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SEDIMENT FALLOUT RATES IN TANJUNG RHU CORAL REEFS

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This study was conducted in Tanjung Rhu, Pulau Langkawi, which is located in the northwest of Peninsular Malaysia. The objective of this study was to measure and compare the sediment fallout rates of Teluk Dedap in Tanjung Rhu with its control site in Teluk Datai during the wet and dry seasons to shed light on the sedimentation problem faced by the coral reefs of north Pulau Langkawi. Sediment fallouts were collected from the spring tidal periods of both the wet and dry seasons. Results showed that sediment fallout rates in Tanjung Rhu were 1,403.48 ± 125.60 g/m^2/day (dry season) and 6,550.77 ± 641.43 g/m^2/day (wet season). In Teluk Datai the sediment fallout rates were 1,532.99 ± 201.81 g/m^2/day (dry season) and 12,446.45 ± 237.81 g/m2/day (wet season). Sediment fallout rate is typically lower during the dry season compared to the wet season, and it is lower on the reef flats than the reef slopes. Paired sample t-tests revealed that there were significant differences in the sediment fallout on the reef flats and reef slopes. Sediment fallout was significantly higher on the reef flat than the reef slopes for both sampling locations during both the dry and wet seasons. However, based on a single-factor ANOVA (p = 0.05), no significant difference was observed between the overall sediment fallout and fallout rates between the two sampling locations during the dry and wet seasons. Microscopic analysis was also performed to examine the possible composition of the analysed sediment fractions. Results showed that the main components of the coarser sediment fractions were biogenic materials and lithified sediments, while for the finer sediment fractions, the main components were feldspar and siliceous and quartz materials.

Keywords: sediment fallout, coral reef, coastal zone, dry season, wet season

INTRODUCTION

Erosion of upland soils is a major problem around the world (Brown, 1984; Brown and Wolf, 1984; Pimentel et al., 1987). Approximately 50% of this detached soil reaches a waterway, where it adversely affects water quality (Robinson, 1971), aquatic productivity (Cooper, 1986), wildlife habitats (Ritchie, 1972) and other components of aquatic ecosystem structure and function. Sedimentation is an explanation for the absence or paucity of coral reefs, especially in South and East Asia, Indonesia and Melanesia, where rivers deliver 70% of the global sediment transported to the oceans (e.g., Ganges-Brahmaputra: 1670 million tonnes/year; Yangtze/Chan Jiang: 480 million tonnes/year; Irrawaddy: 265 million tonnes/year; Mekong: 160 million tonnes/year; Taiwan rivers: 185 million tonnes/year; Purari and Fly in Papua New Guinea: 110 million tonnes/year) (Milliman and Meade, 1983). Settled particles may be resuspended several times before their final burial in bottom sediments.

Sediment particles are classified in two different ways—by source and by size. The size of particles determines how far they can be transported by moving water or air. Small grains such as clays can reach the middle of the ocean in very slow currents, while pebbles can be moved only by fast moving rivers or waves on beaches. In general, larger particles are deposited close to land, while the smallest particles dominate sediments in the open ocean.

When classified by source, sediment particles are divided into lithogenous or terrigenous, biogenous, hydrogenous, volcanic and cosmogenous particles. The names of these particles indicate their origins. By size, sediment particles are classified into seven categories based on the Wentworth Scale. Particle size is an important property of sediments because it determines the mode of transport and also determines how far particles travel before settling to the bottom. How well sorted the sediments are in the environment depends greatly on the wave and current actions. A well-sorted sediment is one in which a limited size range of particles occurs; the other-sized particles have been removed, usually by mechanical means such as waves and currents. Beach sand is a typical well-sorted sediment, in which particles have been segregated by size. Poorly sorted sediments contain particles of many sizes, usually indicating that little mechanical energy has been exerted to sort the different particle sizes.

Sediments are usually defined as solid particles of particulate organic or inorganic matter accumulated in a loose, unconsolidated form that fall under gravity to the lowest point possible. Sediments also include the finer particles that remain in suspension in a water column, which are normally termed suspended particulates or suspended solids.

The major contributor to sedimentation is resuspension, which on reefs is caused by the wave and current forces acting on sediment particles, lifting them off the bottom. Such natural sedimentation is tolerated by the reef corals. Basically, the sediment fallout on a coral reef can arise naturally from the resuspension of the bioeroded skeletal remains of reef organisms, which are then transported by water movement to living corals elsewhere on the reef. The sediment naturally produced in the reef system consists predominantly of organic carbonates, which are known as bioclastics (Randall and Birkeland, 1978). Because these sediments are continually produced, the organisms associated with reefs are generally well adapted to the long term patterns of production and distribution.

Also contributing to the sedimentation affecting reefs is allochtonous sedimentation, especially from terrigenous processes, such as the physical and chemical breakdown of soils and soil erosion. These sediments consist largely of non-calcareous clay, silt and organic detritus. The sediment derived from terrestrial sources is not uniform in quality, quantity and time. Generally, the sediment is concentrated around river mouths and is transported in the form of pulses associated with periods of heavy rainfall. The distance transported depends on the strength and continuity of local ocean currents. Fine particles, particularly clay, tend to remain in suspension longest and are transported furthest due to their low settling velocity. The degree of mixing of the river water in the sea will affect the concentration of suspended sediments, which is dependent on sea conditions and therefore weather. This suspended sediment gradually falling out of suspension may be considered true "sedimentation" as opposed to "sediment fallout", which includes re-suspended bioclastics. The suspended fine terrestrial sediments cause the water to be turbid, reducing visibility and light penetration.

Human activities can lead to significant sedimentation, which can be harmful to reefs. Activities that generate sediment include coastal development from land reclamation, marina construction, golf course development, shrimp farm development, airport construction, tourist resort construction and coastal road construction (Yasin, 1993).

The chosen study area was Tanjung Rhu (Tanjung = Cape, Rhu = Casuarina), located in the northeast of Pulau Langkawi (Pulau = Island) in Peninsular Malaysia. Pulau Langkawi is located between the latitudes of 6° 10'N–6° 30'N and 99° 35'E–100° 00'E on the northwestern coast of Peninsular Malaysia. A control site, Teluk Datai, was chosen for the purposes of this study, and it is located in the northwest of Pulau Langkawi. Teluk Datai is the preferred control site for this study because it provides similar natural habitats to those found in Tanjung Rhu. Locations of the study area and the control site are shown in Figure

1. The differences between the two sites lie in the riverine-estuarine network, which does not exist in Teluk Datai. Development of Teluk Datai stopped in 1994. The natural environment of Teluk Datai is well maintained and is considered pristine.

