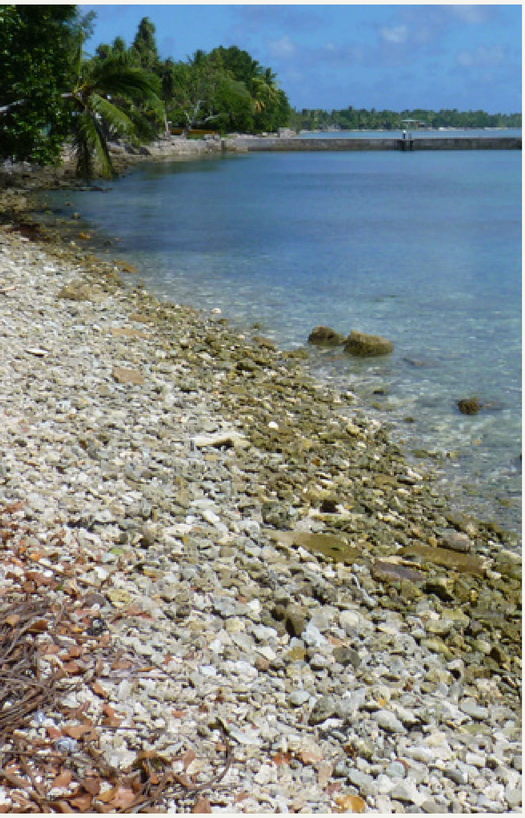
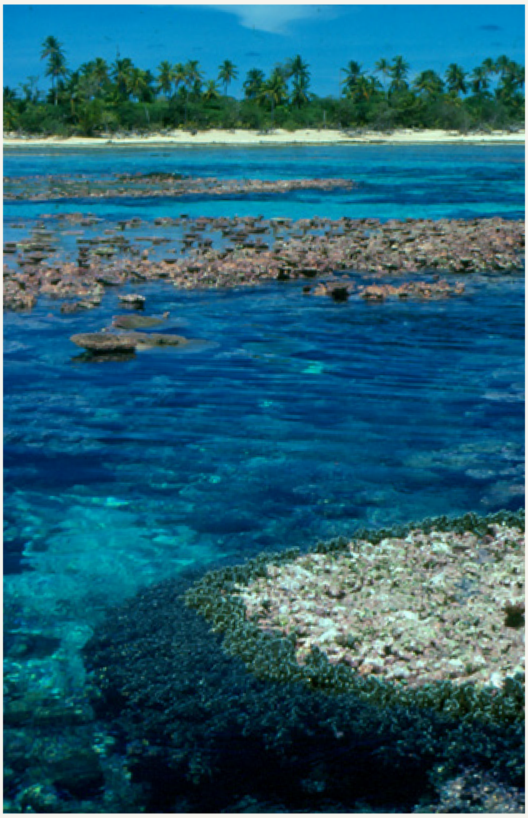
Regional coastal susceptibility assessment for the Pacific Islands: *Technical Report*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Executive summary

A major objective of this report was to develop a regional assessment of Pacific Island sensitivity to projected climate change as a component of the Pacific-Australia Climate Change Science and Adaptation Planning (PACCSAP) program. The PACCSAP Program is intended to help partner countries including Cook Islands, Fiji, Kiribati, Marshall Islands, Federated States of Micronesia, Nauru, Niue, Palau, Papua New Guinea, Samoa, Solomon Islands, Tonga, Tuvalu and Vanuatu and their communities better understand and respond to climate-associated impacts. Here the area covered by the PACCSAP Program is referred to as the Pacific Islands region, or the region, for convenience.

Globally, the Pacific is a huge ocean. It encompasses a large number of islands, including many small and remote islands. The islands and their coastlines display a diverse range of physical characteristics and are subject to a wide variety of meteorologic and oceanographic processes. They have been changing in situ for millennia, with the changes taking place at all rates from short to long timeframes in response to island building and weathering processes. How the coastlines of the islands have responded to climate and ocean processes varies across the region because of the different geomorphic features of islands; differences between the dominant climate and ocean drivers and their interactions; and increasingly, because of human actions.

Climate change presents challenges that are not without precedent in the history of the Pacific or its island landforms. However, the projected rates of change may be faster than previously experienced. Many buildings and significant infrastructure particularly that built on low land close to the shore in coastal areas are likely to be affected by the projected changes. This has been demonstrated by previous assessments of climate change impacts for coastal areas in the Pacific, most of which have demonstrated a relationship between coastal management problems presently occurring at local scales, albeit not always with a common investigative methodology. The local-area studies completed call into question possible interrelationships between studies, their geographic context, the degree to which they represent the different types of islands apparent in the Pacific and their relationship to regional variation in climate and ocean processes.

This project differs from the past studies in two respects. First, it involved compilation of a digitally-accessible database of 1532 islands within the area of interest. These had a combined land area of 138,958 km^2 and were from 15 Pacific Island countries. Second, the database enabled a regional catalogue to be developed, including a typology of island and coastal characteristics based on lithology (geology), elevation, island shape, area and location. The regional approach adopted in Chapter 2 facilitated a rapid, consistent and systematic approach to identifying the huge and largely-unacknowledged diversity of islands in the Pacific. Excluding the island of New Guinea from the analysis owing to its exceptionally large size, analysis of the database revealed the following:

- Despite the great geological diversity of islands across the Pacific there is also much similarity;
- There are 18 islands with a land area greater than 1,000 km^2 and comprising 76% of total land area;
- Conversely, islands with a land area of less than 5 km^2 account for nearly three quarters of islands, but comprise just 0.86% of the total land area;
- The rock type and elevation of each island in the database allows its classification as one of eight types, each of which is uniquely susceptible to change; and

- The most numerous island type is 'reef islands' which comprises 34% of all islands in the database, followed by 'volcanic high islands' (29%).

Both the geological diversity and similarity across the region are important. The diversity explains the scope of geologic and geomorphic attributes comprising context for risk assessment, and is relevant to informing a science-based monitoring and evaluation program—to track change over time. Not everywhere can be studied in detail; a regional assessment can help to identify priority areas where we need to take a closer look. The similarities facilitate construction of an approach to transfer knowledge or identify knowledge gaps across the region. Understanding that there are large numbers of similar island types across the Pacific, with similar risk profiles, means that lessons learnt from one studied area can be used to inform other similar areas.

Maps and graphs respectively showing the distribution and comparing the distribution of island types for different countries within the Pacific Islands region are presented in Chapter 2. Examination of the typology in relation to projected changes to climate and ocean processes, as demonstrated in Chapters 3 to 6, shows the database and maps can be used for regional and national adaptation planning.

Certain island types are inherently more susceptible to coastal change than others. For example, higher-elevation islands tend to be less susceptible than low elevation, while low limestone and reef islands are more susceptible to change than volcanic islands because their physical structure is not as 'hard'. The physical characteristics of islands in the Pacific at a whole-of-island scale are considered in Chapter 3. High-level physical, geological and geomorphological attributes—such as shape, elevation, maximum elevation and rock type—have been compared to *indicate the susceptibility* of the island to coastal change.

A susceptibility rating was identified in Chapter 3 for each of the seven island types examined, with low to moderate susceptibility ratings for volcanic islands contrasting with moderate to very high ratings for reef islands. Of the 1,532 island in the database 12% of the islands were classed as having a **very low** susceptibility to change, 23% were **low**, 25 % **moderate**, 31% **high** and 9% **very high**.

- Most of the islands with a high or very high susceptibility rating are in the north Pacific, whereas most of the low or very low susceptibility islands are in the south;
- Six of the 15 countries examined have islands in all five categories of susceptibility, whereas three countries—in addition to two single-island countries—fall within a single category;
- Countries with islands with a high proportion of very high susceptibility ratings are the Cook Islands, Marshall Islands, Tokelau and Tuvalu: and
- The Federated States of Micronesia, Kiribati, Papua New Guinea and Solomon Islands have a high proportion of islands with high susceptibility.

It is important to note these results are *indicative* only, although they are useful for strategic planning and identification of areas with similar risk profiles. They do not refer to the coastal fringe of islands, the landforms immediately adjoining the shore where most coastal management problems are encountered. This requires down-scaling from regional-scale estimations of the *susceptibility* of whole islands to local scale assessments of landforms adjoining the coast.

A two-step procedure to do this using the same approach as outlined in the primary assessment of Chapter 3 has been described in Chapter 4 in order to establish a pathway for downscaling landform assessments suited to the use of sparse or coarse information.

- The secondary assessment focused on 36 islands (using additional diagnostic criteria—insularity, proximity, seabed (shoreface) gradient) and island coastal fringes and permit measures of indicative *susceptibility* to be estimated. Eight islands had a high susceptibility; four had low susceptibility, and the majority (24) show moderate susceptibility.

- Tertiary assessment used a sample of five islands to demonstrate a fine-scale assessment of the *susceptibility* of landforms around the coastal fringe of 5 islands.

Full analysis of all 1532 islands in the database could not be applied at a secondary or tertiary level due to a lack of readily accessible information at each scale. Hence, the analysis was applied to a variety of island types sufficient to demonstrate utility of the framework at a whole-island scale and, separately, for sections of coast having a common landform assemblage. The results indicate:

- Changes in the *susceptibility* of island-scale coast and individual landforms for sectors of coast are apparent at increasingly detailed scale, with more focus on a country and local community scale; and
- The method of analysis uses expert knowledge and available photographic information to provide a reasonably low cost, rapid, consistent and repeatable analysis of the susceptibility of coastal landforms around an island shore to change.

Present day shorelines throughout the Pacific have been shaped by the geology and history of islands as well as by the suite of physical and biological processes that interact with island margins. Future coastal change to Pacific islands will occur at a range of geographical and time scales and vary between islands and on different locations around islands. Ultimately, climate and ocean processes driving landform change will need to be considered at all scales for whole islands and coastal landforms considered to be of high or very high susceptibility or sensitivity to changes in climate-ocean processes. The detailed information required to do this at for individual island shores is not available to do this at present. At a regional scale, climate and ocean information presented in Chapter 5 indicates:

- The most important climate and ocean processes driving coastal change in the Pacific region are tide type and range, prevailing wind –wave action, tropical storms, extra-tropical swell, sea-level variability associated with ENSO phase and longer-term sea-level change.
- There are large differences in the relative importance of these processes across the Pacific and their potential impacts on island coasts.
- Projections of changes to climate and ocean processes over the next few decades indicate that: both tidal levels and ENSO range will shift upwards with rising sea-level though the magnitude of sea-level rise will not be uniform across the Pacific; a small reduction in wave height can be expected in the equatorial zone but this may be offset by an increase in distant-source swells from the southern ocean; the frequency of tropical cyclones may be reduced and intensity increased in the future.
- Geographical variations in these processes means that similar island types but located in different parts of the Pacific will be exposed to different climate-ocean regimes resulting in dissimilar coastal impacts.

In Chapter 6 the geophysical characteristics of islands (Chapter 3) are combined with selected climate-ocean processes and projections (Chapter 5) to understand the sensitivity of Pacific island coasts. The measure of island susceptibility to climate and ocean processes developed here is known as *geomorphic sensitivity* and is a measure of the sensitivity of island coastal areas to projected future climate conditions.

- Geomorphic sensitivity rankings for all 1532 islands in the database show that most islands are either highly (28%) or very highly (25%) sensitive to future climate-ocean processes including sea-level rise.
- Profiles of coastal geomorphic sensitivity for individual countries in the Pacific Islands region vary considerably and provide a valuable tool for regional and national planning. States with the highest coastal geomorphic sensitivity include Tokelau, Marshall Islands, Federated States of Micronesia, Tuvalu and Tonga.

Overall, this project provides the first regional assessment of potential coastal response to climate change across the Pacific.

- It identifies the biggest change is at the extreme ends. Fewer islands are classed as very low sensitivity and a significantly higher proportion are classed as very high sensitivity to change.
- The analysis also identifies a science-based assessment process that can guide decision makers through identifying susceptible and sensitive areas at regional through to local scale.
- Future changes in climate and ocean processes will have implications for many Pacific islands, particularly where managing coastal change already is an ongoing challenge for communities, governments and agencies. Projected exacerbation of coastal change could drive movement of people:
  - Inland from the coast and local response measures such as engineering will be important;
  - To another island which means land use planning approaches become involved, or
  - To another country when migration settings become more of a focus.
- Coastal decision makers need a mix of information and response options that can work across scales from addressing local issues through to national and regional scales. In this context, a regional understanding of the scale of change is useful to inform strategic response settings, for example:
  - Determination of the relative balance of protection, accommodation and retreat strategies based on much greater emphasis on building land use planning capacity in the Pacific, adapted to customary land tenure arrangements.
- Ideally a regional analysis would have been completed to the secondary, national level of characteristics identified in this assessment process. However the lack of data for the Pacific meant it was not possible for this project and strategic decisions on adaptation measures should not be taken using the regional assessment alone.
- Further detail needs to be added to the database, to enable well-informed assessments of coastal risk and encourage the development of robust adaptation responses. This should include finer detail regarding the geomorphologic characteristics of island shores as well as estimates of population and descriptions of coastal infrastructure.

The project has developed a methodology that could be applied to other areas of islands, tweaked for different purposes, and could eventually become a standard for the assessment of susceptibility to change. In a future world where change becomes more rapid at the same time as funds to assist poorer countries to cope with that change become inevitably scarcer, the development of tools of this kind is a priority.

Chapter 1.
Project Context and Objectives

Key points

- Owing to their oceanic locations, Pacific Islands are highly exposed to external change meaning that their coastal fringes are often dynamic and subject to rapid change compared to many of those on larger landmasses.
- Most people and revenue-generating activities are concentrated along Pacific island coasts meaning that coastal change has the potential to severely impact island populations and economies, particularly on islands that are comparatively small and isolated.
- Coastal changes in the Pacific islands over the next few decades are likely to be unprecedented in terms of their rapidity and their impact.
- This report provides a regional susceptibility assessment of coastal risk for Pacific islands. It considers their physical characteristics and their susceptibility to projected changes in climate and ocean processes.
- The regional dimensions of this coastal susceptibility assessment will allow the rapid and informed identification of priority areas for intervention to reduce the impacts of future climate-driven environmental changes.

1.1. Context

Dotted across an ocean area that is almost one third of the Earth's surface, the Pacific islands are different to most other landmasses, particularly in terms of their origins, their landscapes and the processes that mould these, and their exposure to external forces of natural change, both regular and extreme. Home to around 10 million people, most Pacific island groups were inhabited well before Europeans even knew the Pacific Ocean existed. For this reason, the inhabitants of these islands developed unique cultures, contextualised within livelihood systems distinguished by their use of marine foods, particularly from nearshore coral reefs and shallow lagoons. For this reason, most early settlements were coastal and, even during the centuries-long period of conflict within most island groups during the middle of the last millennium when settlements were located in more-easily defendable locations, coastal foods were still important. The period of European colonisation that began for most island groups in the late 19th century saw most of their inhabitants relocated to coastal settlements and the consequent upscaling of their use of marine resources, something that has continued since then as populations have risen and urbanisation has spread on many islands.

There is no doubt that Pacific Island Countries face unprecedented challenges over the next few decades as a result of environmental and societal changes forced by changing climate. Of particular concern in a region where most people and most revenue-generating activities are located along coasts, the current and projected rise of sea level is likely to impact heavily on island peoples and economies. Rising temperatures, both on land and at the ocean surface, will likely bring about ecosystem changes that are likely to impact food security. Coral reefs and related lagoonal ecosystems, on which many Pacific Island people depend on for food, are likely to be significantly degraded by the middle of this century as a result of warmer and more acid ocean water. Concerns about changes to the amount and seasonal distribution of precipitation in these islands are also widespread, with changes likely to the nature of the El Niño-Southern Oscillation (ENSO), a major cause of drought in the region, and tropical cyclones. It is also clear that major disruptions to life on Pacific islands could be significantly lessened by informed and appropriate advance adaptation and that the uptake of such adaptation strategies by countries and communities throughout the region would ensure that they remain effective and are sustainable for the foreseeable future. To this end, this study was undertaken, the aim being to produce a readily-used tool for the rapid and accurate assessment of island susceptibility throughout this vast region.

A major objective of this study was to develop a Regional Coastal Susceptibility Assessment as a component of the Pacific-Australia Climate Change Science and Adaptation Planning (PACCSAP) program. The PACCSAP Program is intended to help partner countries including Cook Islands, Fiji, Kiribati, Marshall Islands, Federated States of Micronesia, Nauru, Niue, Palau, Papua New Guinea, Samoa, Solomon Islands, Tonga, Tuvalu and Vanuatu1 and their communities better understand and respond to climate-associated impacts. This coastal susceptibility assessment has been prepared in accordance with terms of reference outlined by the Australian Government's Department of the Environment. It is intended to assist in understanding the dimensions of island- and coastal-change for more efficient adaptive management and planning.

Before proceeding further, it is advisable to define key terms used in this report.

Adaptation is defined as the process of adjustment of human systems to actual or expected climate and its effects, in order to moderate harm or exploit beneficial opportunities. In natural systems, the process of adjustment to actual climate and its effects; human intervention may facilitate adjustment to expected climate (Seneviratne and others, 2012).

Resilience is the ability of a system and its component parts to anticipate, absorb, accommodate, or recover from the effects of a hazardous event in a timely and efficient manner, including through ensuring the preservation, restoration, or improvement of its essential basic structures and functions (Seneviratne and others, 2012).

This report employs two terms referring to island and island-coast response to change. The term 'susceptibility' (defined in more detail below) refers to changes experienced or observed at the whole-island scale, which is the central focus of the report, while 'sensitivity' (also defined in more detail below) is used to refer to individual sections of coast, even specific land units or landforms.

Sensitivity is the degree to which a section of an island's coast may experience physical changes, such as erosion or accretion, inundation, and groundwater salinisation as a result of the impact of variations in climate and ocean processes. Sensitivity refers to the likelihood that coastal landforms will change in response to changes in climatic and oceanographic processes. An estimate or index of sensitivity is an indicative measure and the comparison is based on geomorphic knowledge of landform development.

Susceptibility is a comparative estimate of the potential magnitude of change in island form and structure in response to a change in climate-ocean conditions. It is based on comparison of the overall physical character of an island. Susceptibility can also be viewed as a comparative measure of an island's resistance to change. For example a high volcanic island is likely to be less susceptible (or more resistant) to physical change from external environmental processes than a low sandy island. It is important to note that the comparison is indicative rather than absolute or predictive.

Three important principles were articulated at the outset of this project.

- First, the diversity of both island types and island susceptibility in the Pacific region is huge, far greater than most previous vulnerability assessments have been able to incorporate. The challenge is to develop an

1 Hereafter referred to in this report as the (Pacific Islands) region.

assessment which encompasses the diversity and facilitates identification of island and coastal types at different space and time scales.

- Second, this project recognises that the diversity of island types results in a diverse susceptibility to change and to future climate-ocean drivers and hence to adaptation circumstances. A key message to those concerned with adaptation policy and implementation in this region is simply that 'one size does not fit all'. Questions of what approaches are best suited to what island type and what scale remain open, although they have significance for the approach used by island communities or countries to adapt to projected coastal change.
- Third, susceptibility goes beyond country boundaries: something that is especially true when associated with external (non-human) drivers of change such as waves and winds. So while it may often be politically expedient to undertake studies by country or on an island-by-island basis, this study intentionally treats political boundaries as subordinate. Application of this principle is intended to facilitate development of a consultative and consistent approach to adaptation between jurisdictions sharing common problems wherever appropriate. It also enables comparison between jurisdiction applying disparate techniques to similar problems.

Especially in the last 10-20 years, Pacific Island countries have experienced changes in their climates, typically involving increasing air and sea-surface temperatures, shifts in rainfall patterns, changing frequencies of extreme events, and rising sea levels (Barnett and Campbell, 2010). These changes are projected to continue into the future and exacerbate existing vulnerabilities, affecting peoples' lives and livelihoods including important commercial activities such as agriculture, fishing and tourism as well as subsistence activities (Nunn, 2013; Nurse et al., 2014).

Given the influence of climate and ocean processes on coastal areas in Pacific countries, the precise goal of this report is to establish a framework for development of a coastal susceptibility typology based on available information describing the potential impacts of climate-ocean processes. To achieve this, a regional methodology is developed that is relevant to understanding the present and potential future impacts of climate-ocean variability and change in the Pacific.

Four secondary goals are identified to achieve this aim.

- Develop a rigorous classification of Pacific Islands based on key biophysical attributes that is used as the basis of the coastal susceptibility assessment, but could also be used (or modified) for other purposes.
- Develop a contemporary geomorphological baseline against which future impacts for a range of island types can be identified.
- Produce a coherent narrative that informs an understanding of the degree to which climate is relevant to past, present and future coastal change in the region.
- Establish a baseline by which to prioritise ongoing investment in adaptation responses.

Although there have been a few attempts at Pacific-wide synthesis, most past vulnerability and adaptation studies in the Pacific Islands region have focused on individual islands or even specific areas within islands (Hay and Mimura, 2013). This project differs from these studies in two respects. First, this assessment refers specifically to island geology and geomorphology as a first step to a susceptibility assessment. People and infrastructure are not included in the broad scale analyses presented. Second, this assessment develops measures of susceptibility and based on the most common geomorphologic features apparent at three scales: regional, whole-island (and whole island-coast), and coastal segment scale. These features can be used as criteria to determine the likelihood of coastal change.

The disciplinary foundation for this project is geomorphology, something predicated on the belief that a region-wide understanding of the geomorphic stability and instability of island coasts under current and projected future climatic conditions will both enhance the capacity of decision-makers to consider climate risks in their planning and management, and enable the Australian Government to invest in targeted and transferable adaptation projects with Pacific Island country partners.

