along the harbour beaches. A study of sediment transport is essential to identify the challenges encountered by the stakeholders in coastal management. Darwin Harbour, located in the tropical, cyclone prone area of Australia, was, until recently, considered a near pristine estuary. A semi-diurnal macro-tidal embayment, the tidal variation in the harbour reaches up to 8 m with a mean tidal range of 3.7 m. The beach morphology consists of sandy pocket beaches between coastal cliffs, sandbars, rocky shore platforms, tidal flats and mangrove fringes. A two-dimensional depth averaged finite-element hydrodynamic model (RMA-2), coupled with a sediment transport model (RMA-11) from Resource Modelling Associates, has been used to infer the sources and the depositional areas of sand in the harbour. Grain size distributions and geochemical analysis are also used to characterize the sand and its source(s). Initial results show that the beach sand is mostly of offshore origin with small sand input from the rivers. Potential supplementary sand sources are the eroded materials from the shore platforms and the rocky cliffs. Due to the rapid development in Darwin Harbour, this study is fundamental in understanding coastal processes to support decision making in coastal management, particularly in a macro-tidal, tropical estuary.

Keywords: Darwin Harbour, macro-tidal, sand transport, coastal erosion, RMA

1. Introduction

Coastal erosion is a natural phenomenon. In fact, coast lines change continually, controlled by the interaction of the local hydrodynamics and their morphology. Coastal change is a longstanding problem that mankind has had to deal with to provide safety from flooding and to protect transportation infrastructure. Conventionally, coastal erosion is managed locally using hard engineering approaches, such as sea walls or breakwaters, which do not guarantee good outcomes and often create erosion in other areas [1, 2]. These consequences often stem from engineering decisions that only consider the immediately affected area, underestimating the processes that are occurring in the wider coastal zone.



The coastal zone is composed of diverse complex environments, shaped by coastal processes, coastal geology, variations in coastline characteristics and coastal sediment budgets [3]. A more technically and environmentally satisfactory coastal engineering design should include each element and its interaction, incorporating how they affect the whole system [1]. Coastal processes relate to physical processes such as tides, waves, currents and winds that act upon and shape the coastline, while coastal geology determines the origin, structure and characteristics of the sediments that make up the coastal region. Considering that coastal erosion essentially indicates an imbalance in the sediment supply and removal in the area, an ideal way to deal with the problem is to study the complete cycle of sedimentation in a theoretically confined coastal area called a sediment/coastal cell [3]. The boundaries of a sediment cell can be marked by features such as headlands, submarine canyons or river mouths, where the sources, transport paths and sinks of sediment occur.

The sources of coastal sediment can be examined by means of provenance indicators using mineralogical or geochemical properties. Among a number of suitable indicators of provenance, carbonate minerals and rare earth elements (REEs) are often used. In coastal sediments, carbonate mineral constituents, such as calcite and aragonite, can be used to distinguish whether a sediment is of marine or of terrestrial origin [4]. REEs are excellent in determining sediment sources because the ratios of individual REE are not easily fractionated during transport and show consistent behaviour during weathering [5].

This study examines the coastal processes in Darwin Harbour, a macrotidal estuary situated in cyclone prone tropical northern Australia. The semi-diurnal tides record the highest astronomical tide at 8 m and the smallest low tide at 0.3 m with a mean range of 3.7 m [6, 7]. A large embayment, Darwin Harbour covers the area from Charles Point in the west to Gunn Point in the east with Blackmore, Elizabeth and Howard Rivers, the major streams that flow into the harbour. Presently coastal cells have not been defined in Darwin Harbour, therefore this study was carried out within two prominent headlands of the harbour i.e. Charles Point in the west and Lee Point in the east (Figure 1).