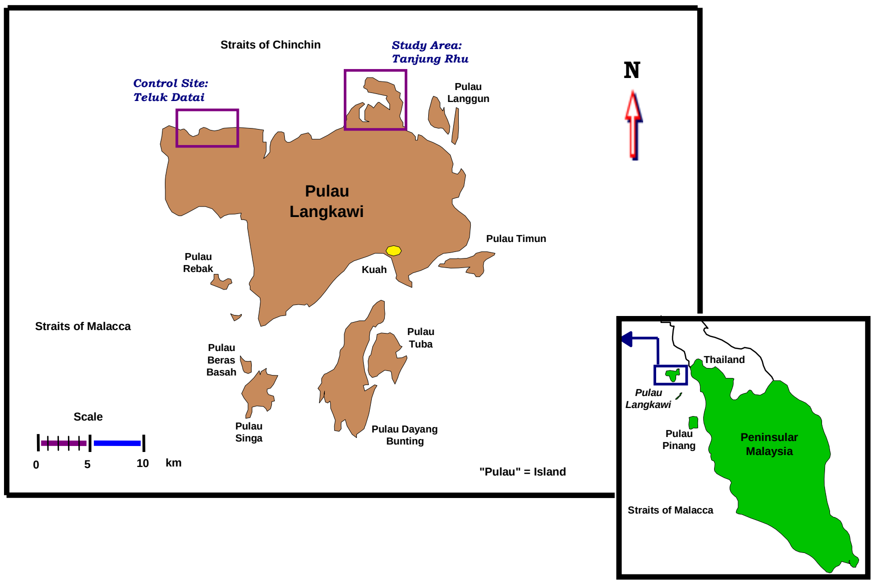

Figure 1: Location of the study area and control site in Pulau Langkawi, Peninsular Malaysia

Pulau Langkawi was declared a free port in January 1987. Since then, development on the island has proceeded rapidly. During this period, there has been a gradual increase in the development of infrastructure for the tourism industry. Initially, this development was concentrated in Kuah, the largest town in Pulau Langkawi, located in the southeast of the island. Later development spread to the beaches of Pantai Chenang on the west. This latter development is meant to support the tourism industry by relying on the natural beauty of the coastline. Beachfront properties at Pantai Chenang were soon occupied, and development proceeded to other areas such as the northwest coast of Pulau Langkawi (Lee, 1994). At present, one of the new sites for development is on the northeast coast of Langkawi. This is the study area.

Tanjung Rhu is relatively undisturbed, although there are some small scale developments within the region. Its relatively pristine condition renders it a suitable area for this study. There are a number of natural habitats within this relatively small study area, including coral reefs, mangrove forest, mudflats, sandflats and an estuarine-riverine system. These habitats, particularly the coral reefs, are complex ecosystems with high biological diversity that occur in shallow waters throughout the tropics. Their proximity to the coast exposes coral reefs not only to subsidence pressures but also to other human-induced (anthropogenic) stresses such as pollution (industrial, chemical and sewage) and sedimentation (land clearing, reclamation and mining).

The objective of this study is to measure and compare the sediment fallout rates of Teluk Dedap in Tanjung Rhu with its control site in Teluk Datai during the wet and dry seasons. We believe that this study provides insight into the sedimentation problem faced by the coral reefs of north Langkawi.

METHODOLOGY

Sediment Trap Design

A survey of the literature revealed that there is no standard method for collecting sediment particles in a coral reef environment (Gardner, 1977; Newman, 1984). Methods used to date have generally shown a high loss of sample (Randall and Birkeland, 1978) and a very high variability between traps within a group (Liew and Hoare, 1979).

Laboratory experiments conducted by Gardner (1977) and Lorenzen, Schuman and Bennett (1981) on the design of sediment traps revealed that the basic design used should have a minimum aperture-to-length ratio of 1:3 to prevent resuspension and eventual loss of material from the trap.

The rate of sediment fallout is proportional to the area of the base of the trap, therefore a trap should be cylindrical in design, although the absolute size can vary. A trap too large would be unmanageable and hard to place, while one too narrow may present serious fouling problems. The narrow tubes used by Randall and Birkeland (1978) were often inhabited by fish, which kept all the tubes clean. This can be overcome by using a grill or wire mesh to block animal entry.

Two other factors required consideration in designing the traps for this study. First, traps must be heavy to provide stability so that they will not be affected, moved or swept away by the strong currents within the coastal region of Tanjung Rhu. Because the reef area of Tanjung Rhu and its control site, Teluk Datai, are subjected to open ocean currents, a heavy sediment trap base is preferable. The second important factor is the sediment fallout sample collection container. It needs to be secured to the heavy base of the trap so that the swift strong currents will not wash it ashore or into the ocean. At the same time, the container should be easily removed from the trap during the course of the sampling period.

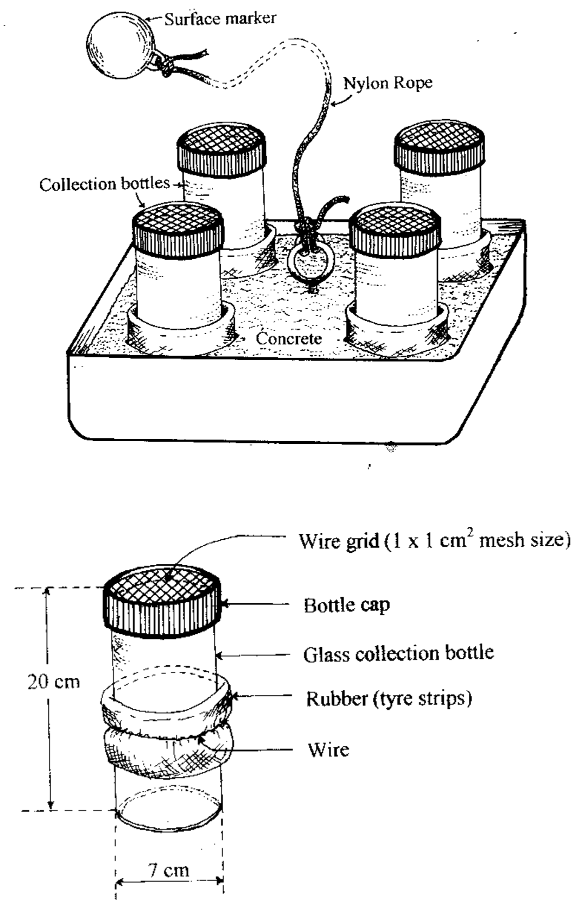

Figure 2: Sediment trap
Source: Adapted from English, Wilkinson and Baker (1997)

Based on previous experiments [e.g., Randall and Birkeland (1978), Lorenzen, Schuman and Bennett (1981)] and the requirements of the study area, a final design was chosen, which incorporated the various recommendations for a good and reliable sediment trap described above. The sediment trap based on the one described by English, Wilkinson and Baker (1997) was redesigned by the author and constructed with help from members of the Reef Research Group (Universiti Sains Malaysia). The design is shown in Figure 2. The trap consisted of a concrete base made from a cement and sand mixture to contain four collection bottles. Each collection bottle was made of glass and had an internal diameter of 7.2 cm and surface area of 41.87 cm^2. The height of the bottle was 20.0 cm. The inner circle of the bottle plastic cap was cut out, and a 1-cm-size wire mesh was fitted to it. The mesh was used to prevent large molluscs and fish from entering the collection bottles. Unused inner tyre tubes were cut into strips to be wrapped around each collection bottle and secured with copper wire. This was done to ensure that the collection bottles stayed intact and in place within the sediment trap.

The total height of the sediment trap (concrete base plus collection bottles) was approximately 30 cm. This allowed the traps to be placed among the coral heads or on the seabed with the top no higher than the upper edge of the coral heads. This was thought to provide satisfactory results in terms of collecting resuspended sediments and sediment fallout.

Design of Sediment Sampling Program

Based on the topography of the reefs of Tanjung Rhu (Teluk Dedap) and its control site in Teluk Datai, two zones were selected for sediment trap placement: reef flat and reef slope. Ideally, there should be three zones, for example, reef flat, upper reef slope and lower reef slope, which would allow a more comprehensive comparison. However, because the reef slopes within the study area (Teluk Dedap) were not steep but rather shallow and gradual, only two zones were considered. Although the reef slopes at the control site (Teluk Datai) were a little steeper, only two zones were selected to provide uniformity for data comparison at later stages.

The locations of the sediment traps in Teluk Dedap and Teluk Datai are shown in Figures 3 and 4, respectively.

