Export of reef-derived sediments on Vabbinfaru reef platform, Maldives

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Abstract. The off-reef export of reef-derived sediments is an important component of the detrital sedimentary budget for a reef system and has implications for reef geomorphology and the development and maintenance of associated sedimentary deposits. The rate and magnitude of off-reef sand and gravel export was assessed experimentally using an array of sedimentation traps on Vabbinfaru reef platform, North Malé Atoll, Maldives. Sand and gravel collecting traps were attached to the fore-reef slope (at approximately 5 m depth) at 8 sites around the platform periphery over a period of 13 months. Texture of accumulated sediments was examined using settling velocity and fragment mass. Results show that off-reef export rates were high, reaching a maximum of 12.58 $kg.m^{-1}.y^{-1}$ for gravel-sized sediments and 122.84 $kg.m^{-1}.y^{-1}$ for sand-sized material. Sediment export was spatially and seasonally variable around the platform with lower rates of export recorded in areas of high wave exposure and vice versa. An estimated 127,120 kg of sediment is exported off-reef annually with sand-sized material accounting for 87% of total export. The absence of high intensity storm events at Vabbinfaru means the continual export of detrital sediment exerts a major control on reef geomorphology and sediment facies development.

Key words: sediment transport, export, Indian Ocean

Introduction

Coral reefs are highly productive systems that represent the end product of a variety of constructive and destructive processes. As reefs break down they shed large quantities of biogenic sediments. Detrital sediments are an important control on reef geomorphology as they contribute to the internal structure and net accretion of reefs, provide material for reef island development and maintenance, and contribute to lagoon infilling. However, reef systems typically produce greater amounts of sediment than can be accommodated internally and therefore excess material is redistributed and transported off-reef. The adverse impacts of excess sedimentation on reef ecological functioning are well documented (Rogers 1990), and therefore efficient transport of sediments is necessary for maintaining reef health (Fabricius 2005).

Previous studies of reef sedimentation have largely focused on the response of reef organisms to terrigenous sediments as a result of changes to land use practices (Ogston et al. 2004; Storlazzi et al. 2009), provided case studies of transport and deposition of sediment during high energy events (Hubbard 1992; Keen et al. 2004; Harris and Heap 2009), and examined the role of biologically-mediated processes in the transport of sediment (Bellwood 1995; Bellwood 1996; Goatley and Bellwood 2010). These studies have typically focused on reefs associated with high islands or near continental shores that yield terrigenous inputs, with few quantitative investigations generating direct estimates of sediment flux or transporting processes on mid-oceanic reefs.

Hughes (1999) provides a notable exception by conducting a long-term (4 year) quantitative assessment of the export of coral fragments on a fringing reef at Lizard Island, Great Barrier Reef. He showed that under non-storm conditions significant down-slope transport occurs and that the reworking of reef material can promote lateral reef growth by creating new substrate for recolonisation. However, Hughes (1999) focused solely on the export of coral fragments and neglected sand-sized material which, despite not actively prograding the reef structure, is an important component of the reef sedimentary budget.

This study provides a quantitative assessment of the off-reef sediment export at Vabbinfaru reef, a mid-oceanic atoll platform in the central Indian Ocean. Direct measurements of the rate and magnitude of sand-sized and gravel-sized sediment export is estimated for the platform periphery using an array of sedimentation traps. The textural characteristics of export sediments are examined based on sediment mass and settling velocity. The implications of these results relating to reef geomorphic development and the detrital sedimentary budget are discussed.

Study Site

This study was undertaken on Vabbinfaru reef (4° 18'N, 73°25'E), an elliptical-shaped platform in the southern region of North Malè Atoll, Maldives (Fig. 1). The total platform area is 323,000 m² and reef geomorphology is characterised by an outer live coral zone that encloses a shallow central lagoon (~1.17 m BMSL). The lagoon surface comprises bare sand, large rubble deposits (total area 78,000 m^2) and isolated stands of live coral. Reef sediments are comprised wholly of calcareous skeletal material from the surrounding reef ecology. The reef crest is higher in elevation (0.6 m – 1.5 m BMSL) and provides a distinct transition between sandy lagoon sediments and the rigid reef substrate. The reef crest is dominated by live coral framework (50% - 75% live cover). Sediments in the live coral zone comprise a mix of sand and gravel. The reef slope is steep and extends to the atoll basin floor at 40 m depth. The reef slope is characterised by sand deposits, dislodged reef material and sparse coral growth. A small (47,000 m^2), low-lying reef island (~1.2 m AMSL) is positioned at the eastern side of the platform.