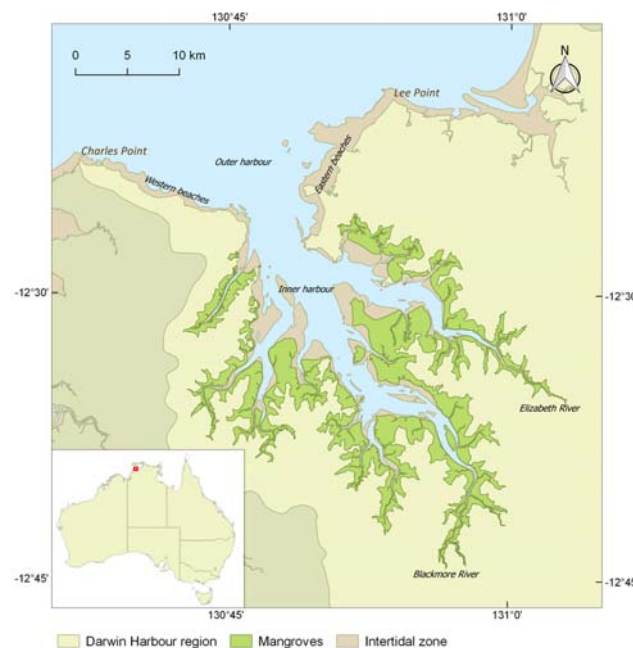


Figure 1. Darwin Harbour, the study area.

The western part of Darwin Harbour consists of mainly rocky shore platforms interspersed by sandy pocket beaches. The eastern part of Darwin Harbour comprises longer stretches of sandy beach and less extensive rock flats. The beaches are backed by either coastal cliffs or sand dunes. Mangrove forests border the intertidal areas of the inner harbour and to a lesser extent on the west and east beach areas.

Similar to other areas in the world, coastal problems encountered in Darwin Harbour arise from mixed uses of the area and conflicting concerns among the stakeholders. Previous coastal erosion studies mainly focused on the eastern part of the harbour. The studies documented coastal cliff erosion rates averaging 30 cm y^{-1} [8], while the sandy beaches experience seasonal changes in both climatic and oceanographic events [9]. Visual observation at several sites and anecdotal information indicates that the eastern beach dunes and the western beaches have also experienced substantial erosion in recent decades. Sand dynamic studies were carried out on relatively small areas in the harbour for specific purposes, e.g. shipping channels development work. Despite long term beach erosion, no study on sand dynamics, incorporating coastal processes, has been carried out for Darwin Harbour. This study is an attempt to make a start at filling this gap, and aims to contribute to understanding the role of coastal processes occurring in the area, i.e. to determine the sand pathways in the harbour, to infer the sources of beach sand, and thereby assist with coastal management in Darwin Harbour. Two potential sand sources are investigated: the inflow from offshore and the contribution of Elizabeth and Blackmore Rivers, while the potential sand sinks are the western and eastern beaches of the harbour.

2. Methods

A 2-D depth-averaged hydrodynamic (RMA-2) and sand transport modelling (RMA-11) software package from Resource Modelling Associates [10, 11] was used to simulate the hydrodynamics of the study area and to infer the sources and sinks of sand in Darwin Harbour. The simulations were run on the calibrated and validated Darwin Harbour modelling-mesh constructed by the Australian Institute of Marine Science (AIMS) based on 2012 bathymetry. Numerous surveys of tidal currents profiling by AIMS have confirmed that a 2D modelling method is valid for Darwin Harbour hydrodynamic simulations, i.e. the vertical profiles of currents are of similar magnitude and direction during the tidal cycle. In multiple AIMS projects it was also proven that the computation of bed shear gives similar values compared to a 3D model.

The model mesh consists of 10,227 elements and 21,219 nodes. The cell sizes range from 20 m² at the wharf area to 3,000 m² 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 results from the RMA-2 hydrodynamic simulations were used as the input to simulate sand transport pathways in the harbour with RMA-11. The fine, medium and coarse sand transport were simulated using the sand transport potential method based on Van Rijn's 1984 computation, which is most suitable 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 simulate the transport pathways in the harbour, 5 mg L⁻¹ of sand was introduced from the network boundaries with no initial bed thickness in the harbour. The sand transport pathways were inferred by the bed level changes in the modelling area. Positive bed change indicates sand deposition, which shows the sand sink areas, therefore, any positive bed change in the model domain can be inferred as the sand direction from the source to the sink area. In order to distinguish between offshore and terrestrial sources area, offshore and river sand simulations were run separately. River sand simulations were carried out from Elizabeth and Blackmore Rivers (Figure. 1).