The sediment traps were placed at their respective locations during low water spring tides, and collections were made in the following low water spring tides. Two replicates of the tidal cycles were performed for the dry and wet seasons at both sampling sites of Teluk Dedap and Teluk Datai. The rationale behind the low water spring tidal condition chosen for this sampling was that highest sediment fallout was expected to occur during these times as compared to the neap tidal conditions. Lesser sediment fallout is expected during neap tides, and therefore it may not portray any greater sediment fallout scenario experienced by the reefs.

Samplings were performed during the dry and wet seasons. The dry season sampling was performed on 2–19 February 1999 for Teluk Dedap (17 days) and 3–19 February 1999 for Teluk Datai (16 days); the wet season sampling was performed on 10–24 July 1999 for Teluk Dedap (14 days) and 11–25 July 1999 for Teluk Datai (14 days). The tidal range was 2.9 m during the wet season and 3.1 m for the dry season.

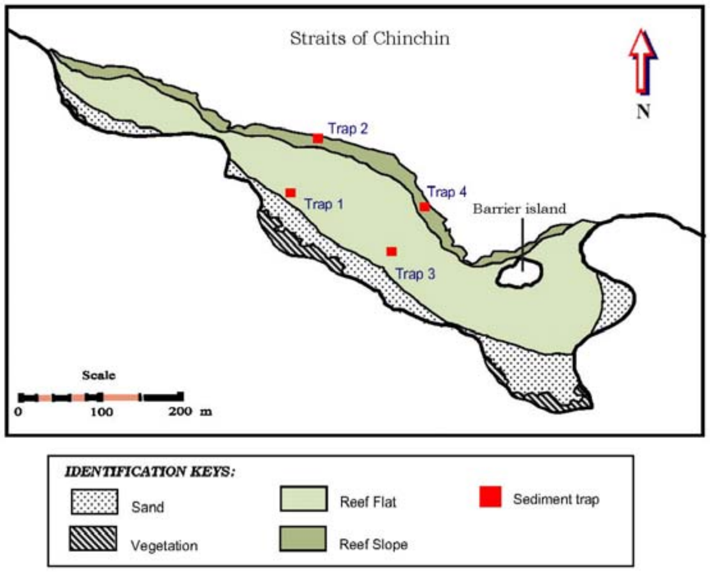

Figure 3: Location of sediment traps in Teluk Dedap, Tanjung Rhu

Sediment Analysis
Particle Size Analysis (Wet Sieving Method)

The sediments collected were returned to the laboratory and emptied into glass beakers. The beakers were then filled with fresh water, and fine material was decanted off into a second beaker and allowed to settle. The clear water was siphoned off and replaced with fresh water in both beakers. This process was performed a minimum of three times to remove salts, until most of the fine material was separated.

The fine material was then wet-sieved through a 63-µm sieve to separate the silt/clay particles. The washings were retained and allowed to settle, and the clear water was siphoned off. The coarser sediment remaining in the sieve was added to the beaker of coarse sediment, and both beakers were dried in the oven at 105°C until they reached a constant weight. It was necessary to remove the fine material before oven drying as, otherwise, due to the high proportion of clay, the sediment formed concretions when dried and could not be sieved for particle size and further analysis.

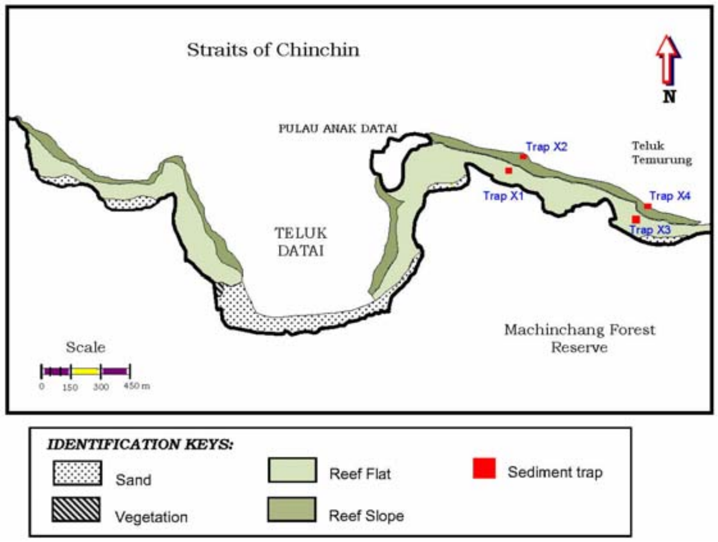

Figure 4: Location of sediment traps in Teluk Datai

After oven drying, the coarse sediment was sieved into the following size groups: > 1000 μm, 710–1000 μm, 500–710 μm, 250–500 μm, 212–250 μm, 125–212 μm, 63–125 μm and < 63 μm.

The weight of each particle size fraction was recorded. From the total sediment data, a rate of sediment fallout in $g/m^2/day$ was calculated as follows.

Sediment fallout rate = $W/(A * T)$ $(g/m^2/day)$

where W = mean weight of dry sediment fractions (g)

A = surface area of sediment trap bottle (41.87×10^{-4} m^2)

T = number of days during collection period

The particle size distribution is given as the per cent contribution of each particle size to each sample.

Microscopic Examination

Representative portions of each sediment sample collected from each zone were examined under the microscope to obtain a clearer view of the sediment types.

RESULTS AND DISCUSSION

Sediment Fallout During the Dry Season (2–19 February 1999)

A comparison of particle size for sediment collected in traps located at the reef flats of Teluk Dedap (Traps 1 and 3) and in Teluk Datai (Traps X1 and X3) showed that Teluk Datai experiences larger variations in its particle size distribution. This is particularly true for particles ranging up to 0.2 mm in size. These variations are shown in Figure 5. Based on the summation curves, the composition of sediment collected within the western section of the reef flats of Teluk Dedap and Teluk Datai (Traps 1 and X1) tended to have fewer of the finer sediment particles of < 0.2 mm than in the eastern section of the reef flats (Traps 3 and X3). However, it was observed that larger amounts of finer sediment particles (< 0.2 mm) were collected within the reef flats of Teluk Dedap and Teluk Datai compared to the larger particles. The percentage of sediment particles of < 0.2 mm size ranged from approximately 15% to 80%, while for the larger particles of > 0.2 mm size the amount collected were approximately 65% to 100%. The similarity of sediment trap placements between the two reefs (Teluk Dedap and Teluk Datai), coupled with the possibility of similar water circulation within these reefs may have resulted in the similar characteristic of the general composition of larger and finer sediment particles collected during the dry season.

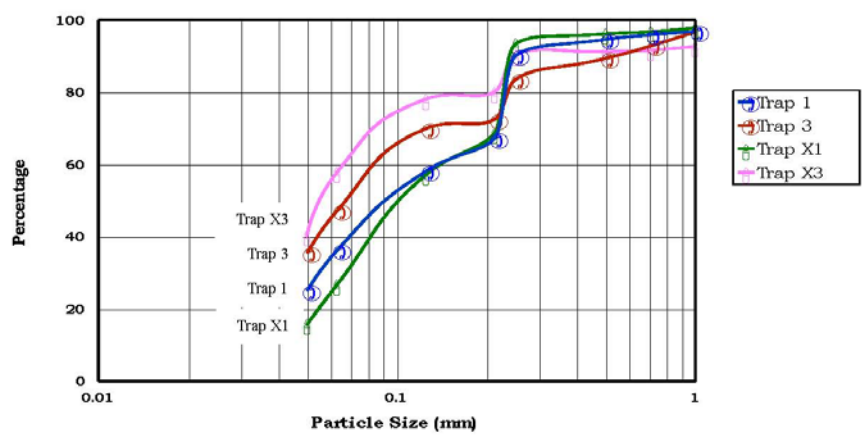

Figure 5: Summation curves off sediment particle size for sediment traps at reef flats of Teluk Dedap (Traps 1 and 3) and Teluk Datai (Traps X1 and X3), Pulau Langkawi, during the dry season (2–19 February 1999)