The purpose of the assessment is to develop, at each of these scales, a suite of criteria suitable for informed rapid assessment of susceptibility and adaptation that can provide a general context for more detailed and targeted in-country studies. This assessment can also be used at regional, national and community scales by governments, agencies and organisations to develop appropriate adaptation programs. For example, it could be used by Australian Aid to identify hotspots of susceptibility in the region towards which particular attention could then be given.

1.2. Background to regional coastal susceptibility assessment

Islands, largely because of their size and exposure to the ocean, are more vulnerable than larger land masses to environmental changes driven by climate and ocean processes (Connell, 2013). In the Pacific, where there are thousands of habitable islands scattered across almost one-third of the Earth's surface, the susceptibility of particular islands may be exacerbated by their locations, by their comparatively small size and remoteness, as well as by the actions and aspirations of the people who inhabit them.

Impact thresholds have shifted markedly in the past few decades in the Pacific Islands region, as a result of both regional environmental changes relating to temperature, sea level, and ocean acidity, as well as internal factors ranging from land and coral-reef degradation and the effects of increasing urbanisation and population densities. The challenges that face Pacific Island nations and peoples in the future are profound. There are many direct threats to island living, particularly the threat presented for coastal dwellers by sea-level rise, but there are also many threats to islander livelihoods, ranging from unsustainable management of natural food-producing systems to the increasing dependence on imported food (Barnett, 2007; Barnett and Campbell, 2010; Nunn, 2013).

Over the next few decades some of the most serious challenges for Pacific Island countries will arise from the changing climate and include sea-level rise, coral-reef ecosystem deterioration, and changes in patterns of extreme events like tropical cyclones and ENSO-linked droughts. Those challenges resulting from sea-level rise are likely to be most widespread and are likely to displace numerous coastal communities from the vulnerable locations they currently occupy.

Such challenges are not without precedent in the history of Pacific Island peoples, but in a globalised age when all land is owned and population densities are at unprecedentedly high levels in many countries, there is a need for more systematic and planned adaptation than occurred in the past (Nunn, 2007). Adaptation in the Pacific Islands region needs to be both effective and sustainable, to which ends it should be informed by excellent science and developed in conjunction with island governments and communities.

This report constitutes some of the science that can be used to understand the susceptibility of Pacific Islands as well as to underpin effective and sustainable adaptation for coastal peoples throughout the region. Yet it should be noted that this report does not aspire to be a 'vulnerability assessment'—it lacks the necessary links to human/societal behaviour that might make it so—and this is intentional. Measuring 'indicative' susceptibility of islands in the Pacific to external change provides a data-informed baseline that could be used for many different purposes, including that of developing a regional or subregional vulnerability assessment.

1.3. What is covered in this report

The development of a coastal susceptibility typology based on geomorphic features comprises a series of three nested scales constituting the assessment framework. For convenience these are described as primary (regional-scale), secondary (whole-island scale), and tertiary (coastal-segment scale) scales according to an increasing spatial and temporal resolution at each step. The geomorphic information incorporated at each scale ranges from island type to coastal type to geomorphic attribute. The objective is to provide meaningful geomorphic information to determine the relative susceptibility of coastal landform changes at each scale.

The primary scale is that of most use for regional decision-making and informed priority-setting while the secondary scale captures the diversity of islands at sub-regional scale. The tertiary (coastal type) is seen as the principal level in the development of coastal typology. It is also the level that has most relevance for adaptation planning and management. Additionally, at each scale change, the linkage between the response of the coastal exposure unit and climate-ocean drivers is expected to become more precise (Figure 1.1).

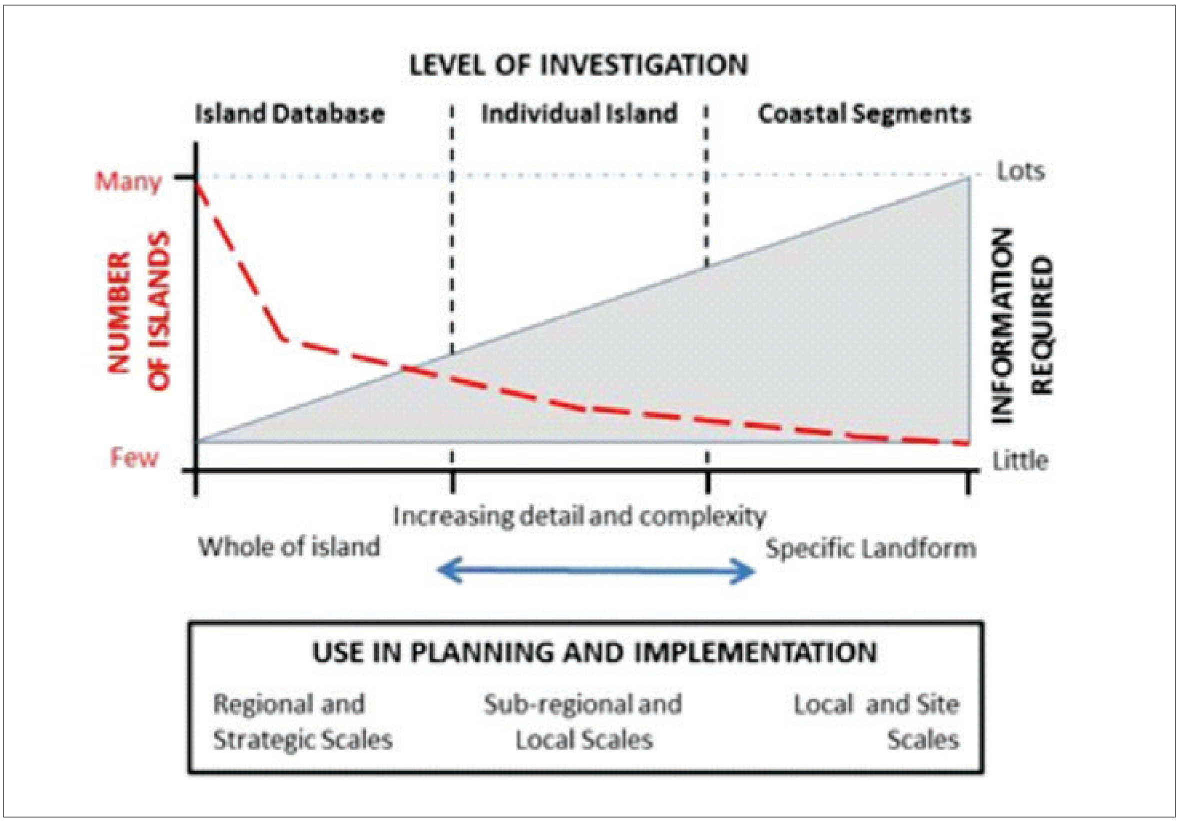


Figure 1.1 Conceptual framework of present study showing three levels of investigation: regional (whole data set), whole single island and coastal subdivisions of an island.

The first step is to develop a classification of island types in the Pacific that has meaning from a coastal geomorphic point of view. This is achieved in **Chapter 2**. Eight island types are identified based on lithology and elevation[2]: volcanic high, volcanic low, limestone high, limestone low, composite high, composite low, continental, and reef islands. The division between high and low islands is taken at 30 m. Results are presented in map form with an explanatory text describing the criteria and methodology used.

2 Lithology means 'rock type', in this case the dominant rock type on a particular island. Elevation means height of the land relative to the average sea level around a particular island, usually used to mean 'maximum elevation' in this report.

Chapter 3 uses these island types to assess susceptibility to landform change for all islands in the database. Four variables: lithology (as a surrogate for erodability; hard rock to unconsolidated sediment) maximum elevation, area and circularity (shape) are used in the development of this measure. **Chapter 3** identifies the range of coastal types found in the Pacific islands, recognising that one of the distinguishing features of 'islands' is their high ratio of coastal length to island area.

In **Chapter 4**, the measure of susceptibility is applied both to whole islands incorporating additional criteria, which is intended to facilitate sub-national comparisons within island groups, as well as to the coastal fringes of 36 case-study islands. This chapter also extends the susceptibility assessment to coastal segments within a particular island, something that is demonstrated for five representative islands, and is intended to be a tool for island-level coastal management.

The focus on change is introduced in **Chapter 5** in which the key meteorological and oceanographic drivers of coastal change in the Pacific islands region are described and their likely future changes, which are critical to understanding future coastline behaviour in various parts of the region, are outlined.

How these processes will manifest in the coastal zone is described in **Chapter 6** through the development of a measure of geomorphic sensitivity showing the susceptibility of coastal landforms of a particular island to future change, based on its location and the projected changes (as in Chapter 5) expected in that part of the Pacific. Geomorphic sensitivities are calculated for all 1532 islands in the database and the ways in which these vary between sub-regions within the Pacific are illustrated.

Chapter 7 of this Report summarises the implications of this susceptibility assessment for coastal and island planning and management in the Pacific.

Chapter 2.
Pacific Islands—Geological Diversity and Commonalities

Key points

- There is a huge and largely-unacknowledged diversity of islands in the Pacific.
- This project developed a database of 1,532 islands from 15 Pacific Island countries with a combined land area of 138,958 km^2. The island of New Guinea is excluded from analysis owing to its exceptionally large size.
- The rock type and elevation of each island in the database allows its classification as one of eight types, each of which is uniquely susceptible to change.
- The most numerous island type is 'reef islands' which comprises 34% of all islands in the database, followed by 'volcanic high islands' (29%).
- Maps showing the distribution of island types within the Pacific Islands region can be used for regional adaptation planning.
- Graphs comparing the distribution of island types in different countries can also be used for regional and national planning.

2.1. Introduction

The region of interest for this project stretches from Palau in the western Pacific to Kiribati in the east (Figure 2.1) and comprises the Pacific Islands region as defined in Chapter 1. The islands of French Polynesia, Hawaii and New Caledonia are excluded, together with others administered by the United States in the central Pacific, as are those in the easternmost Pacific administered by Chile and Ecuador.

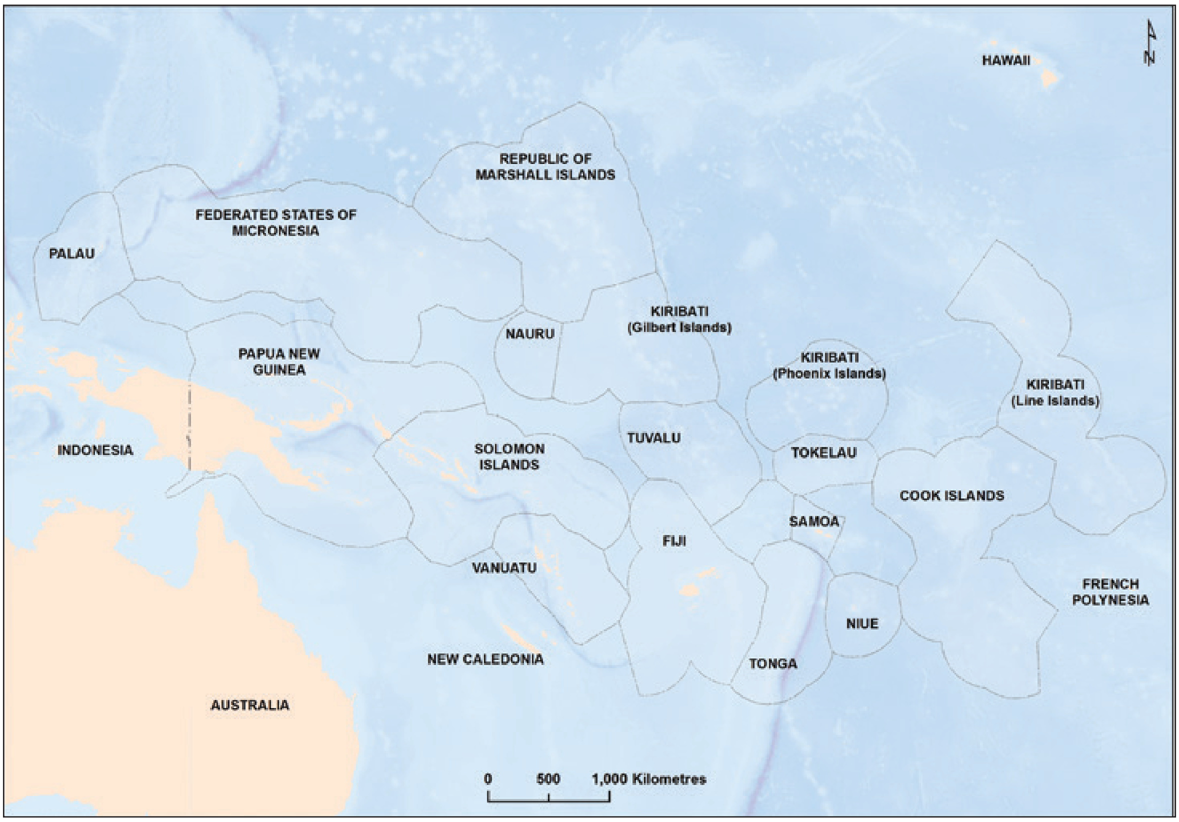


Figure 2.1 The Pacific Islands region for the purpose of this project showing locations of the island countries included.

A fundamental question for any discussion about the common characteristics of islands is "what is an island?". In this report, which looks only at Pacific Islands, the answer to that question is easier than for global surveys (Fairbridge, 1968; Grigor'yev, 1971; Kaplin, 1981; Nunn, 1994). All discrete landmasses within this area that comprise above mean high-water level contiguous areas of land greater than 0.01 km^2 (one hectare) are considered. This is the minimum area that is considered for a potentially habitable island. This ranges from islands as large as New Guinea (~786,000 km^2) to numerous others, mostly off the shores of larger islands, that are around the lower size limit. For the purposes of this project, reefs (lacking islands) are not considered islands, although they are in some island lists (e.g. Motteler, 2006). Transient islands, such as those that may appear or disappear during storms, are not included unless they had existed for more than 20 years at the time of data collection. Likewise islands that formerly existed, perhaps at times of lower sea level in the past, are not included. The data used in this report represent a snapshot, albeit an imperfect one, of the situation in this part of the Pacific around the start of the 21st century.

2.2. Classification and methodology

The intended uses of any classification of natural phenomena (such as islands) are key to the way in which it should be organised. For the purposes of this analysis, given that the classification seeks to capture the diversity of physical and natural attributes of islands in order to assess their relative susceptibility, the most appropriate classification is one based at its highest level on lithology (or rock type) and elevation. The choice of these variables reflects the dominant controls on a broad range of characteristics of Pacific islands, including their erodability and resistance, their drainage (surface and subterranean), and their landscapes (and major landscape processes). It was decided not to include a measure of climate because this is implicit in elevation[3] nor any measure of exposure to particular natural hazards (like volcanic eruptions, earthquakes, tsunamis, tropical cyclones) given that this is highly variable both spatially and temporally within the Pacific Basin.

Lithology is considered a primary basis for island classification because it reflects numerous physical-natural attributes of islands as well as their recent development through which it links to island-forming processes. Yet it should be noted that few islands are effectively of just one lithology and contrasting lithologies often have comparable attributes. For this reason and in order to make this classification as easy to use as possible, we distinguish five types of lithology—volcanic (igneous), limestone (calcareous and non-volcanic sedimentary)[4], composite (less than 80% volcanic and less than 80% limestone), reef (unconsolidated sediment) islands[5], and continental (non-oceanic) islands.

Elevation is also an important first-order classifier because it can be used as a proxy for resistance to erosion (or rock hardness) but also recent island development, capturing both island building (including tectonics) and denudation (or land-surface lowering). There is great diversity in the elevation of islands in the Pacific, and this analysis uses a simple binary distinction between high and low islands, separated as either above or below 30-metre above mean sea level. The use of 30 metres as the divider between high and low is arbitrary but, in our experience, separates lower (less resistant, greater surface lowering) islands from higher (more resistant, less denuded) ones. Similar methods have been used to separate younger (upstanding) volcanic islands from older (more denuded) ones (Menard, 1983; Ramalho et al., 2013).

2.3. Database creation and sources

A total of 1646 islands greater than or equalling 1 hectare (0.01 km^2) in area were identified from aerial imagery in Google Earth during the period April-June 2013. Of this total, it was not possible to verify details (location, vector polygon, name, type) for 114 islands (7%) so these were excluded. In this database, reef islands scattered along an elongate reef are generally counted as one island rather than several islands[6]. The island of New Guinea is also removed from the database because, given its comparatively huge size (787,900 km^2), it would otherwise comprise 85% of the total area of islands in the database and would render most analyses meaningless.

2.3.1. Island locations

In the island databases created for this project, latitude and longitude were initially obtained for almost all islands from Google Earth, the cursor being placed over the centre of an island and coordinates recorded. The advantage of this approach is its consistency and the resulting impossibility of islands overlapping in location. One disadvantage is that a single pair of coordinates does not say anything about the size or shape of a particular island or its proximity to other islands. This is less of a problem with islands (of any size) that are approximately circular in form but does pose challenges for those that are less uniformly shaped. Many (atoll) reef islands, for example, are long sinuous entities and sometimes a degree of subjective judgement is needed to identify the approximate centre. Sometimes it is unclear whether two islands form a single continuous body or not; indeed it is possible

3 Islands that are more readily eroded, perhaps because of their climate (particularly temperature and precipitation and extreme events), are likely to be lower than those that are more resilient to surface lowering.

4 We favour "volcanic" and "limestone" as descriptors rather than "igneous" and "calcareous" respectively because the former words are more familiar to the non-specialists who might eventually use this classification.

5 For reasons of simplicity, we favour "reef" islands for all low islands made from surficial materials, even those not of (primarily) biogenic (reefal) origin.

6 Islands on atoll reefs are often transient, often changing shape over decadal periods, sometimes connected to others (at low tide or by causeways), sometimes separate by subtidal channels (after storms).

that they do at low tide (when people may be accustomed to walk from one to the other) but not at higher tide levels[7].

While having no reason to doubt the accuracy of the latitudes and longitudes reported in Google Earth for the vast majority of islands, each location was verified using another source, usually a list of islands generated for a particular country or island group[8]. In some cases, usually for smaller, more isolated island groups, the only source of earlier locational information found was a map, from which coordinates were read. For some smaller (typically more isolated) islands, no source of latitude and longitude other than Google Earth was readily available.

The sole purpose of cross-checking was to determine whether the latitude and longitude recorded in Google Earth was approximately the same as that recorded previously. This was an important check on whether the correct (named) island is identified in Google Earth. Where minor differences were found in the coordinates for a particular island, it was assumed that those in Google Earth were superior. Often a disparity was found to arise because coordinates from Google Earth were centred within a particular island whereas coordinates from other (earlier) sources for an island were often those of a particular place of interest (like a coastal settlement) within that island not at its geographical centre. Where there was significant disagreement, further investigations were undertaken to ascertain the correct location.

2.3.2. Island names

The main reference for island names was Motteler (2006). This text is widely regarded as the standard listing of islands in particular Pacific Island groups although it is incomplete. In some island groups, the names of even sizeable islands are not listed while others may be spelled in ways that are clearly not those preferred by the nation of which the particular island is part. In some island groups, the names of even the smallest islands—often uninhabited rocks of less than 1 ha in area—are given whilst in others they are omitted. Many reefs (not reef islands) are also included in the Motteler list but were not included in the project database. The prevalence of European names (and earlier European names) for islands rather than current (and previous) local/vernacular names is a weakness of the Motteler list (2006); one source that was especially useful in rectifying this was Langdon (1978) who gives two gazetteers of equivalent and obsolete names for many islands. Despite such concerns, by and large, the Motteler text represents the most complete source of information about Pacific island names and is accompanied by a series of excellent maps.

Google Earth and Google Maps often provide island names, although these may be misplaced, especially with the smaller islands, or misspelled. It was found that Google Earth often confuses islands of the same name (or similar names) and as a result in some instances may place the names considerable distances from the islands to which they correctly refer[9]. The use of photos (uploaded by Google Earth users without apparent quality control) in Google Earth is helpful but potentially a source of serious error both because island names are often wrong but also because the photos may be wrongly located, particularly in more isolated areas. Other sources of location information were obtained from various atlases, maps and encyclopaedia entries as well as a variety of internet sources, although these were not always reliable.

7 Examples are the islands of Foa and Lifuka in the Ha'apai island group in Tonga or the islands of Namalata and Vanua Balavu in Fiji. In both these instances, the pairs of islands have been regarded as two islands.

8 Particular use was made of the UNEP Island Directory (islands.unep.ch).

9 A good example is the island name Futuna that refers to islands in both the Wallis Islands and in Vanuatu and is also sometimes used to refer to islands (or parts of islands) elsewhere.

Most Pacific islands have been known by more than one name within the past century, something that is not routinely recorded in information sources. Yet some islands continue to be referred to, often by different language speakers, by two different names and in such instances both have been recorded in the project database[10]. Minor differences in name, such as the expression of a name as a single word or two, or hyphenated or not, are not recorded in the database. Some habitable islands appear to have no recorded name and are referred to as 'unknown' in the database.

2.3.3. Island elevations

For the purposes of this project, the only information about elevation that is required for classification is whether or not the maximum elevation of a particular island is less than 30 m (above mean sea level) or not. This information, which is crucial to determining island type, is obtainable using Google Earth but errors were significant (there were apparent differences between the elevation at Point A in Google Earth and that on a topographic map of the island). Further it was not always straightforward to identify the highest point on a particular island in Google Earth. Thus for the purposes of determining island maximum elevation, other (library, online, expert knowledge) sources of information were used with Google Earth providing confirmation only.

In addition to those cited above, other important library sources were used (Dahl, 1980; Karolle, 1993; Lobban and Schefter, 1997; Mueller-Dombois and Fosberg, 1998; Rapaport, 2013). Expert knowledge was used from experienced geoscientists (particularly authors McLean and Nunn) to verify elevations of particular islands.