The Maldives is positioned outside the storm belt and therefore does not experience high intensity storm events. Climate is controlled by the reversing Indian Monsoon. During the northeast monsoon, from December to March, Vabbinfaru platform experiences calm sea conditions (H_s = 0.11; T = 5.54), strong inter-atoll currents, and weak winds (0 - 6 $m^{-1}.s^{-1}$) from the northeast. From June to September the southwest monsoon brings high rainfall and periodic strong winds from the southwest (>10 $m^{-1}.s^{-1}$) and generates rough sea conditions (H_s = 0.21 m; T = 4.59).

Materials and methods

Annual rates of off-reef sand and gravel export were assessed using an array of sedimentation traps at eight locations around the periphery of Vabbinfaru. Sedimentation traps targeting sand-sized and gravel-sized sediments were attached adjacent to one another on the fore-reef slope at approximately 5 m water depth. Sand-sized export was examined using a series of modified rectangular PK traps (25 cm x 5 cm) fitted with a 100µ mesh bag to collect exported material. Sand traps were deployed for a period of three weeks in both northeast and southwest monsoons (February 2010, June 2010 and March 2011). After deployment, the traps were retrieved and the accumulated material was rinsed, dried and the aggregate weight of the sample was recorded. In the laboratory, fine material (> 4□) was removed by wet-sieving and a 15 g sub-sample was taken for textural analysis.

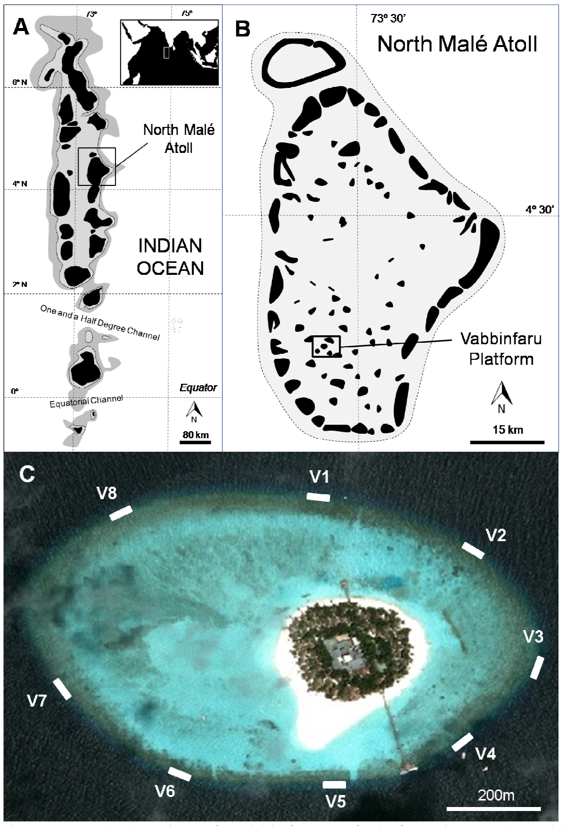

Figure 1: The location of Vabbinfaru reef platform in North Malé Atoll, Maldives. Squares indicate the arrangement of sedimentation traps at sites V1 – V 8 around the platform margin. Image: Google Earth (2012).

Off-reef gravel export was assessed using sedimentation traps constructed from galvanised steel mesh (1.5 cm diameter). Each trap opening had a diameter of 25 cm (490 cm^2 total trap area). Gravel traps were attached to the steep fore-reef slope which allowed sand-sized material to pass through the trap easily, capturing only coral rubble and preventing movement of fragments once inside. Traps were deployed for a period of 13 months before removal (February 2010 – March 2011). Accumulated sediment was collected by hand in June 2010 and immediately before removal of the trap in March 2011. Gravels retained in each trap were rinsed with freshwater, photographed, sun-dried and weighed. Sediment mass (g) was used as a proxy for sediment size due to irregularities in shape between fragments. Each coral fragment was weighed individually to determine the weight distribution of sediments at each site. The number of live coral specimens collected was recorded and calculated as a percentage of the total number of fragments.

