CONTEMPORARY COASTAL PROTECTION ON RAROTONGA, COOK ISLANDS

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Arts in Pacific Studies at the University of Canterbury

by

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Aerial photo view of the Rarotongan Resort Hotel site in 1991. Note the use of rock groins used to mitigate erosion and saltwater inundation.

Aerial photo view of the Rarotongan Resort Hotel site in 1993, two years after the scheme installation of Coastal Protection Units. Progradation and beach change has occurred behind the wall at the eastern end of the site.
ABSTRACT

This thesis examines the effects of coastal protection structures upon the sandy coastline of Rarotonga, Cook Islands. The coastline is surrounded by a fringing coral reef which is continuous except for six passages. Water from the open sea enters the lagoonal area by waves breaking over the reef and propagates towards the shore as reformed waves. A detailed analysis of beach change and adjustments in front of and adjacent to coastal protection structures is presented. While there has been a substantial increase in data in the nearshore oceanographic regime and the nearshore coastal zone on Rarotonga, generally there has been a lack of monitoring of coastal structures, and in the effects on tropical coastal environments.

Five sites in the west and southern coast of Rarotonga were selected for monitoring. All sites were located on sandy beach coastlines. An examination of the beach sediment at each site by determination of settling velocities in a 2 metre water column using a MacArthur Rapid Sediment Analyser indicated a medium grain size range. This finding differs from earlier measurements for the Rarotongan Resort site when predominantly coarse grain sediments were found. Such a finding has impact implications for the stability of coastal sediments.

The principal method of data collection was by repeated profile surveys over a ten week period between May and July 1995. The profiles were examined first, by the conventional method of profile plots and secondly by excursion distance analysis. The excursion distance analysis was used to examine temporal and spatial variations for each site.

During the study period a storm of swells originating from a southern source area brought unusually high waves in the seas around the Southern Cook Islands on the 8th and 9th June. All study sites were affected by up to 6 metre swells with energetic wave periods in the range of 10-15 seconds. The impact of the swell storm helped generate results for this study.
Five factors were noted from this study as important to the way the beach profile in front and adjacent to coastal protection structures responded in the short term to the incident coastal processes during the study period. These are the position of the coastal protection structure in the beach profile, the structural configuration of the coastal structure, how the structure is tied in with the land behind it, the seaward volume of beach sediment and the sediment characteristic within the foreshore. Most of the foreshore adjustment occurred in the lower and middle foreshore with flattening and steepening respectively taking place during the high energy swell storm. In the recovery period the profiles tended to broaden out.

A spatial analysis of the field data showed both along-shore and across-shore variations in the morphology of the beach and the topography of the lagoon floor. Movement of sediment in discrete amounts were identified in generally three positions in the beach profile: lower foreshore, nearshore and the mid-lagoonal area. Following the storms across-shore movement of sediment was identified, presumably rehabilitating areas in front of the coastal structures. Overall it was observed that beach change in front of coastal structures was similar to beaches without structures if there is abundant sediment offshore. The erosional response to storms, however, was typically different with bars forming offshore where coastal structures had been established.
ACKNOWLEDGEMENTS

Let me take this opportunity to thank the many individuals and organisations who have assisted in the production of this thesis. First and foremost I am in debt and grateful to the MacMillan Brown Centre for Pacific Studies for providing the necessary financial assistance to fund my travel to Rarotonga and back. To the Director, Mr Uentabo Neemia-Mackenzie who has assisted this research in many ways, I thank you for your support, encouragement and also for the opportunity to work in my own back yard. Appreciation is also extended to Dr Garth Cant (former Acting Director) for his support, assurance and optimism. His contribution and that of the Macmillan Brown Centre resuscitated an otherwise ambitious thesis proposal.

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The final word is reserved for the following Polynesian proverb which cautions our every move, "Aere marie e aku potiki kia kite koe i nga inapotea." (Go quietly my sons [and daughters] so that you may see many moonlights. Go slowly and be careful so that you may live long.)
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CHAPTER ONE

1.0 Introduction to the Research Problem

1.1 Introduction

This thesis is composed of three principal parts. The main objective is to examine the effects of Coastal Protection structures upon the sandy coastline of Rarotonga, Cook Islands, a tropical South Pacific high volcanic island, surrounded at the fringes by a predominantly carbonate coral reef. It examines current methods of Coastal Protection that are being used on Rarotonga and their effectiveness in light of available scientific data and literature. It examines localised effects of selected coastal protective measures by monitoring and observing these over a ten week period noting in particular beach response. To help this study along, midway through the field study phase ocean swells inundated the south and west coasts of Rarotonga. The storm that originated from the southern ocean south of New Zealand and Australia affected all the sites monitored by this study providing some useful observations and measurements pertinent to this investigation, in particular, process and beach response in front of coastal structures. Finally, this thesis investigates the process-response relationship between nearshore processes, beach response and coastal structures.

In the last two decades there has been a substantial increase in scientific data collection in the South Pacific Commission area (Figure 1.1, page 2) which has lead to a better understanding of the natural forces of nature against a background of human endeavour to exploit the coastal zone for reasons other than its preservation. While such voluminous data exist, there is a lack of monitoring of coastal structures, hence, little is known about their effects especially in tropical coastal environments. It could be argued that many mistakes have been made simply because of our lack of understanding of the coastal processes involved.
The complexity and variability of coastal processes often means that coastal protection is site specific. One form of protection that may work effectively for one location may not be as effective for another site. Hence, the importance of this study, as coastal processes differ from site to site “and no embracing rules can be set down for the design and use of coastal protection devices” (Foster 1982). It is important though that any assessment of coastal protection wherever it may be should give detailed description of the coastal processes apparent so as to adequately assess their use in other areas (Foster 1982).

1.2 The Research Problem in Context

It is well known that any disturbance in the littoral zone can have a profound effect on coastal processes, that is, on water circulation, sediment movement, and beach evolution (Kraus 1988; Kirk 1993). For example, the placement of a seawall on the beach alters the hydrodynamic environment if the wall interacts with the waves having consequences for sediment transport and ultimately beach morphology (Griggs and
Tait 1988; Kraus 1988; Plant and Griggs 1992). With increasing utilisation of the coast where about 70 percent of the world’s population live within 80 kilometers of the coastline, with 50 percent of the world’s cities with populations over one million located on or near tidal estuaries, with a very high coastal concentration of people on tropical islands, concern has been raised about the combined effect of rising sea levels, large storm waves, coastal erosion and construction in or near the surf zone. The concern is now often expressed that there must be integrated management and sustainable development of coastal areas otherwise "...the present faint imprint of humanity will become an unforgiving blot on sustainable development and devalue the inheritance of future generations" (Coastal Zone Canada 1996).

In the eighties a watershed of scientific debate emerged on a number of significant scientific issues such as the discovery of the ozone hole, evidence of accumulating carbon dioxide in the atmosphere, the ‘greenhouse’ effect and its likely scenario of accelerated sea level rise (Buddemeier and Smith 1988; Roy and Connell 1988). This, in effect, gave rise to a greater public awareness of the impact of human-made changes on both the physical and biological environment regardless of the prospects for climate and sea level change. In 1987, the Bruntland Report promoted the concept of sustainable development and recognised the interdependence of economy, environment, and society, such that if one was not managed properly, the others would also be adversely affected, particularly in the long term.

O’Hara (1989) points out that the main reason for current coastal erosion lies not with natural change but with the ‘destructive’ engineering approaches to forcefully control natural environments". Komar (1976) observed that many severe cases of coastal erosion can be attributed to human interference and modification of the coastal environment, and that the only way to prevent further erosion associated with jetties and breakwaters is to remove them. This has led to a ‘do-nothing’ philosophy which argues that the only acceptable changes are those that occur naturally. In other words, in the long term, it makes more economic sense to sacrifice inappropriately sited human developments than to become committed to the ongoing expense of trying to maintain them (Pilkey 1988; Weggel 1988).
Weggel (1988) on the other hand, argues that human ability to control nature has never been good but that has not stopped humans from using technology to satisfy their wants and needs. The fact is, humans exercise almost no control over what nature deals. However, humans can generally control, even to a limited extent, how nature controls. For example, humans cannot control the sea but they can build seawalls and other structures to protect their property or even to control erosion.

Society has basically three alternatives available for the management of eroding coastlines. Pilkey and Wright (1988) broadly state these alternatives as:

(i) **Hard Stabilisation**: refers to the placement of any ‘permanent’ and hard structure with a fixed location. Hard structures as generally defined include those built perpendicular to the shoreline (for example, groins) and those built on the beach and parallel to the shoreline (for example, seawalls, revetments, bulkheads).

(ii) **Soft Stabilisation**: refers primarily to beach replenishment, that is, replacing the beach which has disappeared with a new one. The best example is beach nourishment. Precast concrete Coastal Protection Units (C.P.U) designed and installed at the Rarotongan Resort Hotel site, Rarotonga, may be considered in this category.

(iii) **Retreat or Relocation**: as the name implies, refers to the practice of moving structures back apace with the shoreline retreat.

The traditional response to coastal hazards has been hard stabilisation, an option that is generally designed to protect property and structures behind it. This anthropocentric response which is ‘coastal protection’ is a misnomer for it is rare for the coastline to be protected, rather the assets behind it. In many cases, as Kirk (1991) found on Rarotonga, ‘traditional’ techniques of coastal protection once installed had ‘become’ the coast and many were not designed to fulfil that role. Such structures may increase the hazard they were designed to mitigate, or create
another, or most commonly, refer hazard to neighbouring areas of the coast. Thus, the relative degree of success in design of a coastal protective structure for a particular site is highly variable, depending on firstly, its intended function and purpose; secondly, its quality of design taking into consideration site specific details such as the coastal climate, storm history and the like; thirdly, the construction parameters and finally, "such schemes work best where they are part of a coordinated programme of coastal policy and management" (Kirk 1993).

In general, the experience worldwide is that the purpose and function of coastal engineering structures are often misunderstood. This is due to the fact that too many coastal works have basically failed to perform their intended function and in some cases generated unexpected or undesirable secondary effects. Weggel (1988), on the defensive, argues that seawall construction is perceived as the cause of erosion rather than the response to a pre-existing problem. The key to understanding the behaviour of coastal structures, says Weggel (1988), is to recognize that sand is conserved in the littoral system. Coastal structures neither produce sand nor do they destroy it but they may simply redistribute sand, return it or slow its loss, keep it where it is wanted and/or exclude it from where it is not wanted. Thus, the questions one must ask are:

(a) How much do coastal structures alter sediment transport in the front of them and along adjacent beaches both upcoast or downcoast?

(b) How do coastal structures function to redistribute sediment?

(c) What extent do coastal structures affect the beach?

This study provides for a fundamental requirement, that is, for more quantitative data on the effects of coastal protective structures which is found to be inadequate worldwide and in environments of tropical nature. It is generally found that many statements are made about coastal structures and beaches but few scientific studies have been carried out in their support. This thesis will contribute to the current circulation of information about coastal structures which is increasing due, in part, to
the vastly improved methods of measurement and scientific analysis, and also the increasing worldwide interest and participation in activities of coastal nature.

This thesis is concerned with shoreline changes in front, upcoast, and downcoast of selected coastal protection types. Measurements are made by way of re-surveying profile lines established by previous workers and in also setting out new profiles. To date, there has been little or no description of work related to a pre-storm condition, concurrent changes in waves, currents, beach profile, and beach plan shape through a storm, and post-storm conditions. Sonu (1970) notes that although all three conditions may be documented, there is little or no description of these conditions being recorded in single events.

The field study related to this thesis was carried out within a ten week period during which there was an aborted Tsunami warning and the uncharacteristic arrival of large swell waves pounding the south to south west beaches of Rarotonga. All sites selected for this study were affected. As a consequence, this thesis provides an invaluable description of all conditions described above for a smaller event than Sonu (1970) envisaged and the subsequent beach response.

Finally, it must be recognised that this thesis is focused on and concerned with the complex relationship which exists between coastal processes, beach response and coastal protective structures. In particular, it focuses on the quantification of beach response in front of and adjacent to selected coastal protective measures which in turn will be related to the process elements for a specific site.

1.3 Coastal Protection Research Base

1.3.1 Introduction

Although coastal protection measures include, but are not limited to seawalls, groynes, detached breakwaters and beach nourishment; much of the emphasis in this section with respect to past and current research review will focus on the hard
stabilisation alternative. It is found to be the most used option on Rarotonga besides “doing nothing”. In fact, of the selected sites monitored by this study, all are considered to be hard options with seawalls in common, except for arguably the Rarotongan Resort site where precast concrete “Coastal Protection Units” or CPU’s, detached from the backshore and placed in littoral zone, sometimes in the surf is used to optimise recovery of the historical beach plan shape and the beach itself.

1.3.2 Coastal Protection Research

Although a great many training and irrigation walls, dams or dykes were built in the Far and Middle East (Bruun 1972) and early Polynesians barricaded their coastal settlements with coral-like revetments against the fear of tropical cyclones (Crocombe, University of the South Pacific, pers comm, 1995), coastal protection per se probably first developed in the low countries of Europe where rivers poured soft materials, mainly clay and silt, out in the ocean for settling (Bruun 1972). The Dutch in particular, were considered to be the early pioneers of coastal protection because it was a struggle for twenty centuries to lift their race above the dangers of the sea. Not until 1600 or 1700 was some reasonable security from flooding achieved. During those long treacherous centuries, artificial mounds in native clay made their survival possible. The earliest reference to the art of accelerating the natural rate of accretion is the manuscript Tractaet van Dijckagie (Treatise on Dikebuilding), written by the Dutch dykemaster, Andries Vierlingh, between 1576 and 1579 (in Bruun 1972).

Modern study of coastal processes, though, stems from research undertaken during World War II to provide knowledge of nearshore dynamics necessary to undertake military operations in Europe and the Pacific. In North America, this resulted in the formation of the United States Army Coastal Engineering Research Center (CERC), whose Shore Protection Manual (CERC 1984) has become the “bible” of the Coastal Engineer. It must be remembered that the experience and studies involved in the compilation of the Shore Protection Manual were gained around the coasts of North America and Europe. There is a fundamental difference between the nature of these areas and those of many island nations in the tropics and subtropics, hence, caution
must be considered when using the manual (Burne 1991). Generally speaking, there is sufficient information on coastal processes and process-response scenarios to understand the fundamental difference between a protected beach and a non-protected one. The following studies point out some of the relationships.

Kraus (1988) conducted the most comprehensive and exhaustive literature review in which over 90 technical reports and articles were identified which covered laboratory, field, theoretical and conceptual studies on the effects of seawalls. He concluded that:

... beach change near seawalls, both in magnitude and variation, is similar to that on beaches without seawalls, if the sediment supply exists. Sediment volumes eroded by storms at beaches with, and without seawalls are comparable, as are poststorm recovery rates. In addition, the shape of the beach profile after construction of a seawall is similar to the preconstruction shape if a sediment supply exists, showing the same number of bars with approximately the same volumes and relative locations. The form of the erosional response to storms at seawalls is typically different. Limited evidence indicates that the subaqueous nearshore profile on a sediment-deficient coast with seawalls does not steepen indefinitely, but approaches an equilibrium configuration compatible with the coarser-grained particles comprising the bottom sediment.

In order to better utilise seawalls as one of several forms of coastal protection which may used singularly or in combination, their advantages and disadvantages according to Kraus (1988), must be known for "...effective rational management of the coast". He recommends an effort be made to review historical data on shoreline position, beach profile, and littoral processes in the vicinity of seawalls (and the like), and to initiate comprehensive monitoring programs in accordance with characteristics of a particular site and objectives of the monitoring.

Weggel (1988) makes a point that while there has been some research on seawalls, the research has been "...uncoordinated, nonsystematic, undirected, and not widely disseminated". The primary effects of seawalls on coastal processes are believed to be their effect on:

(i) scour in front of the wall;
(ii) the cross-shore distribution of the longshore current velocity;

(iii) the long-shore sediment transport distribution; and

(iv) the onshore-offshore sediment transport.

‘End’ effects at the seawall’s updrift and downdrift ends are also important since erosion along adjacent beaches is often perceived as being caused by seawalls.

Griggs and Tait (1988) reported results of an approximately one-year long intensive study of four small seawalls of different types on beaches along northern Monterey Bay, California. Their main findings were:

(i) the summer berm disappeared sooner in front of walls relative to adjacent nonstabilised beaches with arrival of winter storm waves;

(ii) the berm in front of a vertical impermeable wall eroded before the berm on an adjacent beach backed by a permeable sloping revetment;

(iii) there was no essential difference in matured beach profiles in front of walls and on adjacent beaches without backing structures;

(iv) wave reflection and impoundment accelerated berm retreat and scour as far as 150 meters downcoast of a wall; and

(v) spring and summer buildup of the berm proceeded the same on beaches with and without structures.

1.3.3 Coastal Protection Research in the South Pacific

A technical report on “Coastal Protection in the South Pacific” (SOPAC/SPREP 1994) identifies the fact that, in general, there has been a lack of monitoring of
coastal protection projects in terms of their relative success or failure and any undesirable environmental impacts. In fact environmental impact assessments in the South Pacific region were rarely carried out in the past until recently. As part of any project regardless of size or purpose it is introduced and most effective during the planning stages when impact on the environment has not occurred. Although environmental impact assessments are widely accepted due to the growing evidence of environmental degradation, in practice it may be resisted in favour of economic and market driven forces.

Coastal protective structures, harbour development, and causeway construction projects, in particular, have caused unintended coastal degradation which have not been properly documented. If monitoring of coastal construction projects was carried out as standard practice, it is argued that such baseline data would enable better coastal management and service for the construction industry. An example of monitoring a coastal engineering structure is the beach profile program which has been carried out on the Nippon Causeway and other causeways in South Tarawa. Profile locations were established and surveyed prior to construction and repeated surveys have been conducted approximately every year (Howorth 1985, 1991).

A principal contributor to marine based research in the South Pacific region in the last two decades has been the South Pacific Applied Geoscience Commission (SOPAC). Formerly known as CCOP/SOPAC (the Committee for Coordination of Joint Prospecting for Mineral Resources in South Pacific Offshore Areas, established in 1972), its initial work programme was to investigate mineral potential in the coastal, inshore, nearshore and offshore areas of its member countries. In 1984, CCOP/SOPAC changed its legal status to become an independent, regional inter-governmental body, also changing its name to SOPAC in 1989. Today while work continues on a variety of topics in all marine environments, geological investigations of the coastal and nearshore environment remains its prime interest (Kotobalavu 1991). Another regional organisation that is contributing to improving the understanding and management of the coastal area of Pacific Islands is the South Pacific Regional Environment Programme (SPREP). The mandate for SPREP was
established in (Rarotonga 1982) the Action Plan for Managing the Natural Resources and Environment of the South Pacific region as adopted by representatives of Pacific Island governments. SPREP is directed by the Action Plan to coordinate environmental assessment, management, planning, training and educational activities in the South Pacific region (Holthus 1991).

In 1992, concern about protection from coastal erosion was expressed by Pacific Island Leaders at the South Pacific Forum meeting held in Honiara, Solomon Islands. The forum:

...noted the need for effective coastal protection in the region and requested that SOPAC and SPREP together: firstly, investigate various coastal protection systems being developed or that are already in place that might be beneficial throughout the region; and secondly, convene jointly such meetings as may be necessary for that purpose (SOPAC/SPREP 1994b).

In 1993, the twenty-fourth South Pacific Forum held in Nauru "reiterated its concern". Within the Forum, concerns and interest in coastal protection were also expressed at the summit for Small Island States comprising such countries as the Cook Islands, Kiribati, Tuvalu, Niue and Nauru.

In 1994, two ‘Coastal Protection’ meetings were conducted jointly by SOPAC and SPREP for the purpose set out earlier by the South Pacific Forum. The meetings recognised that the need for effective Coastal Protection systems in the region was due to increased demand for, and pressure on the coastal zone for infrastructure, commercial, residential, and recreational uses. Healthy coral reefs, beaches and mangroves were perceived as the most effective coastal protection systems, however, with increase pressure on these, alternative options to the natural system were now necessary in certain situations. For an effective coastal protection system, it was recognised that treatment of a problem should be considered in the broadest context, with a long term design ‘life’ and part of a coordinated programme of coastal policy and management. To ensure these provisions for an effective coastal protection system the meetings recognised research and education as particularly fundamental (SOPAC/SPREP 1994b).
In 1995, a third coastal protection meeting was held on Rarotonga to address important issues that needed to be presented at the 1995 Forum. Most significant amongst the discussions was a call for a coastal engineering manual for Pacific Island Countries. Similar to the US "Shore Protection Manual" (CERC 1984), the meeting acknowledged the US manual was outdated and generally it did not address many matters relevant to tropical regions such as the South Pacific.

The meeting was also unable to endorse the design claim that the cessation of coastal erosion and promotion of sand accumulation at the Rarotongan Resort Hotel site, Rarotonga, was caused solely or predominantly by the CPU’s (Coastal Protection Units) placed at the site in 1991 (SOPAC/SPREP 1995). It is believed that the surge of interest in coastal protection in the South Pacific most recently is due partly to the work carried out at the Rarotongan Resort Hotel, funded by New Zealand’s Overseas Development Assistance programme, developed by Mr Don Dorrell and the University of Canterbury, New Zealand and vigorously promoted by the government of the Cook Islands.

1.3.4 Coastal Protection Research in the Cook Islands

The earliest scientific investigators of the coastal zone were more interested in the morphology and extent of coral reefs. For example, Darwin (1842), Marshall (1913) and others. Over the years, the principal contributors to research have “focussed mainly on the terrestrial biology and geology of the islands” (Miller 1980).

In recent years though, there has been a significant increase in the amount of studies conducted in the nearshore coastal zone and the nearshore oceanographic regime of the Cook Islands, particularly bathymetric work and nearshore process-response studies. The majority of which have been carried out on the island of Rarotonga; the administrative, social and economic centre of the Cook Islands and provided for mainly by aid-donor support.
New Zealand has been the main donor of aid to the Cook Islands since its annexation in 1901 from Great Britain. For sixty four years the Cook Islands remained a part of New Zealand until they became 'independent', with free association, in 1965. Free association means that New Zealand assumes responsibility for the Cook Islands external affairs and defence while Cook Islanders retain New Zealand Citizenship. Today, under New Zealand's Official Development Assistance (ODA) programme, the Cook Islands receives budget support "to meet its social and development objectives" and project aid. The most relevant (to this study) and notable aid projects in recent years is the construction of an International Airport on Rarotongan the early seventies, Harbour development on several islands, development of the Cook Islands Conservation Service, and the monitoring and management of the coastal erosion and saltwater inundation hazard at the Rarotongan Resort Hotel site. In addition to direct ODA, the Cook Islands also benefits from New Zealand regional programmes. New Zealand contributes funds to the South Pacific Forum Secretariat, South Pacific Commission (SPC), South Pacific Regional Environmental Programme (SPREP), University of the South Pacific (USP) and others. Most recently though, the value of grants from New Zealand made for budget support has declined, this is in recognition of the growing strength of the Cook Islands economy (Thompson 1993).

Perhaps the single most significant contributor to research literature in the Cook Islands, in recent years, with respect to nearshore and nearshore oceanographic studies, is the South Pacific Applied Geosience Commission (SOPAC). SOPAC related research of the nearshore include the work of Lewis et al (1980) and Gauss (1982) on the study of reef channel sediments and nearshore areas. A relatively large scale study of coastal morphology and processes around the entire island of Rarotonga was carried out by Richmond (1990) and Reidel et al (1990) carried out a brief review of coastal development and coastal engineering planning in the Cook Islands. SOPAC had a waverider buoy moored southeast of Rarotonga from July 1987 and retrieved in 1991 with the aim to map the ocean wave climate offshore. Barstow and Haug (1994a) present the collected waverider data which is useful to coastal defence, harbour design and improved wave forecasting.

The most innovative and controversial work conducted on Rarotonga is originally set out in a report to the Cook Islands Government by Dorrell (1988) incorporating earlier work on coastal erosion and its management at the "Rarotongan" site by Kirk (1983, 1986). The use of pre-cast concrete Coastal Protection Units (CPU), a new technology developed by Mr Dorrell, was installed and monitored by Kirk (1990, 1991, 1992). Further development by Mr Dorrell into a Coastal Protection and Energy Dissipation (COPED) system is currently in progress.