2.3.4. Island areas

Areas for islands were calculated directly from the polygon file created for the database. This was derived from the World Vector Shorelines File (WVF) (Soluri and Woodson, 1990) which contains shorelines along the ocean-land interface at a nominal scale of 1:250,000. It is a standard US Defense Mapping Agency (DMA) product that has been designed for use in many applications but mainly to support geographic information systems at regional and global scales.

Shorelines were developed by contouring the land-sea interface and generalising the vertices. The satellite-derived raster data set was converted into vector form to create the WVF. For areas of the world not covered by the DLMB data (e.g. the Arctic and Antarctic), the shoreline was taken from the best available hard copy sources at a preferred scale of 1:250,000. Political boundaries and country names were added from separate sources. The spatial precision of the WVF is in the order of 50-500 m (Wessel and Smith, 1996).

Since the World Vector Files was created at very broad scales from satellite imagery, there will inevitably be slight distortions in the positional accuracy and shapes of the islands. However, for the spatial scale and resolution of this project, this data source was deemed acceptable and is not considered to cause any discrepancies.

While the areas of many islands were also available from literature, often there are differences between the values reported in different sources, meaning that any particular figure could not be used with confidence. In addition, it is likely that some island areas stated as referring to single entities do in fact subsume smaller offshore islands, so are unreliable for the purposes of this project. To ensure consistency, available vector files were imported from the WVF and in those rare instances where information for specific islands was not available in the WVF, the shapes of these islands were digitised from available maps or from Google Earth and their areas calculated.

10 Examples include the island of Piherarh/Pisaras in the Federated States of Micronesia, and Nukutavake/Queen Charlotte in French Polynesia.

2.3.5. Island lithologies

Archival (written) sources of information about Pacific island lithology are too numerous to review here. Of the Pacific regional sources used, several were especially helpful for providing context (Gillespie and Clague, 2009; Menard, 1986; Neall and Trewick, 2008; Nunn, 1994; Nunn, 1998; Nunn, 1999; Vacher and Quinn, 1997) while at a subregional level a wider range of publications proved useful (Anthony, 2004; Bonatti et al., 1977; Bonvallot et al., 1993; Brocher, 1985; Coleman, 1970; Derrick, 1957; Dow, 1977; Greene and Wong, 1988; Jost, 1998; Keating and Bolton, 1992; Macdonald et al., 1983; McBirney et al., 1969; Scholl and Vallier, 1985; Tracey et al., 1964; Wood, 1967).

There are also numerous sources of sub-national (island group) information about lithology available, usually in the form of academic publications (found in libraries but identified using Google Scholar) that describe the geology of a particular island or group of islands. While invariably focused on research questions requiring more than descriptions of island lithology, these are often included as essential details and were extracted to include in the project database.

Solely online sources of information about island lithology were used principally to confirm details obtained from library sources (see above). Online sources included photographs in Google Earth which, unless misplaced (see above), were often able to provide good information about lithology particularly for smaller islands in more isolated locations. The most useful photographs were those of the island's coast which show the composition of cliffs or the form of the island itself, both of which aid in confirming its dominant lithology. While both volcanic and limestone islands have cliffs, those of the latter generally tend to be flatter-topped and straighter-sided, particularly in the low-latitude Pacific. The form of an emerged limestone island is generally marked by flat tabular surfaces (former reef surfaces), a stark contrast to the form of volcanic islands where flat surfaces are generally rare and the topography is often dominated by peaks and valleys.

2.4. Island types

On the basis of the data generated in the ways described above, a classification of islands in the Pacific was produced based on the lithology and elevation of each island. The classification system has eight categories:

1. Volcanic high islands
2. Volcanic low islands
3. Limestone high islands
4. Limestone low islands
5. Reef islands
6. Composite high islands
7. Composite low islands
8. Continental islands

Each category has a unique set of attributes that allows generalisations about the islands in it. Eight is considered to be the optimum number of categories given the purposes of this classification, although more could have been used. This classification system is used as a basis for the analyses in subsequent sections of the report.

2.4.1. Volcanic high islands

Volcanic high islands are those composed of at least 80% igneous rock types that rise to a maximum elevation of at least 30 m above mean sea level. In the Pacific, these island types are commonest in those places where there is active volcanism occurring within 100 km. Such places may be in the volcanic island arcs that develop above convergent plate boundaries, as in parts of Solomon Islands, Tonga and Vanuatu in the Southwest Pacific. But such islands are also common around mid-plate hotspots where magma reaches the ocean surface and builds chains of volcanic islands, as in the island groups of Hawaii and Samoa.

2.4.2. Volcanic low islands

Volcanic low islands are those which are composed of at least 80% igneous rock types and rise to a maximum elevation of less than 30 m above mean sea level. In the Pacific, these island types are common where higher volcanic islands are found (see above) but also tend to occur farther away from contemporary sources of volcanism. Along hotspot island chains, as in Hawaii and Samoa, for example, the highest islands are usually close to the hotspot itself while farther away, the volcanic islands (largely through progressive subsidence) are generally lower. Elsewhere, once removed from the area in which volcanic islands form, such islands tend to become reduced in elevation by subaerial erosion.

2.4.3. Limestone high islands

Limestone high islands are those which are composed of at least 80% calcareous rock types and rise to a maximum elevation of at least 30 m above mean sea level. In the Pacific, these island types are commonest in those places where (tectonic) uplift has been occurring for several hundred thousand years, most commonly as a result of one (oceanic) plate being pushed up over another as is usual along convergent plate boundaries. High limestone islands commonly develop along such forearcs and examples are found in Papua New Guinea, Solomon Islands, Tonga and Vanuatu. Elsewhere collision/compression of lithospheric plates may cause uplift of islands in places where subduction is not taking place; examples include the Lau Islands of eastern Fiji, and the isolated islands of Nauru and Niue.

2.4.4. Limestone low islands

Limestone low islands are those which are composed of at least 80% calcareous rock types and rise to a maximum elevation of less than 30 m above mean sea level. In the Pacific, these island types are common where high limestone islands are found (see above), the distinction often largely attributable to the degree of net uplift particular islands have experienced. Low limestone islands are also found in many places (not tectonically active) where reef islands are found (see below) and it is sometimes difficult to distinguish the two types. The low limestone islands tend to be significantly older and typically formed (in part at least) from reefs that were growing around 6 m above present sea level during the Last Interglacial period, around 125,000 years ago, and sometimes during earlier Quaternary interglacial periods.

2.4.5. Reef islands

Reef islands are those which are composed of at least 80% unconsolidated sediments that have accumulated on a shallow flat (shoal), commonly biogenic (reefal) in origin. While sometimes easily confused with lower types of low limestone island (see above), reef islands tend to rise no more than 3 m above mean sea level and to be characterised by shorelines that change position faster than those of other island types. Often reef islands are long and sinuous, accumulated on sub-circular (atoll) reefs that have grown up from the submerged flanks of a drowned volcanic island. Reef islands also develop on other types of reef. Of all the island types in this classification, reef islands are the most transient, many of those that exist today having formed only after sea level in the Pacific began falling from its Holocene maximum around 4000 years ago. Reef islands are widespread in the low-latitude Pacific, concentrated along atoll reefs in its equatorial central part where most islands in Kiribati, Marshall Islands, Tokelau and Tuvalu are of this type. For the purposes of this project, this category also includes other islands composed of unconsolidated sediments, such as occur in deltas and estuaries; many such islands are found at the mouths of large rivers in the region, such as those which occur on larger islands in Fiji and Papua New Guinea.

2.4.6. Composite high islands

Composite high islands are those which are composed of both less than 80% volcanic and less than 80% calcareous rock types and rise to a maximum elevation of at least 30 m above mean sea level. Such islands also include those which are partly composed of unconsolidated sediments (reef islands—see above). In the Pacific, composite high islands are commonest in places where long-term subsidence (allowing thick reefs to develop around a volcanic island) has been interrupted by long-term uplift (causing those reefs to emerge). The resulting island type[11] is common in the southern Cook Islands as well as along remnant island arcs such as the Lau Islands of eastern Fiji and the Bellona-Rennell group in the southern Solomon Islands. Other more diverse composite high islands occur around convergent plate boundaries, typically formed over long time periods by processes associated with alternating volcanism (along a volcanic island arc) and uplift (along a forearc). Many of the larger islands in the central Solomon Islands and eastern Vanuatu are of this kind. This category also includes high islands, generally comparatively small in area, around the sides of which sediments have accumulated, giving rise to large areas of 'reef-island' lowlands.

2.4.7. Composite low islands

Composite low islands are those which are composed of both less than 80% volcanic and less than 80% calcareous rock types and rise to a maximum elevation of less than 30 m above mean sea level. In the Pacific, these island types are common where composite high islands are found, the difference often being that island-forming processes (volcanism and/or uplift) were less active and therefore produced a lower island. Also it is clear that such processes often produced composite high islands that are comparatively large in area (and like Choiseul in Solomon Islands or Pentecost in Vanuatu) surrounded by smaller islands, representing peripheral parts of the structure, that are lower.

2.4.8. Continental islands

Continental islands are those that are composed of at least 80% continental (not of oceanic origin) rocks. Given that these island types are so few within the study area and that almost all are above 30 m maximum elevation, this island type is not subdivided on the basis of elevation. Such islands are found almost exclusively in the New Caledonia group, where the main island (La Grande Terre) and its closest satellites are continental in origin.

This classification is a descriptive one, easily applied and used by non-specialists, yet one that acknowledges the two diagnostic criteria that cause Pacific island coasts to differ—lithology (rock-type) and elevation (height above sea level). Its essence is that of the scheme adopted by Darwin and others who around one hundred years ago attempted to make sense of the diversity of island types they had encountered in the world's oceans (Darwin, 1839; Wallace, 1881).

11 These island types were named *makatea islands* by Nunn (1994).

There are no continental islands in the Pacific Basin as defined for this project but mention of this category is considered to be important as such islands are found elsewhere in the region.

2.5. Summary statistics for the whole database

The database contains a total of 1532 islands that have a combined area of 138,958 km^2 (Table 2.1). The smallest-sized island in the database is 0.013 km^2 and the largest is 35,780 km2. The mean area is 90.7 km^2. By country, the largest number of islands in the database is in Papua New Guinea (439/29%), followed by Solomon Islands (413/27%) and Fiji (211/14%). The countries of Nauru and Niue have one island each.

A similar rank order understandably applies to total area by country although it contains some interesting variations from this. For example, Vanuatu comes 4th in the latter rankings because of the large size of many of its islands (average 167 km^2) compared to countries like the Federated States of Micronesia and Tonga which have far more islands but of a smaller size.

Table 2.1 also shows average areas for islands within each country. Average area is both a measure of island diversity as well as a crude proxy for population potential: the larger the area of habitable land, the larger the potential of that country to accommodate people. Another example would be the realisation from looking at data on total in-country area and percentage of total regional area that smaller countries cannot afford to 'lose' land to inundation or shoreline erosion in the same way that larger countries can.

Table 2.1 Number of islands in database by country

Country	Number of Islands	% of total by number	Total area of islands (km^2)	% of total by area	Average island area (km^2)
Cook Islands	15	1.0	296.63	0.21	19.8
Federated States of Micronesia	127	8.3	799.47	0.58	6.3
Fiji	211	13.8	20,856.96	15.01	98.8
Kiribati	33	2.2	994.93	0.72	30.1
Marshall Islands	34	2.2	286.2	0.21	8.4
Nauru	1	0.1	22.64	0.02	22.6
Niue	1	0.1	297.9	0.21	297.9
Palau	33	2.2	495.3	0.36	15.0
Papua New Guinea[1]	439	28.7	67,756.59	48.76	154.3
Samoa	7	0.5	3,046.19	2.19	435.2
Solomon Islands	413	27.0	29,671.95	21.35	71.8
Tokelau	3	0.2	16.06	0.01	5.4
Tonga	124	8.1	846.83	0.61	6.8
Tuvalu	10	0.7	44.47	0.03	4.4
Vanuatu	81	5.3	13,526.18	9.73	167.0
TOTAL	***1532***		***138,958.29***		***90.7***
1 This excludes the large island of New Guinea itself					

Given that adaptive management options for islands varies with their size, there is interest in knowing more about the range of island sizes in the Pacific. Table 2.2 gives a summary of island sizes, grouped into eight size categories. 745 islands, forming 48.62% of all the islands in the database, have an area less than 1 km^2; these 745 islands make up less than 0.20% of the total area of islands. 1136 islands (74.15%) of the islands have an area less than 5 km^2 and they account for a total of 0.86% of the total area. There are 18 islands that have an area greater than 1000 km^2, making up 76.32% of the total area. Such insights are not always readily appreciated by people interested in adaptive management in the Pacific Islands but they are clearly an important expression of the diversity of the islands.

Table 2.2 Summary data for island sizes

Area (km^2)	Number of islands	% of islands	Total area (km^2)	% area
< 0.1	145	9.46	8.62	0.01
0.1 to 1.0	600	39.16	267.14	0.19
1.0 to 5.0	391	25.52	917.18	0.66
5.0 to 10.0	100	6.53	722.86	0.52
10.0 to 50.0	173	11.29	3,941.58	2.84
50.0 to 100	41	2.68	2,851.62	2.05
100 to 1000	64	4.18	24,190.74	17.41
> 1000	18	1.17	106,058.56	76.32
TOTAL	***1532***	***100***	***138,958.30***	***100***

2.5.1. Analysis of island types

We now turn our attention to island types, as introduced in Section 2.3 above and identified for all 1532 islands in the database. Figure 2.2 presents counts of different island types within the Pacific.

The most numerous island type is 'reef islands', with a total of 522 islands making up 34% of all islands in the database. It should be noted that many reef islands have not been counted and recorded in the database due to difficulties in identifying and naming them, and that many of these are parts of groups of reef islands that were not recorded individually. Had this been otherwise, it is estimated that reef islands would make up well over 50% of the islands in the Pacific. The reason why reef islands are so numerous relates to their comparative ease of formation, many being thrown up on shallow reef flats or river beds following storms. Successive storms can cause these islands to persist, sometimes for millennia (Dickinson, 2009; McLean and Hosking, 1991; Rankey, 2011).

The second most numerous type are 'volcanic high islands' which number 452 or 29% of the total. This high number reflects the preponderance of contemporary and recent volcanic activity throughout the region, both close to convergent plate boundaries and around intraplate hotspots (Neall and Trewick, 2008; Nunn, 1999). It also reflects the tendency of above-sea (island) volcanoes to reach more than 30 m in elevation at such locations.

The numbers of 'limestone low islands', 'volcanic low islands' and 'limestone high islands' are approximately the same and reflect a diversity of island-forming processes in different places.

While, as noted above, most volcanic islands are more than 30 m high—and often much more—because of the nature and persistence of island-forming processes, this also explains why low volcanic islands are fewer (almost one-third) in number. For even allowing for a few volcanic islands to never grow above 30 m and thus be created ‘low’, most islands in the ‘volcanic low’ category are erosional remnants of (once) larger volcanic islands, either reduced in elevation by denudation or severed from the main volcanic island of which they were originally part.

The converse situation applies with limestone islands and explains why there are significantly more ‘limestone low islands’ than ‘limestone high islands’. Many limestone islands found in the Pacific region represent uplifted coral reefs or similar features that were once at sea level. Uplift of this kind commonly occurs close to convergent plate boundaries, past and present, but it is uncommon for such uplift to reach 30 m, something that generally requires successive phases of uplift over periods of several million years (Ota and Yamaguchi, 2004). It is therefore more usual to find low limestone islands rather than high ones.

Composite islands vary so greatly in their nature that it is more difficult to generalise about them than for other island types. Together they comprise just 7% of islands in the database yet are dominated by ‘composite high islands’, which are nearly six times as numerous as ‘composite low islands’. This reflects the dominance of volcanic components in the composite islands group; most composite high islands are primarily ‘volcanic’ with subordinate amounts of ‘limestone’ and ‘reef’ islands. Thus for the same reasons that ‘volcanic high islands’ are much more numerous than ‘volcanic low islands’ (see above), so ‘composite high islands’ are more common that ‘composite low islands’.

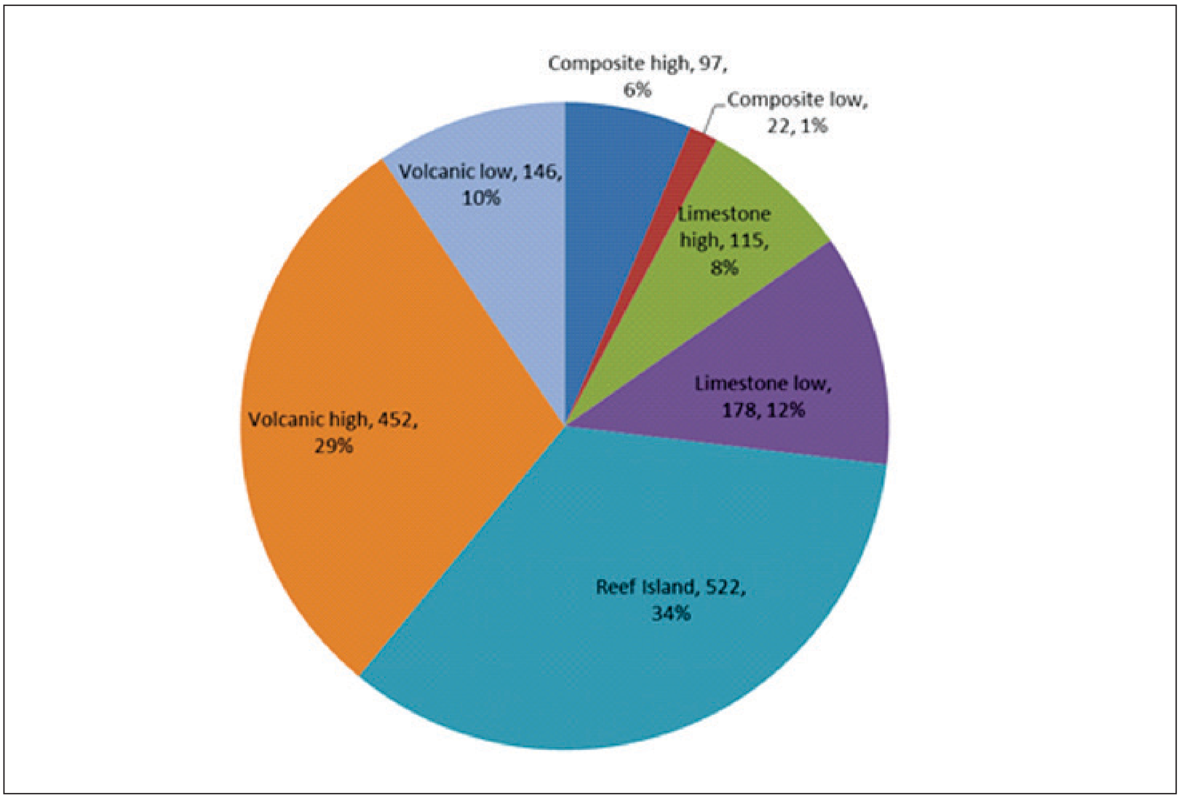


Figure 2.2 Distribution of island types by number/count in the Pacific region.

The same analysis in Figure 2.2 is performed for island area by type in Figure 2.3. This shows some interesting statistics.

While reef islands are the most common in the Pacific, their total area is only 3,438 km^2, 3% of total area. The average size of a reef island is 6.59 km^2.

29% of islands in the Pacific are 'volcanic high' but the total area of these (31,237 km^2) is just 23% of the total area of islands. The average size of volcanic high islands is 7.61 km^2.

In terms of area, composite high islands dominate the dataset, largely because of the inclusion of large islands in Papua New Guinea and Solomon Islands, with 72% of total area in the Pacific. Limestone low, volcanic low and composite low each made up less than 1% of total area.

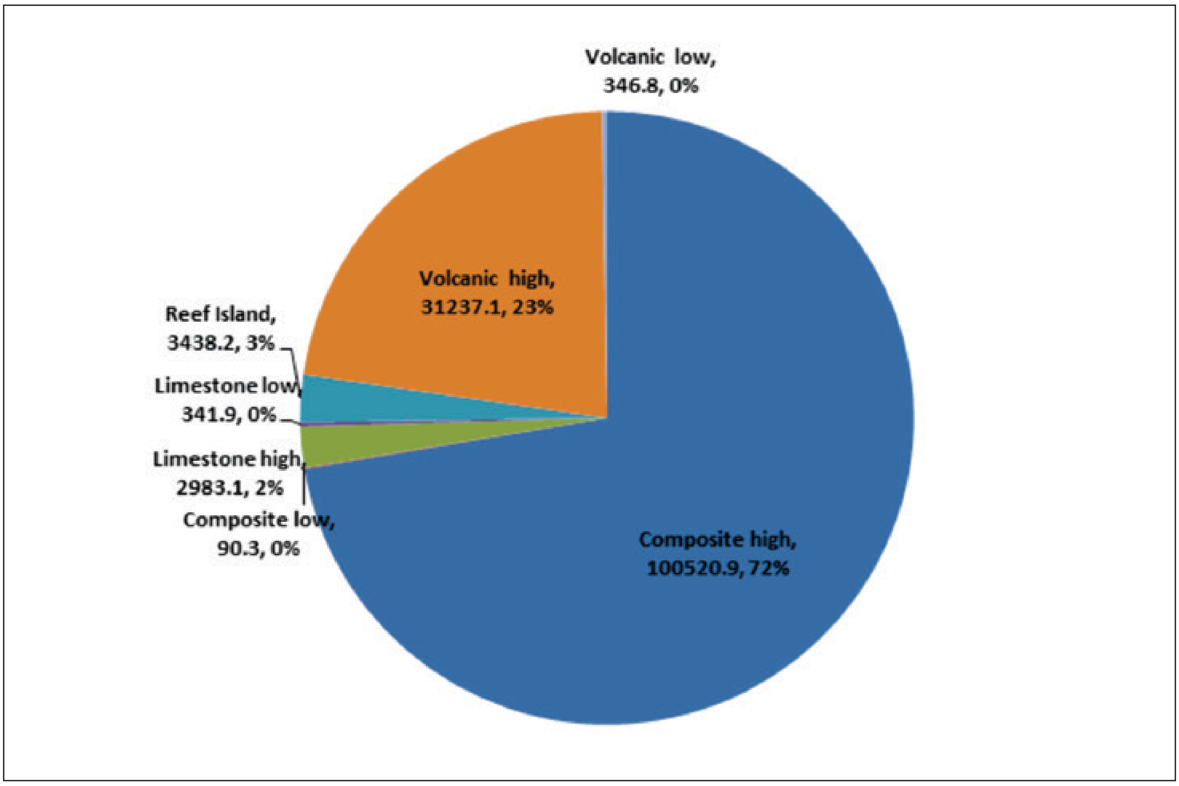


Figure 2.3 Distribution of island types by area in the Pacific region.