A rate of sand and gravel export per metre of reef front ($kg.m^{-1}.y^{-1}$) was calculated for each trap location using the mass of sediment accumulation (kg), the width of the trap (m) and the interval of deployment period (d) (Hubbard 1986). Total platform export (kg.y^{-1}) was determined by extrapolating the rate of sand and gravel export at each location across the length of the reef perimeter (m) between consecutive trap locations and then summed to generate a total platform estimate.

Results

Rate and magnitude of off-reef sand export

Off-reef sediment transport varied between trapping locations and oscillating monsoon seasons on Vabbinfaru (Table 1). Annual rates of transport ranged between 6 kg.m^{-1}.y^{-1} and 123 kg.m^{-1}.y^{-1} between trapping locations. Maximum export was recorded at sites that were sheltered from prevailing wave exposure at the northern (V1 and V8) and southern (V5) platform margins (Table 1). More energetic regions on the western (V6 and V7) and eastern (V3) platform flanks had the lowest annual rates of sediment loss and were much lower than other locations. The remaining northeast and southeast sites (V2 and V4) exhibited moderate sediment export. Overall, total sand-sized export was estimated at 113,438 kg.y^{-1} across the entire reef perimeter, equating to an average of 52.2 kg per linear metre of reef front (Fig. 2).

Seasonal variability in sand export between northeast and southwest monsoons was observed. During the northeast monsoon, moderate amounts of sediments were collected at every trap location with an average (±SD) export rate of 25.2 ± 14.8 kg.m^{-1}.y^{-1} (Table 1). The southwest monsoon was characterised by much higher rates of export and greater variability between trapping sites (Table 1). Transport pathways were more clearly defined as several sites recorded no or very low sediment accumulation and others in close proximity recorded high rates. Maximum sediment loss was recorded at the northern and southern platform, and the lowest rates were recorded at the northeast and southwest (Table 1).

From the total 113,438 kg of annual sand export, it is estimated that 34,065 kg is transported under lower energy conditions during the northeast monsoon, compared to 79,336 kg in higher energy conditions during the southwest season (57% increase in the magnitude of sediment loss).

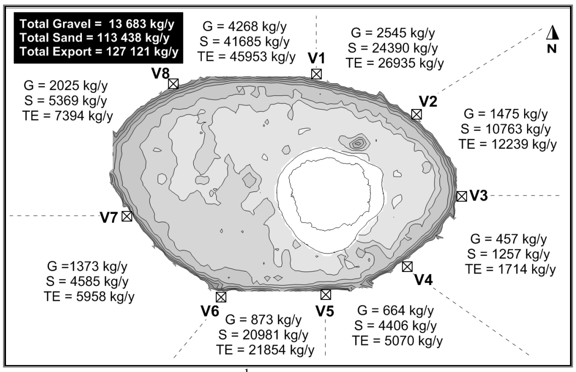

Figure 2: Magnitude (kg.y^{-1}) of sand (S), gravel (G) and total export (TE) for each section of reef on Vabbinfaru. Estimates are derived as a function of the rate of sediment export (kg.m^{-1}.y^{-1}) at each trap location scaled to the length of the reef perimeter (m). Grey lines represent reef bathymetry at 0.5 m intervals relative to MSL.

Texture of sand-sized sediments

The texture of export sand varied spatially and seasonally. Mean grain size ranged from 1.90□ (medium sand) to 3.09□ (very fine sand) during the northeast monsoon, and 1.68□ (medium sand) to 2.71□ (fine sand) during the southwest (Table 1). The grain size distribution of collected sand showed that >95% of sediments ranged between -0.25□ and 3.5□ (Fig. 3). The degree of sorting ranged from poorly sorted (1.04) to very well sorted (0.45) in the northeast season and from poorly sorted (1.41) to moderately sorted (0.77) during the southwest. It was difficult to make seasonal comparisons of sediment texture at individual trap locations due to insufficient quantities of sediment during the southwest monsoon. However, of the sites where adequate seasonal data was available (V1, V4, V5 and V8), three out of the four collected finer sediments in the northeast monsoon than during the southwest (Table 1).