The summation curves in Figure 6 show different characteristics in the general composition of sediment collected in the reef slopes of Teluk Dedap and Teluk Datai during the dry season. The differences in the amount of different fractions of sediment particles analysed are large, ranging from near 0% to 100%, compared to the reef flats where the range is 15% to 100%. Within the reef slope regions of Teluk Dedap and Teluk Datai, larger amounts of sediment were collected from Trap 2 (Teluk Dedap) and Trap X4 (Teluk Datai). There is no distinction between the east and west as seen in the sediment fractions collected for the reef flats. This shows that the sediment particles would be subjected to more complex physical activity within the water column at the reef slopes before finally settling to the bottom. The range of finer sediment particles collected is also broad. Trap 4 (Teluk Dedap) and Trap X2 (Teluk Datai) collected a lower percentage of sediment particles of < 0.2 mm size, and this percentage ranged from near 0% to approximately 35%. The reverse is observed for Trap 2 (Teluk Dedap) and Trap X4 (Teluk Datai).

Based on the two summation curves (Figures 5 and 6), it is apparent that most of the finer sediment particles ($0.06 < \chi < 0.2$ mm) settled rather quickly within the reef flats of Teluk Dedap and Teluk Datai. The shallowness of the reef flats and their full exposure to air during low water springs probably provide the explanations for the larger portion of finer materials settled within the reef flats here. Furthermore, the small depth and greater intensity of wave actions and erosion occurring along the reef flats may have trapped the finer particles and resulted in more of such materials settling here. It is also observed here that the following assumptions do not apply for the reef flats of Teluk Dedap and Teluk Datai: (1) finer particles are able to be carried a far greater distance to settle further out into the sea, and (2) that larger particles will be carried only a shorter distance and settle faster due to their weight. These, however, are probably applicable in conditions where the fringing reef areas are relatively deeper and perhaps larger. The other factor that explains the lesser amount of fine sediment particles collected within the reef slope region is the higher physical wave activity. Constant movement of finer materials, coupled with the subtidal conditions of low water springs, would make it difficult for lighter, finer materials to settle.

Figure 7 shows a breakdown of the sediment fractions analysed during the dry season for both Teluk Dedap and Teluk Datai. In Teluk Dedap, sediments of particle size >1000 µm were collected mostly in Traps 3 and 4, which were located on the eastern reef flat and reef slope, respectively.

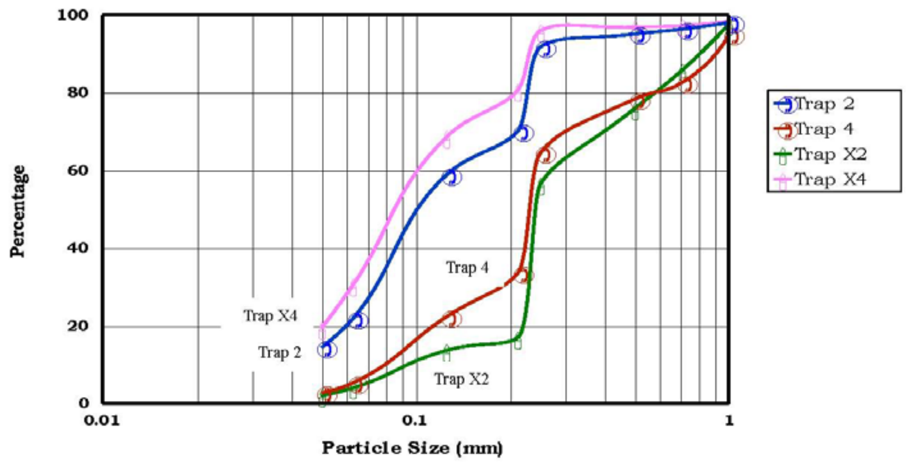

Figure 6: Summation curves of sediment particle size for sediment traps at reef slopes of Teluk Dedap (Traps 2 and 4) and Teluk Datai (Traps X2 and X4), Pulau Langkawi during the dry season (2–19 February 1999)

Generally, the sediments collected from Teluk Dedap showed larger proportions of sediment with a particle size of > 1000 µm. At least 60% of the sediment fractions collected for Teluk Dedap fell within the ≤ 212 µm range, with the exception of Trap 4. When comparing the sediment fractions collected for traps in Teluk Dedap alone, it was expected that Trap 2, which was located at the start of a sudden slope, would naturally have a larger portion of finer materials of < 0.06 mm. This is because, particularly during low water spring, most fine materials would have been swept directly down from the reef flat onto the slope. Trap 4, on the other hand was placed on a more gradual slope, and a smaller amount of fine materials would have been trapped here. Trap 4 also contained the largest portion of sediment particles > 1000 µm. For Teluk Datai, sediment fractions showed greater variation in their composition. Similar to Teluk Dedap, a larger amount of sediment fractions were also from the ≤ 212 µm range.

A summary of the mean total sediment collected during the dry season for Teluk Dedap and Teluk Datai is given in Table 1. Very similar mean total sediment and standard deviation values were measured for the reef flats of the study area of Teluk Dedap (112.5 ± 28.84 g–119.2 ± 27.08 g). Higher variation is observed for sediment traps located on the reef slope of Teluk Dedap (99.9 ± 8.94 g–338.4 ± 38.30 g). The same cannot be said for the control site (Teluk Datai) because the measurements of mean total sediments varied considerably 102.7 ± 13.52 g–680.8 ± 26.64 g). Mean total sediment appears to be comparatively lower for

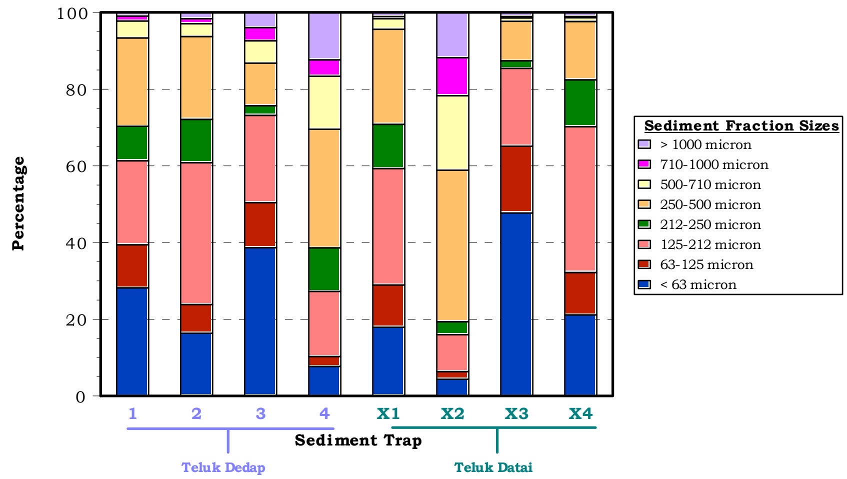

Figure 7: Distribution of particle size fractions at Teluk Dedap (2–19 February 1999) and Teluk Datai (3–19 February 1999), Pulau Langkawi during dry season

sediment traps placed on the western region of Teluk Dedap reef (i.e., Traps 1 and 2) as compared to Teluk Datai (Traps X1 and X2). The reverse is observed for sediment traps placed on the eastern region of both reefs.