2.5.2. Analysis of the distribution of island types

The spatial distribution of island types in the Pacific is mapped in Figure 2.4. Many islands, particularly in the southwest Pacific, formed as a result of processes operating along convergent plate boundaries, marked on this map by (darker blue) deep ocean trenches.

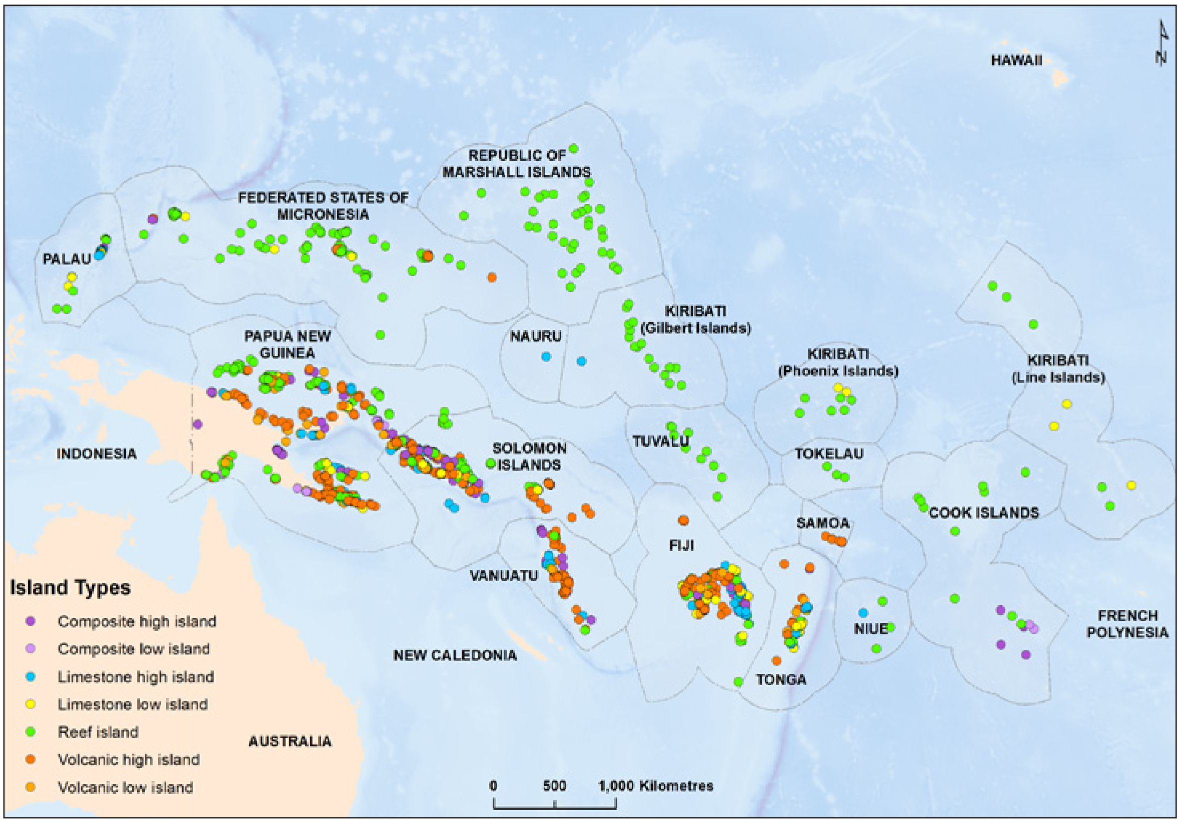


Figure 2.4 *Spatial distribution of island types in the Pacific.*

Note that this map also shows bathymetry which allows identification of ocean trenches (darker areas—marking convergent-plate boundaries) around which many volcanic and limestone islands formed. Also shown are the political boundaries (Exclusive Economic Zones) of the 15 Pacific Island countries considered.

From the southern side of the map, the long Tonga-Kermadec Trench can be seen, the islands of Tonga arranged along its western side where a lithospheric plate is being pushed up and over the Pacific Plate on the eastern side of the trench. The islands of Tonga are arranged in two linear groups running parallel to the trench axis, a (mostly high) limestone group defining the forearc closest to the trench, and a (mostly high/young) volcanic chain of islands farther away (Nunn, 1998). On the eastern side of the trench here, Niue is a high limestone island uplifted along a line of lithospheric flexure associated with proximal convergence (Nunn and Britton, 2004).

At the northern end of the Tonga-Kermadec Trench is a hook to the north of which lie the high volcanic islands of Samoa, an intraplate hotspot chain along which rupturing associated with convergence along that hook has produced more recent volcanism in several places (Nunn, 1998). The Fiji islands occupy a 'microplate' that is buffeted by two much larger plates, the Pacific Plate in the north and east, and the Indo-Australian Plate in the west and south. As a result, the distribution of island types is not straightforward to interpret although the high limestone islands in the north-south trending Lau Group of eastern Fiji represent a remnant forearc and the high volcanic islands of the Kadavu Group in southern Fiji represent an intermittently active volcanic arc (Nunn, 1998).

The (dark blue) convergent plate boundary is visible again to the west in the islands of Vanuatu where on the eastern side of the trench there are three sub-parallel lines of islands, two volcanic and one limestone forearc (Greene and Wong, 1988). The Vanuatu Trench continues northwest along the southern side of the main group of Solomon Islands and into central Papua New Guinea in both countries of which there are numerous high volcanic islands which owe their origins to plate convergence along this trench. There are also many high limestone islands as well as high composite islands, some of the largest of which represent uplifted volcanic/composite island that became draped with reef limestones as they emerged (Nunn, 1994). Shorter plate boundaries explain the distribution of other islands in Papua New Guinea as well as many outlier islands to the southeast.

In the northwest of the study area shown in (Figure 2.4) is another ocean trench—the Marianas Trench—along which islands are clustered. Most of the high volcanic islands associated with this trench occur outside the study area and most within are high limestone islands, parts of uplifted and crumpled forearcs (Neall and Trewick, 2008).

Almost all islands in the rest of the Pacific Basin as shown in (Figure 2.4) owe their origins to island-forming processes that occurred in the middle of plates. They are mostly 'hotspot' islands, formed in lines of discrete volcanoes when a lithospheric plate moved slowly over a fixed mantle 'hotspot' through which magma rose. Islands close to the hotspot (as in Samoa) tend to be volcanic but, as they are carried on moving plates farther away, they subside and frequently form atolls on which reef islands develop. This explains the existence of lines—often parallel lines—of reef islands throughout the study area, from the Line Islands (eastern Kiribati) in the east through the northern Cook Islands and the atolls of Tuvalu, (western) Kiribati, and the Marshall Islands (Nunn, 1994).

2.5.3. Pattern of island types by country

Details of each island type by count and by proportion (based on island counts) found in each of the 15 countries of the study area are shown in Figure 2.5.

Volcanic high islands are found in 8 of the 15 countries. Papua New Guinea has the highest proportion (30%), followed by Solomon Islands (28%), Fiji (23%), Vanuatu (9%) and Federated States of Micronesia (6%). Cook Islands, Kiribati, Marshall Islands, Nauru, Niue, Tokelau and Tuvalu do not have volcanic high islands.

Volcanic low islands are found in only 6 of the 15 countries, namely Solomon Islands (46%), Papua New Guinea (36%), Fiji (10%), Vanuatu (4%), Federated States of Micronesia (3%) and Tonga (1%).

Limestone high islands probably have the most even distribution, spread over 13 countries, with the highest proportion being 22% (Papua New Guinea), followed by Tonga and Fiji (21% each), Palau (13%), Solomon Islands (11%) and Vanuatu (9%). Six countries (Cook Islands, Federated States of Micronesia, Marshall Islands, Samoa, Tokelau and Tuvalu) do not have any limestone high islands.

The majority of **limestone low** islands are found in Tonga (37%), followed by Solomon Islands (26%), Papua New Guinea (17%) and Fiji (10%). Limestone low islands are found in only 8 of the 15 countries in the database, with Cook Islands, Marshall Islands, Nauru, Niue, Samoa, Tokelau and Tuvalu not having any limestone low islands.

Most of the **composite high** islands are found in Papua New Guinea (33%), followed by Solomon Islands (29%), Fiji (16%) and Vanuatu (11%). The remaining 11% is distributed roughly evenly between Tonga, Palau Cook Islands and Federated States of Micronesia. Seven countries (Kiribati, Marshall Islands, Nauru, Niue, Samoa, Tokelau and Tuvalu) do not have any composite high islands.

63% of the **composite low** islands are found in Papua New Guinea, followed by Vanuatu (14%), Solomon Islands (14%), and Cook Islands (9%). The other 11 countries do not have composite low islands.

Reef islands are found in 12 of the 15 countries in the database, with Papua New Guinea having 29%, Solomon Islands 25%, Federated States of Micronesia 17%, Fiji 6%, Kiribati 5% and Tonga 4%. Nauru, Niue and Samoa do not have reef islands.

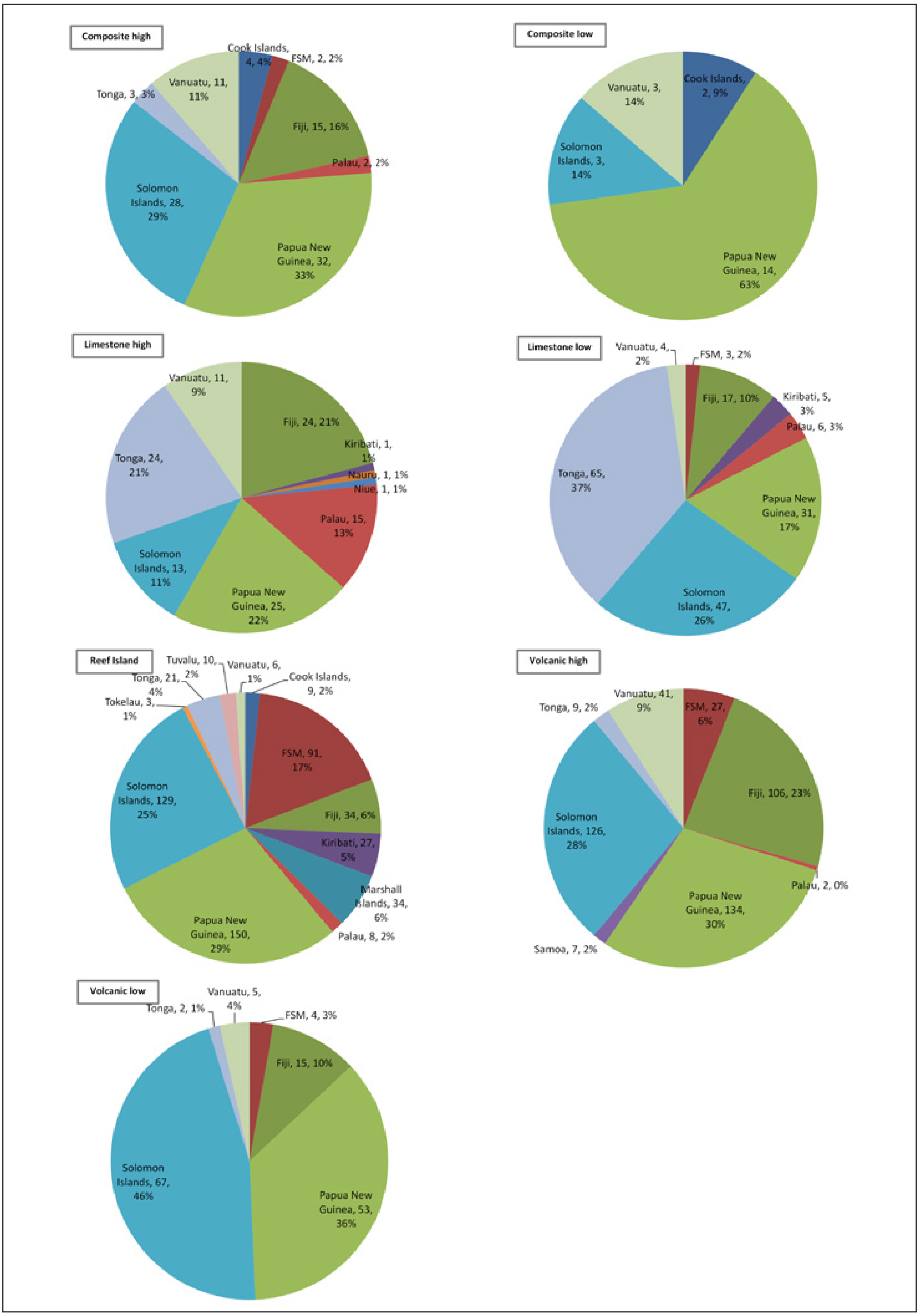


Figure 2.5 *Detailed breakdown for each Pacific Island country of each island type by counts and the proportion found in each country.*

The numbers give the total number of islands in that category and the percentage is the percentage count in that particular category.

Details of each island type by area and the proportion (based on island area in km^2) found in each country are illustrated in Figure 2.6.

Papua New Guinea has 35% of the area of **volcanic high** islands, followed by Fiji (27%), Vanuatu (15%), Solomon Islands (11%) and Samoa (10%).

Papua New Guinea has 84% of the area covered by **volcanic low** islands, followed by Solomon Islands (13%).

37% of the area of **limestone high** islands is found in Solomon Islands, followed by Tonga and Papua New Guinea (19% each), Niue (10%), Fiji (6%), Vanuatu (5%) and Nauru (1%).

Kiribati and Papua New Guinea each have 26% of the area of **limestone low** islands, followed by Solomon Islands (21%), Tonga (20%), Fiji (3%), and Vanuatu and Federated States of Micronesia with 1% each.

Papua New Guinea dominates the **composite high** group, with 54% of composite high islands (in terms of area), followed by Solomon Islands (24%), Fiji (12%) and Vanuatu (9%).

The Cook Islands has 53% of **composite low** islands in terms of area, followed by Papua New Guinea (36%), Solomon Islands (6%) and Vanuatu (5%).

For the **reef islands**, 45% of the area is in Papua New Guinea, followed by 26% in Kiribati, 13% in Solomon Islands, and 8% in the Marshall Islands.

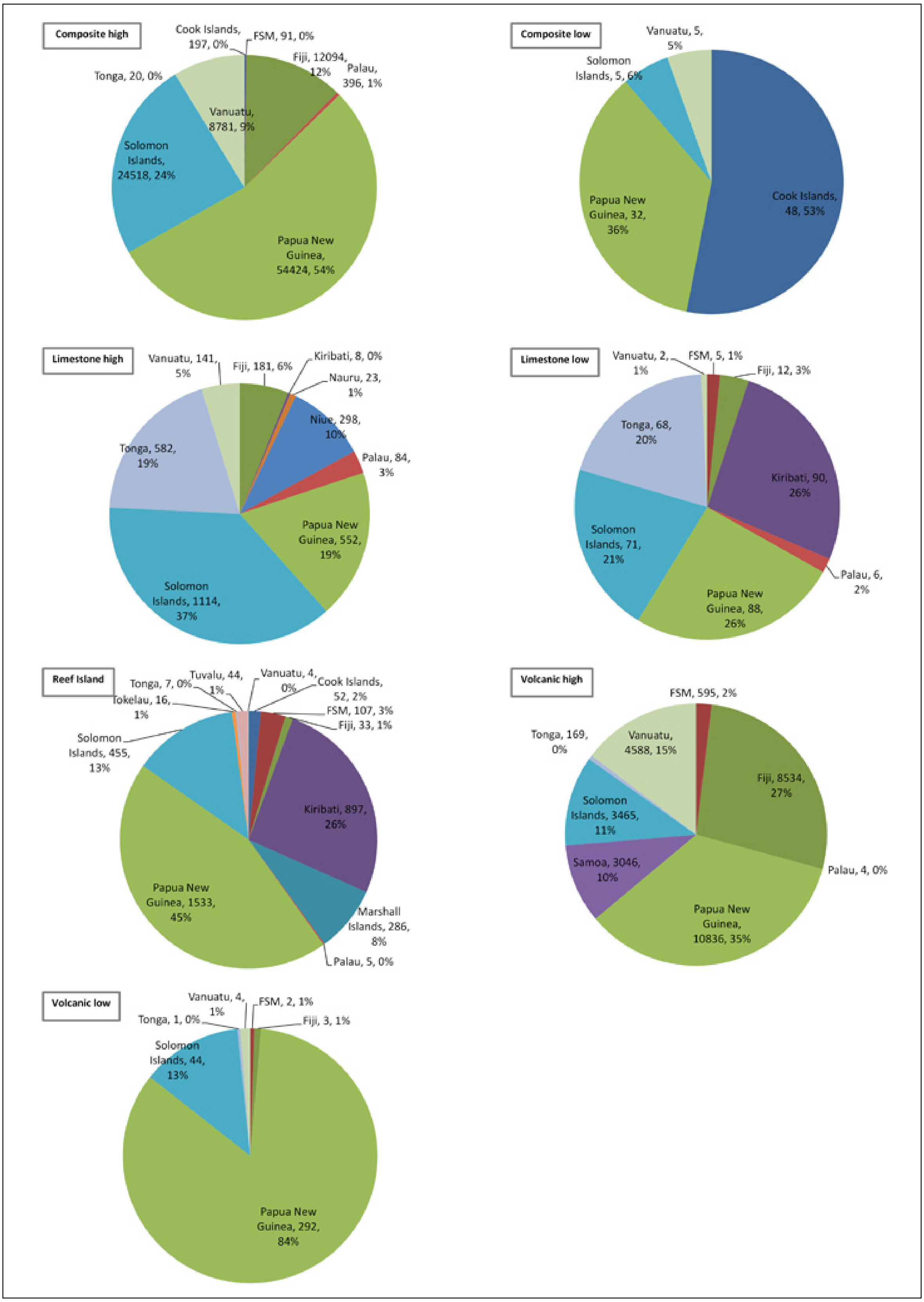


Figure 2.6 *Detailed breakdown for each Pacific Island country of each island type by area and the proportion found in each country.*

The numbers give the total area (km^2) and the percentage of that area in the particular category.

The data in Figure 2.5 and 2.6 can be used to readily identify commonalities across national boundaries and allow for interventions based on geological conditions rather than political boundaries. For example, were a particular adaptation strategy designed that was appropriate to low limestone islands, then it is straightforward for planners to see in which countries these types of island are most common, both in terms of frequency (count) and in terms of area: both measures might be important for different types of strategy. Once a particular strategy had been trialled in a particular country, then these data can also be used to apply the results of this trial to comparable environments.

Whereas the data in Figure 2.5 and 2.6 allow for effective regional evaluations, the data in Figure 2.7 and 2.8 (below) allow ready inter-nation comparisons.

Figure 2.7 shows the number of islands of each type, expressed as a proportion of the total for that country. Six of the 15 countries are made up of just one island type only; these are the Marshall Islands, Nauru, Niue, Samoa, Tokelau, and Tuvalu. Of the remaining 9 countries, two have three island types, two have five island types, two have six island types, and the other three are made up of all seven island types. The principal use of such data is to provide persons/agencies concerned with adaptation in the Pacific Islands region with a data-informed snapshot of island types, that might then be used to identify islands with large numbers of particular island types for particular types of intervention. Figure 2.7 demonstrates what proportion of islands in a particular country are of a particular island types and therefore potentially how important impacts or adaptive strategies for that particular country.