1.4 The Research Problem

1.4.1 Thesis Framework

Geographers and Coastal Geomorphologists alike find it to their advantage to approach investigative research and particularly the study of complex and dynamic systems such as the coastal zone by applying conceptual frameworks or models to better understand the whole of a process or product (its eventual outcome) by isolating its integral parts. In this way the complexity of reality is broken down into isolated parts (either in fact or in theory) so as to provide a world that is simply much more readily understood. However, the point must be made here that the real world is continuous and conceptual models, though largely qualitative in their approach must still be complex but yet simple to comprehend and investigate. Conceptual models:
point the way towards a choice of observations and measurements and can be used to implement the model, either to test its validity in terms of real-world phenomena or to use the model as a predictive advice (Chorley et al, 1971:20).

Three models have been selected to represent this study. The first (Figure 1.2, page 15) is a "process-response model" of the coastal system which was developed by Krumbein (1965). It demonstrates the manner in which three main process elements (energy factors, material factors, and shore geometry) are related to process (beach geometry and beach materials). That is, it identifies the relationship between a process and the forms resulting from it. It assumes that response elements are dependent upon the dynamic nature and interaction of processes. Although, what is not shown in the model but should be understood in the real world situation is the distinction of time, such that beach response is not immediate and that "changes can take time to reach its new equilibrium stage" Krumbein (1965).

![Diagram of process-response model of a beach](Source: Krumbein 1965:9)
A feedback loop indicates the elements continuation to strive for equilibrium or a steady state by mutually adjusting themselves to changing input-output relationships. The feedback can be either negative or positive. Negative feedback occurs when the "work done by the feedback mechanism opposes the main driving force" (Chorley et al, 1971:349). And positive feedback occurs when the "...feedback mechanism reinforces the main driving force" (Chorley et al, 1971). An example of positive feedback occurs when human action in the physical system affects the process elements; such as, sand extraction, harbour development, coastal protection structures and the like.

The second model (Figure 1.3, page 17) is required to compliment the process-response model of Krumbein (1965). The 'Coastal Sediment Budget' model indicates most importantly that coastal systems are open systems that allow for the losses and gains of both mass (materials) and energy across its boundaries to ultimately produce a steady state or equilibrium. The model describes the potential variety of sediment movement both into and out of the beach system; it is especially useful in understanding and determining net beach gain or loss of sediment within the dynamic beach system.

With respect to the coastal environment of Rarotonga, Kirk (1980:16) adapted and developed Figure 1.3, a sediment budget model for Ngatangiia Harbour and Muri lagoon. The model indicates the highly complex nature of tropical coastal environments, in particular, it indicates the source and sinks of terrigenous, lagoonal, reef and nearshore ocean sediments. The model requires perhaps a minor modification or consideration before it can be used for this study and that is the inclusion of coastal structures such as seawalls, random tipped basalt revetments, even buildings in the active littoral zone. Such structures are apparently becoming widespread on the mainland beaches of Muri and threatening the existence of a beach in their vicinity, even to the structures themselves.

The third model is concerned with the complex relationship between people and the natural world or the natural event system which in essence is the thesis of this study.
One way to conceive this relationship is in the form of a cause and effect model or a basic interaction model with feedback to both the natural and human systems depicted by Figure 1.4, page 18 (in Ericksen 1990). The model suggests the response to a perceived hazard involves first an awareness of threat and then of the opportunities for making adjustments to it. Which adjustments are chosen by individuals or communities depends on a range of behavioural, technical, political, economic, and factors (Figure 1.4(4), page 18).

![Figure 1.3: A Sediment Budget Model for Ngatangia Harbour and Muri Lagoon (Source: Kirk 1980:16)]

Essentially the model recognises three main types of adjustments to hazardous effects, that is:

1. Modifying the natural event by manipulating the earth processes in the natural event system, for example, building seawalls against large waves, reef blasting altering the hydrodynamics having consequences for beach sediment transport
and the entrainment of high water levels during extreme events of high seas, and the like;

(2) Modifying the human use system in areas at risk from extreme events, for example, zoning ordinances aimed at making land use more compatible with levels of risk to which various areas are exposed, building codes to ensure safety during extreme events, and the like; and thirdly,

(3) To modify or re-distribute the losses that are experienced (or might be experienced) by individuals through adjustments like insurances, tax concessions and relief programmes; and communities to the wider population by mainly subsidised rehabilitation programme.

As Ericksen (1990) points out that whatever planning responses are taken to reduce hazardous effects, they must be underpinned by adequate information about both the natural and social processes.
1.5 **Thesis Aims and Framework**

This thesis therefore has five broad aims:

1. To describe and assess current Coastal Protection methods used on Rarotonga.
2. To examine localised effects of select Coastal Protection measures on both the beach morphology and processes.
3. To examine beach response at the toe and ends of select Coastal Protection measures.
4. To measure process-response relationships at select Coastal Protection sites.
5. To provide a database for future research

To achieve these aims, this study has utilised the most (cost) effective, efficient, and available methods. The principal technique used to collect direct measurements from the littoral zone, sometimes under difficult tidal conditions, was by way of shore normal beach profiles using a battery-powered Sokkisha (DT 5) theodolite. This thesis is testimonial to methods used; and, in particular, it reflects the principal goals outlined above.

Chapters 2 and 3 draw mainly on established knowledge of South Pacific environments which is necessary for a reasonable level of understanding, particularly of complex relationships, so that the communication of ideas is not impeded.

Chapters 4 and 5 present the quantitative and qualitative results relating to a ten week field study conducted on the island of Rarotonga by the author. Chapter 4 presents information relating to the attributes of the selected study sites, field methodology, data treatment, and a view on the difficulties encountered in the field. Chapter 5 presents the results and observations collected in the field and it also
provides an interpretation of these. The most significant is the survey profile data which was collected to elaborate on the complex relationship between process-response elements and Coastal Protection structures.

Chapter 6 interprets and explains the findings relating to the field research work in the context of the overall research project.

Finally, Chapter 7 presents the conclusions drawn from the descriptions and analysis of nearshore processes and beach response near coastal protection structures and suggestions are made for further research.
CHAPTER TWO

2.0 Coastal Environments of the South Pacific

2.1 Introduction

In general, all coastal zones are determined by some interaction and/or linkages between the terrestrial and marine environment which are frequently influenced, either directly or indirectly, by variations in the weather and climate. "Nowhere are such interactions more evident than within the coastal environment of islands in the South Pacific" (in SOPAC/SPREP 1994a).

South Pacific island coastal zones are characterised by a number of distinctive physical features. Many of these features are not unique to the region and can be found elsewhere in the world. However, the fact that these features may be found together in one region is unique. These distinctive features include:

(i) Islands and groups of islands with a diversity of geological origin, composition, age, size and elevation.

(ii) Marked temporal and spatial variations in climatic and oceanographic regimes.

(iii) Wave conditions which have a dominant role in physical coastal processes and which also vary significantly in the region.

(iv) Coral reefs which are a common and often dominant feature and other carbonate related coastal features.

(v) Water levels and currents in the coastal zone which are strongly modified by fringing reefs.
(vi) Natural beach material supply which may be from either entirely terrigenous or carbonate sources, or a variable combination of both.

(vii) Mangroves are often a prominent and important feature of the coast.  

(After Gillie 1994)

The focus of this chapter is to present background knowledge about South Pacific coastal environments and in particular, the physical processes that are important to the understanding of the characteristics observed in the coastal zone. To conclude this chapter, a review of current coastal protection systems is presented.

2.2 Geology and Coasts of South Pacific Islands

Within the South Pacific Commission area (Figure 1.1, page 2) there are three main distinctive types of islands classified on the basis on their geologic origin, composition, age, size and elevation above sea level. These are:

(i) Volcanic islands

(ii) Low lying coral atolls

(iii) Emergent limestone islands  

(After Gillie 1994)

This study is particularly focused on volcanic islands since Rarotonga, the study area, is of this type. Related to this range of island types and their tectonic setting is a corresponding variety of coastal environments. Combinations of these geologic settings can also be found, for example, elevated reefs on volcanic islands and smaller volcanic islands surrounded by an atoll-like lagoon.

Volcanic islands may vary considerably in age, elevation and size. Each characteristic may affect the coastal zone directly as well as indirectly. For example, rugged cliffs and pocket beaches are associated with relatively recent volcanic islands like Western
Samoa. Extensive plains and associated deltas are found on larger, older in age type islands which is characteristic of Melanesian based islands such as Fiji, Solomon Islands, Vanuatu and Papua New Guinea. Younger volcanic islands tend to be fringed at the outer limits by a narrow coral reef, for example, Rarotonga island in the Cook Islands, while older volcanic islands have extensive barrier reefs with wide, deep lagoons such as Viti Levu, Fiji (Gillie 1994).

Atolls and reef islands are commonplace in the South Pacific, for example the Republic of Kiribati, Tuvalu, Marshall Islands, Federated Stated of Micronesia, Tokelau, French Polynesia and the northern Cook Islands. These islets are the most vulnerable to natural and human-induced coastal hazards.

Emergent or elevated coral islands are former coral atolls or reef islands which have been lifted above the ocean surface leaving near vertical limestone cliffs (Makatea) or a very narrow limestone platform. Examples of such islands are Nauru, Banaba, and Kiribati. Variations of this type may include a makatea which is an annular ring of raised reef around a volcanic core, for example, Mangaia, Atiu and Mauke in the Cook Islands. Some island groups may be composed of an archipelago of volcanic islands with uplifted and tilted coral reefs, for example, the Tongan islands (Gillie 1994).

It should be emphasised that the islands and their coasts have been far from static over geologic time. Tectonic activity of both horizontal and vertical crustal movements are variable but a common characteristic of most South Pacific Islands. Tectonic activity may generate some unseasonally high waves or tsunamis that can be threatening to low lying atolls. South Pacific Island tectonic regimes include convergent and divergent plate boundaries (associated with island arcs, subduction zones and back-arc basins) and mid-plate areas associated with hot spots and areas of rising and sinking sea floor. Past changes associated with these tectonic settings and climatic variations both past and current have either singularly or in combination created the coastlines that are apparent today (Gillie 1994).
2.3 The Climatic and Ocean environment

The Pacific Ocean is the largest feature on the earth’s surface and even the designated South Pacific Commission (SPC) area which covers approximately 27.5 million km$^2$ and extends 130° W to 130° E, on either side of the international dateline between two tropics. From Micronesia in the northwest Pacific where the islands represent only a small fraction of the ocean area, Polynesia in the east where its remoteness from continents gives an impression of isolation to Melanesia in the west where land area is much more pronounced; the SPC area consists of only 2 per cent of emerged land while water represents 98 per cent (Wauthy 1986).

In the southern hemisphere isobars are approximately zonal; the sub tropical high pressure belts are practically continuous although there is some increase in pressure over Australia during the southern winter, while in summer, the north of the continent is invaded by the Indonesian equatorial low pressure zones. This pressure field ultimately determines the low level wind patterns which are responsible for the agitation of the ocean surface and the creator, in part, of wave breakers that affect all coastlines and beaches in the region. Hence, an understanding of the wind field (speed and direction) is of paramount importance to the Coastal Manager. In the Pacific inter-tropical zone, the wind field is characterised by the trade winds. Ocean-atmosphere exchanges, which determine weather to a large extent, depend on the wind field (speed) and also the seasonal thermal factor of solar radiation. Clouds, precipitation, ocean circulation, atmospheric circulation and tropical cyclone development to name a few depend upon low level winds and ocean temperature (Wauthy 1986).

The Pacific ocean is so large that it creates its own atmospheric circulation system known as the ‘Walker Circulation’ which pivots around two centres of action. One lies between Indonesia and Australia, and the other lies off the coast of Peru. Low pressures over northern Australia and high pressures over the eastern Pacific characterise the ‘Walker Circulation’ in its normal or neutral mode (Hay et al 1993).
Because of the interaction between ocean and atmosphere, there is a semi-periodic (two-to-seven-year) cycle of disturbance in the Walker Circulation termed the Southern Oscillation. Over the tropical Pacific, the Southern Oscillation is notably associated with rainfall fluctuations, widespread sea temperature warmings, and the movement of the Intertropical Convergence Zone (ITCZ) and the South Pacific Convergence Zone (SPCZ). During El Nino events the Walker Circulation is weaker than normal and may even reverse. Pressures are lower over Tahiti as warm air rises, while over Darwin, high pressure dry air descends. In contrast, during La Nina events, the normal state of the Walker Circulation intensifies. The changing winds of the Walker Circulation force alterations in the state of the surface ocean waters, creating a vast internal oscillator (Hay et al 1993). These long distance pressure indicators throughout the Pacific Basin are responsible for uncharacteristic and sometimes extreme climate events.

There were ENSO (El Nino, Southern Oscillation) events in 1957-1958, 1965, 1972 (moderate), 1977-78 (moderate), 1982-83 (strong), 1987 (moderate) and a recent prolonged moderate event from 1990-1993. The timing of actual ENSO characteristics such as deviations in wind strength and direction, rainfall, and sea level deviations will vary across the region and can also vary within similar Southern Oscillation Index (SOI) values (Gillie 1994).

As a result of the extreme El nino event of 1982-83, higher than normal pressures over Australia brought clear, dry, descending air, and crippling droughts. Over the eastern Pacific, low pressures and moist ascending air caused storms and floods in Peru, Argentina and California (McGlone et al 1991). Tahiti being relatively free of Tropical Cyclones for years was struck by several cyclones in one season.

Tropical Cyclones are extreme climatic events that occur with a variable seasonal frequency in all parts of the tropical and subtropical Pacific island region, with the exception of a relatively narrow zone (5-10 degrees) either side of the equator. The mean incidence of tropical cyclone activity for Rarotonga is 1.4 per year. The most active region of tropical cyclone activity in the SPC area is the western north Pacific.
The high winds, large waves, storm surge and heavy rainfall associated with tropical cyclones have short term catastrophic and permanent impacts on all coastal environments in general, in particular, low lying islands (Gillie 1994). In this respect, it has been noted that tropical cyclones

...represent a high magnitude, low frequency event necessary for the long term replenishment of sediment on shorelines, but that in the short term such storms will seem to have mainly destructive effects (Bayliss-Smith 1988 cited in Gillie 1994).

2.4 The Wave Climate

Wave characteristics and wave conditions in the South Pacific Commission area vary significantly in time and location principally because of the vast oceanic hemisphere it encompasses. The wave environment of the South Pacific region is considered to derive from the following:

(i) Prevailing, trade wind generated, northeast to southeast seas and swell waves.

(ii) In equatorial regions, seas generated by westerly gales during the wet season (typically December-February in the southern hemisphere).

(iii) Tropical storm or cyclone generated sea and swell waves, and

(iv) Swell waves generated by mid-latitude storms in both the south and north Pacific Ocean. (After Gillie 1994)

The wave climate of each country, island or coastline is a product or variation of these four major components. As there is also seasonal and annual variation (ENSO events) to consider, the wave climate can vary significantly over time and cause cycles of coastal erosion and deposition.

Trade winds generate local seas and swell waves on eastward facing coastlines that are generally persistent and may form the dominant component of the local wave
environment. For this reason, the eastern sides of most islands are the so-called 'windward coast' and the western sides the 'leeward' or sheltered coasts. In atoll islands, most islets are on the windward side of the atoll. However, most villages are located along the lagoon shoreline, on the leeward side of windward islets and are sheltered from the prevailing winds (Gillie 1994).

In the low latitude equatorial regions the 'normal' easterly trade wind dominance is reversed for periods of time during the westerly or wet season and especially during prolonged El Nino events. Gale force westerlies can generate moderate sea waves in the open ocean which may pass over the submerged reefs on the leeward side of an atoll and into the normally sheltered lagoon environment (Gillie, 1994). This results in phases of erosion on lagoon shorelines beaches which are otherwise normally stable (Gillie 1994). Coastal movements in Kiribati, for example, were recognised to correlate with strong westerlies which were related to negative values of the Southern Oscillation Index (Howorth 1983).

Waves, currents and storm surges associated with tropical cyclones generate extremely high energy conditions in the coastal zone for short and usually infrequent periods of time. The immediate effect of cyclones on the coastal zone is extensive foreshore erosion, wave damage to buildings, structures and vegetation, raised seawater levels, and accumulated coral rubble along the beach fronts (Cowan et al. 1991, Gillie 1994).

Although tropical cyclones do not normally occur over equatorial islands, the common presence of coral rubble and boulders (For example, on atolls in Kiribati) suggests that cyclone storm swells can penetrate beyond the cyclone belt, occasionally contributing to local reef erosion and islet coastline deposition (Gillie 1994). The role of storms in the accumulation of coastal deposits on reef islands and their contribution to the sediment budget supply of coastlines is well documented. This natural process has enabled the periodic renewal of coral reef fauna and the long term replenishment of sediment on shorelines.
Swell waves generated by large storms in the mid-latitude regions of the north and south Pacific Ocean can travel vast distances with relatively little energy loss. The south facing coasts of most South Pacific island countries are particularly vulnerable to persistent southerly swells in all seasons. Swell waves may be moderate (2-4 m) to heavy (4-6 m) during the southern hemisphere winter (May to September) on the south facing coasts of the exposed southern islands of Fiji, Tonga, the Cook Islands and French Polynesia. However, heavy southerly swell conditions resulting in coastal damage are possible at any time of the year as reported on the south coast of Rarotonga in mid December 1993. Low swells (1-2 m) may also be experienced on the north facing coasts during the northern hemisphere winter (November-March) (Gillie 1994).

More detailed descriptions of the wave climate of Vanuatu, Fiji, Tonga, the Cook Islands, Western Samoa and Tuvalu are available in a series of SOPAC Technical reports (Barstow and Haug 1994c). Until recently there had been little direct measurement of the wave environment in the South Pacific. Characterisation of the wave climate was based upon wind and weather systems, about which the long term pattern and variability is better documented. With a wave measurement programme carried out recently by SOPAC using the deployment of wave rider buoys at six sites across the region, more detailed descriptions of the wave climate are now available contributing to the understanding of coastal processes.

The results of the wave measurement programme are summarised by Barstow and Haug (1994c). In the open ocean, average annual wave heights vary from a little under 2 meters to the west of the Kiribati group at the equator and to the west of the Vanuatu group in the Coral Sea, to close to 3 m at 30° south of the southern Cook Islands. Seasonality in wave heights is modest, particularly in the low latitudes. Wave heights do tend to be somewhat higher in the south in the winter and higher in the north in summer. In the north this is due to higher influx of northerly swell in the northern hemisphere winter, and in the south, a combination of higher winds and southerly swell contributes (Barstow and Haug 1994c).
2.5 Coral Reefs

"The coral reefs of the southern Pacific are the most prolific in the world, and provide a habitat for the most diverse reefal flora and fauna. This variety has been produced by mega-structural elements and processes of plate tectonics" (in Hopley 1991).

The most significant coastal difference between the South Pacific islands and other countries in more temperate areas is the coral reef that surrounds most of the shorelines. Coral reefs may be classified as:

(i) **Fringing reefs**: Adjacent to the shoreline or separated from the shoreline by a shallow body of water or channel. Although generally smaller than other types of reefs, they are the most common throughout the Southern Pacific particularly away from the influence of freshwater and sediment at river mouths (Hopley 1991).

(ii) **Barrier reefs**: separated from the shoreline by a deep channel. The best example is the ‘Great Barrier Reef’ of Australia.

(iii) **Atoll reef**: a reef rim enclosing a central lagoon.

(iv) **Reef islands**: table or platform reefs without a central lagoon.

Nature provides many examples of coastal protection for which reef systems are the most common and widespread in the South Pacific. Coral reefs are also important because of the effect they have on beach morphology, affect water levels and currents within the coastal zone and ultimately supply beach material from which beaches, small islands (islets or motu) and larger islands are constructed.

Coral reefs may vary in width from a few tens of metres to over a kilometre. They act as a first line of defence against ocean waves and will always initiate wave breaking when the wave height exceeds the water depth over the reef. In the case of
fringing reefs, it has the benefit of limiting the wave height to a little more than half of the water depth that exists at the time. The energy transmitted by waves to the shore is proportional to the cube of the wave height. Therefore, the ability of the reef to limit this wave height is a critical factor in the relative stability of tropical shorelines (Byrne 1994).

The width and depth of the reef is critical in determining the residual energy of the wave that acts on the beach. If the reef is narrow or deep (that is a reef width of less than 50 m) the wave that starts to break on the reef edge will maintain most of its energy when it reaches the beach. In this case, the reduction of wave energy that acts on the beach is limited and the erosive force may be large. Hence, during cyclones the waves acting on the beaches may exceed heights of 5 metres. If the reef is wide and shallow, then most of the wave energy may dissipate on the reef before reaching the shoreline (Byrne 1994).

The effect of fringing reefs on waves as they travel over the reef also has a secondary effect that is important but has received little attention until recently. This secondary effect is the substantial increase in water level that occurs on the reef flat due to the breaking waves pumping water onto the reef at a much greater rate than the water can run off the reef. This localised increase in water level on the reef in turn generates currents over the reef and along the beach front, which may contribute to the rate at which sand is transported along a beach. The effect of “wave pumping” of reef lagoon currents has been well documented in the case of Muri lagoon on Rarotonga (Kirk 1980, Holden 1992).

An impervious basalt rock breakwater extending from the beach to the reef flat on the west flank of Avarua harbour entrance, Rarotonga, was removed because it impeded the drainage of water from the lagoonal area during cyclone Sally (1987). By increasing the water levels close to the shoreline the hazard potential in the area was also heightened (Dorrell, Coastal Protection Consultant, Rarotonga, pers comm 1995). Avarua harbour and areas adjacent to it were not so fortunate, experiencing
extreme wave heights with saltwater inundation and debris reaching sometimes two hundred metres inland.

The preservation of coral reefs may be argued as the most effective and economical form of coastal protection for many South Pacific countries, in particular atoll countries. Therefore its preservation must be of paramount importance. But due to the increasing contemporary demands of the human habitat on the natural system by, for example, the disposal of household and industrial wastes offshore, the leaching of agricultural fertilisers causing eutrophication of lagoons, siltation of waterways due to mining and development and the like, the survival of reef systems is most vulnerable.

2.6 Sources of beach material

This section is provided to highlight sources of sediment supply of South Pacific island beaches which differ from that of temperate regions mainly because of their carbonate sources. It is important to note that reef systems which provide most of carbonate sediment supply are dependent on micro-organisms such as the blue green algae. Anything which alters the productivity of these algae will greatly affect the whole reef system (Hopley 1991) and consequently carbonate sediment supply.

Natural beach material supply may be terrigenous or carbonate sources or a combination. Terrigenous materials dominate shorelines near large rivers in the larger volcanic islands of Melanesian based islands. However, the most distinctive and widespread source of beach material is from carbonate sources (coral, foraminifera, algae and shells) (Gillie 1994).

Fringing reefs can grow quite rapidly in geological terms (that is, in the order of millimetres per year). Their rapid growth is periodically offset by wave action during extreme storm events and dumped over the reef as rubble to eventually replenish the beaches. On atolls where there are quiet lagoons, carbonate production can be very high in areas not affected by wave attack. For example, Funafuti and Muri lagoon
(Rarotonga), the calcareous algae Halimeda is a significant source of carbonate sediment. In other lagoons such as the atolls of Kiribati, foraminifera are a major contributor to carbonate sediment supply (SOPAC/SPREP 1994b).

The understanding of natural sources of beach material and carbonate sediment budgets is fundamental to coastal management and coastal protection systems of South Pacific Islands.

2.7 Coastal Erosion

This section focuses primarily on those common factors that contribute to coastal erosion in the South Pacific region. Although the point is made earlier that due to the variability of coastal processes often coastal protection is site specific (Foster 1982), physical erosion on the other hand can be regarded as a universal problem having a common effect regardless of location. It is caused by an agent which humans have limited or no control over, nature.

In principle, two basic erosion problems with sandy coasts do exist, viz:

(1) erosion/recession during a storm (surge) event during which erosion occurs rapidly in response to the high energies of storm waves, and

(2) gradual long term.  

(After Van de Graff and Bijker 1988)

Depending on the cause and duration of erosion an appropriate method of coastal stabilisation is formulated if permanent resources such as roads, buildings, and even the beach itself are threatened. Figure 2.1 (page 33) depicts strategies to deal with coastal erosion (Kraus 1988).

One of the most commonly thought of causes of widespread contemporary coastal erosion is the rise in global sea level which can produce coastal retreat and severe
land loss to areas of low elevation such as atoll islets, deltas and lowland areas. But beach erosion may not be the product solely of sea level change, but rather the result of a range of controls. For example, the quasi-biennial El Nino/Southern Oscillation (ENSO) in the Pacific produces sea level elevations that are as significant as those produced by global sea-level rise (in Hansom and Kirk 1990). Further, it is difficult to obtain a consensus among the scientific community as to what presently constitutes evidence of coastal erosion associated with sea level rise.