Trapping Location	Reef Perimeter (m)	Off-Reef Sediment Export (Sand and Gravel)					Sediment Texture		
		NE Sand Export (kg m^{-1} y^{-1})	SW Sand Export (kg m^{-1} y^{-1})	Annual Sand Export (kg m^{-1} y^{-1})	Annual Gravel Export (kg m^{-1} y^{-1})	Total Sediment Export (S + G) (kg m^{-1} y^{-1})	NE MGS (□)	SW MGS (□)	Mean Gravel Mass (g)
V1	248	17.0	108.9	98.4	10.3	109	2.38	2	4.6
V2	237	36.4	0.0	45.5	6.2	52	2.4	-	-
V3	223	12.3	0.7	5.6	2.0	8	-	2.56	3.6
V4	193	18.8	18.0	22.8	3.4	26	2.46	2.45	4.9
V5	220	23.5	102.2	95.4	4.0	99	3.09	2.77	7.5
V6	327	27.3	3.4	14.0	4.2	18	2.63	-	8.2
V7	399	10.8	0.0	13.5	5.1	19	1.9	-	4.3
V8	339	55.9	119.0	122.8	12.6	135	2.08	1.68	15.4

Table 1. Sediment export rate and texture on Vabbinfaru

Export of gravel-sized material

Off-reef gravel export ranged from 3.4 kg.m^{-1}.y^{-1} to 12.5 kg.m^{-1}.y^{-1} between trap locations. Maximum gravel loss occurred at the northern platform margin (V1 and V8), where export measured 10.2 kg.m^{-1}.y^{-1} and 12.5 kg.m^{-1}.y^{-1} (Table 1) respectively. Collectively, these two locations accounted for 50% (6,813 kg) of total gravel export. The remaining trapping locations recorded lower rates of sediment loss (Table 1). Total gravel-sized export was 87% lower than sand-sized material collected in adjacent traps. Gravel export around the reef platform perimeter was estimated at 13,683 kg per annum, equating to an average (±SD) of 6 ± 3.6 kg per linear metre of reef front each year. The number of coral fragments collected varied between 335 fragments m^{-1}.y^{-1} and 1744 fragments m^{-1}.y^{-1}, with an average of rate of 844 fragments per metre of reef.

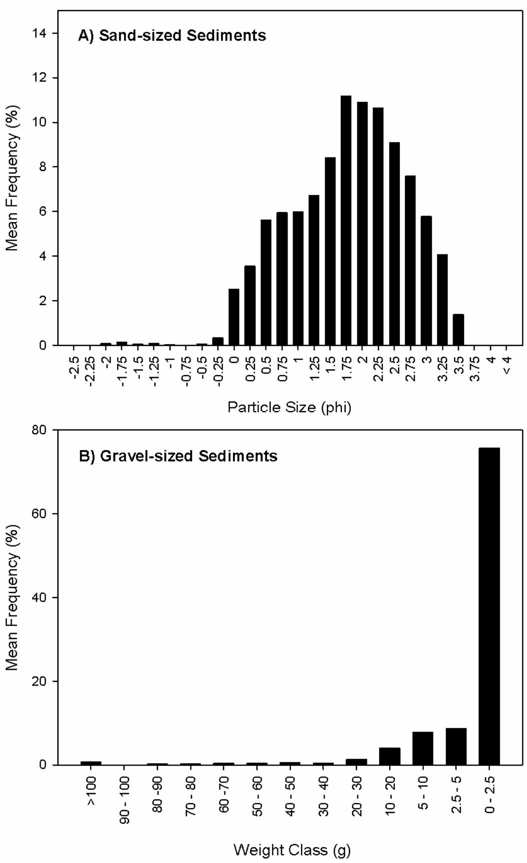

Figure 3: Mean grain size distribution of export material from reef sites V1 – V8 on Vabbinfaru. (A) sand-sized export material, (B) gravel-sized export material.

Weight distribution of gravel-sized sediments

A total of 1701 gravel fragments were collected during the experimental period. Gravel size and shape varied extensively from small shell fragments to large sections of reef substrate. The majority of sediment was unidentifiable due to its size and extensive erosion. Live coral comprised < 1% of total fragments with the maximum values recorded at sites V7 and V8. Small gravel fragments were dominant at every trap location. Sediments weighing less than 2.5 g comprised 75% of the total gravel collected, and sediments less than 10 g comprised 92% of all gravel (Fig. 3). The largest clast exported was a digitate *Acropora* colony weighing 792 g. Collectively, the proportion of gravels weighing over 100 g comprised less than 1% of all gravel exported. The weight distribution of gravel material was relatively consistent between locations, however, northwest (V8) and southwest (V6) sites had greater proportions of larger gravel material (Fig. 3). Large material was absent at the northern platform (V1).