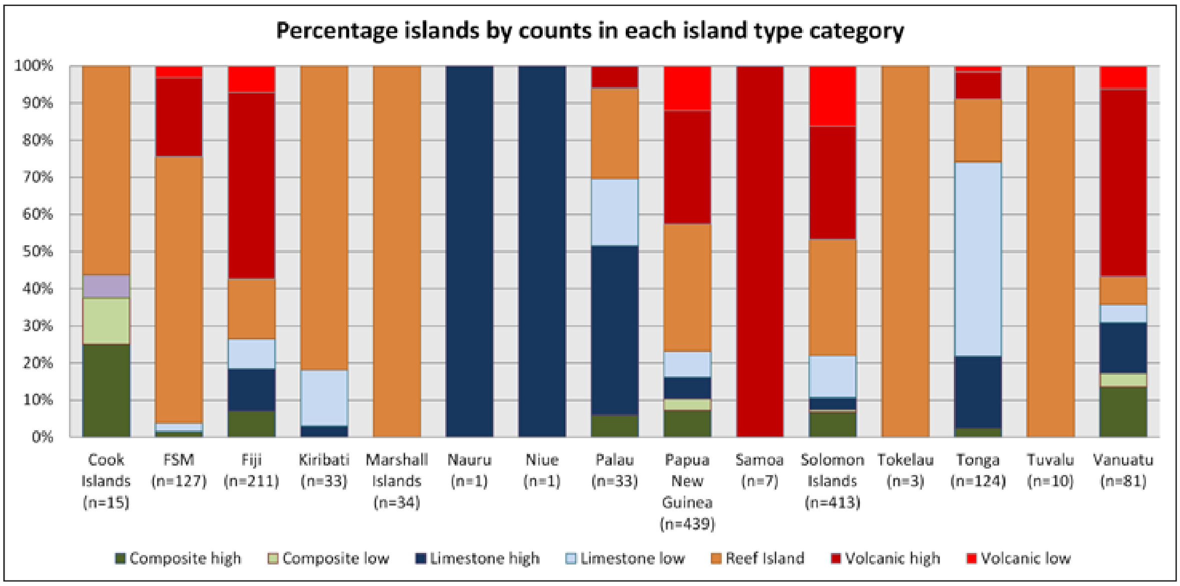


Figure 2.7 Distribution of island-type by counts expressed as proportions for each country in the Pacific Islands region.

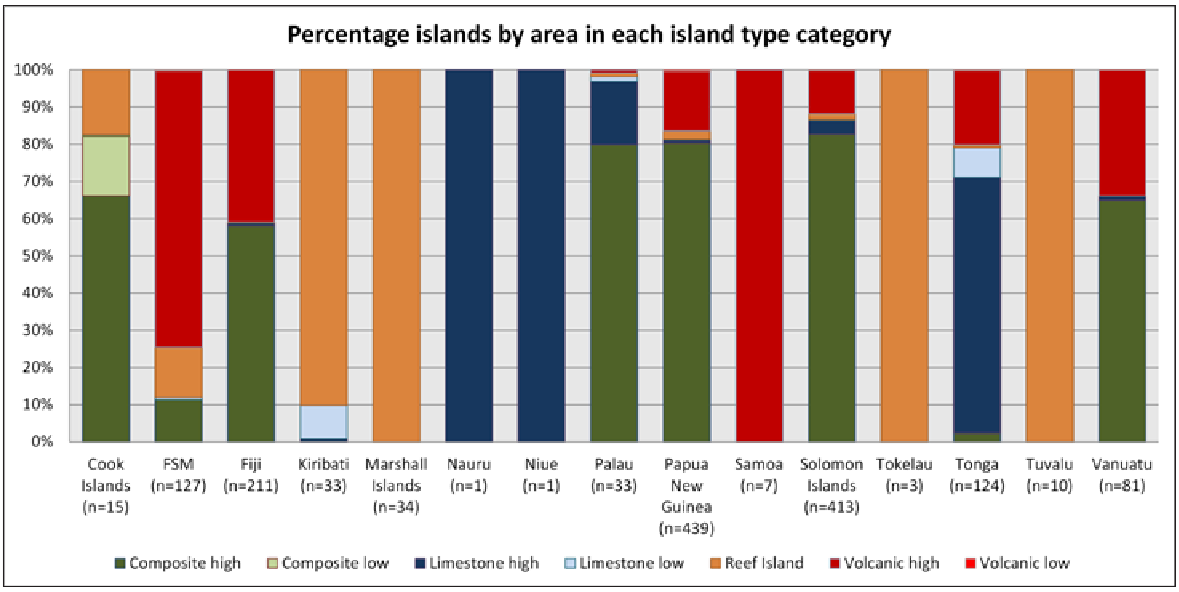


Figure 2.8 Distribution of island-type by area expressed as proportions for each country in the Pacific islands region.

Figure 2.8 shows the area of islands of each type, expressed as a proportion of the total area of that country. One immediate impression of Figure 2.8 is that each country is dominated by one island type in terms of area so that common characterizations of Country X as being a 'reef-island' nation or a 'volcanic-island' nation are supported by data; in 14 of the 15 countries, a single island type covers more than two-thirds of the total land area of that country. Composite high islands make up the highest area in six countries, reef islands in four countries, limestone high islands in four countries, and volcanic high islands in two countries. Volcanic low, limestone low and composite low islands types do not dominate in any island country in terms of area. The use of the data in Figure 2.8 also provides a data-informed snapshot of national island types which can be readily linked to particular issues including groundwater, soils, hazards and coastal susceptibility, the principal driver of this project.

Chapter 3. Regional Assessment of Island Susceptibility to Climate and Oceanographic Conditions

Key points

- The project has, for the first time, produced regional-scale maps of the gross physical characteristics of 1532 Pacific islands.
- A susceptibility rating was identified for each of the seven island types examined, with low to moderate susceptibility ratings for volcanic islands contrasting with moderate to very high ratings for reef islands.
- Six of the 15 countries examined have islands in all five categories of susceptibility, whereas three countries—in addition to two single-island countries—fall within a single category.
- Countries with islands with a high proportion of very high susceptibility ratings are the Cook Islands, Marshall Islands, Tokelau and Tuvalu.
- The Federated States of Micronesia, Kiribati, Papua New Guinea and Solomon Islands have a high proportion of islands with high susceptibility.

3.1. Context and aims

In this chapter, regional-scale descriptions of differences in island lithology and their physical shape from Chapter 2 are compared within and between island types for all 1532 islands in the database. The aims of the comparison are to:

- Determine the relative susceptibility of islands at a broad, regional-scale—essentially to comparatively establish whether an island is likely to incur structural change in response to long-term climatic and oceanographic conditions; and
- Describe regional and within-country variation in the susceptibility of each island type.

Every island in the Pacific Ocean is unique having its own physical strengths and weaknesses; each contextualised by particular climate and oceanographic conditions (Ramsay, 2011). Despite the physical differences between islands, coastal management decisions are made at a variety of scales related to a hierarchy of landforms, an overview of the processes affecting them and the time scales over which they change. Each management scale in the hierarchy accords with the geographic area to be managed as well as the meteorological and marine processes affecting it. Decisions range from those appropriate for site-specific locations to formulation of policy and strategic decisions for countries or regions. Ultimately, local problems with very specific objectives will be those requiring direct action; for example those concerning maintenance of a harbour entrance or establishment of shore stabilisation measures at a particular place. Broad, regional-scale problems are of a more general nature and overview issues related to the governance of administrative areas or regions. These also need to be addressed by management; for example, a joint intergovernmental decision may lead to region-wide adoption of a procedure for responding to landform changes caused by catastrophic events such as tropical cyclone or tsunami impacts. In this chapter, regional-scale, strategic information is used to examine the gross physical characteristics of 1532 Pacific islands and comparatively estimate their *susceptibility* to climatic and oceanographic processes. As stated in Chapter 1, the comparison is *indicative* rather than absolute or predictive.

3.2. Regional-scale change of landform

Coastal landforms change over time with different landforms responding to particular climate and marine processes in different ways, which means the relationship between landform and process is complex. It is not always easy to predict how a particular coastal landscape will respond to particular forcings. The rates at which they change are determined by their lithology, other physical characteristics such as area and elevation, and their location with respect to climate and ocean processes. The complexity is further compounded by human impacts on the natural interactions between coastal landforms and climate-ocean processes. Human activity occurs at a wide variety of time and space scales, ranging from direct changes (such as beach mining or harbour construction) to indirect changes (such as ocean acidification and hinterland deforestation) with the effects of both possibly persisting for centuries.

Despite the complexity of inter-relationships between landforms and processes, some coastal landforms are closely tied to physical processes that are observable, for example, migration of a beach ridge in response to recurrent storms. Interannually observed alteration of landforms over periods for which historical photographic or survey records are available may serve as proxies for processes in places where there are no measurements of process drivers (Webb and Kench, 2010; Yamano et al., 2007). In this context it is possible to discern whether one type of landform is more susceptible to change than another.

Other coastal landforms are linked to processes that are more difficult to directly observe because they occur slowly over very long periods, or perhaps because they are no longer as dominant as they once were. For example, hard rock landforms such as rocky headlands and reefs may not be changing within a planning horizon of 100 years but still affect the impact of climate and ocean processes on an island's coast and so warrant consideration in any assessment of island susceptibility. Long-term changes in coastal landforms are not directly observable. However they are commonly inferred from geophysical investigations to establish a chronology of change to landforms comprised of unconsolidated sediments. Additionally, long-term changes are conceptualised in sequences used to explain landform development, such as the development of stellate islands from volcanic cones.

3.3. Indicators of regional variation in island susceptibility

At the regional scale considered in this chapter, analyses of where landforms fit in an observed or conceptual sequence of change indicates whether an island, or a substantial part of an island, is likely to be susceptible or resistant to changes driven by climate and ocean processes compared with another island. In this context, the susceptibility of an island at a regional-scale is based on relative differences between the physical characteristics of whole islands for a range of variables including lithology, circularity, height and area (Table 3.1)**.** The conceptual models of islands describe change likely over interdecadal and longer periods. They indicate phases in the geomorphic development of an embayed coastline (stellate island) and submerged barrier reef; the morphology of island platforms; and stages in erosion of volcanic island coasts from a smooth to an irregular coastline (Menard, 1983; Nunn, 1994). Where available the conceptual models have been used to rank different levels of susceptibility in each variable. For example roundness, the measure of circularity, may indicate steps in the transition from a smooth to an irregular coastline or development of a stellate island associated with complex fringing and barrier reefs.

Table 3.1 Criteria for primary assessment of hierarchy

(1) Lithology		(2) Circularity		(3) Height		(4) Area	
Material	**Rank**	**Roundness**	**Rank**	**Maximum elevation (m)**	**Rank**	**Area (km2)**	**Rank**
Volcanic high or Volcanic low	1	Round 0.75-1.00	1	>100	1	>100	1
Composite high or composite low	2	Subrounded 0.5-0.749	2	30-99.99	2	10-99.99	2
Limestone high or limestone low	3	Subangular 0.25-0.499	3	10-29.99	3	1-9.99	3
Reef island	4	Angular 0-0.249	4	<10	4	<1	4

Each variable was ranked on a four-point scale and the criteria applied to all 1532 islands in the database. Rationale for the rankings of each variable is as follows:

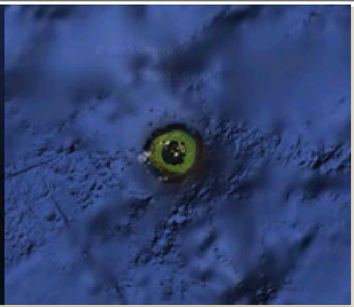
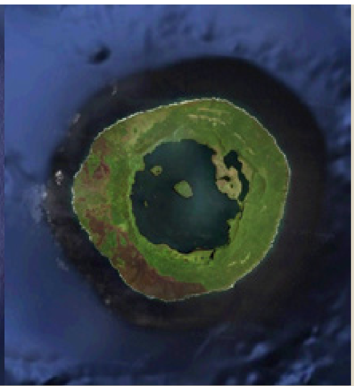
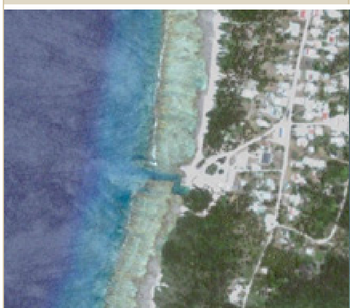
- **Lithology** refers to relative hardness and hence resistance to change by meteorological and oceanographic processes. Arguably, an island comprised of unconsolidated sediments is more likely to change its form over an extended period than a hard-rock volcanic island.
- **Circularity (Roundness)** is measured as roundness or conformity to a circle. A circular island is one with the smallest possible perimeter. In general, the susceptibility of an island's coast to change increases with reduced roundness. Yet an island landmass may have an overall round shape but its actual shoreline may nonetheless be quite complex with bays and inlets; Pohnpei in the Federated States of Micronesia is an example.
- **Height (maximum elevation)** provides a measure of the susceptibility of an island to marine inundation. It is important to stress this is a whole-of-island measure. Use of maximum elevation as an estimate is misleading because in many places, land subject to inundation is on narrow plains and terraces skirting higher land. This point is addressed at lower, more detailed levels in the hierarchy.
- **Area** is another variable related to whole-of-island geometry and also requires modification for finer-scale assessment. Arguably at a regional scale it has relevance only in combination with the other variables such that the larger an island the less susceptible the whole island may be to changing meteorologic and oceanographic conditions.

3.4. Regional scale estimation of the susceptibility of an island to physical change

In the analysis, all four criteria (lithology, circularity, elevation, area) had equal weightings, with no weighting of variables applied for each island type in the database. Subsequently, rankings were summed and a susceptibility rating determined. The rating is referred to as the *susceptibility* of each island because it provides an estimate of the long-term susceptibility of each island coast to possible physical change driven by key climate and ocean processes. The coarse nature of the susceptibility estimates is stressed. This is a relatively 'high-level' first-pass assessment that is intended to provide a basis for more detailed analyses.

In this primary analysis, no indication of key factors such as the influence of reefs on adjacent shores, effects arising from the proximity to adjacent islands, or any identification of vulnerable landforms is apparent or derivable from the analysis; this is illustrated by a composite low island (Mitiaro) and a volcanic high island (Niuafo'ou) in (Table 3.2). However, the results enable interpretation at a regional scale for strategic purposes, regional scale comparisons, and to provide a context for finer-scale analyses. Demonstration of how to drill down to finer scales is provided in Chapters 4 and 6.

Table 3.2. Steps in the landform hierarchy and the variables used to assess potential landform change

MITIARO, COOK ISLANDS A composite low island	NIUAFO'OU, NIUAS, TONGA A volcanic high island	SCALES USED TO DETERMINE THE LIKELIHOOD OF LANDFORM CHANGE
 Solitary island	 Solitary island	**TECHNIQUE DEVELOPMENT REGIONAL SCALE** Information: Whole island, including island lithology, geometry (eg, elevation, roundness, & area). Use: Identify different island ocean settings and determine the island lithology and geometry for regional strategic planning purposes.
 Sub-rounded shape	 Round shape	**PRIMARY: SCOPING SURVEY REGIONAL SCALE** Information: Whole island descriptors, including island lithology, geometry and offshore bathymetric setting (Number of neighbouring islands), bathymetric gradient and most common reef structure Use: Estimation of indicative susceptibility of land system to long-term change in coastal morphology for regional planning.
 WNW facing coast	 NW facing coast	**SECONDARY: CONTEXT SETTING LAND SYSTEM SCALE** Information: Land system descriptors identifying landform components of a discrete segment of the coast; including reef, lithology, geometry coastal landforms and nearshore bathymetric setting. Use: Estimation of indicative susceptibility land system response for landform planning and management purposes.
 Landing and infrastructure	 Landing and infrastructure	**TERTIARY: SITE SURVEY INDIVIDUAL LANDFORM SCALE** Information: Specific site descriptors, including reef, lithology, geometry coastal landforms and nearshore bathymetric setting affecting the site. Use: Implement recommendations arising from broader studies as well as those derived from detailed case studies.

Susceptibilities were calculated for all 1532 islands in the database. As an example, the values and ranking for each of the four criteria, together with the final susceptibility ranking, are shown in (Table 3.3) for 36 islands selected for finer scale assessment. The rationale behind each of the rankings is included for each of the four criteria in Table 3.1.

Table 3.3 Example of the calculation of susceptibility for 36 islands considered in the assessment

	Island	Island Type		Roundness (conformity to a circle)		Maximum Elevation (m)		Area (km2)		Susceptibility	
		Type	Rank	Value	Rank	Value	Rank	Value	Rank	Total	Rank
1	Aitutaki, Cook Islands	Composite high island	2	0.3	3	123	1	22	2	8	L
2	Aniwa, Vanuatu	Limestone high island	3	0.7	2	42	2	22	2	9	M
3	Aore, Vanuatu	Limestone high island	3	0.7	2	99	2	66	2	9	M
4	Atafu, Tokelau	Reef island	4	0.2	4	5	4	5	3	15	VH
5	Atiu, Cook Islands	Composite high island	2	0.9	1	71	2	33	2	7	L
6	Banaba (Ocean), Kiribati	Limestone high island	3	0.8	1	81	2	8	3	9	M
7	Bellona, Solomon Islands	Limestone high island	3	0.7	2	79	2	23	2	9	M
8	Eluvuka, Fiji	Reef island	4	1	1	3	4	0.2	4	13	H
9	Emananus, Papua N. Guinea	Composite high island	2	0.5	2	50	2	5	3	9	M
10	Kiritimati, Kiribati	Reef island	4	0.3	3	3	4	478	1	12	H
11	Lifuka, Tonga	Limestone low island	3	0.5	2	9	4	14	2	11	M
12	Loun, Solomon Islands	Volcanic high island	1	0.9	1	49	2	5	3	7	L
13	Mangaia, Cook Islands	Composite high island	2	0.9	1	169	1	60	2	6	VL
14	Manihiki, Cook Islands	Reef island	4	0.2	4	3	4	9	3	15	VH
15	Manono, Samoa	Volcanic high island	1	0.8	1	110	1	4	3	6	VL
16	Manuae, French Polynesia	Reef island	4	0.4	3	5	4	9	3	14	VH
17	Mauke, Cook Islands	Composite low island	2	0.9	1	30	3	23	2	8	L

	Island	Island Type		Roundness (conformity to a circle)		Maximum Elevation (m)		Area (km2)		Susceptibility	
		Type	Rank	Value	Rank	Value	Rank	Value	Rank	Total	Rank
18	Nauru	Limestone high island	3	0.9	1	71	2	23	2	8	L
19	Niuafo'ou, Tonga	Volcanic high island	1	0.9	1	260	1	57	2	5	VL
20	Niue	Limestone high island	3	0.8	1	60	2	298	1	7	L
21	Onotoa, Kiribati	Reef island	4	0.2	4	2	4	14	2	14	VH
22	Oreor (Koror), Palau	Composite high island	2	0.4	3	130	1	12	2	8	L
23	Ovalau, Fiji	Volcanic high island	1	0.7	2	120	1	626	1	5	VL
24	Penrhyn, Cook Islands	Reef island	4	0.1	4	4	4	15	2	14	VH
25	Pohnpei, FSM	Volcanic high island	1	0.4	3	791	1	356	1	6	VL
26	Pukapuka, Cook Islands	Reef island	4	0.6	2	4	4	2	3	13	H
27	Rakahanga, Cook Islands	Reef island	4	0.8	1	4	4	10	3	12	H
28	Rarotonga, Cook Isands	Composite high island	2	0.9	1	658	1	81	2	6	VL
29	Savai'i, Samoa	Volcanic high island	1	0.7	2	1858	1	1823	1	5	VL
30	Tarawa, Kiribati	Reef island	4	0.1	4	3	4	33	2	14	VH
31	Tongatapu, Tonga	Limestone high island	3	0.4	3	82	2	305	1	9	M
32	Tonowas, FSM	Volcanic high island	1	0.6	2	349	1	10	3	7	L
33	Upolu, Samoa	Volcanic high island	1	0.5	2	1100	1	1215	1	5	VL
34	Utupua, Solomon Islands	Volcanic high island	1	0.3	3	380	1	76	2	7	L
35	Vaitupu, Tuvalu	Reef island	4	0.6	2	5	4	8	3	13	H
36	Vogali, Papua New Guinea	Volcanic low island	1	0.6	2	30	3	1	4	10	M

The ten volcanic islands listed in Table 3.3 ranged from very low to moderate susceptibility whereas higher rankings are generally attributed to volcanic islands that have a smaller area and are less circular. The seven composite islands also ranged from very low to moderate susceptibility with higher rankings attributed to islands that had a smaller area, lower maximum elevation and were less circular. The eight limestone islands ranged from low to moderate susceptibility, with the two lower rankings attributed to islands that were more circular and had a larger area. The 11 reef islands ranged from high to very high, all eleven islands having a maximum elevation of less than 10 m. Variations in the rank of these 11 reef islands are attributed to circularity and island area.

3.5. Regional-scale susceptibility of islands

Susceptibility estimates are presented for the 1532 islands in the database per island type and per country for the 15 countries in the study area (Figure 3.1). There is a broad geographic trend with most of the islands having very high and high susceptibility occurring in the north, whereas most of the islands with very low and low susceptibility are in the south.