Sand mining of beaches in the South Pacific region for both construction and land reclamation purpose ranks highly as one of the most common contributory factors to coastal erosion. SOPAC have investigated numerous sites perceived to have been degraded by sand extraction. Tongatapu, Tonga (Lewis et al 1991); Mulinu’u Point, Western Samoa (Carter 1991); Mele Bay, Vanuatu (Rearie 1990); and Ranadi Beach, Solomon Islands (Gillie 1993). In some cases, alternative sources of sand have been investigated either offshore such as on Rarotonga (Lewis et al 1980; Gauss 1982) or from lagoon sources (Smith 1991, Smith and Gatliff 1991).
Land reclamation of the active beach zone usually backed by storm or beach ridges can increase the likelihood of erosion both upcoast and downcoast. Land reclamation, like seawalls, restricts the supply of sand from the buffer zone or backshore ridges into the active beach system that would under normal conditions be used to stem coastal erosion. Harbours, causeways, airports, boat ramps, jetties and the like, that require modification of the beach to accommodate will promote coastal erosion in their lifetime. For example, the causeway construction on South Tarawa, Kiribati; small nearby islets have completely eroded since its construction. According to Byrne (1991) it is possible that before the causeways were built, the water level was lower in the local area because water would drain through into the lagoon. Now that the causeways are in place, waves breaking on the outer reef cause the water to build up higher on the reef. This allows more wave energy to reach the shore of the islands thus causing erosion.

Finally, it must be emphasised that coastal erosion is a naturally occurring phenomenon sometimes assisted by human-made structures or by human activities such as the removal of material from the beach. It may be long term, temporary or episodic (Van de Graaff et al, 1988).

2.8 Coastal Protection

This section will focus primarily on a description of existing coastal protection systems throughout the South Pacific Commission area and report briefly on the attributes of these. The primary source of information used in this section was presented by participants representing member countries of the South Pacific Forum at a series of 'Coastal Protection' meetings organised by SOPAC and SPREP (1994b, 1995).

A review of the responses and papers presented by the participants of the various South Pacific island countries point to some distinct features relating to the natural and human use of the coastal system. The following account is an attempt to facilitate a classification of the responses in order to describe the contemporary
environmental, social and economic values which people in the South Pacific place upon the coastal zone.

With respect to the natural and human uses of the coastal zone the interactive systems model (Figure 1.4, page 18) is useful. Often choices to reduce a problem can lead to the proliferation of problems. "Systems modelling can be helpful in exploring these various effects" (Ericksen, 1990).

Typical coastal problems usually lead to hazard proliferation. In general, there are three distinct adjustments to hazards that are recognised:

(1) To modify the natural event. The best example is the engineering adjustments using the skills of engineering to affect the cause of the problem or modify the hazard itself (Figure 1.4(1), page 18).

(2) To modify human use in areas at risk from extreme events through, for example, land use management (Figure 1.4(2), page 18) or

(3) Some combination of (1) and (2)

(After Ericksen 1990)

In the South Pacific region it is found that the use of artificial coastal protection is limited by several distinct factors. These factors are governed by economic, cultural and environmental constraints. For example, on high coral islands such as Nauru and Niue the rugged coral (makatea) coastline and the coral reef flats provide a natural coastal protection system that is arguably superior to any artificial system. Nauru, historically has been free of tropical cyclones or storms. But during Cyclone Ofa large waves overtopped the vertical-faced coral (makatea) coastline and damaged a hotel in Niue. The main concern for these types of islands is not artificial coastal protection but the preservation of their natural coastal protection systems (in SOPAC/SPREP 1994b).
For coral atoll countries such as Tuvalu, Kiribati, Palau, northern Cook Islands, and the Marshall islands to name a few; artificial coastal protection may be perceived as necessary due to the low level elevation of atoll islets relative to absolute sea level and also the increasing pressure of population on the scarce resource of land. Population pressure on Majuro and Ebeye in the Marshall islands, for example, where sixty per cent of the population is concentrated means these two atolls have probably exceeded their basic ecological carrying capacity whereby they are now vulnerable to environmental degradation and extreme high intensity wind and wave events. Since land is privately owned, exploitation of the coastal zone can be uncontrolled. Sand mining is a principal contributor to coastal erosion and generally it is a universal problem in the South Pacific region. For the Marshallese, sand for construction is sourced from the beaches and dredged from lagoonal nearshore areas. Armour rock for artificial coastal protection is derived from reef blasting on the lagoon and ocean side of the atoll. However, the annual demand for building materials and in particular sand is exceeding sustainable limits hence alternatives are being sought by encouraging the use of coconut timber. Scrap metal such as bulldozer and diesel engine parts are being utilised as offshore breakwaters. For most atoll countries since the coastal zone is very vulnerable to storm hazards, setback lines or hazard zoning may be established. However, it must be pointed out that in most cases the coastal zone may include the entire atoll islet. Artificial coastal protection systems may be the best solution to remedy hazard but there are pitfalls. For example, gabion baskets filled with rocks failed in Kiribati and the Marshall islands due to corrosion induced by the wave climate. Rock revetments and seawalls were used with limited success due to primarily the lack of large sized and high density rocks. Concrete cement structures were perceived as too costly (in SOPAC/SPREP 1994b).

On larger predominantly volcanic islands such as Rarotonga, in the Cook Islands; Upolu and Savaii in Western Samoa; Viti Levu and Vanua Levu in Fiji; Tongatapu in Tonga; and Efate island in Vanuatu; to name a few; the use of artificial coastal protection may be widespread particularly about areas of economic and cultural importance. For example, a significant proportion of artificial coastal protection on Rarotonga fronts the central business area of Avarua. This area is also most
vulnerable to extreme storm events. On Tongatapu the seawall at Nuku’alofa at 2.7 kilometres long, was re-built after Cyclone Isaac (1982) because of the economic value of assets in this area. In Vanuatu, although the extent of artificial coastal protection structures is not well documented, there is a seawall in the waterfront area of Port Vila harbour. This seawall has been damaged by cyclones Uma and Betsy (in SOPAC/SPREP 1994b). For these relatively larger islands and to some extent atoll islands that are the focal point of internal politics and economic development, the economic benefits bestowed upon them have surpassed their peripheral counterparts. As a result, uneven development within island countries has eventuated which partly explains why artificial coastal protection is not widely distributed within countries.

Because of the high capital costs involved in the design and resourcing of artificial coastal protection systems and the magnitude of hazards in the coastal zone, such projects are usually only feasible by local government assistance and/or by donor-aid. Where there is private or non-governmental involvement, it is usually to resource such large scale projects with materials and labour. Unless directly affected by coastal hazards to their property, private and non-governmental interests will resort to coastal protection themselves. Often these responses are piecemeal and sporadic with a tendency to refer hazard to neighbouring sites. In the context of this study, the contribution of private and commercial owners is important because their activity in the coastal zone is increasing, thus, having a significant effect on the use and distribution of artificial coastal protection.

The purpose and function of artificial coastal protection as it is understood in the South Pacific region (SOPAC/SPREP 1994b) is to protect economical valued assets such as roads, airports, harbours, central business areas property of land, human dwellings and the like from the threat of hazards. The emphasis is on the use of the skills of engineering to affect the cause of the problem or to modify the hazard itself (Figure 1.4(1), page 18).

Another approach to reducing hazard effects involves the modification of human use and/or behaviour so that human activity is less exposed to the impact of the hazard
event. The best example is the use of planning techniques such as zoning to modify the losses (Figure 1.4(2), page 18). For atoll islets setback lines may be used, however, as pointed out earlier, it must be appreciated that the coastal zone which is both complex and dynamic may include in some cases, the whole atoll islet. For island countries where legislation of the coastal zone exists, setback or hazard zonation may already be enforced. Where legislation has been less effective, it is primarily due to cultural customs and traditions at the village level where guardianship of foreshore may be disputed. For example, in Kiribati, people have a mentality that they own the foreshore, adjacent to their piece of land. In this sense, they are free to erect coastal protection structures once they experience erosion or if they want to reclaim more land (SOPAC/SPREP 1994b). In Western Samoa, "the development of the coastal zone [was] not an option - it [was necessary]" (Bell 1994). The majority of the population on both Upolu and Savaii is concentrated in the coastal fringe while it is very rugged with difficult terrain in the interior to be settled extensively. Due to political pressure from the village level, the roading system was forced seawards and today it follows closely the coastline. An infrastructural asset of high economic value was perceived by villagers to have lesser significance than land holdings whereby excessive roadworks (involving hard stabilisation at the land/sea interface and extensive land reclamation) was utilised to distance human settlements from known hazards as well as increase land holdings (Bell 1994).

The third approach to hazard effects noted in the systems diagram in Figure 1.4(3) (page 18) is to redistribute losses that are experienced (or might be experienced) by individuals and communities to the wider population. In effect, these adjustments overtly spread the burden of loss away from the affected parties to the population at large (Ericksen 1990). This is commonly achieved through adjustments like insurance cover and relief programmes. In the Cook Islands, however, after Cyclone Sally in 1987, the insurance companies withdrew all cover on wave surge damage, a move which had significant implications on the commercial sector, the general public and the government. The withdrawal of insurance cover on coastal properties meant that property owners were obliged to undertake drastic measures to protect their assets at their own cost or face losing their property to hazards. Such a move has resulted
in the proliferation of artificial coastal protection on Rarotonga (SOPAC/SPREP 1994b).

In general, the most favoured combination of adjustments adopted in the South Pacific region by areas prone to coastal hazards is to relieve and rehabilitate losses as they occurred, and then build artificial coastal protection works to prevent further losses. However, this traditional pattern of adjustment may have changed in recent years due to, for example, the fact that it is difficult to obtain insurance cover and governments do not provide subsidy for coastal damage unless it is available through relief and rehabilitation programmes provided by donor-aid. In which case, assets are re-located inland or property owners are obliged to set up artificial coastal protection barriers at their own expense or face total loss of their property.

On the other hand, adjustments in support of land use management are primarily promoted by local government authorities having a mixed response to its adoption. With the recent introduction of television to a majority of Pacific Island countries, it has been a useful medium, for example in the Cook Islands, for relating effective coastal land use management strategies. As well, there are many factors at the local level which discourage widespread adoption, these are more likely to be influenced by customary and cultural practices.

2.9 Summary

The vital commercial and national assets, essential infrastructure, and population of most South Pacific island countries lie in the coastal zone. With the increasing use of the coastal zone and a greater awareness of its associated hazards, coastal protection has become a topical issue. Not only in the scientific and political community but also in the marketplace where recent innovative designs, particularly in regard to the precast portable concrete products developed in Rarotonga, has provoked debate.
The driving force behind almost every coastal process is due to waves. Because of the vast area of ocean in which Pacific Island countries are located, wave conditions vary significantly in time and location. The Pacific ocean is so large that it creates its own atmospheric circulation system known as the ‘Walker Circulation’ causing annual and periodic variations in the weather and climate.

Often there is a perception to apply expensive artificial coastal protection measures when natural beach and coral reef restoration may be the most effective response to hazard. Nature provides many examples of coastal protection of which reef systems are the most widespread in the South Pacific region. Coral reefs may be nature’s response to an effective coastal protection system.

Considerable sediment supply of South Pacific island beaches is derived from carbonate sources. Sand mining, which is widespread, can often result in the long term depletion of sand resources on beaches and significantly reduce the natural protection which beaches provide. As a rule of thumb, sand mining from beaches should be prohibited. Sand mining is regarded in the South Pacific region as the principal cause of coastal erosion.

Traditionally, artificial coastal protection in the South Pacific region has been hard stabilisation, designed or generally intended to preserve upland property and structures. The use of such structures is governed by economic, cultural and environmental constraints. In general, the most favoured combination of adjustments to coastal hazards is to relieve and rehabilitate losses as they occur, and then build artificial coastal protection works to prevent further losses. However, this traditional pattern of adjustment may change due to primarily the withdrawal of insurance cover and the lack of government subsidies.
CHAPTER THREE

3.0 RAROTONGA - The Study Area.

3.1 Introduction

In recent years, the Cook Islands has benefited from a substantial increase in studies conducted in the nearshore coastal zone and also in the nearshore oceanographic regime. A majority of these studies have originated from work relating to the prospecting of economic resources in the marine environment. For example, numerous studies have been carried out by SOPAC (formerly known as CCOP/SOPAC) of manganese nodules, cobalt-rich crusts and deep-sea sediments in the northern Cook Islands, studies of reef channel sediments and nearshore areas by Lewis et al (1980) and Gauss (1982) for the purpose of identifying an alternative source for sandmining, and mapping of the wave energy source of Rarotonga needed to study the feasibility of developing wave power as a future energy source for the region (Barstow and Haug 1994a).

Coastal hazard and Coastal Engineering studies have made a significant contribution to knowledge of coastal processes and beach dynamics in the Cook Islands but a majority of these studies are confined to Rarotonga; the administrative, social and economic centre of the Cook Islands.

This chapter presents background information relating to the physical and cultural conditions that have shaped Rarotonga island as it is today. It describes the social conditions pertinent to coastal protection and also the coastal processes specific to the Rarotonga coast and the morphological character of its beaches with the purpose of developing an understanding of the study area as an interacting coastal system.
3.2 The Physical and Cultural Environment

The relationship between people and their environment has been one of long standing interest to Social Scientists. In particular, questions relating to cultural behaviour and environmental phenomena. The 'orthodox' view appears to be:

...culture can be understood primarily only in terms of cultural factors; but...no culture is wholly intelligible without reference to the noncultural or so called environmental factors with which it is in relation and which condition it (in McMath 1976:2)

The coastal zone may be viewed by human populations as an important resource having historical, cultural, ecological, recreational, aesthetic, economic and political value.

Rees (1989:365) points out that:

...although resources are products of the physical system they are defined by human ability and need, not by nature. Human beings evaluate the natural environment and classify those substances, organisms or physical properties which they are technically capable of utilising and which provide desired goods and services. Resources are therefore, dynamic and cultural conceptions. Perceived resources have changed, and will continue to change dramatically over time, not only in response to increased knowledge and technological innovation but also in line with economic, social and political developments which alter the demand for resource products and services.

Hence, coastal systems may be conceptualised as the resultant of natural and cultural phenomena where nothing is constant but change. The coastal zone must therefore be viewed as resource of finite extent, with limited capacity to meet all the demands for its use.

3.2.1 The Physical Setting and Environmental Conditions

The first significant geological mapping of Rarotonga was published by Marshall (1930) who documented the physiography and geology of the island and the fringing reef. Major geological work was completed in 1970 by Wood and Hay of the New Zealand Geological Survey who described the physiography, stratigraphy, and sediments of the Cook Islands. Grange and Fox (1953) documented soils in the lower
Cook Islands while Leslie (1990) classified the soils of Rarotonga on the basis of underlying rock type and geomorphology. On the climate of the southern Cook Islands, Thompson (1986) provides a comprehensive source. These baseline studies provide some useful descriptions of Rarotonga's physical setting. For a classification of the coastal morphology, sediment characteristics of Rarotonga and a description of the incident coastal processes Brown (1985) and Watkins (1993) are useful. This section is concerned primarily with a brief description of the physical and environmental properties of Rarotonga island.

Rarotonga is the social, economic, and administrative centre of the Cook Islands (Figures 3.1a, b, pages 45-46). It is a high volcanic or basaltic lava island (Te Manga is the highest point at 652 metres) of pliocene age (2-3 million yr, Lewis et al 1980) densely forested, highly dissected geomorphically, with a circumference of 32 kilometres. Surrounding the island is a coastal fringe that is intensely settled and cultivated and a fringing coral reef delineating the boundary between the open ocean depths and the relatively shallow lagoon waters. The largest island in the Cook Islands archipelago, Rarotonga, has a land area of 67 square kilometers.

The fringing coral reef which circumnavigates Rarotonga is narrower on the northern side and eastern side of the island, recognised as the 'windward coast' and relatively wider on the southern and western sides or the 'leeward or [relatively] sheltered coast' (Gillie 1994). The reef is continuous except for six passages which are used as access to the open sea by boats and marine life species. Water from the open sea enters the lagoonal area by waves breaking over the reef and the impact is greatest at higher stages of tide. Water levels are elevated within the lagoonal area resulting in incremental current flow in the direction of reef passages or toward shallow water at the basin margins (Kirk 1980).

There are several reef islets off the southeast corner of the island in Muri lagoon. These are not settled permanently, however, they are frequently visited by locals, sunbathers and organised tourist tours. An islet that disappeared recently was situated off the northwest coastline adjacent to the Rarotongan International Airport. During
the construction of the airport in the seventies a principal sand mining site was established adjacent to but inland of the islet. Today, evidence of a former islet continues to erode with significant geometric change apparent on the nearby beach.

Rarotonga is one of fifteen volcanic and coral islands comprising the Cook Islands. These islands are scattered over an area of 1.95 million square kilometres of the South west Pacific Ocean between latitudes 8 degrees to 23 degrees south and longitudes 156 degrees to 167 degrees west. The land area, however, is only 240 square kilometres. The fifteen islands that comprise the Cook Islands is divided into two groups: the Northern Group, consisting of seven low lying coral atolls; and the Southern Group, a group of predominantly raised coral (makatea) islands and Rarotonga, a high volcanic island.

The Southern Cook Islands lie in the South Pacific trade wind zone, where winds from the easterly quadrant dominate. Easterly winds blow for over 50 percent of the time (Figure 3.2, page 47). Both wind speed and direction on Rarotonga are influenced by orographic effects. Monthly wind speeds average between 7 and 13 knots (Thompson 1986).

There is a marked seasonality in the rainfall regime of Rarotonga; a dry season (May to October) and a wet season (November to April) associated with the movement of the South Pacific Convergent Zone (SPCZ). In general, approximately two thirds of the total rain falls during the wet season. Rainfall distribution is a function of the effects of elevation of the interior and regional exposure to the southwest tradewinds. The Rarotonga airport on the north-westerly coast receives the lowest mean annual rainfall (2000 mm-yr) while the rugged interior around the peaks of Te Manga, Te Atukura and Te Kou receives 4500 mm per year. The mean annual temperatures of the Southern Cook Islands are 24 degrees celsius to 26 degrees celsius (Thompson 1986).
Figure 3.1: Map of the Cook Islands
Figure 3.1b: Map of Rarotonga
Figure 3.2 Wind Rose diagram for the Southern Cook Islands (Source: Thompson 1986)
3.2.2 Existing landuse

This section describes the existing human land use system of Rarotonga which is provided to highlight patterns of environmental, (social) institutional and cultural adaptations because such patterns represent an adjustment to the particular environment.

Approximately 68 percent of the total land area of Rarotonga is regarded as mountainous, covered by dense tropical rain forest and not recommended for human development. Areas of relatively flat topography is on the coastal fringe which is intensively cultivated and settled. The most densely populated area is between Pue and Pokoinu village in the northern coastline, this delineated area is also known as Avarua, the capital centre of the Cook Islands. Vital commercial assets and essential infrastructure are located in this area where the land is barely two to five metres above mean sea level (Figure 3.3, page 49).

This northern coastline has been the main benefactor of government funded projects. Most recently it has been the recipient of foreshore development especially between the two harbours of Avatiu and Avarua. Extensive land reclamation works and stabilisation at the land/sea interface by a sloping basalt rock revetment was provided to mitigate hazards that are notorious in the area and also to support upgrading of the local road system (Plate 3.1, page 50).

Other vital infrastructure assets located in the northern coast include the Rarotonga International Airport, JUHI bulk fuel depot, Triad bulk fuel depot, Mobil bulk fuel depot, reticulation of domestic services such as water, electricity and telecommunication (a majority of which are underground due to the potential of aerial hazards and follow closely the coastline), the Government Parliament buildings, fuel pipelines to service the bulk fuel depots, and the local road system.
Figure 3.3: Map of part of the northern coastline where contemporary development has been most prominent
Plate 3.1: Aerial view of Avarua, the Capital Centre of the Cook Islands (Photo courtes Survey Department, 1993)
Tourism is a major force in the Cook Islands economy (Neemia-Mckenzie 1995) which is administered and principally set up on the island of Rarotonga. Tourism based development is widespread with siting in or near the coastal zone as particularly favoured but not always possible. Muri lagoon, for example, has been the focus of tourist based activities and accommodation over the years, however, the land tenure system of Rarotonga (which prevents land being sold) is reported to stand between significant foreign investment by way of ownership of properties adjacent to the beach and further tourist based developments (CI Press 1995).

Recreational value and in particular sandy beaches may be perceived as a vital asset of the southern coast. Human settlement in this area is concentrated in or near the coastal zone and it is relatively dispersed into the foothills. Cultivated land for mainly horticultural purposes is widespread behind the coastal zone utilising all available flat land. Vital infrastructure assets, particularly, the reticulation of services such as water, electricity, telecommunication and the road system closely follow the coastline. Coastal protection in the southern coastline is sporadic and the works are predominantly private or commercially owned and funded.

Land within fifty metres of the high water mark is under the jurisdiction of the local government and the Conservation Act 1986/87. The Act effectively provides for Coastal Planning and Management of this area (to be carried by the Cook Islands Conservation Service) with the ultimate aim of placing controls on such human activity that may jeopardise the condition and preservation of the coast.

The process whereby any work may be carried out in the coastal zone is such that consent must be sought through the Cook Islands Conservation Council by way of written application. Enforcement of the Act is difficult due to cultural customs and traditions at the village level where there is a misunderstanding as to who exactly owns the foreshore. In some instances, sandmining has been carried out at the directive of village elders who are widely respected, prominent politically, eager to convert opportunities into political or economic gain and ignorant of the laws that govern the preservation of the coastal zone.
3.2.3 Socio-Economic Conditions

Cook Islanders are Polynesians with close cultural and linguistic affinities with the Maori people of Aotearoa/New Zealand and the Polynesians of French Polynesia. The Cook Islands has a human population of 18,400 (1991) of which 55.4 percent live on the island of Rarotonga. The annual population growth is estimated at 0.5. The low growth rate is due to outward migration, mainly to New Zealand, where some 38,000 people of Cook Islands descent live. A sizeable number of people of Cook Islands descent live in Australia, and an estimate 7,000 live in neighbouring French Polynesia (Neemia-Mckenzie 1995).

The Cook Islands faces many physical constraints in its quest for economic growth and development. These physical constraints derive mainly from the geography of the country,

...being small, scattered and distant from major export markets and sources of imports ...and its demographic structure, that is, small population and heavy losses of the economically active proportion of the population through migration (Neemia-Mckenzie 1995).

Table 3.1 (page 53) summarises the economic trend over a period of twenty years (1970 to 1990). Some important points are:

(i) During the period (1970-1978) there was a slow decline in percentage terms of the contribution to GDP of productive activities (that is, agriculture, manufacturing, construction and the like)

(ii) During the same period (1970-1978) the economy underwent structural changes, the Rarotonga International Airport was opened, and the services sector grew threefold.

(iii) The growth of the services sector continued into the nineties especially in the Trade, Hotels and Restaurants component where such activities and in particular the Tourism sector is regarded as the back bone of the Cook
Islands economy. The largest proportion of locally generated government revenue is from direct and indirect taxes. This major source of revenue has helped fill the gap left by the decrease in New Zealand budgetary grant which is scheduled to be phased out in 2007. New initiatives in the development of new sources of revenue are sought, for example, foreign investment, the financial centre, the promotion and development of tourism and the like (Neemia-Mckenzie 1995).

Table 3.1 GDP estimates for the Cook Islands
($000 valued at current production prices)

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>A. PRODUCTION</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Agriculture, Livestock, &amp; Fisheries.</td>
<td>1720</td>
<td>3093</td>
<td>8034</td>
<td>16111</td>
</tr>
<tr>
<td>Manufacturing</td>
<td>907</td>
<td>905</td>
<td>3204</td>
<td>6000</td>
</tr>
<tr>
<td>Other Production</td>
<td>939</td>
<td>844</td>
<td>3119</td>
<td>1480</td>
</tr>
<tr>
<td>Total Production</td>
<td>3566</td>
<td>4842</td>
<td>14356</td>
<td>23591</td>
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<tr>
<td>B. SERVICES</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Public Administration &amp; Public Community Services</td>
<td>1840</td>
<td>4472</td>
<td>14526</td>
<td>19893</td>
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<td>Total Services</td>
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<td>12976</td>
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<td>58609</td>
</tr>
<tr>
<td>Total GDP</td>
<td>7832</td>
<td>17818</td>
<td>64336</td>
<td>82200</td>
</tr>
</tbody>
</table>

3.2.4 Tropical Cyclones.

Rarotonga experiences frequent hurricane to cyclone intensity storms (approximately one each year) which arrive mainly from the north and northwest during the wet
(hurricane) season. In the dry season when easterly and northeasterly tradewinds predominate Rarotonga is buffeted by winter storm swells (Lewis et al 1980).