The sediment transport pathways were also inferred using the Calcium Carbonate concentration and the REE composition of the sand samples. The CaCO₃ concentration was determined using cold acid digestion, while REE compositions were determined using a semi-quantitative ICP-MS method [5].

3. Results and Discussion

The sand transport pathways analysis is discussed based on the beach areas depicted in Figure 2.

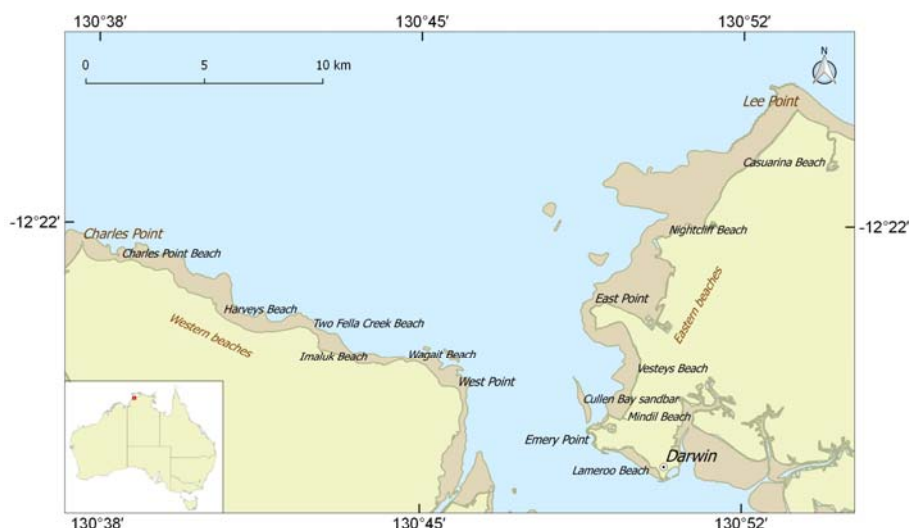


Figure 2. Beach area under study in Darwin Harbour.

3.1. Sand pathways from offshore

The simulation results showed that offshore sand deposited predominantly on the northern parts of the western and eastern beaches and decreased further into the harbour (Figure 3). The extent of deposition was governed by beach morphology, more deposition occurred in embayment areas, particularly on the lee side of the headlands due to the sheltering effect of the headlands [12]. This trend was very apparent in the western beach areas, on the lee side of Charles Point (node 99). The deposition level at this point was significantly higher compared to other beach areas. Apart from the deposition at this node, the long term deposition of offshore sand at the western and eastern beaches showed an analogous trend (Figure 4), inferring similar pathway patterns of offshore sand to the beach area.