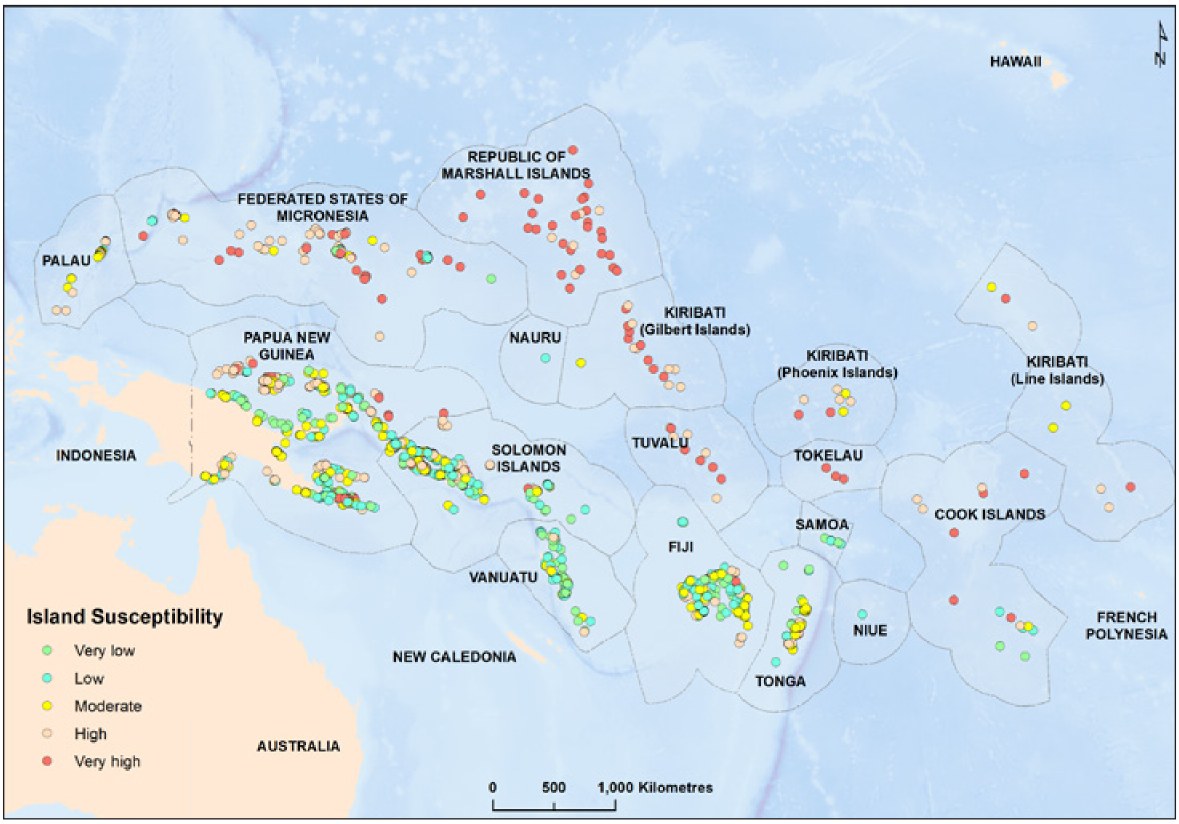


Figure 3.1 Susceptibility for the 1532 islands in the database.

The susceptibilities of whole islands to changes in climate and ocean processes are mainly low (23%), moderate (25%) or high (31%) with fewer falling into the extremes of very low (12%) and very high (9%) (Figure 3.2). These results and the geographic distribution of susceptibility values have meaning when they are related to similar maps showing the distribution of the climate and ocean processes that drive coastal change.

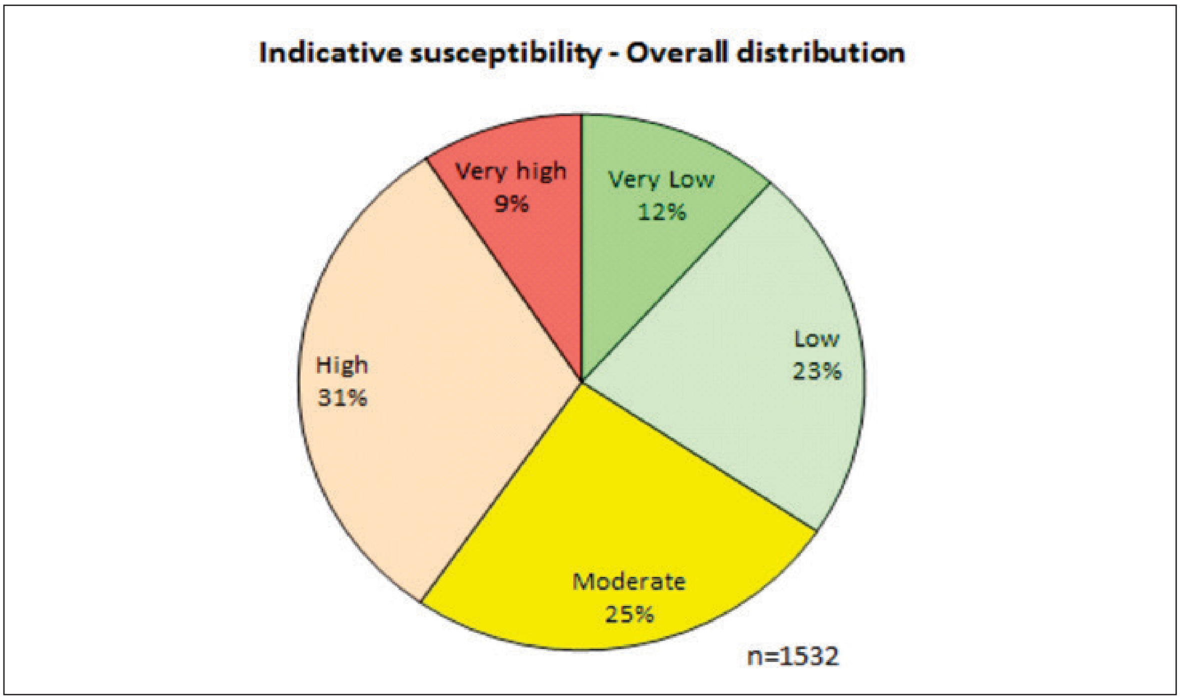


Figure 3.2 Indicative susceptibility as percentage of all islands.

Certain island types are inherently more susceptible than others (Figure 3.3 and Table 3.4). Higher-elevation islands (volcanic high, composite high and limestone high) tend to be least susceptible. The most susceptible islands are the limestone low islands and reef islands.

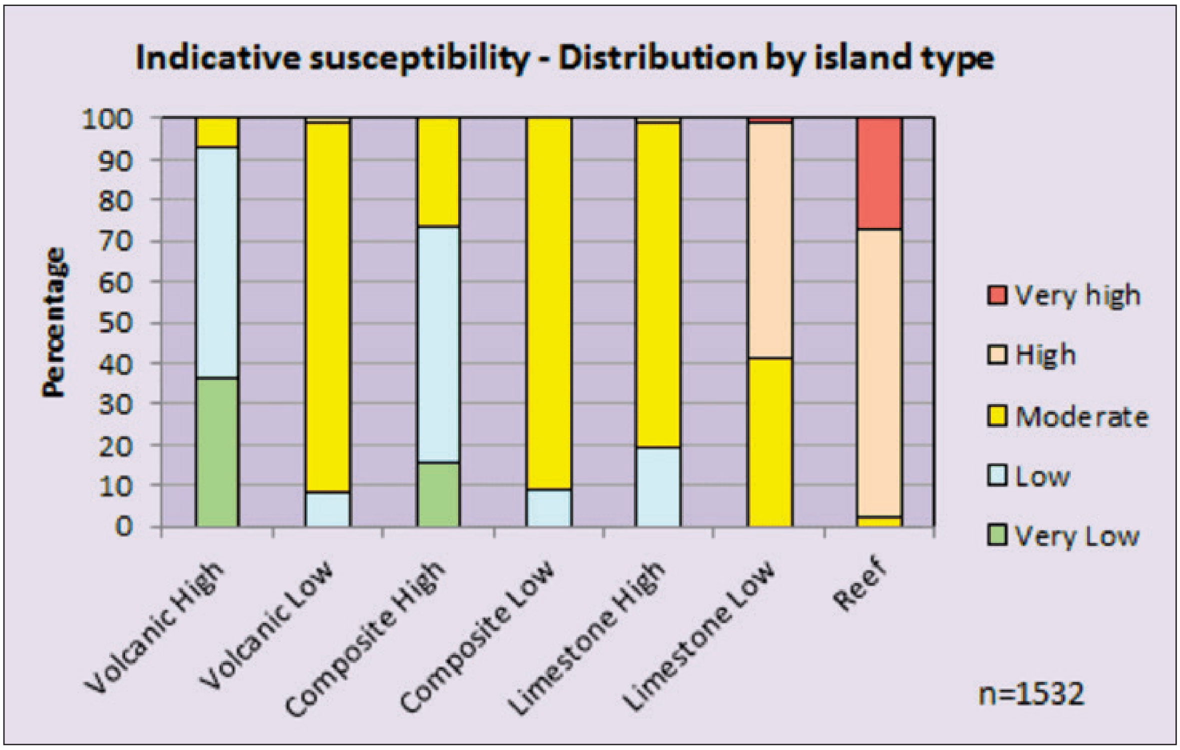


Figure 3.3 Range of susceptibility for each island type (see also Table 3.4).

The distribution of susceptibility for each island type is shown in Table 3.4; the modal susceptibility is shown in bold. If an island is a volcanic high island or composite high island, it is most likely to be in the low susceptibility category, ranging from very low to moderate. If an island is a volcanic low, composite low or limestone high island, it is most likely to be in the moderate susceptibility category, ranging from low to high. If an island is limestone low or a reef island, it is most likely to be in the high category, ranging from moderate to very high. At this scale of assessment, it is clear that the majority of islands with a very high susceptibility are reef islands.

Table 3.4 Distribution of susceptibility for each island type showing modal values in bold

	Susceptibility												
	Very Low		Low		Moderate		High		Very High		Total Island Type	
Island type	Count	% of island type	Count	% of island type	Count	% of island type	Count	% of island type	Count	% of island type	Count	%
Volcanic high	163	36%	**257**	**57%**	32	7%					452	25%
Volcanic low			12	8%	**133**	**91%**	1	1%			146	8%
Composite high	15	15%	**56**	**58%**	26	27%					97	5%
Composite low			2	9%	**20**	**91%**					22	1%
Limestone high			22	19%	**92**	**80%**	1	1%			115	6%
Limestone low					73	41%	**103**	**58%**	2	1%	178	10%
Reef island					11	2%	**371**	**71%**	140	27%	522	29%
Total per rank	**178 (12%)**		**349 (23%)**		**387 (25%)**		**476 (31%)**		**142 (9%)**		**1532**	

3.6. Diversity of estimated susceptibility for each country

Susceptibility estimates for the 15 Pacific Island countries considered in this project are portrayed in Figure 3.4. The geographic distribution of the values demonstrates significant variation in susceptibility between and within different countries.

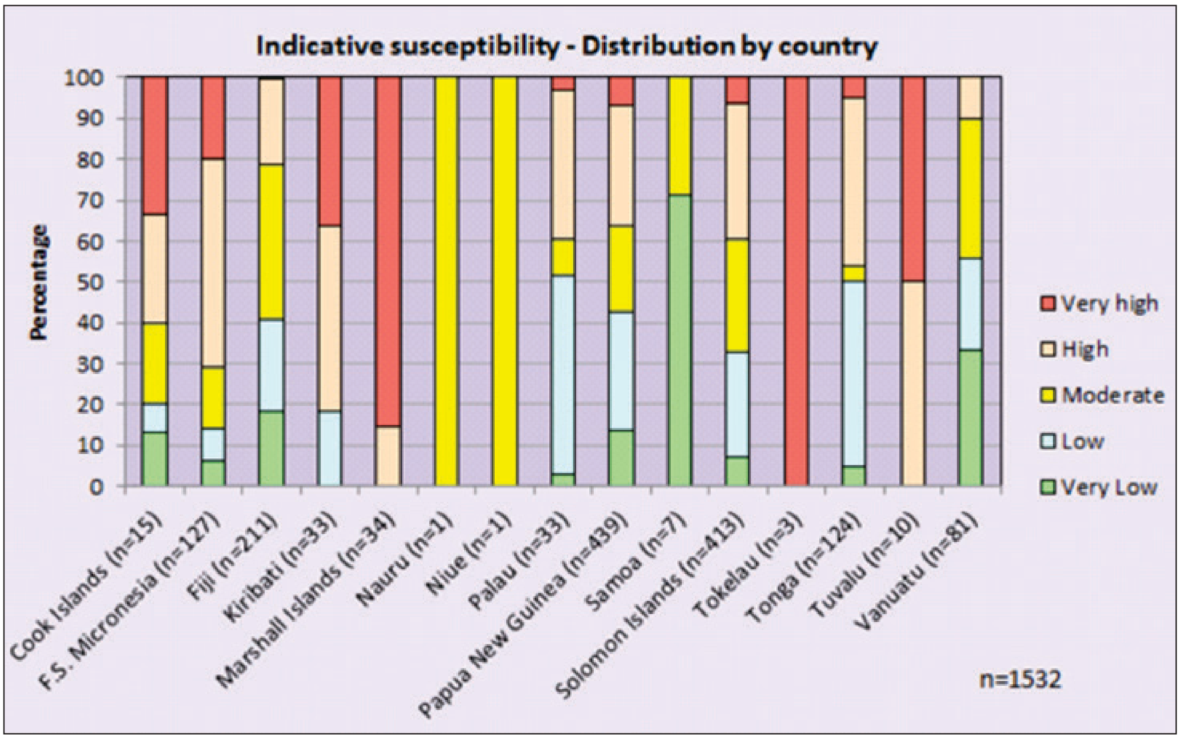


Figure 3.4 Range of susceptibility for each country (see also Table 3.5).

More detailed data are presented in Table 3.5 for each country. With the exception of Nauru and Niue, which are single-island countries, the ranges of susceptibility are listed. The most common *susceptibility rating* for each country is shown in bold in Table 3.5. Samoa has the lowest susceptibility rating (very low). Nauru and Niue are both ranked as having low susceptibility. Other countries with low susceptibility are Fiji and Vanuatu. Most islands in Palau and Tonga have moderate ratings, although there are islands in each country ranging from very low to very high.

The islands of Federated States of Micronesia, Kiribati, Papua New Guinea and Solomon Islands have generally high susceptibilities, with islands ranging from very low to very high except in Kiribati where 27 of the 33 islands have a high or very high susceptibility. The Cook Islands have a very high susceptibility, however there are islands ranging from very low to very high. The Marshall Islands and Tonga both have generally very high susceptibility with some islands in the high category. Tokelau is the only country with all (three) islands classified in the very high susceptibility category.

Table 3.5 Results of the analysis of susceptibility for each country by number and percent of number of islands in country

	Susceptibility											
	Very Low		Low		Moderate		High		Very High		Total	
Country	Count	% of Country	Count	% of Country	Count	% of Country	Count	% of Country	Count	% of Country	No. Islands	% of Islands
Cook Islands	2	13%	3	20%	1	7%	4	27%	**5**	**33%**	15	1%
F.S. Micronesia	8	6%	19	15%	10	8%	**65**	**51%**	25	20%	127	8%
Fiji	39	18%	**80**	**38%**	47	22%	44	21%	1	0.50%	211	14%
Kiribati	0	0%	0	0%	6	18%	**15**	**45%**	12	36%	33	2%
Marshall Islands	0	0%	0	0%	0	0%	5	15%	**29**	**85%**	34	2%
Nauru	0	0%	**1**	**100%**	0	0%	0	0%	0	0%	1	0%
Niue	0	0%	**1**	**100%**	0	0%	0	0%	0	0%	1	0%
Palau	1	3%	3	9%	**16**	**48%**	12	36%	1	3%	33	2%
Papua New Guinea	61	14%	93	21%	126	29%	**130**	**30%**	29	7%	439	29%
Samoa	**5**	**71%**	2	29%	0	0%	0	0%	0	0%	7	0%
Solomon Islands	29	7%	114	28%	107	26%	**137**	**33%**	26	6%	413	27%
Tokelau	0	0%	0	0%	0	0%	0	0%	**3**	**100%**	3	0%
Tonga	6	5%	5	4%	**56**	**45%**	51	41%	6	5%	124	8%
Tuvalu	0	0%	0	0%	0	0%	5	50%	**5**	**50%**	10	1%
Vanuatu	27	33%	**28**	**35%**	18	22%	8	10%	0	0%	81	5%
TOTAL	**178 (12%)**		**349 (23%)**		**387 (25%)**		**476 (31%)**		**142 (9%)**		**1532**	

3.7. Overview

Despite the coarse nature of this primary assessment of susceptibility, the results provide a unique, comparative perspective of 1532 Pacific islands on the basis of consistent information across the entire Pacific region. This is a major achievement and its utility is illustrated in the primary assessment and comparison of the susceptibility of islands by combining the four simple measures of lithology, area, elevation and circularity for each island. Whilst it has been possible to provide a comparative assessment of susceptibility, the broad scale character of this regional-scale first-pass assessment should provide a firm and consistent basis for more detailed, local-scale analyses.

The value of the first-pass primary assessment is that it establishes the considerable similarity of island types between different countries and for which common problems may later be defined and addressed. It also provides a basis for strategic planning by countries within the region and external donor organisations supporting mitigation of the impacts of climate and ocean processes driving coastal change.

This analysis has, for the first time, produced a regional-scale assessment and maps of the physical characteristics and susceptibility of a large number of Pacific islands. Several observations are noteworthy:

- Considerable geographical diversity is apparent regionally and within each country for the broad level at which comparative information is available for all islands.
- A significantly different range of susceptibility was identified for each of the seven island types examined, with low to moderate susceptibility ratings for volcanic islands contrasting with moderate to very high ratings for reef islands.
- Six of the 15 countries examined have islands in all five categories of susceptibility whereas three countries—including two single-island countries—fall within a single category.
- Countries with a high proportion of islands with very high susceptibility ratings are the Cook Islands, Marshall Islands, Tokelau and Tuvalu. The Federated States of Micronesia, Kiribati, Papua New Guinea and Solomon Islands have a high proportion of islands rated as having high susceptibility.

Some of the ratings are expected to change as more detailed information becomes available or as weightings are applied to criteria used in the primary assessment. If, as the framework structure indicates, a similar procedure is followed for finer scale analysis then each scale will incorporate different physical characteristics for comparison and be associated with additional driving processes.

Chapter 4.
Downscaling from primary susceptibility

Key points

- Measures of primary susceptibility (developed in Chapter 3) are downscaled to the level of island components, ranging from whole islands to particular landforms.
- Secondary assessment focused on whole islands (using additional diagnostic criteria—insularity, proximity, seabed (shoreface) gradient) and coastal fringes and permit measures of secondary susceptibility to be calculated. This process is illustrated with reference to 36 islands.
- Tertiary assessment used a sample of five islands to demonstrate a fine-scale assessment of the susceptibility of sectors of the coastal fringe, results from only two contrasting islands are presented here.

4.1. Context and aims

Regional-scale analysis of the physical character of 1532 islands outlined in Chapter 3 enabled an indicative assessment of island susceptibility based on their lithology and three other physical characteristics. The assessment is relevant to high-level strategic planning in that the measures of primary susceptibility provide insight of regional and country-wide evaluation; but it did not identify problems of direct relevance at a local level, either within a particular island subgroup or for the coastal fringe around an island. Yet such foci are necessary adjuncts to the regional approach because environmental problems most acutely occur on coastal landforms skirting the main structural body of an island. For example, retreat of the shoreline along a narrow, low-lying coastal plain adjoining a steeply-rising hinterland is likely to affect built infrastructure. It is therefore desirable to downscale from the high-level primary assessment to more detailed levels for country, district (sub-national) and local community planning and management purposes.

The principal aim of this chapter is to apply the framework, facilitating downscaling from the primary, regional-scale estimations of the *susceptibility* of whole islands to more detailed assessments of the *relative instability* of landforms. Here, the terms *susceptibility* and *instability* are used to draw a distinction between the broad-scale examination of the physical structure of whole islands and landforms or landform elements.

Some additional definitions are needed at this stage.

Coastal fringe is comprised of and submarine and subaerial (terrestrial) landforms adjoining the intertidal shore.

Coastal vulnerability is the term commonly applied to the results of hazard and risk assessments involving people and land use in coastal areas.

Long-term changes to coastal landforms and the processes driving them are those occurring interdecadally, extending over a planning horizon of at least 100 years and longer.

Mid-term changes are those occurring at an interannual to intra-decadal scales, including those in response to ENSO events.

Physical character describes the structural features of an island, its physical shape and the material of which it is mainly comprised. The description refers to each island as a single entity and not to the various landforms the structure supports.

Regional scale refers to interpretation of information at a very broad geographic level. It is commonly a scale used for strategic planning purposes at an international or national administrative level.

Short-term changes occur at seasonal and higher frequencies, such as changes in response to the passage of tropical cyclones.

Relative instability refers to the degree to which an island's coastal landforms, the marine and terrestrial landforms adjoining the shore, respond to change in climate-ocean conditions. A comparative qualitative scale of relative instability is used; for example, a low sandy beach is more sensitive to change from external processes than a high limestone cliff. The comparison is *indicative* rather than absolute or predictive.

In order to achieve its aims the chapter will:

- Extend the range of variables used to estimate the *susceptibility* of island structure to changing climate and ocean conditions (as in Chapter 3);
- Develop criteria to comparatively estimate the *relative instability* of coastal landforms;
- Establish a pathway for downscaling landform assessments at a conceptual level suited to the use of sparse or coarse information;
- Apply the analysis to a variety of island types sufficient to demonstrate utility of the framework at a whole-island scale and, separately, for sections of coast having a common landform assemblage;
- Compare the outcomes for different levels in the hierarchy;
- Comment on potential applications of the approach for planning and management at a country and island scale.

4.2. Approach

Four scales comprise the framework hierarchy, and at all scales a consistent procedure can be used to estimate the susceptibility of the most common geologic and morphologic features apparent at each scale: regional, whole-island, whole- island coast, and coastal segment scale (see Figure 1.1). The selection of these features is intended to provide consistency in methodology bridging the gap between regional-scale assessments of island susceptibility and fine-scale analyses applicable at a community level. At each scale lithologic and morphologic features are used as criteria to determine the susceptibility of an island or its coastal fringe. The criteria vary from scale to scale as the degree of detail required in estimates of susceptibility or instability increases with downscaling in the hierarchy.

Apart from the regional-scale determination of susceptibility in Chapter 3, two further steps in the framework are considered in this section of the report; namely the *secondary* and *tertiary* levels of analysis, as shown in Table 4.1. The fourth is considered to be the first phase of a full risk assessment and is not considered here. The *secondary* and *tertiary* assessments extend estimation of susceptibility to include terrestrial and marine landforms adjoining island shores. They are also intended to demonstrate separate comparative estimations of susceptibility at more detailed, whole-island (secondary) and specifically coastal fringe (tertiary) scale. Landform characteristics within the coastal zone, including terrestrial and marine landforms adjoining the shore, are assessed by using the same procedure as that employed for the regional-scale analysis. As in Chapter 3, the word *susceptibility* indicates the comparative resilience of an island.