This section is principally concerned with a description of the most recent tropical cyclone events that have affected Rarotonga and consideration is for their wave characteristics which is an important parameter in the design of coastal protection structures.

Cyclone Sally (1987) is well known in the Cook Islands because of its impact causing more damage than any other storm on record as it passed directly over Rarotonga. A number of passes of the GEOSTAT satellite occurred close to Cyclone Sally as it passed through the Southern Cook Islands (Barstow and Haug 1994a). Two satellite tracks passed close to the eye of Cyclone Sally. First, on 31st December at 0200 hrs in the area near to Palmerston where Sally made a loop and moved very slowly. Significant wave heights reached a maximum of over 10 meters at the point of nearest approach to the storm centre. On the second occasion, 2nd January at 1500 hrs when the eye had passed Rarotonga, the significant wave height reached 11 meters at the nearest approach to the eye. Reports of waves 10 meters above normal on the reef is no exaggeration. This is confirmed by the “waverider buoy”, which was operating at Avatiu on the north coast of Rarotonga. It recorded a peak significant wave height of 8 meters, a maximum wave height of 12 meters and a peak period (Tp) at 12-13 seconds. The storm peak occurred around 1200 to 1500 hrs on 2nd January 1987 (Croad 1989). Cowan and Utanga (1991) reported on the coastal impact of Cyclone Sally.

Tropical Cyclone Wini (1987) passed the Southern Cook Islands on a southeasterly track late in February 1987. Significant wave height measurements exceeded 5 meters close to its track. The only effect reported in the Cook Islands at the time was higher swell than normal (Barstow and Haug 1994a).
Richmond (1990) described an unusual storm which caused severe wave damage to atolls in the Tokelau group and the Northern Cook Islands. The event was caused by very strong westerlies over a wide area to the north of a slow moving trough of low pressure lasting several days. Tropical Cyclone Wini (1987) developed in the later stages of this event. The highest wave heights occurred close to Suwarrow in the northern Cook Islands on 28 February and wave heights exceeding 6 meters were recorded by satellite in the Tokelau group on both 28 February and 1st March.

Tropical Cyclone Peni on the 15 February 1990 passed about 2 degrees east of Rarotonga moving in a southeasterly direction. Measurements from the waverider buoy off Rarotonga show the significant wave height to reach 8 meters at the time when Peni was closest to Rarotonga (Barstow and Haug 1994a).

### 3.2.5 Coastal Erosion

Coastal erosion is a complex phenomenon which can have a one or more of a variety of causes and visible expressions. It occurs at several time scales. This section is concerned with a description of the current expression of coastal erosion on Rarotonga.

Beaches may be viewed as the resultant of natural and artificial forces upon it. With this in mind, one way to examine the current expression of coastal erosion or beach response is to simply describe its present form. Watkins (1993) carried out a comprehensive description of the Rarotonga coastline of which three main types of coasts were identified. They were defined on the basis of incident coastal processes (winds, waves, currents, tide), beach sediment characteristics and beach geometry (foreshore slope, width and height of berm, and backshore width). In broad terms, these three types of coasts are:

1. **Northern and Eastern Coast**: beaches are steep and are predominantly comprised of coral boulders and coarse sediments and exhibit dominant storm ridges on the backshore. The distance from the beach to the reef crest is
relatively narrow (50-200m) with moderate to shallow lagoon water levels providing little or no protection from incident waves and hurricane seas. The northern coastline generally experiences high wave action during extreme events and hence high energies of shore breaking transformation waves. The impact of higher wave energy is generally preserved by dominant storm ridges present in the backshore. The beaches in these areas are considered to be accretional.

(2) Southern Coast: beaches are relatively flat, narrow and comprise predominantly of sandy sediment. The width of the reef flat, ranges from between 600 to 1000 meters, with lagoon water levels varying between 1 to 3 meters. During periods between storms (or low wave energy conditions) wave heights on the southern coast are higher than those in the north and eastern areas. However shore breaking transformation waves are lower on the southern coasts compared to the northern coasts. During high energy events or swell conditions, there is a higher transformation wave generation lower frictional attenuation due to elevated lagoon water levels and hence increased wave set-up accompanied by strong currents in the lagoon promoting sediment transportation and beach change. Because of the considerable fetch distance on the Southern coast, the ability of the wind field to increase transform wave height is likely. The southern coasts are considered to be erosional but may exhibit accretional forms during lower energy conditions.

(3) Western Coasts: reflects a combination of physical characteristics found in the north, east and southern coasts. It is in the lee of the dominant wind and swell directions, however, high energy wave conditions generated by extreme events may be experienced in the northwest region. Its beaches are wide, moderately steep and comprise of sandy pebble beaches in the southwest or a combination of sands, pebbles, cobbles, and boulders in the northwest. The width of the reef flat is moderate (200 to 500 meters) with shallow to moderate water level depths (0.3 to 0.8 meters). The beaches are considered to be accretional due to the presence of beach ridges in the backshore, beach vegetation and a low incidence of erosional parameters (in particular human activity).
It is clear as Watkins (1993) demonstrates that erosional and accretional features may be examined by a simple descriptive study of the existing coastal morphology.

Intensive studies have been carried out on Rarotonga, particularly in Muri lagoon, of physical environmental parameters pointing to in some cases, conclusive evidence of coastal erosion or lack of.

Kirk (1980) indicated that flushing of the lagoon was impaired by the progadation of the Avana Stream delta. He suggested that delta development was enhanced by poor land use practices in the Avana Stream catchment area, resulting in high soil erosion. The report recommended dredging of the harbour to increase the flushing of the lagoon.

It is uncertain as to who recommended or initiated the works but a causeway was constructed into the channel between the mainland and Motutapu and used as a platform for the dredging. The causeway deflected channel waters onto the beach at Motutapu causing erosion of the beach. Sporadic dredging continued in the harbour area until 1988 when the Conservation Service of the Cook Islands reviewed the dredging site and noted areas designated as ‘no dredging’ were being dredged. Concern was expressed about the potential for sediment instability along the shoreline and as a consequence the works was later aborted. Significantly, about the same time plans to build a hotel on a motu were scrapped.

Holden (1992) concluded that the offshore wave climate was the determining factor in water level set up and the circulation and flushing of Muri lagoon and Ngatangiia harbour. Waves breaking on the reef caused elevated lagoonal water levels which results in the out flow being generally northward and out through Ngatangiia Harbour. It was also concluded that site specific erosion was probably caused by previous sand mining or land reclamation activities. For the beaches to be maintained, Holden (1992) recommended such practices causing adverse effects must be discontinued. These findings were also established earlier by Kirk (1980).
The most comprehensive investigation of hazard assessment, coastal erosion and its management is outlined by Kirk (1983, 1986, 1991, 1992, 1993) and Dorrell (1988) at the Rarotongan (Resort) Hotel site. As well as highlighting the erosion problem along the hotel frontage, Kirk (1993) identified “regional” (island scale) erosion which was both “chronic and widespread” on Rarotonga. This was due to the removal of sands from beaches which has been both widespread and cumulative over the years; for the purpose of construction (Kirk 1980).

The sand necessary to offset energy of storm waves is now increasingly obtained by erosion of older deposits forming the land along the lagoon shores, the effect appearing as episodes of retreat of the coast. Progressive erosion occurring as episodes in storms and hurricanes has generated an increasing number of hazard sites where inundation by seawater becomes more frequent and more severe as the coast retreats. Undermining and loss of support for developed assets are also becoming more frequent, more severe and more areally extensive (Kirk 1991, 1992, 1993).

As with all beaches erosion occurs rapidly in response to the high energies of storm waves. The period between storms are associated with little beach change, or with partial replacement of the sand removed in storms (Kirk 1993).

3.3 Wave Environment and Nearshore processes

In reality at a given location on the shore of a Pacific island, waves may be present arising from several different wind systems which may include local trade winds, storms in the southern ocean or northern Pacific and, occasionally from tropical cyclones. The exposure of the actual location is also very important, in that a location on the southern coast of an island will only experience swell from the southern hemisphere due to the island sheltering the location from northerly swell. It is therefore, important to have information on the variability of oceanic winds on different time scales in both the local area and the source areas for swell in order to understand the variability of the wave climate.
3.3.1 Oceanic Winds

3.3.1.1 General Description

A good overview of the wind climate of the Rarotonga can be found in the New Zealand Meteorological Services publication of "The Climate and Weather of the Southern Cook Islands" (Thompson 1986). Also, it may be useful to know that time series of wind speed and direction may be obtained in digitised form from New Zealand's National Institute of Water and Atmospheric Research Ltd (NIWA).

The winds that are of interest here are those that generate ocean waves. In the South Pacific ocean wind waves are always present and the energy involved is obvious to anyone observing as wave after wave dissipates on the coast.

In the Southern Cook Islands the south easterly trade winds predominate from May to October with average wind speeds of 6 to 7 meters per second, which is slightly higher than winds during the summer months when north easterly winds are more frequent. Westerly winds are most frequent in Autumn and Winter occurring over 10 percent of the time due to extratropical and cyclone influence. (Thompson 1986).

Extreme winds are associated with tropical cyclones which occur on average about 1-2 per year but more frequently during the negative phase of the Southern Oscillation. These negative SOI episodes occur every 4 to 5 years on average. Tropical cyclones occur mostly between February and March. One notable exception in recent years was Hurricane Sally which occurred in late December 1986 causing considerable damage on Rarotonga.

3.3.1.2 Winds in the Source Region for Swell

The region of higher latitudes to the south and southwest is the most important source area for ocean swell observed in the Southern Cook Islands. Barstow and Haug (1994a) attempted to quantify the variability of ocean swell in the Southern
Cook Islands by looking at long term wind measurements in the source area. Unfortunately, there were few meteorological stations in this area.

Using the series of wind speed and direction for Chathams (44°South, 176.6°West) and Campbell Island (52.6°South, 169.2°East), Barstow and Haug (1994) computed a southerly monthly gale index defined by the number of days in each month when wind speed exceeded 10 meters per second (m/s). Such could potentially generate waves later appearing as swell in the Southern Cook Islands.

Barstow and Haug (1994a) found that strong southerlies appeared to occur at different times of the year at the two meteorological stations. At Campbell island the gale index peaks in Autumn and Spring with lower frequencies in mid-winter and summer. At Chatham island May and June are the months with most frequent South westerly gales. In December and January, south westerly gales occur about half as often.

On the relationship between the gale index and the Southern Oscillation Index, Barstow and Haug (1994a) found that based on analysis of 32 years of data (1961-1993) there was almost no correlation between the two indices overall. The 1987 El-Nino is a good example with more than average gale index for 6 months at Campbell Island. On the other hand, in the exceptional 1983 El-Nino more frequent southerly gales did not occur.

3.3.2 Oceanic Waves

Until recently little direct wave measurement data for the South Pacific region was available. For the Cook Islands, direct wave measurements were carried out on the north coast of Rarotonga between March 1985 to April 1989 and also off the southeastern shore of Rarotonga between July 1987 and January 1991 with a waverider buoy. Full details of the measurements and the data analysis together with comprehensive statistics can be found in data reports by Olsen et al (1991) for the southeastern coast and Croad (1989) for the north coast.
Significant wave height was found to be higher in the winter months (March-September) with average values at about 2.1 to 2.5 meters. During summer, wave heights were normally around 2.0 meters or lower. Mean wave period was also higher in Winter with the energy period averaging about 10 seconds. The most frequent peak period was about 11-12 seconds (swell). A secondary wind sea peak occurred at 8-9 seconds. This wind seas and swells were observed to give an important contribution to the wave climate.

An analysis of satellite (GEOSAT) altimeter data for the South Pacific (Barstow and Haug 1994b) reveals that the Southern Cook Islands lie in an area having the highest average significant wave heights; averaging about 2.4 to 2.6 meters for the period 1986 to 1989.

During 1987 (a moderate El Nino year) there were many events observed in the satellite data when the significant wave height exceeded 5 meters. These events were mostly due to low pressure systems further north than normal to the south of the Southern Cook Islands with high pressure over New Zealand and resulting strong westerlies or south westerlies between New Zealand and the Southern Cook Islands. However, an analysis of winds around New Zealand did not reveal any relationship between the SOI and high south westerly winds which could generate swell observed in the Cook Islands. The variability between different El Nino years seems to be quite large as far as oceanic swell generating winds is concerned. This results in higher swells in some El Ninos and lower in others.

Table 3.2 (page 62) is a comparative summary of wave characteristics from the two areas off Rarotonga where wave rider buoy measurements were recorded. It clearly shows on the northern coast that wave heights were significantly lower with average range of values at about 0.92 to 1.13 meters. Wave heights were higher during the summer months (the reverse situation on the south east coast) due to more frequent north easterly wind seas in addition to higher swells from the northern hemisphere at that time of year. A comparison of the distribution of peak period between the northern coast and the south east coast illustrate the greater importance of wind seas
on the northern coast with a peak at 8.6 seconds corresponding to the secondary wind sea peak observed in the waverider data from south east Rarotonga. The average wave power on the northern coast is estimated to be around 6kW/m which equates to a quarter of the level of the southeast coast (Barstow and Haug 1994a).

3.4 Beaches

3.4.1 Morphology and Sediments

"The size and character of sediments and the slope of the beach are related to the forces to which the beach is exposed and the type of material available on the coast" (CERC 1984:1-7).

Table 3.2 Comparative Waverider Measurements off southeast Rarotonga (SE) and off Avatiu harbour during 1985 to 1989 (Source: Barstow and Haug 1994a)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Summer (Nov-Apr)</th>
<th>Winter (May-Oct)</th>
<th>All Months</th>
</tr>
</thead>
<tbody>
<tr>
<td>Location</td>
<td>SE coast</td>
<td>N coast</td>
<td>SE coast</td>
</tr>
<tr>
<td>Hm0</td>
<td>1.85</td>
<td>1.13</td>
<td>1.95</td>
</tr>
<tr>
<td>Tm02</td>
<td>6.13</td>
<td>6.5</td>
<td>6.6</td>
</tr>
<tr>
<td>Tp</td>
<td>11.75</td>
<td>9.3</td>
<td>11.75</td>
</tr>
</tbody>
</table>

Key: Hm0 Modal wave height
      Tm02 Modal wave period
      Tp  Peak wave period

Wood and Hay (1970) described the physiography and sediments of Rarotonga island. They found a ridge of unconsolidated coral sand up to 1 meter thick with underlying sand and gravel as a dominant feature of the coastal plain. The ridge varies in height above the modern storm beach from 1.5 meters at Kavera (Rutaki) to 2.2 meters at Matavera and 4.2 meters at Black Rock (Nikao). The general appearance is that of a continuous ridge with various superimposed smaller ridges. It has been modified
extensively by human activity. Portions of the main road system run along the crest of the ridge. The feature is thought to be a storm generated rubble bank which sits on an older reef flat. Wood and Hay (1970) report C14 ages of between 3510 and 1235 years BP.

Watkins (1993) also described the Rarotonga coastline in which he identified three main types of coasts based on an incident coastal processes, beach geometry and sediment characteristics (see previous section 3.2.5, page 55). The beaches are generally composed of carbonate sand with terrigenous clastics. Sediment texture shows a tendency for fine grain size along the south coast, coarse grain size along the north and east coast; and a combination of fine and coarse sediments on the west coast. Richmond (in Collins 1993) noted an inverse relationship between grain size and the width of the reef flat. In non-storms conditions the beaches are subject to wave attack during high tides. At other times the waves are limited by breakage on the reef. Wave energy at the beach is less where the reef flat is widest. However during high intensity storm events the beaches are subject to significant modification.

The fringing reef consists of beach deposits inner and outer reef flat and the reef crest and fore reef zones. Richmond (in Collins 1993) subdivided the reef flats into the inner reef flat and the outer reef flat. This distinction is related to energy levels, that is, the inner reef flat is a lower a lower energy environment. Sand sized material in places up to 1.5 meters thick, directly overlies algal pavement, but the sediment cover is generally less than 1 meter thick. The sediment is dominated by calcareous algae mollusc, echinoderms, and coral fragments. The outer reef flat is subjected to higher wave energy levels and generally consists of an algal pavement with coral debris on top. Sediment cover is generally thin or absent.

Marshall (1930) described the reef crest on the outer edge of the reef known as the Lithothamnium ridge. Lewis et al (1980) described seaward of the reef crest. The reef front has massive and branching corals which important as a source for beach sediment supply. Seaward of this, the fore reef areas are characterised by spur and
groove topography where of fore reef terrace between 17 and 20 meters deep extend seawards approximately 600 meters

3.4.2 Plan and Profile shape

"Changes in the form, height and width of beach profiles occur with tidal, daily, season and longer term variations in wave energy" (Kirk 1969).

Kirk (1969) identified in the Canterbury Bight (New Zealand) by analysing beach profile forms and changes over short term, seasonal and long term periods, the beach plan-form characteristics. It was established that the distribution of incident wave energy was controlled by offshore relief. Short term changes were related to the changing pattern of wave energy and long term changes were dependent upon the balance between the supply of sediments and losses on the beach (Kirk 1969). A similar study for Rarotonga has yet to receive some attention.

Watkins (1993) cautions that while wave steepness (related to the energy of waves) is significant in shore formation on open continental coasts it may not apply to the beaches around Rarotonga. This is because the reef system controls wave breaking and the associated modification of the wave resulting in energy loss due to shoaling, refraction, reflection and scattering and frictional attenuation.

Much information that is relevant to the plan and profile shape of Rarotonga has already been presented. In general, steep beaches are composed of coarser material, while less steep beaches are composed of finer sandy material. Fluctuations in the profile of a beach is dependent on the wave climate, tides and the nature of the beach materials. Although there are numerous ways to analyse the plan and profile shape of beaches, a direct descriptive approach is also useful.

Numerous beach profiles are presented in a later chapter and the character of these are discussed. On the plan shape of Rarotonga, Lewis et al (1980) points out some relevant and important aspects and describes Rarotonga as:
...a kidney shaped island...there is a fringing reef that is narrower on the northern and eastern sides of the island than on the southern and western sides...Rarotonga is buffeted by predominantly easterly and northeasterly tradewinds, by winter swells from the southern ocean, and by hurricane intensity cyclonic storms that come mainly from the north and northwest.

3.5 Coastal Protection

"The types of coastal [protective] structure and more importantly the location and extent of the structures provide some indication of erosion or perception of potential erosion and the nature of the wave energy experienced at the site" (Watkins 1993: 98)

The distribution and location of coastal protection structures on Rarotonga is documented by SOPAC as (1:10,000) coastal series maps 2A/2B. A wide variety of strategies have used on Rarotonga island to mitigate coastal erosion and coastal hazards. This section is concerned with a basic description of contemporary coastal protection methods used on Rarotonga.

Table 3.3 (pages 65-68) is a summary of select coastal protection sites originally compiled by the Cook Islands Conservation Service as part of its foreshore monitoring programme. It confirms that hard stabilisation is the most used option besides 'doing nothing' to mitigate coastal problems. The primary function of a majority of these structures is to protect the land or human assets behind them from the threat of hazards such as large storm waves, coastal erosion, human induced erosion and the like.

<table>
<thead>
<tr>
<th>Name of Land/Property Owners</th>
<th>Cadastral/Area Name</th>
<th>Protection Type</th>
<th>Year Constructed</th>
<th>Structural Configuration</th>
<th>Purpose/Function</th>
</tr>
</thead>
<tbody>
<tr>
<td>TRIAD</td>
<td>Pt. Sec 206 L.280 Nikao</td>
<td>Mixed Coral/ Basalt Revetment</td>
<td>Rebuilt in March 1992</td>
<td>11.8 from MLWM. 75.0m Long 1.80m High</td>
<td>Protect Fuel Depot</td>
</tr>
<tr>
<td>Location</td>
<td>Section</td>
<td>Study Year</td>
<td>Actions</td>
<td>End Date</td>
<td>Property Changes</td>
</tr>
<tr>
<td>---------------------------</td>
<td>---------</td>
<td>------------</td>
<td>---------</td>
<td>----------</td>
<td>------------------</td>
</tr>
<tr>
<td>Mainline Browne Pt. Sec 208 L. 424 RO 276 Nikao</td>
<td>Basalt Revetment</td>
<td>March 1992</td>
<td>63.0 from MLWM 53.0 x 1.80</td>
<td>Protect Land/ Property</td>
<td></td>
</tr>
<tr>
<td>Frangi Factory Sec 106D1B4 SO 930 Nikao</td>
<td>Cement Grouted Basalt Seawall</td>
<td>November 1982</td>
<td>32.4 from MLWM 32.0 x 1.70</td>
<td>Protect Land/ Property</td>
<td></td>
</tr>
<tr>
<td>Hugh Baker Residence Sec 106D1B2 SO 930 Nikao</td>
<td>Mixed Coral/ Basalt Revetment</td>
<td>November 1984</td>
<td>32.4 from MLWM 34.0 x 0.50</td>
<td>Protect Land/ Property</td>
<td></td>
</tr>
<tr>
<td>Eddie Karika Residence Pt. Sec 106A1B D. 2845 Nikao</td>
<td>Cement Grouted Basalt Seawall</td>
<td>February 1987</td>
<td>12.0 from MLWM 34.0 x 1.70</td>
<td>Protect Land/ Property</td>
<td></td>
</tr>
<tr>
<td>Paula Lineen Residence Pt. Sec 106A2 SO 970 Nikao</td>
<td>Basalt Revetment</td>
<td>June 1992</td>
<td>17.4 from MLWM 53.0 x 1.0</td>
<td>Protect Land/ Property</td>
<td></td>
</tr>
<tr>
<td>Met/Weather Office Sec. 218 SO 524 &amp; SO 753 Nikao</td>
<td>Concrete Retaining/ Seawall</td>
<td>1973</td>
<td></td>
<td>Reclalm Land &amp; Protect Property</td>
<td></td>
</tr>
<tr>
<td>Rarotonga Airport Seawall Reclaimed SO 753 Nikao</td>
<td>Concrete Seawall</td>
<td>1973</td>
<td></td>
<td>Protect Reclaimed Land &amp; Aerodrome</td>
<td></td>
</tr>
<tr>
<td>NZ Representative Residence Sec. 107 SO 702 Nikao</td>
<td>Concrete Seawall</td>
<td>1964. Refurbished 1992 53.0 from MLWM 60.0 x 0.85 51.0 Lg (1992)</td>
<td></td>
<td>Protect Land/ Property</td>
<td></td>
</tr>
<tr>
<td>Rarotongan Sunset Motel Pt. Sec 87E3 RO 434 Arorangi</td>
<td>Basalt Revetment</td>
<td>1986. Rebuilt 1992</td>
<td>20.90 from MLWM 74.0 x 2.3</td>
<td>Protect Land/ Property</td>
<td></td>
</tr>
<tr>
<td>Edgewater Resort Hotel Pt. Sec 84B L. 143 Arorangi</td>
<td>Basalt Revetment</td>
<td>Rebuilt June 1992</td>
<td>14.35 from MLWM 74.0 x 2.1 73.0 x 2.2</td>
<td>Protect Land/ Property</td>
<td></td>
</tr>
<tr>
<td>Mike Benns Residence Pt. 94A2A Lot. 7 SO 889 Arorangi</td>
<td>Basalt Revetment</td>
<td>1989</td>
<td>22.0 from MLWM 23.0 x 1.0</td>
<td>Protect Land/ Property</td>
<td></td>
</tr>
<tr>
<td>Mary McQuarrie Residence Sec. 93C RO 322 Arorangi</td>
<td>Basalt Revetment</td>
<td>1992</td>
<td>14.6 from MLWM 55.0 x 1.50</td>
<td>Protect Land/ Property</td>
<td></td>
</tr>
<tr>
<td>Tere Purea Rentals</td>
<td>Sec. 92C3 RO 322 Arorangi</td>
<td>Basalt Revetment</td>
<td>Rebuilt 1992</td>
<td>11.9 from MLWM 39.0x1.7</td>
<td>Protect Land/ Property</td>
</tr>
<tr>
<td>-------------------</td>
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</tr>
<tr>
<td>Kaena Restaurant</td>
<td>Sec. 83C Onemaru Arorangi</td>
<td>Cement Grout Coral Seawall-Basalt/Rubble Revetment</td>
<td>1971</td>
<td>8.5 from MLWM 110.0x2.25</td>
<td>Protect Main Road System</td>
</tr>
<tr>
<td>Rarotonga Resort Hotel</td>
<td>Sec. 83A, B1 D. 2976 Aroa</td>
<td>Coastal Protection Units</td>
<td>1991</td>
<td>Recover Land Loss in Backshore</td>
<td></td>
</tr>
<tr>
<td>Rutaki Primary School</td>
<td>Pt. Sec 91M SO 587 Rutaki</td>
<td>Basalt Revetment</td>
<td>1992</td>
<td>11.9 from MLWM 290.0x2.0</td>
<td>Protect Land &amp; Main Road System</td>
</tr>
<tr>
<td>Piri Puruto Residence</td>
<td>Pt. Sec 1B2 L. 732 Rutaki</td>
<td>Basalt Revetment</td>
<td>1974</td>
<td>11.5 from MLWM 59.0x2.35</td>
<td>Protect Land/ Property</td>
</tr>
<tr>
<td>Malcolm Sword Residence</td>
<td>Pt. Sec 4 SO 623 Vaiamaanga</td>
<td>Cement Grout Rock Seawall, Basalt/Rubble Revetment</td>
<td>1969</td>
<td>9.60 from MLWM 108.0x1.2</td>
<td>Protect Land/ Property</td>
</tr>
<tr>
<td>Queens Representative Residence</td>
<td>Sec. 34 L. 38 Titikaveka</td>
<td>Cement Grouted Mixed Rock Seawall</td>
<td>1960</td>
<td>13.2 from MLWM 261.0x2.45</td>
<td>Protect Land &amp; Main Road System</td>
</tr>
<tr>
<td>Muri Holdings Property</td>
<td>Pt. Sec 12B1 L. 796 Ngatangiia</td>
<td>Basalt Revetment</td>
<td>1988</td>
<td>80.0 from MLWM 50.0x1.4</td>
<td>Protect Land/ Property</td>
</tr>
<tr>
<td>Mary Harvey Residence</td>
<td>Pt. Sec 7B2A SO 743 Ngatangiia</td>
<td>Concrete Seawall</td>
<td>1973</td>
<td>13.6 from MLWM 39.0x1.05</td>
<td>Protect Land/ Property</td>
</tr>
<tr>
<td>Muri Beachcomber</td>
<td>Pt. Sec 7B1, A D. 2859 Ngatangiia</td>
<td>Coconut Log Wood Seawall</td>
<td>1990</td>
<td>12.9 from MLWM 98.0x1.7</td>
<td>Protect Land/ Property</td>
</tr>
<tr>
<td>Ngatangiia CICC Waterfront</td>
<td>Sec. 6J3B SO 1048 Ngatangiia</td>
<td>Concrete Seawall</td>
<td>1967</td>
<td>50.0 from MLWM 131.0x1.5</td>
<td>Reclaim &amp; Protect Land</td>
</tr>
<tr>
<td>Teariki Jacob Residence</td>
<td>Pt. Sec 127J2 D. 2826 Avarua</td>
<td>Basalt Revetment</td>
<td>December 1992</td>
<td>27.0 from MLWM 41.0x1.4</td>
<td>Protect Land/ Property</td>
</tr>
<tr>
<td>Charlie Brothers Residence</td>
<td>Pt. Sec 127J2 D. 2826 Avarua</td>
<td>Basalt Revetment</td>
<td>December 1992</td>
<td>21.10 from MLWM 64.0x1.37</td>
<td>Protect Land/ Property</td>
</tr>
<tr>
<td>Koekoe Mokotupu Residence</td>
<td>Pt. Sec 127J1 L. 696 Kiikii</td>
<td>Basalt Revetment</td>
<td>December 1992</td>
<td>25.0 from MLWM 58.0x1.0</td>
<td>Protect Land/Property</td>
</tr>
<tr>
<td>---------------------------</td>
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</tr>
<tr>
<td>Kiikii Motel</td>
<td>Pt. Sec 53 L. 74 Kiikii</td>
<td>Basalt Revetment</td>
<td>1988</td>
<td>6.90 from MLWM 60.0x3.0</td>
<td>Protect Land/Property</td>
</tr>
<tr>
<td>[Tamura Resort] Club Raro</td>
<td>Pt. Sec 190D L. 10 Kiikii</td>
<td>Mixed Coral and Basalt Revetment (Demolished)</td>
<td>1988</td>
<td>6.50 from MLWM 50.0x3.0</td>
<td>Protect Property</td>
</tr>
<tr>
<td>Miller Howard Residence</td>
<td>Sec. 130,2 L550</td>
<td>Concrete Seawall capped at toe with Basalt Boulders</td>
<td>1970</td>
<td>23.1 from MLWM 10.0x1.7</td>
<td>Protect Land/Property</td>
</tr>
</tbody>
</table>