Table 1: Summary of mean total sediment collected during the dry season in Teluk Dedap and Teluk Datai (2–19 February 1999)

Teluk Dedap		Teluk Datai	
Trap	Mean ± S.D. (g)	Trap	Mean ± S.D. (g)
1	112.50 ± 29.84	X1	268.20 ± 64.68
2	99.90 ± 8.94	X2	680.80 ± 26.64
3	119.20 ± 27.08	X3	102.70 ± 13.52
4	338.40 ± 38.30	X4	135.20 ± 17.05

Reef flat   Reef slope

Sediment Fallout During the Wet Season (10–25 July 1999)

The summation curves for sediment collected at the reef flats of Teluk Dedap and Teluk Datai are shown in Figure 8. A larger percentage of sediment particles of ≤ 0.2 mm was collected in sediment Traps 1 and 3 of Teluk Dedap, while a smaller percentage was collected for sediment Traps X1 and X3 at Teluk Datai. Sediment fractions ≥ 0.25 mm were almost equally collected in Traps 3, X1 and X3, with the exception of Trap 1. Again, it is observed here that the reef flats tended to trap more of the finer sediment fractions, even during the wet season. The percentage of these fractions, however, is smaller than that measured during the dry season. This may be possible because during the wet season, the physical water activity is of greater magnitude where vertical and horizontal mixing may have occurred more frequently compared to the dry season. Therefore, coarser sediment particles would be able to settle in comparatively greater proportion within the reef flat during this time.

Figure 9 shows the summation curves of sediment fractions collected for the reef slopes in Teluk Dedap and Teluk Datai during the wet season. Larger amounts of coarser sediment fractions were collected in Traps 2 and 4 in Teluk Dedap and Trap X2 in Teluk Datai. The percentage of sediment fractions of ≥ 0.25 mm size collected in these traps was also similar. There is an exception in Trap X4 (Teluk Datai), where larger proportions came from finer sediment particles having the size of ≤ 0.2 mm.

The comparison of summation curves for reef slopes during the dry (Figure 6) and wet seasons (Figure 9) showed that, during the wet season, the variation is much smaller due to the higher physical activity occurring within the coastal and shallow marine system of both Teluk Dedap and Teluk Datai. The constant high amounts of physical activity, such as wave actions and turbulence, may have resulted in a more even distribution of sediment fractions compared to the dry season. However, the physical condition of the reef, such as its structures and degree of slopes may have contributed to the varying degree of variations in the sediment fractions analysed.

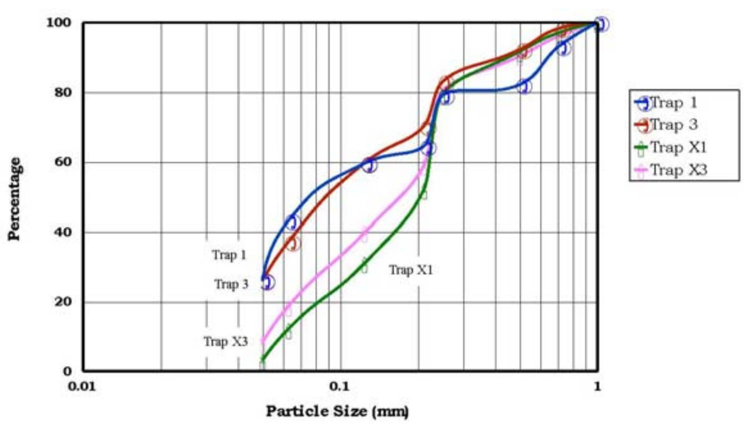

Figure 8: Summation curves of particle size for sediment traps at reef flats of Teluk Dedap (Traps 1 and 3) and Teluk Datai (Traps X1 and X3), Pulau Langkawi, during the wet season (10–25 July 1999)

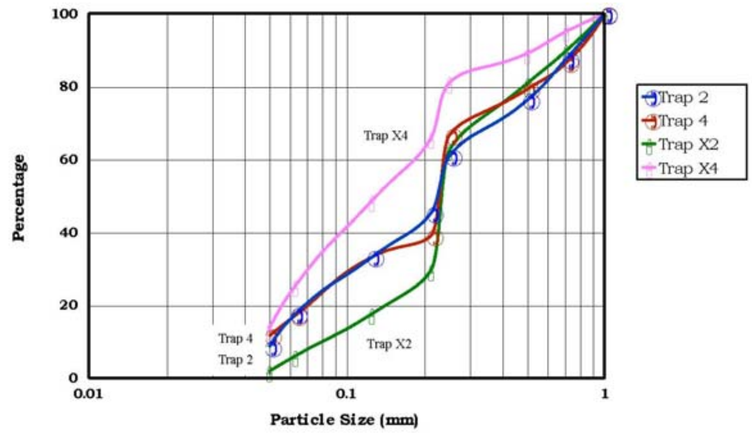

Figure 9: Summation curves of particle size for sediment traps at reef slopes of Teluk Dedap (Traps 2 and 4) and Teluk Datai (Traps X2 and X4), Pulau Langkawi, during the wet season (10–25 July 1999)

Figure 10 shows the different fractions of sediment collected from all the sediment traps in Teluk Dedap and Teluk Datai. The size of the fine sediment fraction (< 63 µm) relatively much lower than that measured during the dry season. These fine particles may have more difficulty settling and would probably stay suspended within the water column during this period, hence the lesser amount trapped in the sediment traps. Sediment particles from 500 µm – > 1000 µm made up a greater percentage of the total during the wet season. This is probably because most reef materials will either be eroded or broken during the higher and longer physical waves that occur during the wet season.

A summary of the mean total sediment collected and corresponding standard deviations calculated for Teluk Dedap and Teluk Datai during the wet season is given in Table 2. Similar mean amounts of total sediment were collected in the sediment traps on the reef flats of Teluk Dedap (160.5 ± 4.45 g–165.9 ± 2.12 g) and Teluk Datai (302.2 ± 12.58 g–350.6 ± 12.41 g). These results showed that there is less variation in the sediment fallout within the reef flats during the wet season. The mean values calculated for sediment traps placed within the reef slopes showed considerable variation. The difference in means for Teluk Dedap reef slope sediments was two-fold (182.5 ± 10.36 g–384.0 ± 37.6 g) while for Teluk Datai was more than three-fold (207.3 ± 13.44 g–729.6 ± 13.94 g).

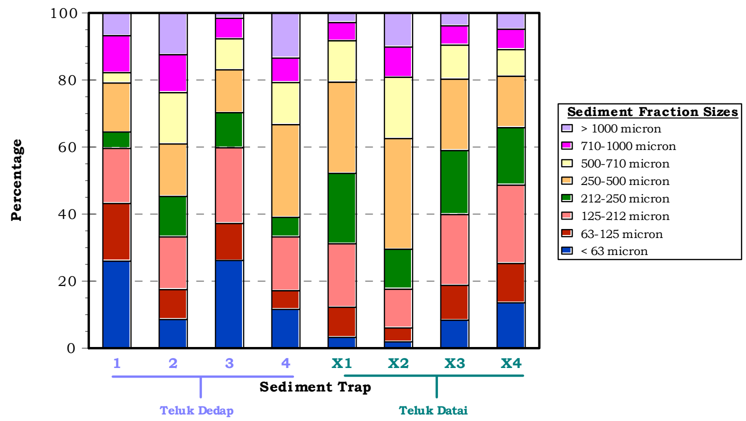

Figure 10: Distributions of particle sizes at Teluk Dedap and Teluk Datai, Pulau Langkawi, during wet dry season (10–25 July 1999)

Table 2: Summary of mean total sediment collected during the wet season in Teluk Dedap and Teluk Datai (10–25 July 1999)