Table 4.1 The susceptibility framework: a hierarchy of assessment and information requirements

Scale	Assessment	Index	Information
Broad Scale: Region, Country & Island Group	**Primary Analysis** Whole island lithology & form (structure)	**Susceptibility**	Based on readily available but not highly detailed information, primarily Google Earth imagery.
Broad Scale: Sub-region, Country & Island Group	**Secondary Analysis** Whole island structure and coastal fringe	**Susceptibility**	Criteria describing the most common landforms interpreted from remotely sensed imagery
Fine Scale: Island Group & Local Area	**Tertiary Analysis** Coastal fringe structure and landforms	**Susceptibility**	Criteria describes the most common landforms adjoining the shore; Interpreted from remotely sensed imagery
Fine Scale: Local Area	**Fourth Order Analysis** Full risk analysis; coastal fringe, processes, people and land use	**Vulnerability**	Based on localised and detailed information, including numerical modelling of landform-process interactions.

Primary analysis in Chapter 3

Secondary and Tertiary analyses in Chapter 4

Fourth Order analysis: Full hazard and risk assessment not in Report

The fourth level of assessment is used to provide a detailed understanding of *coastal vulnerability*, as the term is commonly applied to hazard and risk assessments involving people and land use in coastal areas. Methods for such fine-scale coastal vulnerability assessments are not reviewed here but have been elsewhere (Hay and Mimura, 2013). They are based on regionally sparse albeit locally detailed information, including field surveys, interpretation of imagery and numerical modelling of landform—process interaction. Owing to the scarcity of such information at regional and country scales, and the time required to capture it on an island-by-island basis, there is limited capacity for upscaling to broader scales.

More detailed descriptions of coastal landforms for individual islands are required for the increasingly finer steps in the framework, including the secondary and tertiary analyses. Acquisition of suitable information is at best time-consuming, at worst not feasible because requisite information is not always available. Here the selection of parameters from which criteria could be developed for susceptibility and instability was determined by the availability of data suitable for comparison between islands, countries and landforms. In many instances, the only data readily available without a time-consuming search of archival material was to use Google Earth imagery.

This meant many of the criteria, particularly the images informing rankings on the five-point scale used for each criterion, had to be discernible from aerial photography. Although this carries potential problems of misinterpretation, it also offers an opportunity for tighter definition of the criteria at a country or island scale where authorities can verify their interpretations through direct field observation. Once criteria are determined and the ranking scale for each criterion determined and illustrated, it should be possible for people with GIS skills to identify the vulnerability of landforms comprising an island's coast.

4.3. Secondary assessment of island susceptibility

At the secondary level of assessment, information for comparatively identifying the *instability* of landforms comprising the coastal fringe is added to measures of susceptibility. For each island, susceptibility and instability are then combined to estimate the *overall susceptibility* to changing climate and ocean processes. Here the term *overall susceptibility* refers specifically to a combination of the resilience of island structure (lithology and geometry) with the instability of landforms or components of landforms to changes of climate-ocean conditions. Full definitions are given above.

Further detail on the geometric characteristics and landform features of whole islands was derived from Google Earth imagery and incorporated into the secondary assessment of the 36 islands listed in Table 3.3. The islands were selected for examination from all island types described in Chapter 2 except continental islands and included those separately examined in a study of island groundwater. Parameters describing each island were collated in two separate groups and combined in a matrix. First, lithologic and morphologic characteristics were used to determine an island *susceptibility* ranking, as was done in the primary analysis (Chapter 3). Second, a separate ranking of *susceptibility*, also at a whole island scale, was made from comparison of the most common (modal) landforms of the coastal fringe. In the analysis, the separate rankings respectively relate to potential long- and short-term changes to the island coasts. For each island the two ranking values then aggregated in a matrix to provide an estimate of the *overall susceptibility*. The number of islands examined for each island type was intended to provide a sufficiently large sample of coastal features for comparative determination of susceptibility using both sets of criteria.

4.3.1. Susceptibility indicated by additional characteristics

Potential changes at a whole-island scale are based on the relative differences between the physical structure and location of islands for a range of variables. In addition to lithology, circularity (roundness) and elevation (maximum), which was used in the primary assessment, other physical parameters for each island included an estimate of insularity, proximity to other islands, and the seabed gradient from shore to deep water.

These three new parameters were determined as follows:

- **Insularity** is the ratio of the island perimeter to the square root of its area. This combines a measure of shoreline length, including its irregularity, with the area of the island. Both variables were measured from the database for all 1532 islands in the database and are determined for the 36 case studies (section 4.3.4 below). If insularity is small, the island is considered to be less susceptible to change as it is likely to have a smaller loss of relative area.
- **Proximity** was determined by simple nearest neighbour check. This had two stages: first a count of the number of neighbours within a 20-km buffer around the island was completed; second, the island setting in relation to its neighbours was established from Google Earth imagery. The two variables affect sheltering of an island from meteorological and oceanographic processes. It is noted that this parameter could be strengthened

by a more robust nearest-neighbour analysis and determination of the degree of shelter provided by the neighbouring islands.

- **Seabed gradient** refers to the slope from the island's shore to the edge of any undersea platform or shelf; it is also described as shoreface gradient. It was described centrally on the ocean side of an island within an archipelago surrounded by barrier reef or for the apparently steepest shore of an isolated island. Wave height and surge height are both affected by seabed gradient. The descriptions applied here are an oversimplification derived from interpretation of imagery. The oversimplification may be rectified by direct measurement from bathymetry, when available, and consideration of reef characteristics.

The criteria describing each variable are ranked on a five-point scale (Table 4.2). The final ranking for susceptibility is a ranking of 1-3 (Low Susceptibility, Moderate Susceptibility, and High Susceptibility). Criteria selection was constrained by dataset availability for the Pacific region. Weightings were also considered for specific variables; as a generic weighting and as variable weights based on lithology. The weighting of variables is inevitably subjective but it may be used as an exploratory tool to establish the relative importance of the variables being used.

Table 4.2 Criteria for susceptibility for the secondary assessment

1. LITHOLOGY		2. CIRCULARITY		3. HEIGHT	
Material	**Rank**	**Roundness index**	**Rank**	**Maximum elevation (m)**	**Rank**
Continental	1	Round 0.8 to 1.00	1	>100.00	1
Volcanic	2	Sub-rounded 0.6 to 0.799	2	30 to 100	2
Composite	3	Sub-angular 0.4 to 0.599	3	10 to 29.99	3
Limestone	4	Angular 0.2 to 0.399	4	5 to 9.99	4
Unconsolidated sediment (Reef Island/Sand)	5	Irregular 0 to 0.199	5	<5.00	5

4. INSULARITY			5. PROXIMITY		6. GRADIENT TO DEEP OCEAN SEABED	
Ratio of Perimeter/ Sqrt Area	**Value**	**Rank**	**Number of neighbours within 20km. First check number of islands, followed by check of relationship**	**Rank**	**Descriptor**	**Rank**
Large area / small perimeter	< 4	1	Inner 50% of archipelago; OR >11 islands within 20km coast	1	Extensive submarine platform or ridge 4 to 5 times the width of the island, or wider	1
Moderate area / small perimeter	4-5.99	2	Outer 50% of archipelago; OR 7 to 11 islands within 20km coast	2	Broad submarine platform or ridge >2 and <4 times the width of the island	2
Moderate area and perimeter	6-8.99	3	In central 30% of island chain; OR 4 to 6 islands within 20km coast	3	Moderate width submarine platform >50% and up to twice the island width	3
Small area / moderate. perimeter	9-11.99	4	In chain of dispersed islands; OR 2 or 3 islands within 20km coast	4	Narrow submarine platform or ridge which is <50% of the island width and abuts deep water	4
Small area / large perimeter	>12	5	Solitary oceanic feature; OR One island >20km away	5	Steep drop from shore to deep water	5

4.3.2. Susceptibility of the coastal fringe

Parameters used to estimate Instability describe landform characteristics of the backshore, intertidal zone, inshore and reef. These characteristics are based on conceptual models of landform change over interdecadal periods, observed at more frequent intervals or clearly associated with a coastal process. The parameters include:

- An estimate of modal elevation of the backshore within 25 m of the shoreline;
- Description of the apparent/likely type of sediment on the backshore within 25 m of the shoreline;
- Identification of the modal (most common) landform comprising more than 50% of the land within 25 m of the shoreline;
- Description of the apparent/likely type of sediment on more than 50% of the intertidal shore;
- Determination of subtidal landforms present on more than 50% of the inshore seabed more than 25 m off the shoreline;
- Identification of reef type most commonly sheltering the shore; where two or more reef types are present in the offshore, the most seaward reef type was used;
- Estimation of the proportion of island shore sheltered by reef.

The criteria describing each variable were ranked on a five-point scale (Table 4.3). The final ranking for landform susceptibility is a ranking of 1-3 (Low, Moderate and High). Weightings were also considered for specific variables as a generic weighting as well as variable weights based on lithology.

Table 4.3 Criteria for the secondary assessment of instability

1. BACKSHORE					
1A) Backshore elevation within 25m of HWL	**Rank**	**1B) Backshore Sediment**	**Rank**	**1C) Backshore landform component on >50% of coast**	**Rank**
Elevation >20m	1	Soil over rock or stepped platforms and terraces	1	High (>10m elevation) coastal plain or terrace with a steep gradient to landward	1
Elevation 15-20m	2	Soil over coastal plains or partly infilled embayments, including alluvial fans and deltas	2	Coastal platform or rocky terrace (<10m elevation)	2
Elevation 10-14.9m	3	Soil on an atoll island (core is unknown)	3	Coastal plains (including beach ridge plains, outwash plains, deltas and alluvial fans)	3
Elevation 5-9.9m	4	Washover features on >25% coast or mangrove forests	4	Coastal flats (including partly infilled embayments and mangrove forests) or cuspate forelands or spits	4
Elevation <5m	5	Unconsolidated sediment	5	Tectonically unstable island with active volcanoes	5

2. INTERTIDAL

2A) Intertidal sediment type on >50% of coast	Rank	2B) Intertidal landforms on >50% of coast	Rank
High cliffs or steep rock ramps	1	Cliffs or bluffs, possibly adjoining rock platforms or ramps.	1
Coral rubble (gravel and cobble) beach	2	Rocky headlands and small bay beaches.	2
Mixed sand and cobble beaches	3	Mainly rocky shores, including beachrock ramps and rock platforms.	3
Sandy beaches	4	Island or islet with sandy beaches and overwash features on an atoll coast; OR Long sandy beaches separated by rocky topography such as headlands, cliffs and bluffs on a non-atoll coast	4
Mudflats (mangrove forests)	5	Bare reef platform with passages and washover features (eg. depositional fan) on an atoll coast; OR Irregular shoreline with mangroves, tidal creeks and partly infilled inlets; or long sandy beaches abutting coastal flats, coastal plains or cuspate forelands on non-atoll coast	5

3. INSHORE ZONE

3A) Inshore morphology for >50% of coast	Rank
Stepped subtidal sand terrace grading to beach.	1
Inshore lagoon with patch reef and sand sheets.	2
Inshore lagoon with reef pavement and bare sand sheets.	3
Discontinuous subtidal platform and reef pavement.	4
Continuous subtidal platform and boulder ramp.	5

4. REEF

4A) Seaward reef type	Rank	4B) Seaward reef width	Rank	4C) Reef coverage (reef width >50m)	Rank
Plunging cliffs or boulder ramps	1	Width >200m	1	Continuous reef with >90% sheltering of shore	1
Fringing reef attached to a rocky island	2	Width 150-200m	2	Nearly continuous reef with 70-90% sheltering of shore	2
Barrier reef or attached reef	3	Width 100-149.9m	3	Discontinuous reef with 30-69.9% of sheltering of shore	3
Mixed fringing and barrier reef	4	Width 50-99.9m	4	Discontinuous reef with 10-29.9% sheltering of shore	4
Fringing reef attached to an atoll or reef island	5	No reef or width <50m	5	No reef, <10% sheltering the shore by reef or boulder ramp	5

4.3.3. Overall island susceptibility

Criterion rankings of Low, Moderate and High for the island and coastal fringe susceptibility rankings (Table 4.4) were combined in a matrix to estimate the *overall susceptibility* at an island scale. The outcomes are conservative but illustrate indicative overall susceptibility in a range of values grouped as very low, low, moderate, high and very high (Table 4.5).

Table 4.4 Classification of susceptibility and instability into categories and implications for management

Susceptibility Scores (6-30)	Indicative Susceptibility	Implications for Management
6 to 14.9	Low	A mainly structurally sound geologic or geomorphic feature likely to require limited investigation of minor sites.
15 to 22.9	Moderate	Some natural structural features are unsound. Detailed assessment of coastal hazards and risks is advised.
23 to 30	High	Natural structural features are extensively unsound. Major engineering works are likely to be required

Instability Scores (9-45)	Indicative Instability	Implications for Management
9 to 20.9	Low	Resilient natural system occasionally requiring minimal maintenance
21 to 32.9	Moderate	Management responses to metocean events are currently required and may involve stabilisation work in future.
33 to 45	High	Management responses require repeated installation or repair of major, established stabilisation works

Table 4.5 Combining susceptibility and instability into a measure for secondary assessment

		INSTABILITY		
		Low (Score: 9–20.9)	**Moderate (Score: 21-32.9)**	**High (Score: 33 to 45)**
SUSCEPTIBILITY	**Low** (Score: 6–14.9)	Very Low	Low	Moderate
	Moderate (Score: 15–22.9)	Low	Moderate	High
	High (Score: 23–30)	Moderate	High	Very High

Weightings for island and coastal fringe susceptibility were applied after assignment of the rankings for each criteria and prior to compilation of the matrices (Table 4.6). This was done because not every variable is equally important in defining the three rankings. It is recognised that different weightings might be applied to different island lithologies although this is not done in the present analysis. However, it is a point that warrants further investigation when more robust information becomes available for the classifications. Results are presented as weighted and non-weighted in Appendix 1.

Table 4.6 Weightings for secondary assessment criteria

Susceptibility Criteria	Weighting
Geology	35%
Roundness	15%
Perimeter to √(Area)	25%
Maximum Elevation	5%
Proximity	15%
Gradient to deep ocean seabed	5%
Total	**100%**

Instability Criteria	Weighting
Backshore—slope	20%
Backshore—sediment	5%
Backshore—landform component	15%
Intertidal—sediment type	15%
Intertidal—landforms	15%
Inshore—morphology	15%
Reef—Type	5%
Reef—Width	5%
Reef—Coverage	5%
Total	**100%**

Following the rankings for susceptibility and instability, rankings for overall susceptibility of the 36 islands is shown in Table 4.7. The rationale for how susceptibility and instability results in Appendix 1 were combined was shown in Table 4.5 earlier. Additionally in Table 4.7, the primary assessment ranking for susceptibility is included for comparison.

Table 4.7 Final secondary assessment of overall susceptibility

	Island	Non-weighted			Weighted (Table 15)			Primary Assessment
		Susceptibility	Instability	Overall Susceptibility	Susceptibility	Instability	Overall Susceptibility	
1	Aitutaki Island, Cook Islands	Moderate Susceptibility	Moderate Instability	Moderate	Moderate Susceptibility	Moderate Instability	Moderate	Low
2	Aniwa Island, Vanuatu	Moderate Susceptibility	Moderate Instability	Moderate	High Susceptibility	Moderate Instability	High	Moderate
3	Aore Island, Vanuatu	Moderate Susceptibility	Moderate Instability	Moderate	Moderate Susceptibility	Moderate Instability	Moderate	Moderate
4	Atafu Island, Tokelau	High Susceptibility	Moderate Instability	High	High Susceptibility	Moderate Instability	High	Very High
5	Atiu, Cook Islands	Moderate Susceptibility	Moderate Instability	Moderate	High Susceptibility	Moderate Instability	High	Low
6	Banaba (Ocean), Kiribati	Moderate Susceptibility	Low Instability	Low	High Susceptibility	Low Instability	Moderate	Moderate
7	Bellona Island, Solomon Islands	Moderate Susceptibility	Low Instability	Low	High Susceptibility	Low Instability	Moderate	Moderate
8	Eluvuka, Fiji	Moderate Susceptibility	Moderate Instability	Moderate	High Susceptibility	High Instability	Very High	High
9	Emananus I., Papua New Guinea	Moderate Susceptibility	Moderate Instability	Moderate	Moderate Susceptibility	Moderate Instability	Moderate	Moderate
10	Kiritimati, Kiribati	High Susceptibility	High Instability	Very High	Moderate Susceptibility	High Instability	High	High
11	Lifuka Island, Tonga	Moderate Susceptibility	Moderate Instability	Moderate	Moderate Susceptibility	Moderate Instability	Moderate	Moderate
12	Loun Island, Solomon Islands	Moderate Susceptibility	Moderate Instability	Moderate	Moderate Susceptibility	Moderate Instability	Moderate	Low
13	Mangaia, Cook Islands	Moderate Susceptibility	Low Instability	Low	Moderate Susceptibility	Low Instability	Low	Very Low
14	Manihiki, Cook Islands	High Susceptibility	Moderate Instability	High	High Susceptibility	High Instability	Very High	Very High
15	Manono Island, Samoa	Low Susceptibility	Low Instability	Very Low	Moderate Susceptibility	Moderate Instability	Moderate	Very Low
16	Manuae Island, French Polynesia	High Susceptibility	High Instability	Very High	High Susceptibility	High Instability	Very High	Very High
17	Mauke, Cook Islands	Moderate Susceptibility	Low Instability	Low	Moderate Susceptibility	Low Instability	Low	Low
18	Nauru	Moderate Susceptibility	Low Instability	Low	High Susceptibility	Moderate Instability	High	Low

	Island	Non-weighted			Weighted (Table 15)			Primary Assessment
		Susceptibility	Instability	Overall Susceptibility	Susceptibility	Instability	Overall Susceptibility	
19	Niuafo'ou Island, Tonga	Moderate Susceptibility	Low Instability	Low	Moderate Susceptibility	Low Instability	Low	Very Low
20	Niue	Moderate Susceptibility	Low Instability	Low	High Susceptibility	Low Instability	Moderate	Low
21	Onotoa Island, Kiribati	Moderate Susceptibility	Moderate Instability	Moderate	Moderate Susceptibility	Moderate Instability	Moderate	Very High
22	Oreor (Koror), Palau	Low Susceptibility	Low Instability	Very Low	Low Susceptibility	Moderate Instability	Low	Low
23	Ovalau, Fiji	Low Susceptibility	Moderate Instability	Low	Moderate Susceptibility	High Instability	High	Very Low
24	Penrhyn, Cook Islands	High Susceptibility	Moderate Instability	High	High Susceptibility	High Instability	Very High	Very High
25	Pohnpei, FSM	Moderate Susceptibility	Moderate Instability	Moderate	Moderate Susceptibility	High Instability	High	Very Low
26	Pukapuka, Cook Islands	High Susceptibility	Moderate Instability	High	High Susceptibility	High Instability	Very High	High
27	Rakahanga, Cook Islands	High Susceptibility	Moderate Instability	High	High Susceptibility	High Instability	Very High	High
28	Rarotonga, Cook Isands	Moderate Susceptibility	Moderate Instability	Moderate	Moderate Susceptibility	Moderate Instability	Moderate	Very Low
29	Savai'i, Samoa	Moderate Susceptibility	Low Instability	Low	Moderate Susceptibility	Low Instability	Low	Very Low
30	Tarawa, Kiribati	High Susceptibility	Moderate Instability	High	Moderate Susceptibility	High Instability	High	Very High
31	Tongatapu, Tonga	Moderate Susceptibility	Low Instability	Low	Moderate Susceptibility	Moderate Instability	Moderate	Moderate
32	Tonowas I, Fed. St. of Micronesia	Low Susceptibility	Moderate Instability	Low	Low Susceptibility	Moderate Instability	Low	Low
33	Upolu, Samoa	Moderate Susceptibility	Low Instability	Low	Moderate Susceptibility	Moderate Instability	Moderate	Very Low
34	Utupua I., Solomon Islands	Moderate Susceptibility	Moderate Instability	Moderate	Moderate Susceptibility	Moderate Instability	Moderate	Low
35	Vaitupu Island, Tuvalu	Moderate Susceptibility	Moderate Instability	Moderate	High Susceptibility	High Instability	Very High	High
36	Vogali I., Papua New Guinea	Low Susceptibility	Moderate Instability	Low	Low Susceptibility	High Instability	Moderate	Moderate

The results warrant comparison with those from the primary assessment. This is done in the last two columns of Table 4.7. Differences indicate inclusion of more criteria may result in a higher incidence of moderate values. Hence weightings were used to test the outcome. For the thirty six islands considered in the secondary assessment, the number of islands with very low (2), low (13), moderate (13), high (6) and very high (2) rankings were different to those in the primary assessment (8, 9, 8, 5, 6 respectively) for the same islands. This may be due to the increased number of criteria.

Weightings (as in Table 4.6) were applied to ensure that the most important criteria have greater importance. The weighted results are also included in Table 4.7 with counts of the very low (0), low (6), moderate (15), high (8) and very high (7) categories demonstrating a skewness to higher rankings compared to the non-weighted criteria for the 36 islands selected.