**Volcanic Rock or Rubble Mound Structures:**

Volcanic rock or rubble mound structures represent the most common form of coastal protection strategy implemented on Rarotonga to combat coastal hazards. It is generally the most economical form of construction where a reasonable supply of suitable size of sound rock is available. These structures are commonly composed of volcanic basalt rock because this type of rock is hard, durable, available and has a density that makes it most suitable for the task of absorbing the energy of waves both in wave run-up and backwash. Coral or concrete rubble may be used in some instances but due to inherent deficiencies in their physical properties these are commonly used in combination with other materials or other structural strategies. For example, coral stone in gabion baskets, concrete cement mortared mixed coral stone and basalt rock seawalls, basalt rock revetments mixed with concrete rubble.

Volcanic rock or rubble mound structures are provided by placing large sized rock using heavy machinery into a mound that has sufficient structural form so that it will stand up to nominated design conditions. In some cases a filter cloth may be placed and weighted under the rock material to prevent rapid undermining of the structure by the winnowing away of the fine sand particles. Evidence of deformation and settlement of a majority of these type of structures on Rarotonga indicate that they may have been poorly administered or were desperate attempts for a quick-fix
solution to a complex problem. It must be pointed out though that according to the Shore Protection Manual (CERC 1984), deformation and settlement of these type of structures are expected and the philosophy adopted was that if the structure settled or deformed too much, additional material was added to top up the structure.

The primary function of these rock structures is "...to withstand severe wave action" (CERC 1984). For the Edgewater Resort basalt rock revetment this notion was severely tested by cyclone Val (1992) during which boulder size material was displaced by the storm waves and hurtled into the nearby buildings causing extensive damage even injury to some guests. It has been argued (JICA 1992) that the hotel buildings were built too close to or even in the active zone of the beach and little attention was given to the wave climate of the area. Most recently, in 1992, a new block of guest accommodation units was completed. These were again located close to the beach, in apparent disregard for hazard. With this case in mind, perhaps the problem of siting structures in the coastal zone permeates deeper than it appears on the surface since builders in the construction industry are required by law to obtain a building permit before commencing any work. It is the responsibility of the appropriate authority (building controller) to ensure all building requirements and safety measures are met during the planning stage of any construction otherwise the application is revoked. It is quite clear here judgement in this case is questionable since human lives are endangered.

Basalt rock or rubble mound structures in the coastline of Rarotonga are generally found to be situated high in the beach profile, away from the surf zone (except during periods of high water levels in the lagoonal area), away from deep water and away from the reef flats. During periods of quiescent wave activity and low water levels in the lagoonal area these sites are land bound, aesthetically obtrusive and hazardous to their owners and the general public.' It seems on Rarotonga, at least for now, beach property owners are content to use rubble mound structures despite negative repercussions of its use. But one must be pragmatic in any assessment of these structures and ask the question which property owners have long considered over the years which is, what cheaper and more effective alternatives are their? 'Doing
nothing' is not considered an option because of the importance and value placed upon such vulnerable property.

Revetments:

On open coastlines the method most commonly used for protection is a rock armoured revetment where the rock is placed at pre-determined slope. Similar in appearance to rubble mound structures (where rock material is technically randomly placed), revetments have a pre-determined structural form where rock material size is carefully selected and placed. Between Avatiu and Avarua harbours in the northern coastline of Rarotonga is the largest revetment works on the island to stabilise the waterfront against hazards that are notorious in the area (see Plate 3.1, page 50).

In the sixties a concrete and mixed stone seawall was constructed to reclaim the Avarua waterfront. After successive cyclones, the seawall had become a national liability requiring extensive repair over the years. Following Cyclone Sally (1987), the worst storm yet on record, the Avarua waterfront became the focus of redevelopment plans after it was badly damaged and inundated with saltwater. Today, much more of the waterfront has been reclaimed in an effort to distance hazards from vital commercial and infrastructure assets.

Concrete Coastal Protective Structures:

Before 1960 concrete was mainly used in the South Pacific to build vertical walls or mass concrete gravity structures, however, in recent years concrete is considered to be an expensive alternative (SOPAC/SPREP 1994a). Similarly on Rarotonga concrete structures were common until the late seventies when economically viable alternatives such as basalt rock mounds or revetments were preferred. The most conspicuous concrete structure on Rarotonga located in or near the littoral zone is the western landing approach end of the Rarotonga airport which encroaches the lagoonal area but not the reef system. Constructed during a period of widespread development in
the early seventies, the structure seemed impregnable. But after two decades of being subjected to successive cyclones and an unrelenting wave climate, the airport seawall (as it is known locally) is showing structural fatigue. A recent storm outflanked the northern main road approach causing severe ‘end effect’. Large storm waves severely overtopped the 4 to 5 meter height of the wall causing flooding problems behind the structure and further undermining it. Efforts are being made to restore the seawall because of its national importance. Its loss would affect the important economic sector of Tourism, especially tourist air travel numbers. The northern approach is flanked by large basalt boulders designed to alleviate problems of “end effect” (see Plate 3.2, page 72) and according to Mr Tony Utanga (Cook Islands Conservation Council, pers. comm. 1996) a new technology, COPED (Coastal Protection and Energy Dissipation) system, developed by local entrepreneur and Coastal Protection Consultant Mr Don Dorrell, will be used to augment protection at the southern approach to the seawall. Since the COPED system is newly developed and is untried in the field, there is scepticism about its use right across the site.

Private owners of concrete seawalls are few. Many seawalls have been replaced by cheaper alternatives due to the high cost of maintaining them. Others have merely suffered structural fatigue, lack maintenance and are disintegrating to oblivion. The sturdy survivors of time are usually part of a maintenance programme, periodically upgraded and owned by those who can afford to service them. For example, the seawall at HRH Queen’s Representatives residence in Titikaveka, Meteorological Office retaining/seawall, Ngatangiia CICC Waterfront seawall.

Concrete Precast Units:

The work carried out at the Rarotongan Resort Hotel already briefly outlined is the most relevant and appropriate here. A new proprietary technology developed by Mr Dorrell (1988), the use of pre-cast concrete CPU’s (Coastal Protection Units) was advocated. The design functions of these pre-cast units are to reduce wave energies on their shoreward sides (see Plate 3.3, page 73), to reduce wave runup, and to
trapping and accumulation of sand. The structures were placed in a line broadly parallel to the shore over the eastern half of the site and were associated with stone filled wire gabions installed as training walls around Vaituruma Stream mouth at the eastern boundary of the site. Prior to the CPU installation the coastline was subject to severe constant erosion and several attempts at protection using groins, breakwaters, rock revetments, a rock sill and sand nourishment had all failed. The eastern sandy beach had been severely eroded and a hotel accommodation block was constantly being inundated with seawater and was under threat of being undermined (Kirk 1993).

An important first step in the implementation of the scheme was the removal of the remains of earlier attempts to control hazards in the area. The scheme designers point out that a prerequisite for any erosion control at the Rarotongan Resort Hotel site should not only maintain the shore against net sand loss or mitigate saltwater
inundation, but the “outcome must involve a sandy beach” which is a prime attraction of the hotel. Treatment should be comprehensive across the site and sensitively designed so as to avoid referring hazard to neighbouring sites. Constant monitoring (Kirk 1991, 1992, 1993) has shown that the scheme is accumulating sand and rehabilitating the beach particularly where erosion was worse and unlike most other forms of coastal protection has not transferred erosion to neighbouring sites but has actively conferred benefit (Kirk 1993). After five years since its installation the scheme appears to have fulfilled its design objectives.

Plate 3.3: Precast concrete coastal protection unit at the open end of the wall

In June 1995 high seas originating from ocean swell waves encroached the hotel premises depositing sand in the swimming pool and about beachside units except those in the eastern half and immediately behind the CPU’s. According to Professor Bob Kirk (University of Canterbury, pers comm 1996) the scheme only covers half
the site, therefore, it cannot be expected to provide absolute protection. In fact, no technology is complete proof against the sea. Any building or construction (commercial, industrial or residential) near the sea should expect to get wet, the Rarotongan Resort Hotel like the Edgewater Resort is no exception.

Natural Organic Material Barriers:

Seawalls or barriers constructed from natural organic materials, in particular coconut (Cocos Nucifera) log wood is finding favour with beachside property owners. According to Mr Peter Kemp (Muri Beachcomber Manager, pers. comm. 1995) whose tourist accommodation property is shored at the beach front with a coconut log wood barrier, the decision to implement a barrier was necessary due to the hazards in the area (see Plate 3.4, page 76). The choice of coconut wood was based on availability and cost of material, cost of (local) labour, and aesthetic appeal. According to Mr Don Dorrell (Coastal Protection Consultant, pers. comm. 1995), the Muri Beachcomber site was subjected to severe wave overtopping during a recent storm. Since the incident, the management has been more vigilant by increasing the height and length of the wall, linking the logs together by chain and anchoring it down with steel tie rods. While conducting work at a study site (5) in Muri Lagoon a nearby property owner was constructing a coconut log barrier. Apparently the Conservation Department had not been informed but no immediate action was taken. This may have been due to the fact that efforts about the same time to prosecute three other defiant owners for similar deeds went unpunished by the courts causing a major setback for coastal managers.

Programmes to re-vegetate hotel frontages, for example, the Edgewater Resort and Rarotongan Resort, has been recently implemented to help combat hazard. However, according to Mr William (Bill) Sykes (retired New Zealand Landcare Botanist, pers. comm., 1995), the most effective flora against stormy conditions are those that are already well established in the coastal zone since salt resistant flora on Rarotonga is limited and many of these are ineffective against storms anyway. In the case of the Edgewater Resort site, the old hardy flora has been long removed to make way for its development. Efforts are being made by the Cook Islands Conservation
Department to advise property owners of the importance to preserve foreshore flora. However, according to a recent report in “Forest and Bird” magazine (Barrington 1996), vegetation destruction is still common with venerable old trees hacked back to mutilated stumps in an obsession by locals to be “neat and tidy”. The removal or periodic trimming of big trees is promoted as a hurricane safety measure; the diffusing buffer effect of vegetation, which can break the force of a hurricane, is ignored.

3.6 Summary

In recent years the Cook Islands has benefitted from a substantial increase in studies conducted in the nearshore coastal zone. Rarotonga island, the administrative, social, and economic centre of the Cook Islands has been the main benefactor of these scientific and engineering studies.

Approximately 68 percent of the total land area of Rarotonga is not suitable for human development because it is too mountainous. The area of significant human activity is on the coastal fringe where land is relatively flat and fertile for cultivation purposes. Vital commercial assets and essential infrastructure are located in this area. The fringing coral reef that circumnavigates Rarotonga is narrower on the northern and eastern side of the island and relatively wider on the southern and western sides.

The Cook Islands faces many physical constraints in its quest for economic growth and development. These constraints are derived mainly from the geography of the country. Tourism is regarded as the backbone of the Cook Islands economy. This points to the fact that beaches are a vital and important national resource.

However, Rarotonga is not free of hazards. It experiences tropical cyclones (approximately once a year), oceanic swell storms, and other natural phenomena that may impinge on the human habitat. Coastal erosion is both chronic and widespread on Rarotonga. This is due mainly to the removal of sands from the beaches for the purpose of construction.
Plate 3.4: Muri Beachcomber coconut log wood barrier
Hard stabilisation is the most used option besides doing nothing to stabilise the beach and to mitigate coastal problems. Volcanic rock rubble or revetments are the most common form of coastal protection. The primary function of these rock structures is to absorb the energy of waves both in wave run-up and backwash. It is generally the most economical form of construction where a reasonable supply of suitable size rock is available. Concrete based seawalls were mainly used in the sixties and seventies, however, in recent times these have been regarded as too expensive. However, precast concrete units advocated for the Rarotongan Resort site has been relatively successful in not only protecting the buildings behind them but also in rehabilitating the beach where traditional coastal protection techniques have failed in many respects. While many strategies have been used to mitigate coastal erosion on Rarotonga, precast concrete units, developed by Mr Don Dorrell, continues to defy the odds after a lifetime of five years. Further coastal protection systems are being developed by Mr Dorrell (for example, the COPED system).
CHAPTER FOUR

4.0 Study Methodology

4.1 Introduction

This chapter is concerned with, as the chapter title implies, a description of the methodology used to collect the primary data for this research.

Field Monitoring was carried out from 1 May to the 14 July 1995, a period of more than ten weeks. Five sites in the west and southern coast of Rarotonga were selected for monitoring (see Figure 4.1). In general, all selected sites are located on sandy beach coastlines, away from the cyclone prone northern coast (but not free of cyclones) and most vulnerable to swells from southern source areas.

Figure 4.1 A map of Rarotonga indicating the monitoring sites related to this study
Tropical Cyclones are important to beaches in tropical environments from the point of view that they are necessary for the long term replenishment of predominantly carbonate sediments. But the areas selected for monitoring are generally located away from the cyclone prone northern coastline. However, as recent history has indicated no area is free of tropical cyclones.

During cyclone Sally (1987) after the eye of the storm had passed directly over Rarotonga, the western coastline was caught in the backlash of the storm. In 1990 cyclone Peni (1990) passed 2° east of Rarotonga moving in a south easterly direction. Large waves (significant wave height of 8 metres was measured by the waverider buoy offshore) pounded the reef and the southern coastline.

The incidence of swells are already discussed, however, it is important to point out that these can arrive at any one time and without warning. The description of a swell storm in June 1995 is discussed in chapter five. According to Mr Arona Ngari (Meteorological Office Manager, Cook Islands, pers. comm., 1995), these type of events are difficult to foresee or track unlike Tropical Cyclones or Tsunami where the service to monitor these are well established.

As established earlier the coastline monitored by this study are predominantly sandy beaches. Sand at all sites are medium grained to coarse grain in size with 50 to 80% by weight falling in the 0 to 2 phi (0.25 mm to 0.9 mm) range.

Tide considerations are important. Rarotonga has a semi diurnal tidal range of approximately 1 metre. During high tides lagoon water levels are elevated enabling waves to do most geomorphic work on the beaches. A more serious scenario is when swells, ENSO effects and large storm waves occur with high tides.

Previous monitoring work (most commonly by shore-normal beach profiling) has been carried out at all sites monitored by this study. The most comprehensive collection of data was carried out at the Rarotongan Resort Hotel site by the Local Survey Department and is presented in reports by Dorrell (1988) and Kirk (1983, 1986, 1991,
Muri lagoon is another area that has been studied in detail. There are too many studies to mention here, however, most of these have been acknowledged already.

While collecting data for this study, a team of Ministry of Works engineering surveyors were simultaneously mapping Muri lagoon under the directive of the Cook Islands Conservation department. It is believed this data will be used for coastal erosion analysis. Such work is an ongoing commitment for local government agencies and one that is important to acknowledge since data collection from whatever source is vital to researchers in the field of coastal science.

4.2 Monitoring Sites

The main objective in site selection was to observe different types of protective structures on sandy beaches at different locations around the island of Rarotonga. In this way it is possible to assess various types of coastal structures as well as understand site specific coastal processes and beach response. The sites selected needed to be located in such a position on the beach profile that occasional engagement between the wave climate and the structures occurred. In this way it is possible to observe and measure dynamic beach response in front of structures which is the focus of this study.

It is important to note that while there may be many sites on Rarotonga with coastal protective structures, some are land bound and do not engage with the waves only during very high seas. In the context of this study, sites close to the surf zone were chosen for optimal results over the study period of ten weeks and also, sites that were well maintained were selected over ones that were not. This would ensure that the same sites would be available for future observations.

It could be argued that these sites are well adjusted to the incident coastal processes due to their proximity to the surf hence beach change would be negligible over the study period. Also, the study time frame may be a subject of scrutiny since beach
change is a function of the wave climate and significant change does not occur in a matter of weeks for some beaches. However, as pointed out earlier, a swell storm hit Rarotonga midway through the study period generating some interesting and welcomed results, diluting any pre-research fears.

### 4.2.1 Site 1: Edgewater Resort Hotel Basalt rock Revetment

Located in the west coast, the Edgewater Resort Hotel basalt rock revetment was chosen because it interacts often with waves during periods of high tides. The site consists of a gently convex curving shore line and an 80 metre long basalt rock revetment which is unprotected at the centre to allow access for the hotel guest to a beach and the sea (see Plate 4.1, page 83). Beneath the surface of this area of unprotected beach, an artificial beach slope is maintained by an arrangement of gabion baskets filled with coral and volcanic rock. The beach itself is periodically maintained by importing truck loads of sand. The basalt rock revetment stands two metres above the mean low water mark (MLWM) with a 2:1 slope and sits only metres from the surf zone.

To the north is the hotel tennis courts and a three storey block of hotel accommodation units (intended for high paying guests). Most notable about this area is that it is unprotected and again it has an artificial beach slope maintained by gabion baskets filled with rock material and sand imported by heavy machinery.

Exposed to storm winds from the west and northwest and southwesterly swells, the short width between the reef and the beach provides little in the way of protection from incident wave energy. Current flow is generally in a south direction but due to the dominant south and westerly component of the wind and wave climate, drift currents may predominate especially during high tides moving masses of water in a northerly direction.
4.2.2 Site 2: Rarotongan Sunset Motel Basalt rock Revetment

Also located in the west coast, upcoast (relative to the dominant current direction) and less than a kilometre from the Edgewater Resort Hotel site, the Rarotongan Sunset Motel is protected at the beach front by a two metre high, 80 metre long basalt rock boulder revetment which also has a small unprotected area at the centre to allow access for its guests to the beach (see Plate 4.2, page 85). The revetment is distance from the surf zone and high in the beach profile and only during high seas the water may encroach the armoured wall (see Plate 4.3, page 84). The site has a gently convex curving shoreline that straightens for several hundreds of metres either side of the site. The beach profile has a natural grade which is often landscaped and cleared of coral rocks and debris by an employee of the motel to allow for the comfort of the motel guests.

The incident wind and wave climate is similar to that of the Edgewater Resort Hotel site where it is exposed in the west and northwest and to wave refraction of southerly swells. The short width between the reef and the beach provides little protection from wave energy reaching the shore. Wave energy may be high but this depends on the angle of wave approach.

4.2.3 Site 3: Rarotongan Resort Hotel Precast Concrete Units

Located in the southeast corner of Rarotonga, the Rarotongan Resort Hotel CPU’s (Coastal Protection Units) was chosen because the wall of concrete units is located in the surf zone (see Plate 4.4, page 85) and that it is also the only wall of this type. The Hotel site is situated around the mouth of the Vaituruma stream. The stream was diverted to make way for the hotel construction in the early seventies. To the northwest, the lagoon is 350 meters wide while from the hotel eastward it averages as much as a kilometre wide.
Plate 4.1 A panoramic view (oriented North-South) of the Edgewater Resort Hotel basalt rock revetment at high tide. Note unprotected areas to the north and centre of the revetment are artificially stabilised below the surface. (Views taken on 23 June 1995).
Plate 4.2 View at the centre of the Rarotongan Sunset Motel basalt rock revetment. Note displacement and settlement of basalt boulders in the foreground. (Taken on 4 May 1995)

Plate 4.3 A view northward of the beach profile adjacent to and in front of the Rarotongan Sunset Motel. Note the prominently medium sand and gravel beach sediments. (Taken on 13 June 1995)
Plate 4.4 A panoramic view (oriented West-East) of the Rarotongan Resort Hotel of the Coastal Protection Units at high tide. (Views taken on 3 July 1995).
Because of the predominant southeasterly trades and dominant storm winds from the west and northwest, both the reef and the adjacent beaches are very exposed to wave action, so that the greater width of the lagoon has little effect in reducing the wave energy reaching the shore.

The CPU is a precast concrete unit that is triangular in section, rectangular from the front and rear with a series of vanes to allow a wave to pass through, free standing (1.3 metres high x 1.5 long) in the lagoon and weighing approximately 500kg per concrete unit (See Plate 4.5, page 87). It is designed to give immediate protection to eroding shorelines by dissipating wave energy without reflection and to induce accretion of the beach by transferring sediment and modified energy through the unit. This is most evident during periods of storms and swells when sediments in suspension are abundant.