Teluk Dedap		Teluk Datai	
Trap	Mean ± S.D. (g)	Trap	Mean ± S.D. (g)
1	160.50 ± 4.45	X1	350.60 ± 12.41
2	182.50 ± 10.36	X2	729.60 ± 13.94
3	165.90 ± 2.12	X3	302.20 ± 12.58
4	384.00 ± 37.6	X4	207.30 ± 13.44

Reef flat Reef slope

A Comparison of Sediment Fallout between the Dry and Wet Seasons

1. Teluk Dedap

Sediment fallout at Teluk Dedap was examined for both the dry and wet seasons (Figures 7 and 10). It can be clearly seen that, during the dry season, finer sediment particles (mainly < 212 μm) were the main constituents found in all sediment traps collected, except for Trap 4, which was placed on the eastern part of the reef slope in Teluk Dedap. In some traps, these finer sediment fractions also dominate the total collection during the wet season. However, the proportions were lower during the wet season than in the dry season, with the exception of Trap 4. On the reef flats of Teluk Dedap, where Traps 1 and 3 were placed, the sediment fractions showed that at least 60% of the compositions are made up of sediment particles of ≤ 212 µm. In the reef slope, the largest fraction is particles ≥ 250 µm. However, there is an exception for Trap 2 during the dry season. The larger sediment fraction with > 1000 µm particle size was measured most frequently during the wet season, particularly at Traps 1, 2 and 4.

A *t*-test was used to compare sediment fallout data from the reef flat and reef slope of Teluk Dedap during the dry (Table 3) and wet seasons (Table 4). Results of the paired *t*-tests show that sediment fallout on the reef flat of Teluk Dedap is significantly more than on the reef slope during dry season [$t(1) = -0.89$, $p < 0.05$] and the wet season [$t(1) = -1.22$, $p < 0.05$].

Table 3: A paired two-sample *t*-test for mean sediment fallout between the reef flat and reef slope of Teluk Dedap during dry season

	Teluk Dedap	Teluk Datai
Mean	115.85	219.15
Variance	22.445	28441.125
Observations	2	2
Pearson correlation	1	
Hypothesised mean difference	0	
df	1	
t Stat	–0.89128559	
P (T < = *t*) one-tail	0.268276898	
t Critical one-tail	6.313751514	
P (T < = *t*) two-tail	0.536553796	
t Critical two-tail	12.70620473	

2. Teluk Datai

It was observed that the main component of sediment collected during the dry season (Traps Dry X1–Dry X4) was the finer sediment fraction of particle size ≤ 212 µm (Figures 7 and 10). These fractions were less abundant during the wet season in all sediment traps placed in both the reef flat and the reef slope. It was also observed that larger quantities of the finer sediment particles ≤ 212 µm were collected in traps placed on the eastern side of Teluk Datai (Traps X3 and X4). The coarser sediment fractions having sizes ≥ 250 µm were mainly collected in Traps X1 and X2, and these traps were located in the western region of the reef flat and reef slope of Teluk Datai, respectively. Except for Trap X2, larger quantities of sediment particles > 1000 µm were collected in traps during the wet season.

Table 4: A paired two-sample *t*-test for mean sediment fallout between the reef flat and reef slope of Teluk Dedap during the wet season

	Teluk Dedap	Teluk Datai
Mean	163.2	283.25
Variance	14.58	20301.125
Observations	2	2
Pearson correlation	1	
Hypothesised mean difference	0	
df	1	
t Stat	–1.22438	
P (T < = *t*) one-tail	0.218	
t Critical one-tail	6.313752	
P (T < = *t*) two-tail	0.436	
t Critical two-tail	12.7062	

A *t*-test was conducted to compare sediment fallout data between the reef flat and reef slope of Teluk Dedap during the dry (Table 5) and wet seasons (Table 6). Similar to Teluk Dedap, results of the paired *t*-tests showed that sediment fallout on the reef flat of Teluk Datai is significantly greater than on the reef slope during dry season [$t(1) = -1.17$, $p < 0.05$] and the wet season [$t(1) = -0.59$, $p < 0.05$].

Table 5: A paired two-sample *t*-test for mean sediment fallout between the reef flat and reef slope of Teluk Datai during the dry season

	Teluk Dedap	Teluk Datai
Mean	185.45	408
Variance	13695.13	148839.7
Observations	2	2
Pearson correlation	1	
Hypothesised mean difference	0	
df	1	
t Stat	–1.17101	
P (T < = *t*) one-tail	0.224979	
t Critical one-tail	6.313752	
P (T < = *t*) two-tail	0.449958	
t Critical two-tail	12.7062	

Statistical analysis using a single-factor ANOVA was conducted to compare sediment fallout during the dry and wet seasons between Teluk Dedap and its control site (Tables 7 and 8). Results showed that the F value was much smaller than the F_{crit} at the 5% significance level. This is also clearly shown from the *p*-values, where $p > 0.05$. Therefore, there is no significant difference in sediment fallout between Teluk Dedap and Teluk Datai during the dry season.

Table 6: A paired two-sample *t*-test for mean for sediment fallout between the reef flat and reef slope of Teluk Datai during the wet season

	Teluk Dedap	Teluk Datai
Mean	326.4	468.45
Variance	1171.28	136398.65
Observations	2	2
Pearson correlation	1	
Hypothesised mean difference	0	
df	1	
t Stat	–0.5994936	
P (T < = *t*) one-tail	0.32809769	
t Critical one-tail	6.31375151	
P (T < = *t*) two-tail	0.65619538	
t Critical two-tail	12.7062047	

For the wet season, similar results were observed with the ANOVA; the F value was much smaller than the F_{crit} at a 5% significance level. There is also no significant difference between sediment fall out of Teluk Dedap and Teluk Datai during the wet season.

Table 7: Single-factor ANOVA at the 5% significance level for sediment fallout during the dry season between Teluk Dedap and Teluk Datai

SUMMARY

Groups	Count	Sum	Average	Variance
Teluk Dedap	4	670	167.5	13044.82
Teluk Datai	4	1186.9	296.725	70687.77

ANOVA

Source of variation	SS	df	MS	F	P-value	F_{crit}
Between groups	33398.2	1	33398.2	0.797735	0.406167	5.987378
Within groups	251197.8	6	41866.29			
Total	284596	7				

H_o: No significant difference in sediment fallout between sampling locations during the dry season at $p = 0.05$
H_A: Significant difference in sediment fallout between sampling locations during the dry season at $p = 0.05$

Table 8: Single-factor ANOVA at the 5% significance level for sediment fallout during wet season between Teluk Dedap and Teluk Datai

SUMMARY

Groups	Count	Sum	Average	Variance
Teluk Dedap	4	892.9	223.225	11575.9
Teluk Datai	4	1589.7	397.425	52582.71

ANOVA

Source of variation	SS	df	MS	F	P-value	F_{crit}
Between groups	60691.28	1	60691.28	1.891914	0.21813	5.987378
Within groups	192475.8	6	32079.31			
Total	253167.1	7				

H_o: No significant difference in sediment fallout between sampling locations during the wet season at $p = 0.05$
H_A: Significant difference in sediment fallout between sampling locations during the wet season at $p = 0.05$

Sediment Fallout Rates During the Dry and Wet Seasons

Table 9 compares the calculated sediment fallout rates in g/m^2/day for the Teluk Dedap and Teluk Datai reefs based on the sediment fallout collected during the dry and wet seasons in 1999.