Discussion

Sand export at Vabbinfaru was high (113,438 kg.m^{-1}.y^{-1}), ranging from 6 kg.m^{-1}.y^{-1} to 123 kg.m^{-1}.y^{-1} with a mean annual export rate of 52.2 kg per metre of reef front. Rates of sediment loss measured in this study are comparable to other reef settings during non-storm conditions. Hubbard et al. (1981) recorded sediment transport rates of between 14 kg.m^{-1}.y^{-1} and 151 kg.m^{-1}.y^{-1} on an open-shelf reef at Cane Bay, St. Croix, while Hubbard et al. (1976) estimated sediment export of 100 kg.m^{-1}.y^{-1} to 120 kg.m^{-1}.y^{-1} through sand chutes along the southern edge of Little Bahama Bank.

Sand export was spatially and seasonally variable around the platform with lower export rates in areas with greater wave exposure and vice versa. Increases in sediment export under high energy conditions are well documented in reef systems (Hubbard et al. 1981). As wave height increases so too does the efficiency of oscillatory wave motion and wave-induced currents to entrain and mobilise sediments (Komar and Millar 1973). During the more energetic southwest monsoon physical processes appear dominant on Vabbinfaru and there is an increase in the magnitude of export. Greater platform circulation, as a result of increased incident wave energy, is likely to drive sediments onshore at the seaward reef edge and generate lagoon currents that move sediment off the leeward reef margin (north and south), subsequently increasing export in these areas. Conversely, during the northeast monsoon when wave energy is low, export rates are also lower and more consistent between platform areas. At this time gravitational settling and biologically-mediated transport processes become more important.

Large volumes of sediment loss can occur through biologically-mediated transport, a process that is likely to work independent of season. Bellwood

(1995) showed that large parrotfish species can export up to 10 kg of sand per metre of reef front at North Reef, Lizard Island, Great Barrier Reef. New studies have also indicated that surgeonfish are also capable of transporting sediment off-reef through the ingestion and defecation of reef material. Goatley and Bellwood (2010) estimated that the mass of sediment removed per individual large surgeonfish is comparable to that of parrotfish with 36.5% of sediment ingested at the upper reef crest transported into deeper water. If these general rates are applied to Vabbinfaru, transport from fish assemblages represents a first-order estimate of 43,720 kg.m^{-1}.y^{-1} and a significant component of the sedimentary budget during low energy conditions (accounting for up to 38% of total sand export).

Total export of gravel sediments was conservatively estimated at 13, 683 kg per annum, as logistics associated with trap size limited the upper dimensions of material that could be collected and excluded large sections of reef rock or coral framework. The majority of existing studies have focused on the transport of coral rubble under episodic extreme events (Hubbard 1992; Harris and Heap 2009); however, considerable amounts of export can occur under non-storm conditions. Hughes (1999) estimated the average export of coral fragments as 2 kg per metre of reef front under non-storm conditions on a shallow fringing reef at Lizard Island, Great Barrier Reef. Gravel export in this study had a higher average rate (±SD) of 6 ± 3.6 kg per metre of reef front. In the absence of large storms (e.g. hurricanes), the continual transfer of large reefal material is important to reef development as it can prograde the reef structure and provide new substrate for coral settlement and growth in areas typically dominated by sand (Hughes, 1999).

Total platform export of reef-derived sediments (sand and gravel) on Vabbinfaru was estimated at 127,121 kg per year, equating to an average of 103.5 kg of sediment per linear metre of reef front. If such rates of off-reef sediment export were quasi-continuous over the next decade this would account for a significant loss of material from the detrital sediment budget. Furthermore, Vabbinfaru represents a single platform reef within North Malé atoll. If similar rates of detrital sediment export were to apply to other reefs in the atoll then the cumulative export of reef-derived sediments is likely to have significant implications for the development of the atoll basin over geological time-scales.

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