Current flow is generally in a easterly direction towards the nearby Rutaki passage. But due to the dominant southeasterly winds in the area drift currents and wind waves may form causing flow in a westerly direction. This situation is usually most evident during changing tides and increased water levels in the lagoonal area.

4.2.4 Site 4: HRH Queens Rep’s Resident Seawall

Relatively sheltered from dominant storm winds in the west and northwest and exposed to the predominantly southeasterly trades, little is recorded about storm effects and hazard at this site. It is located in a gently concave shoreline, up coast (relative to the current direction) from the nearby Avaavaroa passage, and although the width of the lagoon is well over half a kilometre protection measures in adjacent sites (towards Avaavaroa passage) suggest little wave energy is lost in reaching the shoreline. The site is protected by a two metre high concrete mortared mixed rock seawall that extends beyond two hundred metres in length and retains the main road system behind it (see Plate 4.6, page 89). During high tides the seawall frequently interacts with the waves.
4.2.5 Site 5: Mary Davis-Harvey Seawall

Located in Muri lagoon, almost opposite Taokoka island, a local resident privately owns and maintains a metre high, 39 metre long concrete in situ retaining seawall (See Plate 4.7, page 90). Constructed in 1973 the seawall is testament of its resilience while many other similar walls have been damaged or completely destroyed. Showing
little signs of structural fatigue, the only concern is the fact that adjacent unprotected sites are eroding backward of the wall causing it severe 'end effect'. This has been met by remedial placement of basalt rock boulders to stem the problem.

As pointed out earlier, Muri lagoon has been widely studied. Kirk (1980) observed current flow directions and noted that the area in the vicinity of Taokoka motu is considered a boundary for bi-directional flow in opposite directions. The boundary may alter under wind and wave conditions whereby drainage of this basin is either northward through Ngatangiia passage or southward through Avaavaroa passage.

The areas in Muri Lagoon most vulnerable to erosion are those of greatest exposure to incident waves, for example, the area in the vicinity of Muri sailing club. And secondary areas subject to erosion are those where the channel narrows, for example, the area in the vicinity if Taokoka island where beach deposits may be eroded in response to increased unidirectional currents (Collins 1993). This observation would suggest that the study site is relatively sheltered from the severity of storm waves and wave energy.

4.3 Data Collection Methods

4.3.1 Historical Data Collection

Data on historical changes in the lagoon and shoreline position has been compiled by a number of sources. A majority of this data on past position of the coast has been compiled by the Cook Islands Survey Department by way of aerial photographs, topographical maps, and shore-normal profile data. Dorrell (1988) reported that air photographs were available for 1945, 1954, 1962 and 1979 at a variety of scales from the Survey Department. However, in 1992 the departments former premises was completely destroyed by fire jeopardising its database. Although much of the aerial photograph archive was destroyed it is believed backup copies exist in New Zealand. The available photographs date back to 1988 which is sufficient for most purposes but inadequate for determining historical coastal change.
Plate 4.6 A panoramic view (West-East orientation) of HRH Queens Representative’s Residence (Turoa) concrete mortared mixed rock seawall at low tide. (Views taken on 14 July 1995).
Two sites monitored by this study have had comprehensive studies of historical change carried out. That is, the Rarotongan Resort and Muri lagoon. It is established by these studies that aerial photographs provide the best details and accurate comparisons of past positions of the coast.

Data collection on Rarotonga by way of shore normal survey profiles have been generally uncoordinated and sporadic over the years. But most recently a network of sites for profiling was established and frequently surveyed by the Survey department and the Ministry of Works under the directive of the Cook Islands Conservation Department. Since the network is relatively new, it is again sufficient for most purposes but inadequate for determination of historical coastal change.

Evidence of coastal change may be best provided by local residents that live along the coast or local fisherman who make frequent visits to the coast. It is important to bear in mind that knowledge will always be imperfect and selection of an informant must be approached with the utmost care. With some local knowledge and familiarity with
the culture, obviously some of these problems are minimised. However, as Don Dorrell (Coastal Protection Consultant, Rarotonga, *pers. comm.*, 1995) pointed out, it is generally the older generation who best understand site specific coastal processes and historical coastal change, unfortunately they are few and difficult to locate.

### 4.3.2 Shore Normal Survey Profiling

The principal data collection methodology used for this study was repeated shore-normal survey profiling. It is arguably the most cost efficient, easy to operate and effective methodology in coastal research. Repeated survey profiles were carried out within a 10 week period between 01 May to 15 July, 1995. A baseline or control traverse was established first on the backshore and shore-normal surveys were carried out along this baseline at intervals of a maximum 20 metres. Profile lines were established perpendicular to the coastal structure extending either side of the unprotected beach as well. Measurements were taken at breaks in the slope, typically 10 to 12 points on each profile, such that profiles could be accurately reproduced with a minimum number of survey points. Care was taken to ensure that profiles were not placed where they would be modified by coastal streams or stormwater drains. In the case of the Edgewater Resort Hotel site locating the artificial beach slope was a first priority.

Survey equipment comprised a compass, 100 metre measuring tape, 3 metre E-staff, pegs, spade, machete, ranging rods, Electronic Distance Reader with locating prisms and a TM5 Sokkisha Automatic (battery powered) Theodolite. This equipment was made available by the Cook Islands Conservation Department, Ministry of Works Planning and Design Services, and the Survey Department. Reliable transport, an essential component of the fieldwork, was kindly supplied by Mr Edwin Utanga.

During high tides it was not possible to carry out surveys at particular sites. By relocating to another site continuity of work was maintained. Initially, water temperatures were pleasant enough to enable two persons (instrument observer and staff person) to carry out a full day of profiling. But following a swell storm on the
8/9th June 1996, the water temperature dropped significantly for the remainder of the field study. As a result, two more survey assistants were acquired to maintain the demanding profile schedule.

It was useful to find that previous survey profile work had been established at all sites monitored by this study. However, (with exception of the Rarotongan Resort Hotel) difficulties were experienced as assumed heights were used as datum in many cases. Hence, approximately a third of the total field study period was spent establishing reduced levels to mean sea level for all sites. In some instances, two groups of surveys were required to meet the demands of the field work schedule. One group would be designated to transfer known heights to a study site by levelling whilst another would continue profiling.

4.3.3 Sediment Sampling

Sand sediment samples (500g) were obtained from all sites along select profile lines on the 15 July 1995 and returned to Christchurch for analysis. The samples were taken from mid tide positions on the beach. Due to the lack of operational sediment analysis apparatus on Rarotonga (Ministry of Works), sediment sampling in the early stages of the field study was not considered but may have been useful for comparative purposes of pre-storm and post-storm influences.

Grain size analysis was carried out at the University of Canterbury by determination of settling velocities in a 2 metre water column using a Mac Arthur 'Rapid sediment Analyser' which is coupled to a computer for processing the final output of data.

In general, it is well known that there is a strong relationship between beach sand particle size and foreshore slope, such that coarser grains will adopt steeper slopes and conversely finer material will adopt lower slopes. It is also well known that accretion of foreshores promotes steeper slopes while erosion creates flatter slopes. But it is equally well known that most conventional coastal protection structures lack a beach in front of them altogether. Using sediment samples it may be possible to
understand some of the effects which coastal structures may have on the beach morphology.

### 4.3.4 Sediment tracing

The fundamental aim of sediment tracing is to understand the mechanisms or processes that take place in the nearshore environment. It is the most critical process in terms of beach formation. Although this methodology was recommended it was not fully utilised due to the demanding profile schedule and the extra work associated with the survey profiles.

It was generally found though that most coastal structures were usually land bound and occasionally they would be affected by waves particularly during the rising tides. To successfully implement sediment tracing about coastal structures, it is perceived the structure would need to be located in the surf zone or interacting with the waves. Only two sites with sandy beaches and coastal structures were recognised to behave effectively in this way, that is, the Rutaki Primary School waterfront basalt revetment site and the Rarotongan Resort Hotel Coastal Protection Units.

Sediment Tracing was carried out at the Rarotongan Resort Hotel site using fluorescent painted grains selected from mid-tide positions on the beach. However, due to discrepancies in the application of this methodology in the first attempt and constrained by time to repeat the experiment, it was finally shelved.

### 4.4 Summary

Five sites in the western and southern coasts were selected for monitoring. These were generally located in sandy coastlines away from the cyclone prone northern coastline (but not free of Tropical Cyclones) and most vulnerable to swells from southern source areas.
The main objective in site selection was to observe different types of protective structures at different locations around the island of Rarotonga. In this way it is possible to assess the coastal structure as well as understand site specific coastal processes and beach response for a particular site. Further, an important criteria in site selection was that the structures needed to be located in such a position where there was occasional engagement between the structure and the wave environment.

The profile sites were a maximum distance of five kilometres and five hundred metres minimum between sites. Data collection was principally carried out by repeated shore-normal beach profiles. These were established at 20 metre intervals along a traverse baseline and measurements were obtained by an Automatic Theodolite using the survey technique of Stadia. Sand samples were collected in the field and returned to Christchurch for grain-size analysis by determination of settling velocities in a two metre water column using a ‘Rapid Sediment Analyser’ coupled to a computer for processing the final output data.
CHAPTER FIVE

5.0 Coastal Protection and Nearshore Observations

5.1 Introduction

In recent years coastal research on Rarotonga has been characterised by a significant increase in factual data about coastal processes and beach response in the nearshore regime, however, little work has been carried out on the monitoring of structures or construction in or near the active beach zone. This chapter provides quantitative results of nearshore beach response in front of and adjacent to various types of coastal protection measures collected over one period of ten weeks in 1995. The principal methodology used, discussed in the previous chapter, was by way of repeated shore-normal beach profile surveys. Observations were also made of nearshore processes using crude visual techniques.

The objective of the field research was to attempt to quantify beach response in front of various types of coastal protection structures in order to understand the effect of such structures on beach morphology and on the apparent processes.

5.2 Meteorological Conditions during Study Period

This section is introduced because it is necessary in coastal protection research as Foster (1982) points out. "...It is important that papers describing case histories of coastal protection give sufficient detail of the coastal processes to adequately assess their use in other areas."

During the study period a storm of swells originating from a southern source area brought unusually high waves in the seas around the Southern Cook Islands from the 8th to the 9th June. This storm caused major inundation of seawater into coastal areas on the southern and parts of the western coastline of Rarotonga and strong
currents in the lagoon. In the context of this study, the storm was welcomed. Prior to this event a tsunami warning for Rarotonga was aborted originating from a tectonic source in the vicinity of Vanuatu in the Southwest region. Apart from the swell event, the situation over the study period was moderately calm in the nearshore area with low wave activity except during high tide.

Table 5.1 (page 97) presents meteorological data which covers the entire study period. The data was provided by the Cook Islands Meteorological Office (Mr Arona Ngari, Manager, Rarotonga) and NIWA provided the wind data. The wind data was collected at Rarotonga Airport. It is important to point out here that most of the sites monitored by this study are located in the south and west coast of Rarotonga but the collecting station for wind data (Rarotonga Airport) is located in the northern coastline. It is well established that on Rarotonga topography influences rainfall distribution and coastal winds. Therefore the wind data is not representative of the wind regime at study sites but it is sufficient for the purpose of this study.

Generally it can be seen from table 5.1 (page 97) that conditions were pleasant. Rainfall was sporadic except for the month of May where there were persistent periods. The winds were moderate to gale force (17.2-24.4 m/s) with the occasional storm force (24.5-32.6 m/s) winds particularly in the month of June. The period of occurrence of a swell storm (8-9 June) shows a significant fall in the temperature and consequently humidity. Winds were from a southern direction of gale force intensity.

5.3 Swell Wave Event of 8-9 June

Information from this section comes from personal experience and that supplied by Dr Stephen Barstow (Oceanor, Norway) via e-mail services.
| DAY | MAY TEMP | RAINFALL | HUMIDITY | WIND(MA) | WIND DIR | JUNE TEMP | RAINFALL | HUMIDITY | WIND(MA) | WIND DIR | JULY TEMP | RAINFALL | HUMIDITY | WIND(MA) | WIND DIR |
|-----|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|
| 1   | 23.6     | 96       | 8        | 40       |          | 18.7     | 92       | 17       | 210      |          | 20.4     |          | 85       | 30       | 360      |
| 2   | 24       | 0.3      | 75       | 18       | 180      | 22.4     | 89       | 18       | 120      |          | 24.5     |          | 81       | 14       | 360      |
| 3   | 23.6     | 14.3     | 82       | 14       | 160      | 23       | 79       | 18       | 130      |          |          |          |          |          |          |
| 4   | 25.5     | 4        | 84       | 19       | 90       | 25       | 88       | 17       | 80       |          | 23.3     |          | 81       | 26       | 350      |
| 5   | 25.7     |          | 81       | 30       | 70       |          | 25.3     | 1.8      | 90       | 21       | 10       |          | 20.6     |          |          |
| 6   | 26.2     | 0.7      | 90       | 17       | 140      | 22.5     | 78       | 19       | 200      |          | 24       | 8.9      | 87       | 17       | 90       |
| 7   | 25       | 0.2      | 92       | 22       | 270      | 19       | 79       | 18       | 180      |          | 21       | 85       | 14       | 140      |          |
| 8   | 22.2     | 4.4      | 97       | 16       | 210      | 8        | 21.6     | 74       | 11       | 160      |          | 24       | 8.9      | 87       | 17       | 90       |
| 9   | 25.3     | 37       | 93       | 10       | 80       | 9        | 23.8     | 62       | 14       | 130      |          | 22       | 0.6      | 90       | 24       | 140      |
| 10  | 25       |          | 91       | 14       | 100      |          | 25.8     | 93       | 21       | 90       |          | 23       |          | 91       | 25       | 160      |
| 11  | 24.5     | 0.7      | 96       | 28       | 100      | 11       | 23.5     | 1.6      | 96       | 15       | 20       |          | 22.5     |          | 83       | 24       | 160      |
| 12  | 22.5     |          | 96       | 28       | 100      | 12       | 24.3     |          | 1.6      | 96       | 15       | 20       |          | 22.5     |          | 83       | 24       | 160      |
| 13  | 24       | 3.9      | 83       | 22       | 20       | 13       | 24       | 86       | 16       | 110      |          | 22.1     | 0.3      | 78       | 25       | 110      |
| 14  | 23       | 12.8     | 75       | 14       | 230      | 14       | 24.1     | 72       | 19       | 100      |          | 22       |          | 74       | 22       | 90       |
| 15  | 22.7     |          | 82       | 17       | 200      | 15       | 25       | 0.3      | 84       | 20       | 80       |          |          |          |          |          |
| 16  | 23.4     |          | 88       | 15       | 60       | 16       | 25.4     | 81       | 15       | 40       |          |          |          |          |          |          |
| 17  | 23.5     |          | 87       | 16       | 160      | 17       | 24       | 84       | 11       | 250      |          |          |          |          |          |          |
| 18  | 22.5     | 19.7     | 63       | 19       | 150      | 18       | 21       | 95       | 11       | 200      |          |          |          |          |          |          |
| 19  | 24.4     | 3.7      | 87       | 18       | 150      | 19       | 22.1     | 82       | 14       | 250      |          |          |          |          |          |          |
| 20  | 22       | 4.5      | 82       | 17       | 240      | 20       | 23.1     | 1.1      | 72       | 12       | 210      |          |          |          |          |          |
| 21  | 22.5     | 14.1     | 68       | 20       | 60       | 21       | 22.5     | 96       | 19       | 270      |          |          |          |          |          |          |
| 22  | 23.1     | 20.9     | 68       | 27       | 160      | 22       | 21.1     | 61       | 13       | 130      |          |          |          |          |          |          |
| 23  | 24.5     | 38.5     | 95       | 30       | 150      | 23       | 20.3     | 91       | 18       | 190      |          |          |          |          |          |          |
| 24  | 24.7     | 14.8     | 92       | 25       | 120      | 24       | 18.5     | 85       | 16       | 170      |          |          |          |          |          |          |
| 25  | 24.1     |          | 92       | 27       | 120      | 25       | 23.1     | 5.5      | 71       | 16       | 150      |          |          |          |          |          |
| 26  | 23.4     |          | 91       | 27       | 80       | 26       | 23.2     | 11.9     | 92       | 19       | 60       |          |          |          |          |          |
| 27  |          |          | 88       | 38       | 300      |          | 22.8     | 29.4     | 95       | 12       | 30       |          |          |          |          |          |
| 28  | 20.4     |          | 94       | 21       | 270      |          | 22       | 5.6      | 91       | 16       | 130      |          |          |          |          |          |
| 29  | 23.4     |          | 95       | 15       | 90       |          | 24       | 48.7     | 87       | 27       | 140      |          |          |          |          |          |
| 30  | 22       | 1.5      | 85       | 11       | 60       | 30       | 23       | 0.5      | 94       | 24       | 90       |          |          |          |          |          |
| 31  | 0.2      |          | 96       | 11       | 60       |          |          |          |          |          |          |          |          |          |          |          |

Table 5.1 Measurements of meteorological parameters for the study period
5.3.1 Situation

On the 8th of June while carrying out some survey and levelling work at the Queens Resident seawall site, Titikaveka, in the morning my son (who was a constant companion) swimming nearby complained that it was getting uncharacteristically cold. At this point in time (11.00 am) the waves breaking on the reef were getting steeper and louder. This was to be the genesis of what we now know as a swell storm.

A low pressure system depicted by Figure 5.1 is located at about 50 degrees south, 170 degrees west moving in a north easterly direction with strong west to southwesterly, winds causing high, long period south-easterly swells which affected the west and south coast of Rarotonga.

![Figure 5.1 Mean sea level atmospheric pressure analysis map; 0800 hours, 7 June 1995. (Courtesy Cook Islands Meteorological Service).](image-url)
Figure 5.2 depicts the wind situation on Rarotonga prior to and during the storm. A gradual southerly change occurred. As pointed out earlier, the Rarotonga Airport collection station for wind data is inappropriate here, nonetheless, the general picture of wind change is clear.

![Wind tick diagram for the period 6th-10th June 1995. Data collected at Rarotonga Airport Station.](image)

### 5.3.2 Wave and Water Levels

Waves are generated by wind blowing over the water and transmitting energy to it. The area over which the wind blows is called the fetch. Waves formed within the fetch area and still under the influence of the generating wind are called the sea waves. As they leave the fetch area and are no longer under the influence of the generating wind, these waves are described as swell. Swell waves decrease as they cross the ocean.

According to Dr Stephen Barstow (Marine Scientist, Oceanor, Norway, *pers. comm.*, 1996) the likely scenario of very high waves which penetrated quite low latitudes is probably as follows. High southwesterly winds blew over a very long fetch from the Southern Ocean south of New Zealand/Australia into the Pacific during several days prior to the event at Rarotonga. The swell waves were generated then moved into an area to the north of the low pressure system on the 7th/8th June. Here winds were strong west to southwesterlies. Thus energy was continually pumped into the existing waves.
Satellite altimeter data extracted from the Topex/Poseidon satellite (see Figure 5.3a-c) measuring significant wave height recorded unusually high waves in the seas around the Cook Islands during the 8th/9th June and very high seas further south reaching 10 metre significant wave height (Hs) towards 40 degrees south on the morning of the 8th June. Winds were also high.

Figure 5.3a (page 101) depicts the satellite tracks that were closest to Rarotonga. At about 20 degrees south, 165 degrees west, Hs around 5 to 5.5 metres was recorded on the 9th at 1100 GMT (Figure 5.3c, page 101). On the 8th at 1100 GMT (Figure 5.3b, page 101) Hs of around 4.5 metres was recorded 26 degrees due south of Rarotonga.

On the Southern coast of Rarotonga wave height increased from Hs about 1.5 metres on the 4th/5th June to a peak as high as 6 metres during the 8th/9th June. Wave direction was from the south west offshore and energetic wave periods were estimated in the range of 10-15 seconds (for a fairly broad band swell).

5.4 Impact on the beach

All the study sites were affected by the high seas, in particular, sites in the south and southwest coastline of Rarotonga. This was evident during the storm and in the aftermath cleanup. The Queens Resident site (4) and the Rarotongan Resort Hotel Site (3) appeared on the surface to have been most affected by the storm. Analysis of the profile data confirms this was so.

The following observations were made during and after the storm. At the Rarotongan Sunset Motel site (2) waves did not affect the basalt rock protection. This was confirmed by the formation of an intermediate berm in front of the wall and the undisturbed nature of the vegetation growth at the toe of the wall. Steepening of the beach, the deposition of gravel material in front of the wall (usually free of gravels due to the attention of motel staff) and pockets of sediment increase in the adjacent lagoon were the most significant changes due to the storm.
Figure 5.3a Topex/Poseidon satellite tracks for 8-9 June 1995.

Figure 5.3b Satellite altimeter wave measurements for 8 June 1995, 1100 hours GMT

Figure 5.3c Satellite altimeter wave measurements for 9 June 1995, 1100 hours GMT
At the Edgewater Resort site (1) due to the proximity of its rock revetment to the surf zone, waves frequently interacted with the wall during the storm. The beach in front of the wall was low or flat, exposing in places basalt boulders that had been previously displaced. Outcrops of the coral basement in the surf zone were also increasingly exposed. At the extreme ends of the rock revetment the beach profile steepened. Sediment set up even accretion seemed to have occurred here where sediment had filled on top of and around the rock boulders. At the centre of the revetment where it is unprotected (except for a artificial slope) the most significant change or damage had occurred. Plate 5.1 shows the impact of the storm which displaced a large volume of sand and exposed in places the gabion support structure beneath the surface. Note in Plate 5.1 there is no sign of a berm in the aftermath of the storm but rather a scarp. Due to the nature of the imported sand from inland sites where the surface tension between grains are high, the sediment is easily winnowed away in relatively large amounts. In contrast, sediment already in the beach system with reduced tension between grains inherit physical properties better suited to hydrodynamic changes. For example, without losing mobility they have the ability to adjust their form or shape collectively as depicted when profiles steepen or flatten out according to the hydrodynamic force applied.

Plate 5.1 Impact of the Swell storm on an artificial beach at the Edgewater Resort Hotel poolside location. (Taken 11 June 1995).
At the Rarotongan Resort Site (3) waves were frequently observed overtopping the CPU’s. Behind the wall the waves did not encroach hotel units except for the area in front of the Whitesands Restaurant where erosion at the toe of the building was evident (see Plate 5.2). The beach slope in this area had been lowered and sediment loss was also significant. Westwards to the unprotected area of the hotel site, saltwater and sand had encroached beachside units as well as the hotel swimming pool service notice of the extent to which swells can generate energy. At the eastern end and downcoast of the hotel site the beach slope had steepened, berms formed in the back beach and generally a nett accretion of sediment was observed. This was confirmed by a visual survey of the nearby Vaituruna Stream which had accumulated levels of sand that appeared to impede the stream flow at a culvert. According to Don Dorrell (Coastal Protection Consultant, Rarotonga, *pers. comm.*, 1995) choking waterways or streams with beach sediment is a sign of a healthy beach and an indication of excess sediment. When flow in the streams are increased the sediment is returned into the littoral system. In some cases on Rarotonga this sand is mined and sold off for capital gain by landowners.

Plate 5.2 Impact of the Swell storm on the beach in front of the Whitesands Restaurant, Rarotongan Resort Hotel. (Mr Don Dorrell surveys the CPU’s. (Taken 11 June 1995).
At the Queens Resident site (4) reflective waves were observed on numerous occasions. On one occasion a local person with a surf board braved the conditions and was observed surfing towards the reef on outgoing waves. Plate 5.3 shows damage to the seawall sustained during the height of the storm. Scour behind the wall was observed. This was probably due to waves overtopping the structure. The beach profile during the storm was completely inundated.

![Plate 5.3 Seawall damage and high seas during the Swell storm in June 1995 at the Queens Rep Resident, Titikaveka. A westward view towards the Rarotongan Resort Hotel (Taken 9 June 1995).](image)

Discoloration or murkiness of the water was observed particularly close to the wall. This was due to the abundance of suspended sediments in the water caused by waves entering shallow water and interaction with the seawall. Following the storm bars were observed offshore but these quickly disappeared in a matter of days.

At Mary Harvey’s site (5) the storminess of incoming waves was distinct and frequently interacting with the seawall (see Plate 5.4, page 105). The beach profile
was low and flat in front of the wall compared to unprotected areas. This is due to the short runup of waves and the location of the seawall in the swash zone. Observations following the storm at sites around Muri lagoon point to evidence that generally Muri lagoon was least affected by the storm as sediment setup in the back beach coupled with relatively steeply inclined profiles was prominent (see Plate 5.5, page 106).