In Teluk Dedap, the calculated sediment fallout rate are similar for both traps placed on the reef flat during the dry season. The range calculated is 1,580.49 ± 419.22 g/m^2/day to 1,674.62 ± 380.44 g/m^2/day. During the wet season, the range of fallout rate is much higher, 2,738.02 ± 75.91 g/m^2/day to 2,830.14 ± 36.17 g/m^2/day. The variation of sediment fallout rates calculated from results obtained in these traps is low. However, the variation of sediment fallout rates calculated for the reef slopes of Teluk Dedap is high both amongst the traps and also between the two seasons. The range fell within the 1,403.48 ± 125.60 g/m^2/day to 4,754.12 ± 538.07 g/m^2/day during the dry season, and 3,113.32 ± 176.73 g/m^2/day to 6,550.77 ± 641.43 g/m^2/day during the wet season.

Table 9: A comparison of calculated sediment fallout rates (g/m^2/day) for Teluk Dedap and Teluk Datai during the dry and wet seasons

Teluk Dedap			Teluk Datai		
Trap	Dry Season	Wet Season	Trap	Dry Season	Wet Season
1	1,580.49 ± 419.22	2,738.02 ± 75.91	X1	4,003.39 ± 968.47	5,980.99 ± 211.71
2	1,403.48 ± 125.60	3,113.32 ± 176.73	X2	10,162.22 ± 397.65	12,446.45 ± 237.81
3	1,674.62 ± 380.44	2,830.14 ± 36.17	X3	1,532.99 ± 201.81	5,155.32 ± 214.61
4	4,754.12 ± 538.07	6,550.77 ± 641.43	X4	2,018.11 ± 254.50	3,536.39 ± 229.28

Reef flat (shaded rows: 1, X1, 3, X3) Reef slope (unshaded rows: 2, X2, 4, X4)

In Teluk Datai, most of the sediment fallout rates calculated varied from season to season, from trap to trap and from location to location. The ranges calculated vary from the lowest at 1,532.99 ± 201.81 g/m^2/day (Trap X3; reef flat east; dry season) to the highest at 12,446.45 ± 237.81 g/m^2/day (Trap X2; reef slope west; wet season).

In general, sediment fallout rates were lower during the dry season and much higher during the wet season for both Teluk Dedap and Teluk Datai. It was observed also that, in general, (with the exception of Traps 1 and 2, dry season; Traps X3, and X4, wet season) sediment fallout rates were lower on the reef flats compared to the reef slopes in Teluk Dedap and Teluk Datai for both seasons. However, although some differences were observed, it is logical and statistically correct to assume that there was no significant difference in the overall sediment fallout rates between Teluk Dedap and its control site, Teluk Datai, during dry and wet seasons. This assumption was based on the fact that statistical analysis (single-factor ANOVA) of sediment fallout rates will yield similar output for the sediment fallout, because the same baseline data of sediment fallout was used to calculate sediment fallout rates. However, there will be significant differences in the sediment fallout rates on the reef flats and reef slopes, i.e., sediment fallout rates will be significantly higher on the reef flats than on the reef slopes in both Teluk Dedap and Teluk Datai during dry and wet seasons.

Microscopic Analysis

Because the study area is located within a continental shelf, the sedimentation fallout occurring within this region would be considered shelf sedimentation, a type for which the major sediments are biogenic materials that occur within the coral reef region. Biogenic sediments, both macroscopic and microscopic, are derived from the hard parts of organisms, such as shells and skeletons. The macroscopic biogenic sediments are clearly observed for sediment fractions collected from Teluk Dedap and Teluk Datai, particularly the coarser sediment fractions having sizes ≥ 250 µm. Smaller sediment fractions appear to consist mainly of feldspar and quartz, and also some remnants of microscopic biogenic sediments, particularly of molluscs shells and crustaceans. Some fine remnants of coral debris, foraminifera, siliceous materials and calcareous shell remnants of polychaete housing were also observed in the sediment fractions collected in both Teluk Dedap and Teluk Datai. Some of these sediments were long eroded and broken off during its repeated transportation and deposition by wave actions within the area. This is indicated by the rounded ends and edges of the broken pieces of shells, in particular. The types of sediments collected in both reefs are similar, meaning that the coarser sediments are basically biogenic in nature, and the finer sediment fractions were made up of mainly feldspar, siliceous and quartz materials.

Other forms of sediments observed include lithified sediments, as schematically shown in Figure 11. These were found in most of the sediment fractions collected from Teluk Dedap and Teluk Datai. This form of sediment is easily observed in the larger sediment fractions, such as those in the > 1000 µm size range. An example of macroscopic lithified sediment is shown in Figure 12, which was taken from Trap 4 placed on the reef slope of Teluk Dedap during the dry season. The lithified sediments observed are probably of terrigenous origin (Thurman and Trujillo, 1999). The observed lithified sediments could have originated from weathered sedimentary rocks within the study area.

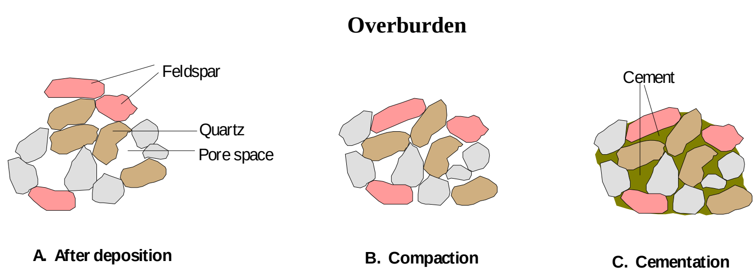

Figure 11: A schematic diagram of lithification of reef sediments: (a) deposition of loose grains, (b) weight of overburden compacts sediment particles into tighter arrangement, reducing pore space, (c) precipitation of cement in the pores binds to form a clastic texture.

Source: Adapted from Plummer, McGeary and Carlson (2003)

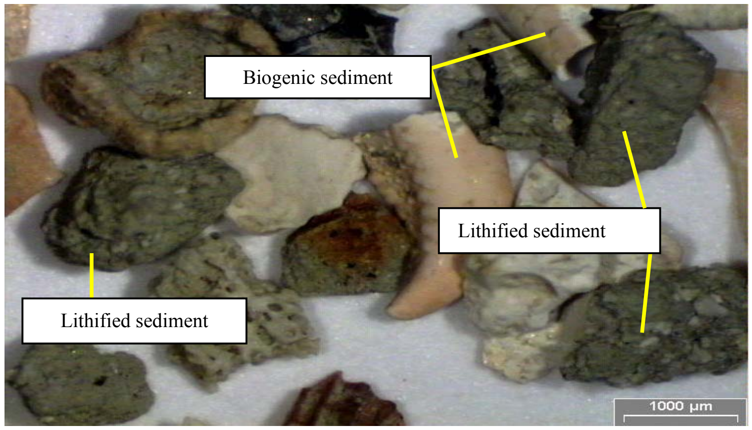

Figure 12: Lithified and biogenic sediments observed using microscope from sediment fraction size > 1000µm in Teluk Dedap during dry season (2–19 February 1999)

The Effect of Sediment Fallout on the Coral Reef Ecosystem

Sediments affect reefs in a number of ways, both directly and indirectly. Sediments lower the value of reefs biologically, aesthetically and economically. Such effects may be subtle if sediment concentrations are low, in which case they may manifest as physiological stress. If the sediment loads are high, acute effects and even colony die-offs may be observed. Sediments may be objectionable in water for several reasons. They are aesthetically displeasing and provide adsorption sites for chemical and biological agents. Suspended organic solids may be degraded biologically, resulting in objectionable by-products. The damaging effects of sediments on coral reefs are numerous:

1. Sediment in water, particularly fine sediment, attenuates light, which is important for coral photosynthesis. Light limits the growth of coral to approximately 5% of surface illumination (Motoda, 1939). At greater depths, the attenuation of light causes species diversity to decline (Sheppard, 1980). In the west coast of Peninsular Malaysia, the average maximum depths of fringing reefs are between 2.5–3.5 m (Pulau Langkawi and Pulau Songsong) to 8 m (Pulau Payar). Hence, the waters are turbid. On the east coast of Peninsular Malaysia, where the waters are clearer, the reefs extend to greater depths (Yasin, 1993).
2. Heavy sediment falling on the reef will smother the coral and suffocate it if the rate of sedimentation is higher than the rate at which the corals are able to shed the sediment. Energy is expended by corals to remove sediment falling onto the colonies. Increased sedimentation means that a higher proportion of

the energy of the corals be spent removing the sediment, and a lower proportion of the energy expended for feeding, growth and reproduction.