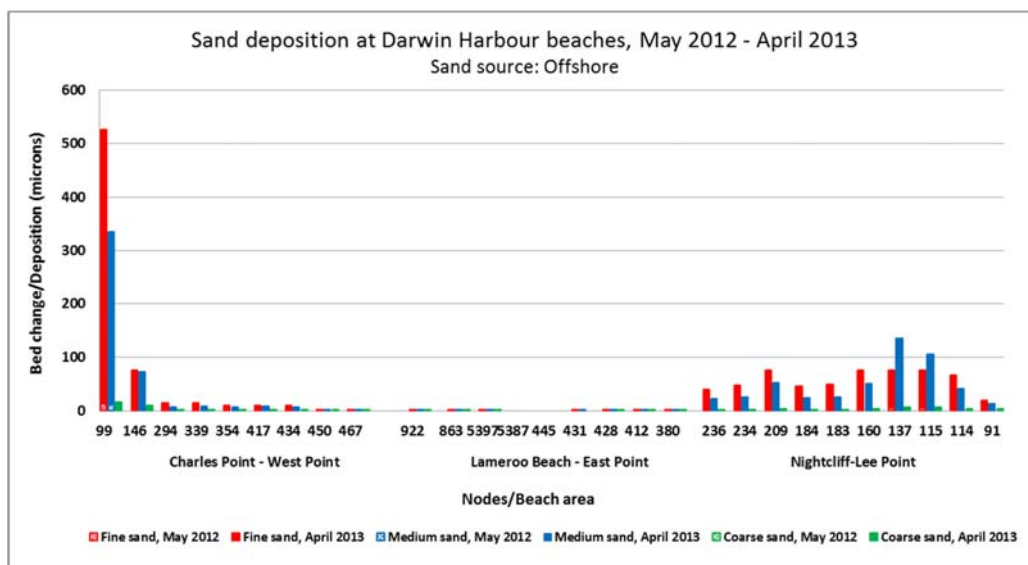


Figure 3. Offshore sand deposition on Darwin Harbour beaches.

As indicated in Figure 4, offshore sand deposition at the beaches in the eastern part of the harbour, between Lameroo Beach and East Point, was substantially lower than at the northern beaches, suggesting that East Point headland, Cullen Bay sandbar and Emery Point prevent the offshore sand from being transported to the area.

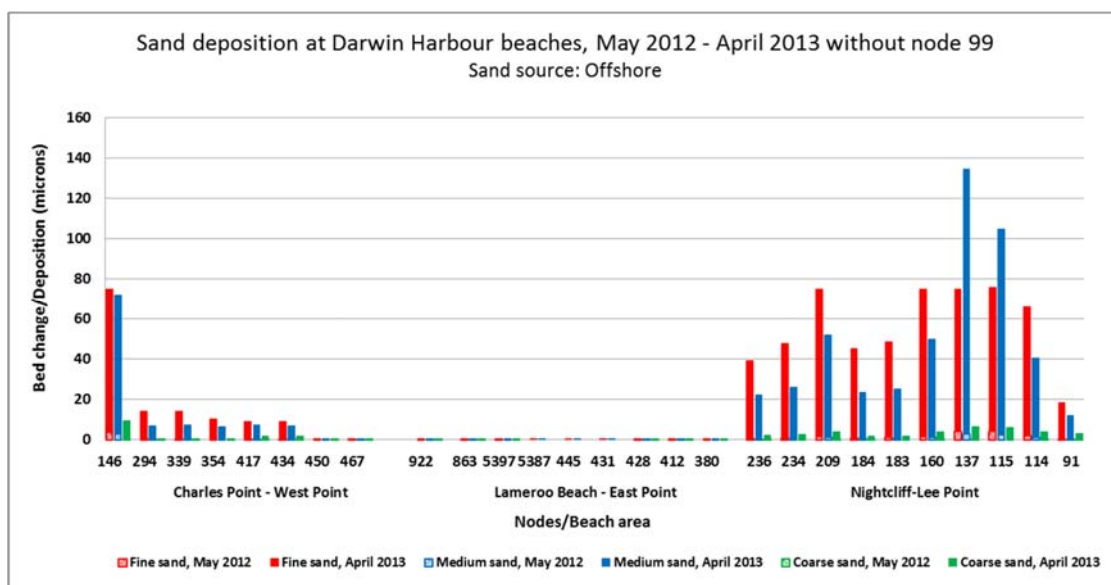


Figure 4. Offshore sand deposition on Darwin Harbour beaches excluding node 99.

3.2. Sand pathways from Rivers

The sand transport simulations showed that the contribution of river sand to the beaches in Darwin Harbour was significantly lower than offshore sand. Albeit of very small quantity, river sand deposited mostly in the embayment facing the inner harbour (Lameroo Beach, Figure 5).