Plate 5.4 Wave runup engages with the seawall at Mary Harvey's site in Muri lagoon during the swell storm in June, 1995.
(Taken 9 June 1995).

5.5 Surveyed Beach Profiles

5.5.1 Description of Profile change

Repeated surveys over an intensive period of time can be tedious and exhausting but rewarding in terms of the volume of data collected. The usefulness and ease with which data can be analysed is dependant on its quality. As a rule of thumb, accuracy
of data is paramount. For this reason some surveyed sites had to be left out due to discrepancies in the data.

Plate 5.5 Wave runup on a relatively steep beach profile at the Muri Beachcomber timber bulkhead site. (Taken 9 June 1995).

The aim of this section is to provide descriptions of the beach profiles for each monitored site. It should be pointed out that the surveyed site profiles have been numbered sequentially, increasing in the dominant direction of current flow.

Site 1: Edgewater Resort Hotel

The placement and location of beach profiles are depicted by Figure 5.4, page 107.
Four profiles are presented from a total of nine. These have been chosen because they best represent the variety of profiles observed at this site (Figure 5.5, page 108).

The most distinctive feature of the profiles in this area is the use of artificial material (rock filled gabion baskets) to maintain a beach profile. These are represented by Profile 03 and Profile 07. During the swell storm Profile 07 was severely affected by erosion exposing the artificial layer. Periodically sand is imported by trucks to maintain the beach. The material is obtained from an inland site.

Profile 05 is characterised by the basalt revetment in the foreshore. The beach itself is narrow with the sweep zone representing the area of most activity, confined to seaward of the revetment. Wave runup is short hence erosion may be persistent in front of the wall.
Figure 5.5 Examples of beach profiles from the Edgewater (EGW) Resort Hotel site, Tokerau/Inave
Profile 09 is unprotected and represents a natural graded beach. The sweep zone or active part of the beach profile is greater than equivalent areas in front of the revetment. Sediment setup observed earlier is not clear from the profile.

**Site 2: Rarotongan Sunset Motel**

The placement and location of beach profiles is depicted by Figure 5.6.

![Site map of Rarotongan Sunset Motel with profile locations](image)

Three profiles are presented here from a total of five surveyed (Figure 5.7, page 110). In general the profiles show a very high crest position maintained by a basalt rock revetment. The beach width is relatively wide and steepening to the crest. Profile 02 and 04 are located in front of the motel where it is periodically landscaped thus berms are notably absent.

Profile 05 on the other hand represents an unprotected beach where a berm may be identified at mid tide level. The scarp in the backshore is due to boulder size coral material which will tend to maintain a steep profile. Generally the beach material in this area is identified as mixed medium sand, gravels and boulder material which may partly explain the steep backshore.
Figure 5.7 Examples of beach profiles from the Rarotongan Sunset Motel site, Pokoinu
The beach sweep zone or beach profile envelope tends to fluctuate about mid-tide level and seaward with little or no adjustment in the lagoonal area due to a hard coral basal platform close to the lagoon floor.

Site 3: Rarotongan Resort Hotel

The placement and location of beach profiles is depicted by Figure 5.8 (page 112).

Six profiles are presented here from a survey that encompassed the whole site (Figure 5.9, page 113). These six profiles represent the areas that are primarily protected by the Coastal Protection units. The distant feature of these profiles is the influence that the Coastal Protection Units have on the beach. The beach profiles are steep and adjustments tend to fluctuate about the CPUs.

It is important to point out that Profiles 07 and 08 were affected most by the swell storm waves but remedial landscaping works soon after may be responsible for the absence of significant change. However, at the opposite and eastern end of the wall, accretion is identified with changes pivoted about the CPUs. Accretion is also significant at the top of Profile 11. The convex shape of the landward profiles indicates a healthy beach which is generally accreting.

Site 4: Queens Rep. Resident Seawall Site

The placement and location of beach profiles is depicted by Figure 5.10 (page 114).

Six profiles are presented (Figure 5.11, page 115). They are all located in front and normal to the wall. The most distinct feature is the narrow beach width and consequently a narrow sweep zone within which sediment movement may be confined.

Profile 02 shows distinctive changes in the topography of the lagoon surface. These may be interpreted as berms or bars forming offshore subsequent to the swell storm. The undulating topography featured in earlier survey profiles may be due to the channeling of waters close to the shore generated by the presence of a coral lobe upcoast and nearby to the profile.
Figure 5.8 Site map of the Rarotongan Resort Hotel with profile locations.
Figure 5.9 Beach profiles from the Rarotongan Resort Hotel site, Aroa
5.10 Site map of Queens Rep Resident seawall with profile locations and lagoon bathemetry (1995)
Figure 5.11 Beach profiles from the Queens Rep Resident site, Turoa
It was recognised during survey work following the swell storm that bars or walls of sand form the lagoon floor topography. Efforts were made to identify these in the survey. These are distinct in Profiles 06 and 07 approximately 80-150 metres offshore. The interesting aspect of these features was that they had disappeared in the following survey.

Site 5: Mary Davis - Harvey Seawall

The placement and location of beach profiles is depicted by Figure 5.12 (page 117).

Two profiles are presented (Figure 5.13, page 118). Profile 03 represents a protected beach while Profile 05 is unprotected.

Profile 03 has a narrow beach and a backshore that is retained by a concrete in situ seawall. The area beyond the beach is characterised by a basal coral platform that is close to the surface of the lagoon floor. From time to time it was observed that sediment would overlay the lagoon floor and on occasions it would return to a coral basement. This may be indicative of sediment movement transpired by current flow or wave activity.

Profile 05 is unprotected and located down coast (relative to the dominant current direction). It is characterised by a relatively broad beach with an erosional scarp in the backshore. Offshore is a coral basal platform that restricts water depth close to the shore.

5.5.2 Discussion

Over the study period, it can be seen that variable patterns of profile change has occurred across each site. In some cases the physical properties of a site determined change or lack of. Site specific coastal processes have also dictated change and so has the geography of a location. These changes in the various beach profiles are extremely complex to comprehend from a single analysis. Therefore, further analysis is required to fully appreciate the dynamics taking place.
Figure 5.12 Site map of Mary Davis-Harvey concrete in situ seawall
Figure 5.13  Examples of beach profiles from the Mary Davis-Harvey seawall site, Aremango
Beach profile data can be further analysed or manipulated so that information about single profiles can be interpreted in terms of retreat or progradation by an excursion distance analysis.

5.6 Excursion Distance Analysis

5.6.1 Methodology

The basis of this analysis is the excursion distance of a point on the beach whereby the "...horizontal displacement of the plan form position of any one point on the beach from one survey to another, is the excursion distance for that point for the survey period" (in Single 1992). In other words the technique which is referred to as 'Excursion Distance Analysis' or EDA may be thought of as a contoured plan view of a particular section or profile in the beach except the view represented is a function of time.

The profiles were compared for patterns of beach change over the study period. The contours are displayed at 0.5 metre intervals above the survey datum of mean sea level. The slope of a line indicates whether there has been erosion or accretion at a particular contour level on the beach. Negative sloping lines indicate erosion as the distance to the contour is shortened over time, while positive sloping lines indicate accretion. The gradient of a line is a measure of the rate of change and greater angles are associated with more rapid change. If the line is horizontal then there has been no change. Similar to topographic contours, lines that are close together indicate a steeper slope than lines further apart. Therefore if the lines of consecutive contours and converging then that section of the beach is getting steeper. Conversely, if the lines are diverging the beach is flattening. Such an analysis contains useful information about the development of a beach profile or beach site over time and also the short and long term response to wave conditions (in Single 1992). A further point to note is that this methodology is most effective for data that has been collected over an extended period of time and at constant and regular intervals.
A basic excursion distance analysis was carried out for selected profiles at any one site.

### 5.6.2 Results of Excursion Distance Plots

The principles of EDA plots are the same as for normal contour interpretation. That is, divergence between contours represents a flat or widening reference plane and conversely convergence between contours represents a narrow or steep reference plane.

**Site 1: Edgewater Resort Hotel**

Three EDA plots are presented (Figure 5.14, page 121). Generally it can be seen that change overall has been minimal.

At Profile 03 the beach has maintained a sameness about it with little or no apparent change. This site is artificially maintained. Likewise Profile 07, change has been minimal with movement of sediment detected in the lagoon following the swell storm. The beach profile close to the shoreline also shows flattening in the aftermath of the storm. steepening of the profile in the lagoon.

Profile 05 in front of the revetment depicts some change close to the shore. In the lagoon the profile steepened perhaps collecting sediment after the swell storm which seems to be moving at a rapid rate. An examination of Profile 07 confirms movement of sediment offshore as the profile steepens. Hence, current flow for the site is in a south direction.

**Site 2: Rarotongan Sunset Motel**

Two EDA plots are presented (Figure 5.15, page 122). Generally activity on the beach in particular and the surf zone has occurred over the study period.
Figure 5.14 Examples of excursion distance plots for the Edgewater Resort Hotel site, Tokerau/Inave
Profile 04 is protected by a revetment and shows that the basalt rock wall in the backshore was unaffected by the swell storm. Between intervals 2 and 3 the beach was affected by the swell storm causing the beach to deposit material close to the revetment indicated by the steepening of the beach. Following the storm this sediment is re-distributed most likely by human landscaping.

Profile 05 is an unprotected beach. With a wide beach width relative to the protected beach, change has occurred at the surf zone offshore sediment movement is detected.

Site 3: Rarotongan Resort Hotel

Four EDA plots are presented (Figure 5.16, page 124). In general the effect of the Coastal Protection Units clearly shows it is responsible for maintaining a beach behind it. Whereas dynamic changes are occurring in front of the wall, behind it change is minimal with some accumulation of sediment in the backshore.

Profile 06 is located at the end of the wall. Influenced by the swell storm, offshore the profile tended to flatten out also depicting erosion. However, it quickly recovered as depicted by the subsequent steepening of the profile. This variation offshore may be interpreted as movement of sediment.

Profile 09 depicts a stable beach located at the middle of the CPU. Neither eroding or prograding stability is maintained by presence of the CPUs. Offshore flattening of the profile occurs after the storm.

Profile 11 is located at the eastern closed end of the CPU wall near the Vaituruma Stream. Most significant about this site is the backshore area where sediment is accreting. Offshore there is a gradual accretion of sediment consistent with evidence from the previous two profiles of sediment movement in a easterly direction.
Figure 5.16 Examples of excursion distance plots for the Rarotongan Resort Hotel site, Aroa.
Profile 12 is an area that is unprotected on the east bank of the Vaituruma stream outlet. Offshore is the most significant change with gradual increases indicated in sediment deposition. Following the storm the general trend on the beach is erosion but this is rapidly modified to indicate progradation.

Site 4: Queens Rep. Seawall

Three EDA plots are presented (Figure 5.17, page 127). In general it shows a steep profile close to the wall and a small beach width with a generally flat topography offshore. Little significant change is evident in all profiles following the storm with the exception of sediment movement detected offshore in Profile 03. Due to insufficient survey points offshore it is difficult to depict the trend here.

Site 5: Mary Harvey’s Seawall

Two EDA plots are presented (Figure 5.18, page 128). In general the unprotected and protected wall depict similar behaviour over the study period.

Profile 03, a protected site, depicts a period between interval 1 and 2 where the foreshore steepens by receiving sediment. After the swell storm the profile tends to lower and generally flatten out.

Profile 05 shows a steepened profile between intervals 1 and 2 reflecting aggradation. Following the swell storm the beach remains steeper inland but flattens in the lagoon and offshore.

5.6.3 Discussion

From this EDA (excursion distance analysis) the general and specific behaviour of particle or profiles are better understood. Such an analysis has highlighted some of the attributes of coastal protection measures monitored by this study. For example, the location of the coastal structure in the beach profile will influence the way the
beach responds to incident processes. Structures high in the beach profile having no interaction with the coastal processes will not affect the beach and its behaviour. However structures situated in the swash-backwash zone tend to limit the width of the beach and the size of the sweep zone where sediment activity is concentrated. Under a restricted regime, sediment activity tends to move offshore as the EDA plots have indicated. At the Rarotonga Resort Hotel site the EDA plots have shown how effective the CPUs are in maintaining a beach behind the wall as well as not interfering with sediment activity in front of the wall but enhance it. Since wave reflection is minimal secondary effects due to the wall are also minimised. In general, the CPUs from the EDA plots have performed exceptionally well under the storm conditions and have enhanced its capabilities by maintaining a beach similar to an unprotected beach.

A striking feature of the EDA plots is the degree of sediment movement taking place in the surf zone as well as offshore. This is clearly evident in all the plots. To appreciate this spatial interaction a further manipulation of the profile data is carried out.

5.7 Spatial Interaction of Adjustments to the Study Profiles

5.7.1 Methodology

The excursion distance information for the study sites are plotted for each profile at a specific time against the distance of the profile alongshore. Five time periods are displayed in this way for three of the five study sites. The time interval between each plot varies between one to two weeks. These intervals reflect the periods of profile surveys carried out in the field. They are used here to analyse the spatial distribution of beach change.
Figure 5.17 Examples of excursion distance plots for the Queens Rep Residence site, Tuoro
Figure 5.18 Examples of excursion distance plots for Mary Harvey's Seawall site, Aremango
Each plot represents a simplified topographical map of the foreshore of a specific site or area at a particular time. The shoreline is simplified by removing any natural irregularities. However for the purpose designated longshore variations stand out clearly. The EDA information has been plotted at 0.5 metre intervals to collect some foreshore slope detail.

5.7.2 Analysis of longshore variation in Standardised Excursion Distance

Site 1: Edgewater Resort Hotel Site

Figure 5.19, page 130 presents the excursion distance plot.

5 May 1995

A benchmark plot for the study period. Overall it indicates that due to the uniformity of width between the contours in the foreshore there is also uniformity in the beach slope across the site. At Profile 06, offshore it is relatively flat in the lagoonal area, however, in the southern part of the site the topography offshore is steeper.

19 May 1995

From Figure 5.19 (page 130) the most significant change has occurred offshore at Profile 06 where sediment movement is identified in the southern direction. In the foreshore sediment transport is also indicated about the same area. Little change appears to have occurred elsewhere. The overall picture of the beach adjustment for this time interval is that of steepening of the upper and middle foreshore particularly at Profile 06 and also of the lower foreshore with Profile 05 generally becoming wider.
Figure 5.19 Excursion Distance Analysis of the Edgewater Resort Hotel site at specific time intervals.
13 June 1995

This is the first survey carried out following the swell storm. Significant change again has occurred at Profile 07 where it has steepened in the upper foreshore and broadened on the lower foreshore. Elsewhere broadening of the lower foreshore has occurred but little change has occurred offshore. No sharp changes are indicated.

23 June 1995

In the northern and unprotected area of the site little change has occurred up to this point of the study period. Most of the activity has been concentrated in the southern end of the site. Further sediment movement is occurring in the lower foreshore in this area with the beach profile generally steepening.

06 July 1995

Overall the general picture has been little or no change in the upcoast and northern end of the study site. Most of the activity has progressed towards the downcoast and southern end where sediment movement is identified in the lower foreshore. At Profile 07 the beach has steepened considerably in the lower foreshore while at mid-tide position on the profile the beach has broadened. At Profile 09 it is important to point out that accretion is indicated in the upper foreshore area.

Site 3: Rarotongan Resort Hotel Site

Figure 5.20 (page 132) presents the EDA plot.

8 May 1995

A benchmark plot for the study period, it is generally observed that the lower and upper foreshore area is steeper in the west and broad in the east. The area behind the CPUs shows a uniform beach foreshore width is maintained here. At the eastern end of the site, the upper foreshore and backshore is broadened, especially at Profiles 10 and 11. Offshore at Profile 11 further broadening has occurred.
Figure 5.20 Excursion Distance Analysis of the Rarotonga Resort Hotel site at specific time intervals
29 May 1995

Overall the general picture is steepened profiles in the west and broadening to the west. However, at Profile 06 widening of the profile has occurred. Sediment movement can be traced at several points along the beach with the most significant occurring at Profiles 06 and 08. Elsewhere little change has occurred.

19 June 1995

At this point is the first survey carried out after the swell storm. The beach has steepened in the upper foreshore at Profiles 06, 07, and 08 and broadened in the lower foreshore. Offshore the lagoon floor has flattened out and broadened particularly in the eastern region. At profiles 09, 10, and 11 the upper and middle foreshore has broadened with accretion significant in the backshore. Sediment movement seems to have halted for the moment. Generally the profiles overall have not been significantly affected except for the area in the west established earlier.

03 July 1995

The beach behind the CPUs appear to have achieved some uniformity in the upper and middle slopes of the profile. At Profile 07 the lower foreshore has broadened. The most significant change is occurring in the lagoon and in front of the CPUs where once again sediment movement is identified. At Profile 06 it has widened relative to Profile 08 which has steepened. At Profile 09 it has broadened significantly while at Profile 10 there is accretion.

10 July 1995

Again the beach behind the CPUs have maintained its form with adjustments occurring at the lower foreshore. At Profile 07 and 09 it has steepened at the point where the CPUs are situated. Profiles 06 and 08 on the other hand have broadened of eroded in the same area close to the CPUs. This feature is consistent with
sediment movement in a easterly direction about the position of the CPUs. In the lagoon at Profile 09 accretion has occurred. The overall picture suggests several areas across the lagoon where sediment transport is occurring. In the lower foreshore, in front of the CPUs and in the mid lagoonal area.

**Site 4: Queens Rep Residents site**

Figure 5.21 (page 138) presents the EDA plot.

**15 May 1995**

A benchmark plot for the study period. The most significant feature is the concentration of contours close to the seawall and a flat and broadened topography in the mid-lagoonal area. At Profile 02 in the lower foreshore it is relatively steep close to the wall but flattens out. For the rest of the profiles there is uniformity in the slope in the foreshore. The small width of the foreshore is such that it is almost negligible and irrelevant.

**30 May 1995**

At the lower foreshore there is a significant broadening of the beach profile at Profiles 02 and 03 indicating erosion but at Profile 04 no change is evident. However, at Profile 05 progradation has occurred which points to sediment movement close to the wall. In the mid-lagoon area it has steepened at about centre of the seawall but offshore. The changes taking place indicate dominant direction of sediment transport is westwards.

**14 June 1995**

Again, further erosion and sediment transport is recognised at Profiles 02, 03, and 04 moving westwards. Close to the wall the profiles across the site have significantly steepened. This survey is the first carried out after the swell storm. At mid lagoon
position erosion has occurred at Profile 04 but steepening of the shoreward movement of the contour at Profile 05 is indicated. Further erosion downcoast appears to be the overall picture.

26 June 1995

At Profile 05 the foreshore has steepened. It is also the point indicating westward movement of sediment from the eastern area. Contours close to the wall in the west have broadened indicating erosion here. At mid lagoon position further sediment movement is indicated.

6 July 1995

Close to the wall the profile is steep across the site. In the lower foreshore it has broadened indicating erosion but at mid tide position there is a nett shoreward movement of sediment and changes in the lagoon topography.

5.7.3 Discussion

Neale (in Single 1991) developed a concept of longshore sediment transport involving the movement of ‘slugs’ of material along the beach. This idea involves a ‘slug’ or collective movement of beach sediment rather than sediment spread evenly across the coastal system. It is identified from the EDA plots that sediment movement is prominent moving as discrete masses of material at various positions in the beach profile at different time scales. Questions raised in Chapter One highlighted the need to examine how coastal structures affect or enhance sediment transport. This section provides some useful insights.

At the Edgewater site, sediment transport was identified in the lower foreshore and in the position of mid lagoon. However, at the Rarotongan Hotel site, sediment movement was identified at the lower foreshore, in the vicinity of the CPUs and at mid lagoon position. For the Queens Residence site there was sediment movement
close to the wall and at mid lagoon position. Clearly sediment must be available for transport to take place. In the context of longshore movement, storms such as the swell storm recorded in this study merely inject material into the system for beach replenishment, to stem coastal erosion or to enhance sediment transport.

5.8 Sediment Analysis

As discussed earlier sediment samples were obtained in July 1995 from mid tide positions on the beaches. Sixteen samples were collected from all monitored sites and these are presented by Table 5.2 (page 139).

As can be seen from the table mean particle diameters are presented in both millimetres and phi units. Conversion tables can be found in the Shore Protection Manual (CERC 1984) The sorting coefficient is a measure of the range of grain sizes (standard deviation or spread) in a sample. Larger values indicate a wider range of sizes so that this concept is the reverse of 'grading' as used by engineers.

Skewness is a measure of the presence of excess fine or coarse materials in the "tails" of a distribution relative to a 'normal' distribution of sizes. This measure has positive values when excess fines are present and negative values if a sample is relatively rich in coarse particles.

It can be seen from Table 5.2 (page 139) that the mean size for all sites are predominantly medium to fine sands that are well sorted and strongly fine skewed. It is expected that structures may tend to disperse fine grain sizes and retain the coarser sizes. Small particle may become finer with dispersal away from the site because they can travel further. The results in Table 5.2 (page 139) point to the fact that grain sizes of medium size may be widely dispersed or distributed.

Figure 5.22 (page 139) presents a comparative graph of three grain size distributions obtained at the Rarotongan Resort Hotel site. This site was chosen because no other study site has had previous sediment sampling measured. The significant pattern
identified from the graph is that while there may have been coarser particle sizes in the earlier part of the scheme installation the particle sizes have become finer. This result is consistent across the site where the CPUs are placed. While previous sediment samples have had mixed results in terms of grain sizes this latest result indicates grain sizes have become stable and finer in texture and susceptible to swash interaction.

5.9 Summary

To conclude this analysis of beach response and coastal protection structures, it is apparent from the data presented that variable patterns of profile change has occurred across each site. These changes have been highlighted by the incidence of swell waves that impacted upon the western and southern coastline of Rarotonga. All the study sites were affected by the high seas. In particular, sites in the south and southwest coastline of Rarotonga. The Queens Residence seawall and the Rarotongan Resort Hotel sites were directly affected while Muri Lagoon and the Edgewater Resort Hotel sites received relatively less severe damage due to the angle of approach of the storm.

Two principle analysis were used. Profile analysis, identified that site specific processes and the geography of a site were factors in influencing beach change. The location of the coastal structure in the beach profile also had an effect on beach morphology and processes in front of the wall.

A second analysis was required to identify detailed beach change and adjustments. In particular it was useful to obtain quantitative information such as the distance in metres of retreat or progradation or the patterns of beach sediment change due to changes in the shape of the adjusting profile. The methodology of Excursion Distance Analysis (EDA) was employed. It confirmed that the location of a coastal structure in the beach profile was a factor in influencing beach change. The geography of a site relative to the incident processes was another factor in determining the rate of change and patterns of sediment movement was also identified.
Figure 5.21 Excursion Distance Analysis of the Queens Rep Residence site at specific time intervals
Table 5.2 Results of settling velocity determinations of particle size characteristics for beach sands from the study sites. Samples obtained on 14 July 1995 from mid-tide positions.

<table>
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<th>Sample No</th>
<th>Location</th>
<th>Mean Size (mm)</th>
<th>Mean Size (phi)</th>
<th>Sorting (phi)</th>
<th>Skewness</th>
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</table>

Figure 5.22 Longshore pattern of grain sizes (mm) for the Rarotongan Resort Hotel site. Samples are obtained from mid-tide positions.
A further manipulation of the EDA data presented information regarding profile changes at a specific time against the distance alongshore. It was concluded that sediment movement was prominent in front of coastal structures and at different positions in the profile. The sediment moved in discrete masses and was unaffected by storm events in the long term.

Finally, sediment sampling in all the study sites revealed that sand grain sizes were generally the same, medium sand. A comparison of grain size distribution collected at the Rarotongan Resort site revealed the coarser particles identified in the early part of the scheme installation were now finer and located in the area behind the CPUs. This funding suggests that the sediment may be susceptible to coastal erosion.
CHAPTER SIX
Coastal Protection and Beach Response

6.1 Introduction

The previous three chapters have identified the wind and wave regime for Rarotonga and provided a description of coastal protection while Chapter 5 has provided quantitative results of beach response in front and adjacent to selected coastal protection sites. This is in keeping with Krumbeins process response model (Figure 1.3, page 15) and the focus of this study which is to quantify beach change in front of different types of coastal protective structures at different geographical locations in response to the incident coastal processes in order to elucidate the effects of coastal structures on the beach. It remains now for the field research observations and results to be integrated and related to the principal aims of this study.