3. Reproduction and dispersal of corals will be affected. Coral larvae require a hard and stable substratum to settle. Sediment rain changes the bottom type and may render it unsuitable for coral planulae settlement. This might also cause higher mortality rates of coral planulae before settlement (Motoda, 1939).
4. Sediment from terrigenous inputs may be toxic. Metal ions, such as iron, are toxic to marine invertebrates. The toxicity may also be imparted as nutrients contained in the sediments. Increased nutrients in a naturally nutrient-poor environment such as a coral reef can result in algal blooms.
5. The size of particles in sediments affects both the horizontal and vertical distributions of the sediment. The size of sediments also determines the success of sediment rejection in corals. The horizontal distribution of sediments in the sea is caused by sediment transport by waves and prevailing currents, as well as by the size and shape of the particles concerned. Larger, heavier particles are retained near the point source but light silt can be carried over great distances. At Pulau Songsong (Malaysia), located further south of Pulau Langkawi, the turbid waters were caused by silt particles transported from the Muda estuary on the mainland at a distance of more than 6 km away (Yasin, 1993). Oceanographic features may modify the distribution of sediments. Eddies may cause the deposition of sediments during transportation. Where sediment deposition and resuspension is high, coral diversity and coral cover is low.
6. Stoke's Law states that the velocity of a falling sphere is proportional to the sphere's diameter. Stoke's Law is applicable to silt-size and finer particles with the density of quartz. For larger grain-size particles, fluid inertial forces cause a drag behind the particle that retards its fall. Particle settling is again slowed down in the presence of other grain. In standing water, there is a distribution of particles; the heavier particles lay near the bottom while the lighter particles are located in the upper layers or are continuously in suspension. The gradation is further modified in the presence of a prevailing boundary current that induces resuspension of the settled sediment. This is important on the reef because, even though the injection of fresh sediments into the system may have stopped, the effects of sedimentation may still be felt as resuspension of settled sediments occur.
7. The natural rate of sedimentation on reefs is subject to temporal variations. This is more pronounced on shallow reefs, as they are subjected to both wave actions and near shore currents. In the shallow reefs of Pulau Songsong (Malaysia), where sedimentation rates are high, water turbidity is increased by an average of 112% during spring tides (Yasin, 1993). The local current velocity on the reef during spring tide is 3.5 times that of the neaps. Both the current and wave act on the settled sediment to bring it into suspension.

Sediment concentration and water turbidity also increase during the peak of the wet seasons on the reefs of Peninsular Malaysia. This period is characterised by strong currents and high wave crests. In addition, the fringing reefs that lie in close proximity to a river will receive a higher load of sediment from the riverine inputs.

8. It is a common misconception that turbid waters do not have corals. Even in chronically turbid waters such as Pulau Kendi, Malaysia, where sedimentation can exceed 180 $mg/cm^2/day$, a number of coral genera thrive (Thevathasapillai, 1990). However, coral communities found in turbid or sedimented waters are composed of different reef species. In the turbid waters the few coral genera that usually predominate are Favites, Porites, and Favia. As the sedimentation rate increases, scleractinians (the reef-building corals) begin to disappear, and there is a predominance of the non-scleractinian corals and the soft corals. Weiss and Goddard (1977) discovered that reefs in turbid waters differ from clear water reefs in having lower diversity, less coral cover, lowered overall growth rates and a different species composition.

The Management of Reefs in Pulau Langkawi

Conservation of marine species and their habitats is critical for the successful management of reefs. Approaches similar to those for terrestrial organisms, but with the conservation tools of the former, have to be taken into account. The "Gap Analysis" (Burley, 1988) can be used to determine the priorities for conservation of ecosystems. To conserve the coastal and marine environment in Langkawi, several conservation issues need to be addressed to ensure the success of the rehabilitation and conservation measures. These include:

1. The preservation of high diversity areas.
2. Restoration of damaged habitats.
3. Monitoring the state of the environment and the activities relevant to the conservation exercise.
4. Effective management of the conservation area.
5. The importance of local participation.

SUMMARY

By comparing the distribution of sediment fractions collected during the dry and wet seasons for Teluk Dedap and Teluk Datai, it was observed that, in general, the sediments are poorly-sorted on the reef flats and reef slopes.

The patterns of sediment fallout in the study area (Teluk Dedap) and its control site (Teluk Datai) were dissimilar. On the Teluk Dedap reef, finer sediment particles of ≤ 212 μm were the main sediment components collected on the reef flat, while on the Teluk Datai reef, the finer sediment fractions of ≤ 212 μm were collected on the eastern region of its reef. In Teluk Dedap, the larger quantities of finer sediment on the reef flat explains the reason that the coral debris/dead coral coverage is larger here compared to the reef slope. On the east side of Teluk Datai, where there is less live coral coverage, there was also a larger quantity of finer sediment fractions collected.

The pattern and degree of transportation and deposition differ between the two reefs at Teluk Dedap and Teluk Datai. This could be the result of different water circulation patterns, different reef structures, the wave energy involved and other physical influences. The amount of sediment deposition occurring during the dry and wet seasons in this study may depend on (1) settlement of transported materials when the waves lose energy and can no longer transport its load and (2) accumulation of dead reef organisms or their remnants where no transportation is involved at all. Based on the results obtained from the sediment fallout study, the environment of deposition of finer sediment particles with ≤ 212 μm sizes for Teluk Dedap reef was the reef flat while the reef slope was the environment of deposition of coarser sediment particles. In Teluk Datai, such distinction is not clearly denoted between the reef flat and the reef slope. However, in Teluk Datai, the environment of deposition of finer sediment particles with ≤ 212 μm sizes was within the eastern region of the reef itself, while the western region of the reef is the environment of deposition of coarser sediment particles.

The main component of the coarser sediment fractions collected was biogenic material, namely the shells or remnants of molluscs and crustaceans, coral debris, siliceous materials and lithified sediments. For the finer sediment fractions, the main components appear to be feldspar and siliceous and quartz materials.

Calculated sediment fallout rate in Teluk Dedap had a minimum level of 1,403.48 ± 125.60 $g/m^2/day$ during the dry season and a peak value of 6,550.77 ± 641.43 $g/m^2/day$ during the wet season. In the control site, the sediment fallout rate varied from 1,532.99 ± 201.81g/m^2 during the dry season to 12,446.45 ± 237.81 $g/m^2/day$ during the wet season. Sediment fallout rate is typically lower during the dry season compared to the wet season and lower on the reef flats compared to the reef slopes. Results indicated that if local sedimentation was the cause of live coral coverage deterioration, then Teluk Datai reef would have a higher percentage of dead reef relative to its size compared to Teluk Dedap reef. However, this was not the case. Therefore, there is a strong possibility that the higher percentage of dead coral coverage in Teluk Dedap was caused by sediment plumes transported eastward during ebbing tides from the riverine-estuarine area, resulting in coral death over time.

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