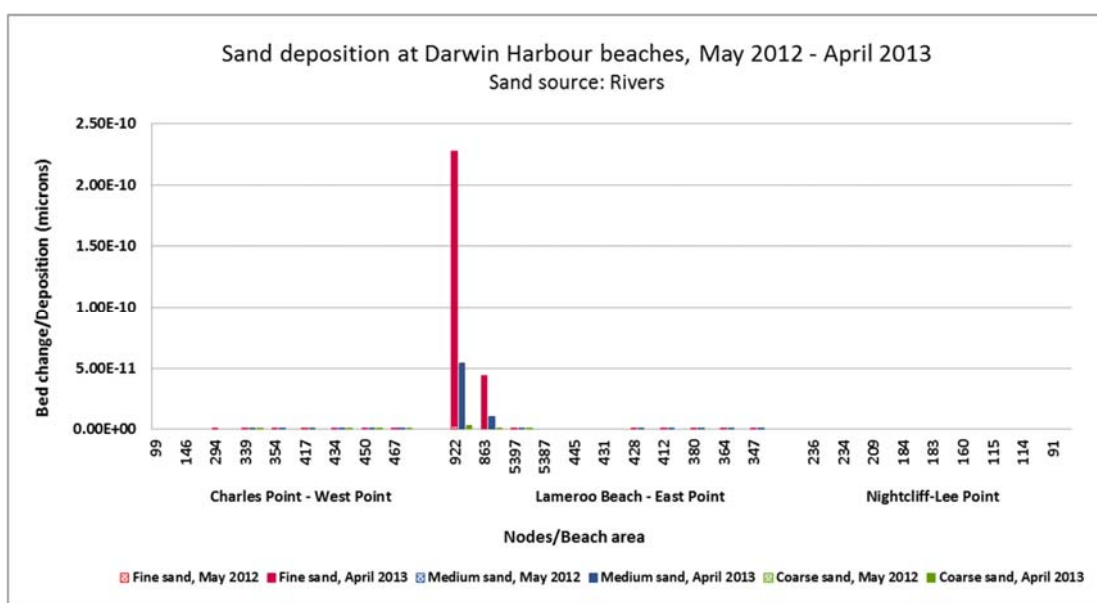


Figure 5. River sand deposition on Darwin Harbour beaches.

After passing Emery Point, the river sand was transported more to the western beaches rather than eastward, confirming that Cullen Bay sandbar and East Point constrain the sand transport pathways eastward (Figure 6).

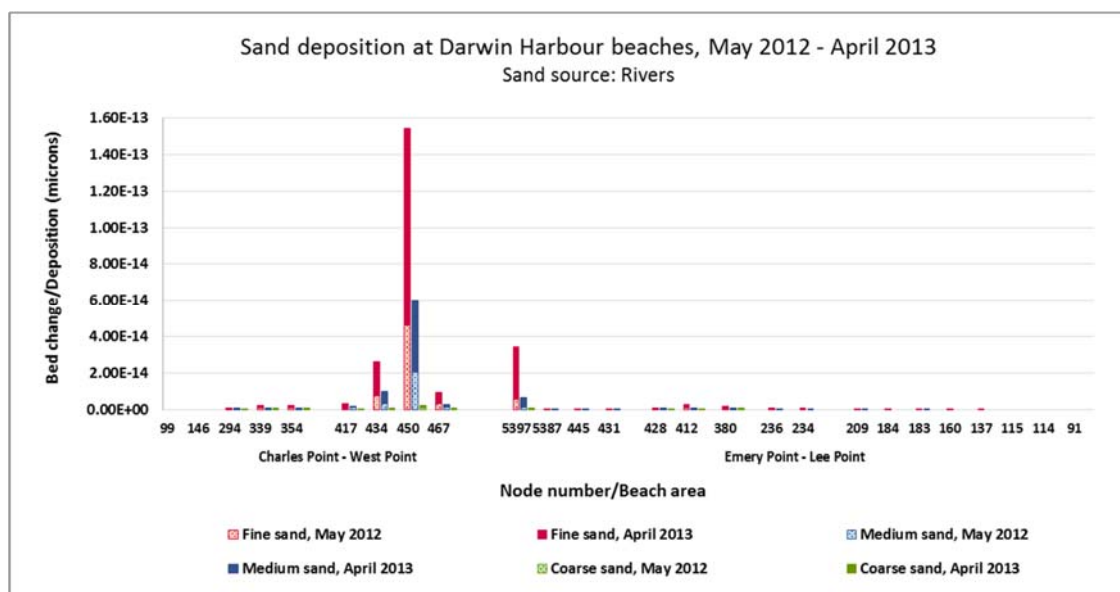


Figure 6. River sand deposition at Darwin Harbour beaches.