Hence, this chapter is presented and is principally concerned with a discussion of the major findings related to this study. The aim here is to integrate the three broad functions of this study which is coastal process examination, coastal morphology description and coastal protection description.

6.2 Short term impact of storm swell

In the context of this study the impact of the swell storm (8-9 June, 1996) is important because it provided some valuable observations and measurements of beach change over a short period of time. It was observed that several factors were important to the way the beach profile in front of and adjacent to coastal protection structures responded in the short term to the storm swell. These are:

(i) The position of the coastal structures in the beach profile.
(ii) The structural configuration and type of coastal structure.

(iii) How the structure is tied in with the land behind it.

(iv) The seaward volume of beach sediment.

(v) The sediment characteristics within the foreshore.

The most obvious factor governing the behaviour of coastal protection structures and their effect on the shoreline during high energy events is the location of the structures relative to the active beach. A coastal structure located well landward of the active beach will not influence coastal processes except possibly during periods of exceptionally high seas. On the other hand, coastal structures located on the active beach will modify the nearshore beach profile as well as the cross-shore distribution of the longshore current and the longshore sediment transport.

The configuration of the coastal structure is another factor such that the length of a seawall, for example, may determine the way the beach profile in front and adjacent to walls respond in high energy events. The length of a coastal structure determines how much sediment is held behind the wall and kept from littoral system as wave-induced longshore currents transport sediment in front of the wall. The coastal structures length and its ability to hold sediment behind it can determine its impact on adjacent beaches. Since little or no sediment is contributed to the littoral system from the area behind the wall, the longshore current must shift seaward and/or the profile must deepen in front of the coastal structure (Wegel 1988).

The use and type of structure may also be a factor. The use of the structure typically determines the selection of the shape of a coastal structure (CERC 1984). A vertical face wall is less effective against wave attack than say a sloping wall. A seawall that reflects incident wave energy will function differently than a seawall that dissipates wave energy. A reflecting seawall causes standing waves, the sum of incident and reflected waves, to develop in front of it while a dissipative seawall will have lower
reflected waves in front of it. Standing waves may cause overtopping of the structure and lowering of the bottom in front of the wall by scour during high energy events (CERC 1984).

"End effects" is another consideration. How the coastal structure is tied in with the land behind it at its upcoast and downcoast ends also determines how much sediment is available to adjacent beaches during high energy events. If end walls that tie a seawall back to higher ground are omitted, the seawall may be outflanked and the land behind it will erode to provide sediment to the littoral system and the beach profile.

Two sites using basalt riprap rock revetments were monitored by this study. Both sites are located in the western coastline of Rarotonga. The acute angle of approach of the swell storm would perceivably have a less severe impact in these western locations than areas where the angle of approach is more frontal (particularly in the south east). Site 1, Edgewater Resort Hotel basalt rock revetment, is located in the active sweep zone of the beach such that the wall frequently interacts with swash especially during high tides and storm events. During the swell storm, waves were observed breaking along the full length and across the width of the wall. At the southern end (EGW Profile 09) of the revetment, sediment setup reflecting accretion of sand material in the upper foreshore was observed in the field and confirmed by EDA. Significant erosion occurred at the centre of the wall where an artificial beach is maintained by terraced gabion baskets and imported sand. At the northern end, flattening of the beach profile in the lower foreshore indicating erosion and steepening of the middle and upper foreshore occurred.

Site 2, Rarotongan Sunset Motel basalt rock revetment, is the only monitored example of a coastal structure located landward and high in the beach profile. During the swell storm wave runup was limited to the foreshore as pointed out earlier. The basalt revetment was unaffected by the storm waves, hence, secondary effects due to the wall was minimised.
Site 3, Rarotongan Resort Hotel, where protection is provided for only half the site and the wall is located in the surf zone, storm waves were frequently observed overtopping the wall. The influence of the wall on the hydrodynamic nature of the waves was such that as the waves passed over the wall, the form and height of the waves were clearly modified affecting swash and backwash intensification. However, waves were observed to propagate towards the shoreline in groups. The first wave (sometimes the largest in the group) would be clearly affected by the wall leaving behind it elevated water levels usually between the CPUs and the shore where the water mass appeared to be "trapped". Subsequent incoming waves were observed passing directly over the wall and reaching relatively higher elevations on the beach.

At the eastern end of the site where there is little distance between the wall and the beach, waves were observed breaking directly onto a steeply inclined beach (maintained in part by the CPUs). As pointed out earlier it was observed that nett aggradation had occurred here. It is thought that deposition by sediment entrained in the breakers contributed significantly to accretion behind the wall in this area. Excess sediment in the nearby Vaituruma stream confirms nett sediment transport is in the east direction and the healthy state of the nearby beach.

Unprotected areas of the beach experienced pronounced swash runup and backwash where hotel units 50-80 metres landward were inundated with saltwater and sand. However, hotel units directly behind the CPUs were less affected except for the area adjacent to the open western end of the wall and the Whitesands Restaurant.

At Site 4, Queens Rep. residence, Titikaveka, the vertical faced seawall is located in the swash-backswash zone. Due to the length of the wall (261 metres long) and its position in the beach profile, sediment is restricted in front of the wall. During the swell storm both the reef and adjacent beaches were exposed to incoming waves. On numerous occasions reflective waves were observed forming standing waves. Evidence of overtopping from scour behind the wall suggest this was probably caused by the sum of incident and standing waves. The characteristics of this wave is increased height and wave steepness that is most devastating during high tide. The impact of
the storm waves was such that parts of the seawall sustained damage. End effect was minimised since the wall is tied in with the land at both ends and a beach in front of it serves as a buffer against storm waves.

Site 5, Mary Davis-Harvey seawall, a vertical face structure, 39 metres in length is located in the swash-backswash zone. During the swell storm, waves would break on the surface of the wall and sometimes cause reflective waves, however, these were quickly dissipated by the incoming waves. It was observed at various sites in Muri lagoon and confirmed by EDA that sediment setup on these beaches implying accretion of sand material had occurred.

On unprotected beaches it is well established that the beach profile responds to high energy events by adjustments to the slope of the foreshore, the formation or removal of intermediate berms from the middle foreshore, and initial volume of beach sediment seaward of the crest. On protected beaches, it is established in this study that the extent to which coastal structures impinge on the beach profile and on the hydrodynamic processes controls their effect on adjacent and fronting beaches.

The sloping foreshore and beach berms are the first line of defence for natural beaches in absorbing most wave energy. The sloping nearshore bottom causes wave to break offshore, dissipating their energy over the surf zone. This process of breaking often creates an offshore bar in front of the beach that helps to trip following waves. At the top of the wave runup after it breaks on the beach a ridge of sand or berm may form (CERC 1984). At the Rarotongan Sunset Motel site (2), a mixed sand and gravel beach, an intermediate berm was located in front of the coastal structure following the storm. Sites with a narrow beach width in front of the wall were generally too close to the swash-backswash zone to enable genesis of berms. Offshore bars were observed. These were pronounced at the Queens Rep. seawall site (5) where in one locality a ‘wall of sand’ was observed.

It is important to note that berms in the foreshore are temporary features which change in form and location quite frequently so that their presence or absence,
though visually impressive, may not necessarily be a reliable indicator of the longer state of beach stability (Kirk 1987).

Where sediment is available in large quantities, protective measures are generally not required or are greatly simplified. The size and character of sediments and the slope of the beach are related to the forces to which the beach is exposed and the type of material available on the coast. In general, the larger the sand particles the steeper the beach slope. Also, accretion promotes steeper slopes while erosion creates flatter slopes (CERC 1984).

Sand at all sites were measured as medium grained with 50 to 80% by weight falling in the 1.6 to 1.8 phi (0.29 mm to 0.39 mm) range. For the Rarotongan Resort site (3), this finding differs from previous measurements. Since the grain size measurements in all study sites fall within the same range it is possible the swell storm may have influenced sediment distribution. This due the fact that medium grain size sediments have the ability to be transported further and faster than the coarser ones. Such active sources of sediment may also contribute to a wide range of sizes to the coastal environment.

6.3 Beach Response

Incremental change will occur during normal and generally low energy conditions but the beaches defence mechanism will become obvious when storms attack (CERC 1984). This section discusses further the effects of coastal structures on the beach dynamics especially in regard to the period prior to the storm and after the storm.

6.3.1 Swash Interactions

During normal and low energy conditions, swash interactions are generally confined to periods of high tide. Since processes that affect the beach are continuous and occur at a variety of time scales, visual observations are the easiest and most affordable means of monitoring these.
Swash consists mainly of landward propagating of white water bores and reformed waves while backwash is seaward directed sheet flow down the beach slope (CERC 1984). Reflected waves form when swash strikes a seawall. For the CPUs, these are minimised by the slots in the structure, however, a vertical faced seawall typically generates reflected waves. A reflected wave propagates seaward after impact usually at a small angle from the shoreline typically colliding with incoming swash and sometimes dissipating the incoming energy as both waves meet in a turbulent clash. A reflective seawall, high tide and infra-gravity swash oscillation produces well developed reflected waves (CERC 1984).

Backwash sometimes occur earlier in front of coastal structures before backwash on adjacent unprotected beaches. This may be due to the forward position of some coastal structures relative to the unprotected beach where wave runup is met earlier.

Bed forms such as ripples, lineations and sediment sorting effects were observed at Site 3. These were prominent in front of the CPUs and behind it. Ripples were strongly developed in front of the CPUs or lower foreshore and sometimes behind the CPUs. These features may indicate sand transport direction or current direction as they are associated with accretion of a soft, medium to coarse-grained bed.

Bars are already discussed developing during the storm swell event at site 4. This feature was strongly developed approximately sixty metres off shore and may have been formed by reflective waves. It is best described as a wall of sand parallel to the seawall extending 10-20 metres with a steep face shoreward and gently sloping towards the open ocean. Ripple and sand morphological wave forms were also observed.

Generally bed forms will occur where sediment is abundant as they are a result of sediment transport by fluids on unconsolidated surfaces such as sandy beach foreshores. At Sites 1, 2, and 5 the nearshore surface is generally comprised of exposed bedrock and coral heads hence bed forms are rare features in these areas except in pockets where sand sediment is plentiful.
6.3.2 Beach Groundwater Interactions

It is proposed that impermeable structures elevate the local ground water surface and this may increase the mobility of the fronting beach. High water tables reduce swash percolation, which increases uprush and backwash velocities and increases hydrostatic pressures, which reduces the effective stress between sand grains. Also, the ground water discharge from the beach adds to the upward directed force on the sediment, aiding erosion, while ground water recharge has the opposite effect (in Plant and Griggs 1992).

The water table may be elevated by precipitation, sea level set up due to high winds and large breaking waves, and overtopping of the berm by these waves.

Beach ground water interactions were visually observed. Ground water conditions at Site 1 and Site 2 in the western coastline of Rarotonga are unknown. There are no nearby streams and waterways. Hydrostatic pressures may be caused by precipitation, stormwater runoff and waves breaking on the beach. It should be pointed out that basalt rock revetments are highly porous and therefore it is generally well drained and effective against pore-water and hydrostatic pressure.

At Site 3, Rarotongan Resort Hotel, the Vaituruma Stream was diverted from its former course (the former outlet was west of the Whitesands Restaurant) to its present location at the eastern end of the CPUs. It is well established that natural drainage is preferred by streams or rivers to an artificial one. Although the new course of the Vaituruma stream may appear to operate on the surface, below the ground, drainage will tend to follow its original course.

According to Kirk (1993), at about midpoint of the structure length there was persistent discharge of freshwater through the beach from a source that was either on the hotel side or inland of it. A “wet” section along the CPU’s which occurs where seepage from this “underground stream” reaches the surface and noticeably slower sand accumulation occurs in this area.
The seawall at Site 4 has a nearby stream in its vicinity and a bitumen seal road above it. Discharge from the area behind the wall, the road surface and the nearby stream induces hydrostatic pressures behind the wall. It is believed that this pressure is partly responsible for the structural weaknesses within the wall that was highlighted by the recent storm of swells. Scouring at the back of wall was evident during the storm believed to be caused by wave overtopping and further hydrostatic buildup promoting its demise.

At Site 5 hydrostatic pressure would be more prominent by wave overtopping since the area is well drained.

6.3.3 Beach Profile Variation

The results of beach profile measurements are presented in Chapter 5. It was apparent from the data collected that variable patterns of profile change occurred across all study sites. The factors of which are already discussed in this chapter. During periods in between storms, high tide is the most influential process in promoting beach change.

Post-storm beach recovery is a further adjustment by profiles to adapt to the normal and prolonged conditions in between storms. An analysis of post-storm recovery in front of and adjacent to protected sites can be analysed by excursion distance plots in chapter 5. Post-storm beach recovery can be evaluated in terms of losses and gains in sand volume or in terms of pre-storm and post storm positions of the beach morphology and this is effectively carried out by continuous shore-normal profiling. Ideal complete recovery of an eroded beach would include replacing the volume of sand eroded from the beach and restoring the positions of the shoreline, berms, and vegetation line to their pre-storm conditions. However, profile variation from site to site influenced by incident coastal processes points to the fact that such recovery may be complicated.
The beach response measured at each profile site related to this study provides the following description of post-storm beach recovery.

Following the storm period it is identified by the excursion distance plots that the initial major adjustment to the beach profiles is the steepening of the foreshore slope and the broadening of the lower foreshore. Where coastal structures are close to the surf zone, sediment may be loss to the offshore longshore transport or deposited as bars offshore. This initial phase of beach recovery began immediately after the storm wave energy waned where sand is re-distributed by wave runup and the rapid landward migration of the offshore bar system.

It was observed that recovery was rapidly achieved by re-establishing the foreshore configuration and a return of large volumes of sand. This rapid recovery is common for all beaches surveyed where sand eroded from the foreshore was available offshore. Accretion occurred at sites on the fringe of the storm but due to the time constraint of the field study it was not possible to fully appreciate recovery in these areas. Presumably the rehabilitation process takes place by further re-distributing sand to areas in most need.

In general it is observed that beach change in front of coastal structures is similar to that of unprotected beaches. In the case of the CPUs at Site 3 there are some inherent advantages of implementing a wall of this type such as energy dissipation of incoming waves, modification of swash and backwash intensification, maintenance and protection of the beach behind it, a relocatable structure, and the like. As the results of profiling have indicated areas behind the CPUs were least affected by high seas compared to adjacent unprotected areas.

Vertical and reflective walls on the other hand are observed by this study to function differently than a wall that dissipates energy. This is because they are less effective against wave attack as established earlier and generally lack a beach in front of it. Similarly basalt revetments in the active beach tend to lack a beach in front of it due to its forward position initiating early breaking of waves in the swash-backwash zone.
However if the revetment is located high in the beach profile as at Site 2 then it is most likely to respond to incident coastal processes as an unprotected beach would.

6.4 Summary

The aim of this chapter was to present a discussion of the findings related to the results collected over the ten weeks of the study period. The principal methodology used was shore-normal profile surveys.

It was observed that several factors were important to the way the beach profile in front of and adjacent to coastal protection structures responded to incident coastal processes. These were identified:

(i) The position of the coastal structures in the beach profile.

(ii) The structural configuration and type of coastal structure.

(iii) How the structure is tied in with the land behind it.

(iv) The seaward volume of beach sediment.

(v) The sediment characteristics within the foreshore.

The most obvious factor governing the behaviour of coastal protection structures and their behaviour on the shoreline during high energy events is the location of the structure relative to the active beach or sweep zone. It was observed by this study that coastal structures located in the active beach modified the nearshore beach profile. At site 3, the coastal protection units are responsible for maintaining a convex shaped beach which is found to be generally prograding. For vertical and reflective seawalls, these have been responsible for the lack of a beach in front of it due to the early breaking of waves in swash and backwash zone.
'End effects' at all sites monitored by this study was generally found to be satisfactory as the respective owners of the walls have maintained their protection very well. At site 5, however, it was apparent that due to the rate of recession of adjacent unprotected beaches the seawall was threatened at the wing wall. Remedial works by employing basalt boulders have only compounded the problem.

Where sediment is available offshore, these have been used to stem erosion on the beaches. It was observed that discrete masses of sediment or 'slugs' were moving in the direction of dominant current flow. In the post storm recovery period it was further observed that the slugs were not affected. With erosion occurring onshore and near the coastal structures in the post-storm recovery phase sediment was transported shoreward.

In general beach change in front of coastal structures was found to be similar to that of unprotected beaches.
CHAPTER SEVEN

Conclusion

7.1 Objectives recalled

The main objective of this thesis as outlined in Chapter One was to examine the effect of coast protection structures upon the sandy coastline of Rarotonga. This was achieved by adopting a process-response approach which involved identifying the main coastal processes responsible for the changes that occur on the beach and examining these in the context of coastal protection.

Chapter One presented five broad goals which this thesis sought to examine.

(1) To describe and assess current Coastal Protection method used on Rarotonga.

(2) To examine localised effects of select Coastal Protection measures on both the beach morphology and processes.

(3) To examine beach response at the toe and ends of select Coastal Protection measures.

(4) To measure process-response relationships at select Coastal Protection sites.

(5) To provide a database for future research.

7.2 Summary of major findings

Chapter One presented the research problem and outlined the study approach and objectives. Recent advances in the collection of scientific data in the South Commission area in the nearshore oceanographic regime as well as in the nearshore
coastal zone has led to a generally better understanding of process-response relationships in the South Pacific. However, the complexity and variability of coastal processes often means that coastal protection is site specific and "...no embracing rules can be set down for the use of coastal protection devices". Many statements are made about coastal structures but few studies have been carried out in their support. In the South Pacific it has been identified that generally there has been a lack of monitoring of coastal protection projects. Many cases of coastal degradation have occurred which have not been properly documented. Most recently a series of regional coastal protection meetings have been held by member countries of the South Pacific Forum. It is believed that the surge in interest in coastal protection in the South Pacific is due partly to the work carried out at the Rarotongan Resort Hotel, funded by NZODA programme developed by Mr Don Dorrell and the University of Canterbury and vigorously promoted by the government of the Cook Islands.

Coastal environments of the South Pacific were examined in Chapter Two. The vital commercial and national assets, essential infrastructure and population of most South Pacific island countries lie within the Coastal Zone. Often there is a perception to apply expensive artificial coastal protection measures when natural beach and coral reef restoration may be more effective. Considerable sediment supply of South Pacific island beaches are derived from carbonate sources. Sand mining is the principal cause of coastal erosion. The use of artificial coastal protection is governed by economic, cultural and environmental constraints. In general, it is observed that the most favoured combination of adjustments to coastal hazards is to relieve and rehabilitate losses as they occur, and then build artificial coastal protection works to prevent further losses.

Chapter Three presented the research area and discussed the coastal processes in detail and environment of Rarotonga. It is recognised that in recent years the Cook Islands has benefitted from a substantial increase in studies conducted in the nearshore coastal zone. However, Rarotonga, the administrative, social and economic centre of the Cook Islands, has been the main benefactor. Vital commercial and infrastructure assets are located in the northern coastline of Rarotonga. Here, coastal
protection is a national priority due to the notorious hazards in the area and the value of development. Coastal erosion on Rarotonga is identified as chronic and widespread. This is due mainly to the removal of sands from beaches. South easterly trade winds predominate for Rarotonga and average significant wave heights range from 2.4 to 2.6 metres. Volcanic rock rubble structures are the most used coastal protection strategy to combat hazards. It is generally used because it is economical and the rock material is readily available.

Chapter Four presented the study methodology. Five sites in the western and southern coast were selected for monitoring. These were located in sandy coastlines. The main objective in site selection was to observe different types of protective structures at different locations around the island of Rarotonga. In this way it is possible to assess the coastal structure as well as understand site specific processes and beach response for a particular site and Rarotonga island. The principal data collection methodology was by repeated shore-normal profile surveys. The profile sites were a maximum distance of five kilometres and five hundred metres minimum between sites. It was found that most surveys previously carried out had used assumed heights as a datum which was inappropriate. A third of the total study period time was spent establishing benchmark levels to mean sea level at all study sites.

Chapter Five presented the results collected in the field. During the study period a storm of swells originating from a southern source area brought unusually high waves around Rarotonga on the 8th-9th June. Significant wave heights measured by the Topex/Poseidon satellite recorded as high as 6 metres. Wave duration was from the southwest and energetic wave periods were estimated in the range of 10-15 seconds. All study sites were affected by the swell storm. From an analysis of the profile data variable patterns of profile change were observed. These reflected site specific coastal processes which dictated change as well as the geography of a location. Also the type of wall and its position in the beach profile was significant.
The beach profile data was further analysed and manipulated so that information about single profiles can be interpreted in terms of progradation or retreat by an excursion distance analysis. Beach changes and adjustment were further appreciated by this methodology which highlighted several factors which were important to the way the beach profile in front of and adjacent to coastal protection structures behaved. A third analysis and manipulation of the profile data was carried out to identify the spatial interaction of adjustments to the study profiles. In this way a simplified topographical map of the foreshore at a particular time is developed.

It was concluded that several factors were important to the way the beach profile in front and adjacent to coastal protection structures responded to the incident coastal processes during the study period. They are:

1. The position of the coastal structure in the beach profile.
2. The structural configuration of the coastal structure.
3. How the structure is tied in with the land behind it.
4. The seaward volume of beach sediment.
5. The sediment characteristics within the foreshore.

7.3 Recommendations for future research

Erosion control involves major effects to reduce the effects of chronic and storm-induced erosion for particular sites along the beach. It attempts to minimise the loss of sediments where it is most valued or where assets of high value occur close to the coast. It is important to reiterate that whether structural or non-structural means of control are employed erosion control can only be partially successful. This is because adjacent areas remain uncontrolled and because control at one point frequently intensifies erosion elsewhere.
It is established in this thesis that coastal erosion on Rarotonga is frequently met by engineering erosion control structures, with some lesser concern for hazard avoidance and for planning which is sympathetic to the natural functioning of beaches. Even the best philosophy and professional (technical) approach will not work unless it is part of an administrative and political plan as well.

For these reasons local governments should have a single agency with the administrative and technical ability, financial resources and enforcement authority to regulate coastal protective measures and provide cooperative support to help blend local interest with the national interests. It should be able to supply some expertise and files of basic data from its annually updated database.

Much has been said about the increasing availability of scientific data in the Cook Islands. However, for effective coastal management the assessment of stability and the monitoring process is required to be continuous, as is the chronic and sometimes spectacular erosion affecting the shore. Data collection should be carried out on an annual basis.

For example, in order to better utilise hard stabilisation techniques, efforts should be made to review historical shoreline position, beach profile and littoral processes, and to initiate comprehensive monitoring programmes. Each monitoring project should be formulated in accordance with characteristics of a particular site and the objectives of the monitoring. It should encompass as much of the following as possible.

(1) Baseline profile data should include the beach prior to construction of coastal structures. Profile surveys should include lines on neighbouring beaches that are not protected.

(2) Immediately after construction profiles should be taken at frequent intervals. The condition of the coastal structure and land behind it should be monitored, in addition to the beach.
(3) Profile surveys should be made immediately before and after major storms and background data should be compiled on storm tidal level and surge; wave height, period, and direction; wind speed and direction.

(4) Sediment samples should be taken when profile surveys are made. Also depending on capabilities wave and current data should be collected throughout the year, and wide area surveys, such as aerial reconnaissance, should be carried out once a year and before and after major storms.

(5) All events at the site of a coastal structure should be interpreted within a regional scale perspective of the coast.

(Adapted from Kraus 1988)

Revetments are the most employed strategy along the Rarotonga shoreline. A generic design is used and one that is used everywhere rather than basing the structure on site specific requirements. On reflective beaches, for example, where beaches come under the attack of breaking waves large structures may be required. However, on dissipative beaches smaller-scale structures may be adequate since the structures should be separated from the breakers and only come under attack by the action of much weakened swash. Hence, as pointed out earlier, an objective of ongoing research to establish improved design criteria should take into account such local environmental factors.

Finally, care must be taken not to divert coastal management efforts to restrict hard stabilisation simply because the scientific community is arguing about the mechanisms of beach behaviour. As the scheme installation of Coastal Protection Units at the Rarotongan Resort site has established, it is possible to also enhance beach behaviour. The most important question is whether such structures negatively impact beaches. More research is certainly needed, but future studies must take into account the fact that previous studies have established that degradation in front of walls is usually a decades-long phenomenon and that there is wide variability in the coastal climate.
affecting coastal structures from location to location. Monitoring of behaviour in front of coastal protection measures in the future is very important.
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