This minor contribution of sand from the rivers is likely due to the small drainage basin areas and consequently small river inflows into the harbour. One important characteristic of Darwin Harbour is the small catchment area relative to the waterways, i.e. about 3:1, which is smaller than other Australian harbours, for example 14:1 for Moreton Bay in Queensland and 10:1 for Port Jackson/ Sydney Harbour [13]. Other factors could be the low erodibility of soils in the catchment area or the ability of the catchment area to retain sediment. The macro-tidal nature of Darwin Harbour also overcomes the ability of river inflow to extend far to the outer harbour. The maximum recorded cumulative catchment discharge into the harbour during floods was estimated to be about 1% of the peak spring tide discharge [14].

Notwithstanding the low contribution, the simulation results showed that the sand transport pathways from rivers in Darwin Harbour were initially inclined eastward in the inner harbour and turned westward after passing the ‘neck’ of the harbour. These pathways are obviously influenced by the current strength and directions, while the location of the rivers, which are on the east side of the harbour, is another important factor.

3.3. The provenance of beach sand

Based on sedimentary composition, sand on Darwin Harbour beaches appears to be a mix of marine and terrigenous sources, with CaCO_3 concentrations in the sand samples from eastern beaches substantially higher compared to the sand samples from the western beaches (Figure 7). The carbonate content in sand from the eastern beaches is likely derived from offshore sources, in-situ sources and reworked sediment within the harbour. There are scattered hard substrates in the harbour providing carbonate sand sources from marine organisms, e.g. corals, molluscs, echinoderms and foraminifera [15] that may contribute carbonate sand to the area. The majority of foraminifera biotopes located in the eastern part of Darwin Harbour contains foraminifera species typically found on the shallow continental shelf [6]. The fact that the local coral reefs are mostly located in the eastern part of the harbour (Lee Point and East Point), demonstrates that a more detailed study confirming the source of carbonate sand is necessary.

The low CaCO_3 concentration in the western beach samples shows a more terrestrial origin compared to offshore elements in the samples. Considering that the river contribution to beach sediment is relatively low, the signature may also be contributed by attrition of the local shore rock platforms, which occur extensively in the western beach area.

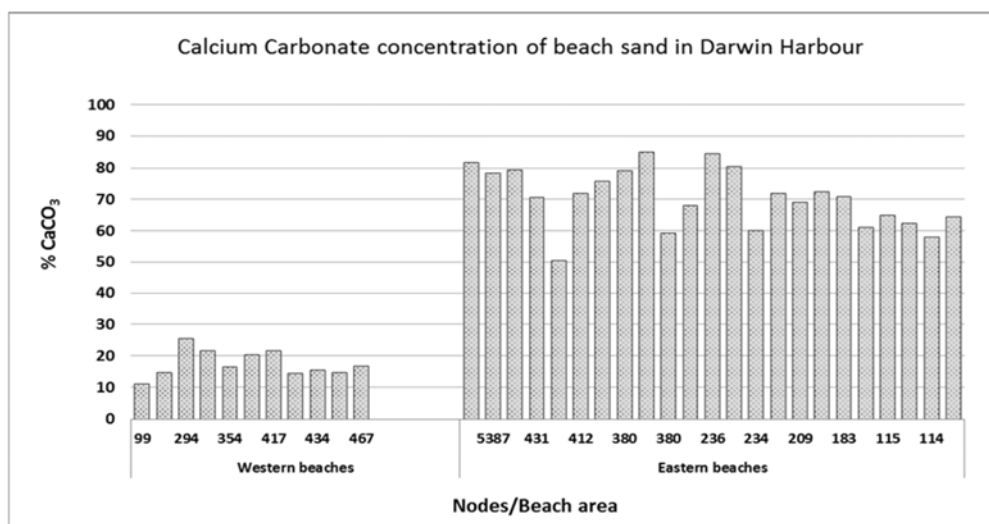


Figure 7. Calcium Carbonate concentration of beach sand samples in Darwin Harbour.

The REE composition of the beach sand samples, as depicted by a light- and heavy-REE bi-plot, shows that the eastern beach sand clusters closer to the outer harbour sand, while the western beach sand shows closer similarities with river sand (Figure 8).

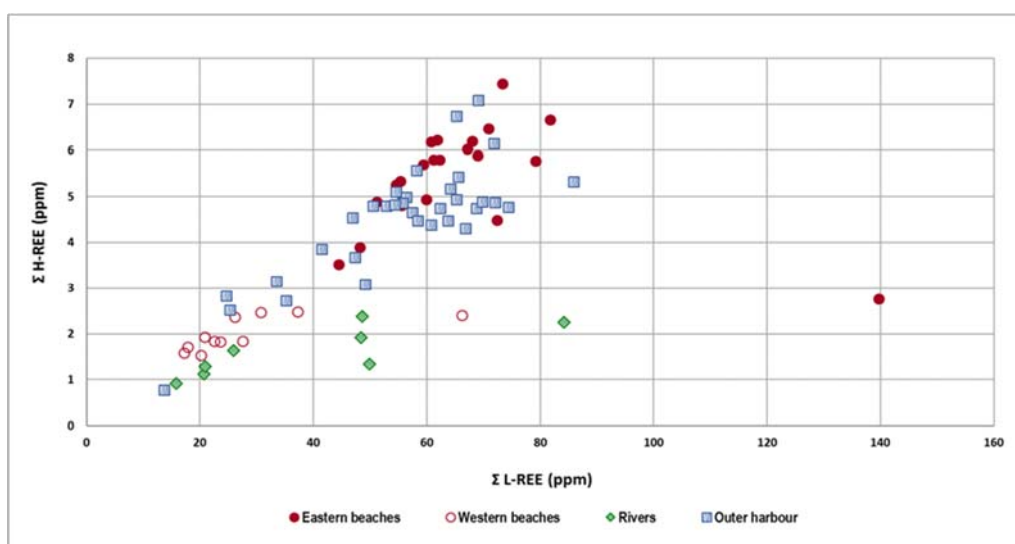


Figure 8. Light- versus Heavy-REE concentration of sand samples in Darwin Harbour.

With the assumption that outer harbour sand is largely of offshore origin, it is evident from Figure 8 that the sand in the east beach area indicates an offshore source, while the west beach sand shows a more river/terrestrial origin. Once again, as the sand transport simulations show that river input to beach sand

is low, the characteristics of the west sand may also be due to the contribution from the local bedrock formations.

Notwithstanding the high signature of an offshore sand source on the eastern beaches, considering the presence of eroding cliffs in the eastern part of Darwin Harbour [7], we cannot overlook the possibility that the rocky cliffs at the back of the beach are also a source of sand to the beach. Future study of the possibility of the rock flats and cliffs as sources of beach sand is necessary.

4. Conclusion

Two-dimensional hydrodynamic and sand transport simulations showed that beach sand in Darwin Harbour is mainly of offshore origin. On the other hand, the parallel geochemical analysis showed a slightly different pattern. The CaCO_3 concentration in beach sand suggests that the eastern beaches received substantially more offshore sand compared to the western beaches. Similarly, parallel Rare Earth Element analysis indicates a closer relationship between sand from eastern beaches and the outer harbour area. While the Rare Earth Element analysis shows that the western beach sand has more similarities with Elizabeth and Blackmore Rivers, a contribution from the local shore platform bedrock is possible.

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