4.4. Tertiary assessment of coastal sectors

Consideration of coastal landform susceptibility at a whole-island scale will inevitably miss small but significant areas subject to hazard and risk, particularly since all islands have distinct assemblages of landforms, geological contexts, reef structures, and connectivity with surrounding/nearby islands. Hence five islands were selected to demonstrate how a vulnerability assessment could be undertaken at a fine resolution focusing on coastal sectors. The islands selected span a range of lithologies with two volcanic (Loun and Pohnpei), one composite (Aitutaki), one limestone (Lifuka) and one reef island (Tarawa) selected. Each island was divided into sectors with common physical attributes; geological features, landform type and aspect. Ten criteria were used in this fine-scale assessment:

- Coastal lithology (e.g. volcanic, limestone)
- Coastal landform (e.g. coastal plain, cliff)
- Maximum width of landform (m)
- Length of landform along shore (km)
- Mid-landform elevation (m)
- Planform of coastal sector (e.g. straight, embayed)
- Inshore morphology (e.g. lagoon, rock platform)
- Reef type (e.g. fringing, barrier)
- Reef distance offshore (m)

* Width of reef (m)

Full details of the criteria with examples are in Appendix 2.

Each of these criteria are ranked on a five-point scale, the final ranking for sector susceptibility is from 1–3 (Low, Medium, High susceptibility). The criteria and weighting are included in Appendix 2.

4.4.1 Examples of sector assessment

Two contrasting examples of volcanic islands are illustrated here. Luon in the Solomon Islands and Aitutaki in the Cook Islands.

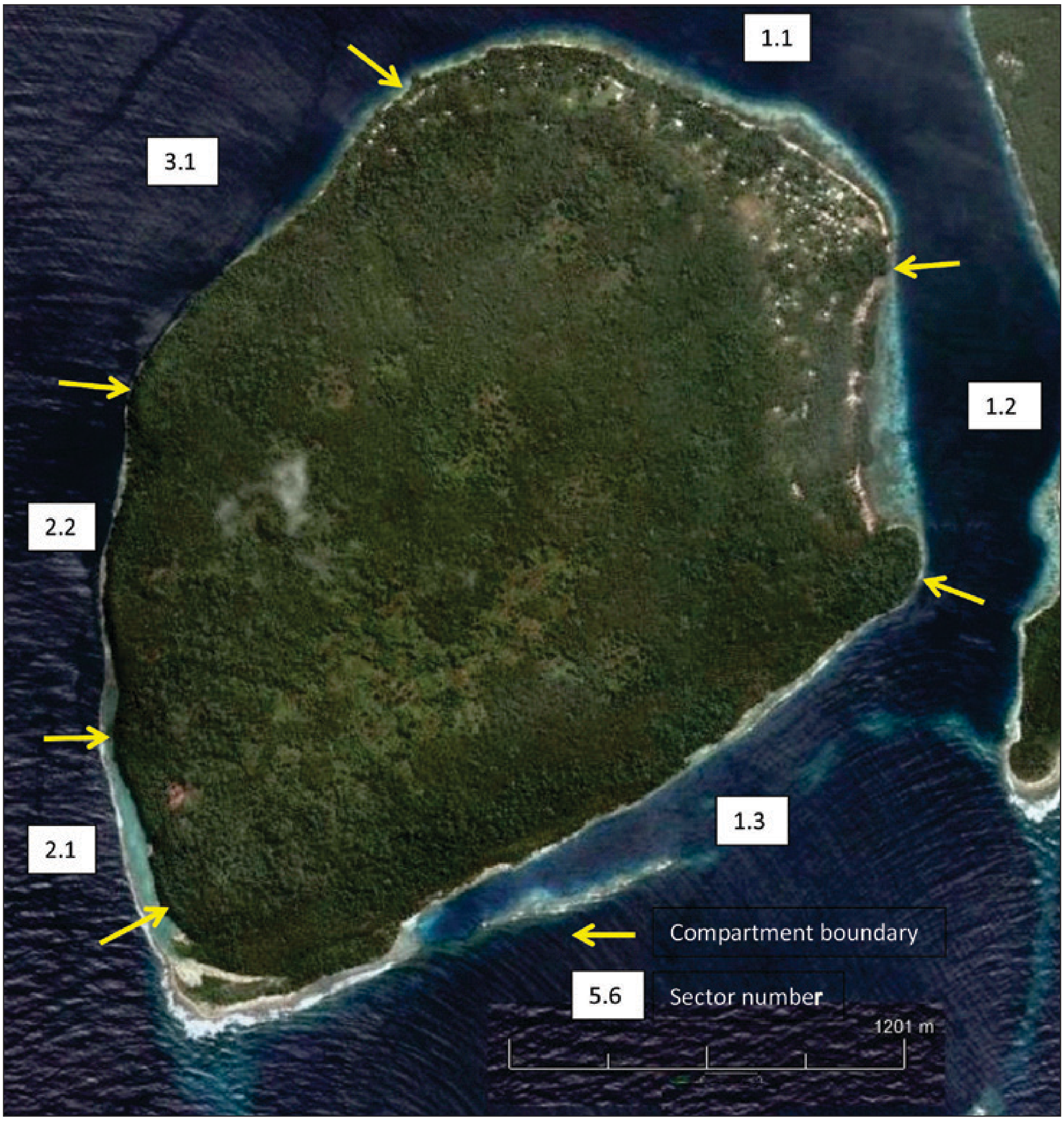


Figure 4.1 Example of coastal sectors recognised around a volcanic island: Loun, Solomon Islands.

Loun Island (Figure 4.1) is surrounded by fringing reefs with some barrier reef present off the south coast. Parts of the shore are rocky with bluffs and rock platforms, particularly along the west coast and around a rocky headland on the central east coast. Beaches are perched on rock platforms seaward of coastal terraces in the northeast and southwest. There is extensive coastal lowland forming a cuspate foreland in the northeast and a spit in the southwest. Mangrove stands are apparent in the northeast (Sector 1.2) and on the spit in the west of Sector 1.3. Luon Island is sheltered by nearby islands to the north and east. The island is divided into 6 sectors. Application of the detailed susceptibility criteria indicate all sectors on Luon Island are of 'moderate susceptibility' (see Table 4.8).

Table 4.8 Results for susceptibility at a tertiary assessment scale for Loun Island, Solomon Islands.

Coast sector	Major sector	Landform	Comments	Seaward aspect
1.1	1	Coastal plain	A coastal plain with a cuspate foreland in the NE extends around the northern and the eastern flanks of the island. Approximately 1km of coast is straight.	NE
1.2	1	Coastal plain	This sector of the coast includes approximately 1km of the coastal plain from the apex of the cuspate foreland in the NE to a rounded, rocky salient in the south.	E
1.3	1	Coastal plain	Coastal plain skirts the volcanic core of the island for approximately 2.5km from the rocky salient in the NE to a spit in the SW. The shore along the coast is mainly straight although with some shallow embayments between rocky salients.	SE
2.1	2	Rocky coast	A rocky coast facing WSW extends approximately 600m from the spit at the southernmost point of the island. The shore along the coast is mainly straight although with some shallow embayments that may support narrow beaches seaward of cliffs or bluffs. A lagoon approximately 70m wide extends along the coast.	WSW
2.2	2	Rocky coast	Approximately 1km of rocky coast faces WNW. It extends NNE from a broad salient at the N of Sector 2.1 to another broad salient. There are two partially infilled embayments in this sector. The fringing reef closes with the coast, varying in width from approximately 50 to 15m with distance N and the lagoon gives way to reef pavement.	WNW
3.1	3	Composite	The sector includes a 1.2km long, NW facing coast comprising two broad salients and an embayment on a nearly straight coast. The coastal lithology changes from volcanic rock to unconsolidated sediments with distance NE and the major landforms from terrace to coastal plain.	NW

	Rank												
Coast sector	Lithology	Landform Element	Max Width of Landform	Length of shore	Mid-feature elevation	Shoreline Shape	Inshore Morphology	Reef Type	Distance to inner reef flat	Mid-reef width	Susceptibility Score	Susceptibility	Weighted Susceptibility (see Table 6.13 for weightings)
1.1	5	3	3	4	3	1	4	2	5	3	33	Moderate Susceptibility	Moderate Susceptibility
1.2	5	3	3	4	3	2	1	2	5	3	31	Moderate Susceptibility	Moderate Susceptibility
1.3	5	2	3	4	3	1	4	2	4	3	31	Moderate Susceptibility	Moderate Susceptibility
2.1	2	2	3	5	1	1	3	3	4	5	29	Moderate Susceptibility	Moderate Susceptibility
2.2	2	2	3	4	1	1	4	2	5	5	29	Moderate Susceptibility	Moderate Susceptibility
3.1	3	2	3	4	1	1	4	2	5	5	30	Moderate Susceptibility	Moderate Susceptibility

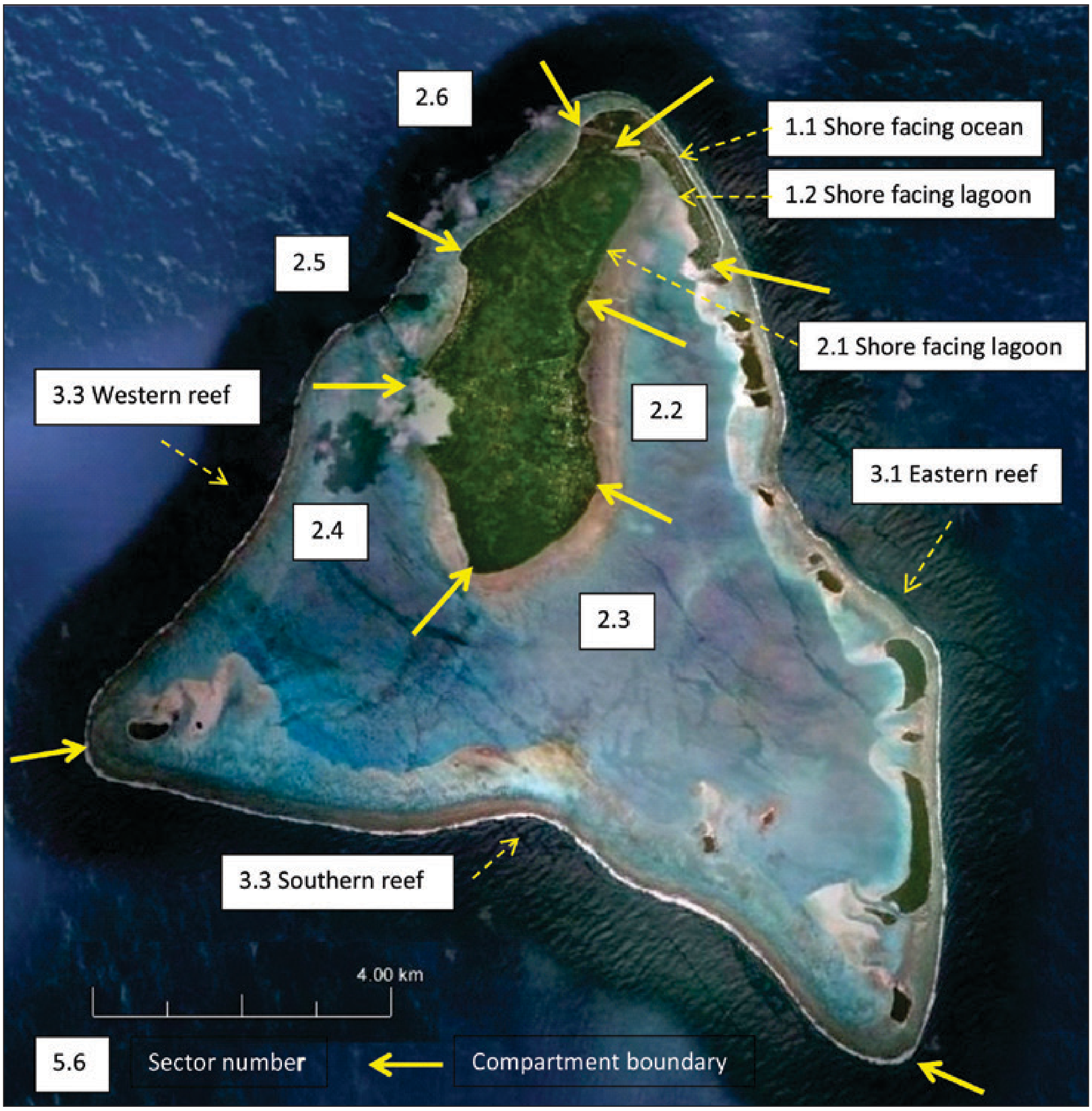


Figure 4.2 Example of coastal sectors around a composite island: Aitutaki, Cook Islands.

Aitutaki (Figure 4.2) is a volcanic island set in a triangular shaped reef system on the Pacific Plate. It is an isolated remnant volcanic cone surrounded by fringing and barrier reefs and cays around a shallow lagoon. Its longest axis measures 8 km including forelands at its northern and southern extremes. Width across the island ranges from 1 to 2 km. During the Pleistocene, the island was volcanically active and is now an 'almost atoll' and is in a stage of transitional development. The island has a narrow coastal terrace with some sandy beaches, perched beaches on a reef platform flanking the coastal terrace, and mangrove forests. A 2-km long, 300-m wide spit with sand and rubble beaches extends from the northern tip of the island south-southeast along the barrier reef. Aitutaki can be divided into 11 coastal sectors with three main coastal types. Application of the susceptibility criteria indicate High for Sector 1.1, Moderate for Sector 1.2 and 3 and Low for Sector 2 (see Table 4.9).

Table 4.9 Results for Susceptibility at Tertiary Assessment Scale for Aitutaki Island, Cook Islands

Coast sector	Major sector	Landform	Comments	Seaward aspect
1.1	1	Cuspate foreland & spit	An extensive spit extends approximately 2.2km ESE off the northern end of Aitutaki Island, and along reef extending a further 12.4km. In Sector 1.1, the shore of the spit is fronted to seaward by an approximately 100m wide fringing reef and the spit terminates at a passage with channel and washover or flood-tide fan. To landward, sandy and rubble beach is perched on beachrock outcropping along the shore. The beach adjoins a raised ridge, possibly with a limestone core, modified by construction of an airstrip.	NE
1.2	1	Cuspate foreland & spit	Sector 1.2 is the lagoonal shore of the spit extending SE off northern end on the island. It is the E arm of a V shapes lagoon open to the S. Along the passage, at the distal end of the spit the shore is sandy and is comprised of a beach extending approximately 400m NE along the shore from a foreland point. Much of the remaining 1.8km of lagoonal shore is vegetated to the water's edge and has been modified. A cut-off lagoon with a tidal inlet and mangroves is at the proximal end of the spit where it joins the main volcanic component of the island.	SW
2.1	2	Volcanic terrain	The northern 2.5km of shore along the main Aitutaki Island faces SE into the lagoon and is sheltered to seaward by the spit and reef. The shore is approximately 1.2km SE from the flood-tide (washover) delta near Ootu Beach. It is bordered by a broad, over 900m wide, rock platform fragmented along its outer edge and continuous along shore. A passage has been cut across the platform and prides a built southern boundary to the sector. Landward of the shore is a narrow coastal terrace and coastal plain rising to over 20m within 100m of the shoreline.	ESE
2.2	2	Volcanic terrain	The central 3.3km of the eastern shore on 7km long Aitutaki Island faces E and is sheltered by a barrier reef 1 to 2km offshore and approximately 500 to 900m in width. The reef supports 4 sandy islets in its N half. These are separated by passages and washover fans. It is bordered by a broad, 350 to 850m wide, rock platform fragmented along its outer edge and continuous along shore. Passages have been cut across the platform in the northern, central and southern part of the sector. Landward of the shore is a narrow coastal terrace and coastal plain rising to over 20m within 100m of the shoreline.	ENE
2.3	2	Volcanic terrain	Approximately 2.5km of the eastern, lagoonal shore of Aitutaki faces SE into a broad expanse of water. Fetch lengths for this part of the shore range from approximately 2km to over 8km from the shoreline to the inner part of the barrier reef. A 300 to 450m wide platform is continuous along the shore. This is backed to landward by a narrow beach, coastal terrace and coastal plain.	SE
2.4	2	Volcanic terrain	Approximately 2.7km of Atutaki Island's lagoonal shore faces SW. At its southernmost point the island is open wind waves generated over fetches ranging from 3 to 6km inside the lagoon. A fringe of mangroves along the shore is fronted to seaward by a 300 to 400m wide pavement, and to landward by a narrow coastal plain.	SW
2.5	2	Volcanic terrain	North of Sector 2.4 the lagoonal shore of Aitutaki faces WNW, the lagoon narrows from 1.7 to 0.6km, and more reef pavement is apparent. The 2.8km long shore of the central third of main Island includes mangroves south of Arutanga Harbour, and an increasingly wide, sandy beach to the north. The beach sits on pavement or platform and is backed to landward by a boulder ramp in places and a narrow coastal plain.	WNW

Coast sector	Major sector	Landform	Comments	Seaward aspect
2.6	2	Volcanic terrain	North of the headland at Pacific Resort the lagoonal shore faces NW and extends approximately to the NW end of the airstrip. Narrow coastal plain, up to approximately 275m, along this coast are fronted by reef pavement and lagoon ranging in width from 500 to 800m. The pattern of reef and unconsolidated sediment suggests a shore normal wave approach or current movement across this part of the lagoon.	NW
3.1	3	Barrier reef	The eastern barrier reef includes 3 segments: The northern faces ENE and is 6km long; the central 4.5km reach of reef is embayed between Cook Island and Akaiami; and the southern 6km of reef faces directly E. All support islets separated by passages and washover fans.	ENE
3.2	3	Barrier reef	Approximately 3.5km south of the main island of Aitutaki the southern reef extends unbroken by passages for 13km from a small islet in the SE to another, Maina, in the SW. The reef is approximately 300m wide and washover flats for over 500m into the lagoon.	SSW
3.3	3	Barrier reef	The western, NW facing reef extends approximately 13.8km. It closes to within 1km of the coast at Arutanga (Aitutaki) Harbour where the reef platform has been excavated to provide a passage and the reef changes from barrier to fringing form.	NW

	Rank												
Coast sector	Lithology	Landform Element	Max Width of Landform	Length of shore	Mid-feature elevation	Shoreline Shape	Inshore Morphology	Reef Type	Distance to inner reef flat	Mid-reef width	Susceptibility Score	Susceptibility	Weighted Susceptibility (see Table 6.13 for weightings)
1.1	5	4	2	4	4	4	1	5	5	3	37	Moderate Susceptibility	High Susceptibility
1.2	5	4	3	4	4	2	2	2	5	2	33	Moderate Susceptibility	Moderate Susceptibility
2.1	2	1	5	4	4	4	2	2	2	2	28	Moderate Susceptibility	Low Susceptibility
2.2	2	1	3	4	4	2	2	2	2	1	23	Low Susceptibility	Low Susceptibility
2.3	2	1	5	4	3	4	2	2	2	2	27	Moderate Susceptibility	Low Susceptibility
2.4	2	1	4	4	2	2	2	2	2	2	23	Low Susceptibility	Low Susceptibility
2.5	2	1	3	4	3	2	2	2	3	3	25	Moderate Susceptibility	Low Susceptibility
2.6	2	1	3	4	3	2	2	2	3	3	25	Moderate Susceptibility	Low Susceptibility
3.1	4	5	2	4	5	2	1	3	5	3	34	Moderate Susceptibility	Moderate Susceptibility
3.2	4	5	1	2	5	2	1	3	5	3	31	Moderate Susceptibility	Moderate Susceptibility
3.3	4	5	1	2	5	1	1	3	5	3	30	Moderate Susceptibility	Moderate Susceptibility

4.5. Overview

Assessments of susceptibility, landform instability and overall (secondary) susceptibility were undertaken at two scales in the framework to demonstrate use of the methodology and assess availability of coastal landform information suitable for its wider application. This was done because determinations of coastal landform susceptibility at a broad, whole-island scale will inevitably miss small local areas that may be subject to more extreme change than elsewhere around the island, and because the different scales of application are relevant for a variety of management purposes. The broadest level provides information relevant to development of strategic, high-level policy; regional management; and production of regional scale maps of relevance to regional organisations and external donor agencies managing aid expenditure. Similarly, the finer-scale tertiary analysis is more directly applicable to policy, planning and management at a country scale.

The broadest level of analysis used a dataset describing island structure for 1532 islands. Unfortunately, detailed information describing the coastal fringe (landform characteristics adjoining and marine features affecting the shore) of all islands, was not readily available. The only geomorphic information consistently spanning the Pacific region of interest is Google Earth imagery and that requires interpretation. Island elevations derived from this source are not always accurate. Other measurements can be made from the imagery. For example, length of a shoreline segment, width of a landform and distance from the beach to an offshore reef can be determined. Additionally, many of the vertical images have associated landscape photographs that are especially useful for landform interpretation. Google Earth imagery is readily available and could be used in-country and in-region by staff with expertise in GIS. There would need to be agreement on the landform features to be used as criteria for assessing susceptibility and instability. Although all islands have different suites of landforms, geological controls, reef structures and connectivity with adjacent islands around them some features are common to each of the island types described in this report. Additionally, more accurate measures of variables, such as elevation of a landform feature, are required in the finer analyses, where it would be appropriate to consider the margin of error in the estimates.

Chapter 5.
The Pacific's climate and ocean processes—now and in the future

Key points

- Coastal impacts on Pacific islands will occur at a range of geographical and time scales and vary between islands and on different locations around islands.
- Present day shorelines throughout the Pacific have been shaped by the geology and history of islands as well as by the suite of physical and biological processes that interact with island margins.
- The most important climate and ocean processes that drive coastal change in the Pacific region are tide type and range, prevailing wind –wave action, tropical storms, extra-tropical swell, sea-level variability associated with ENSO phase and longer-term sea-level change.
- There are large differences in the relative importance of these processes across the Pacific and their potential impacts on island coasts.
- Projections of changes to climate and ocean processes over the next few decades indicate that: both tidal levels and ENSO range will shift upwards with rising sea-level though the magnitude of sea-level rise will not be uniform across the Pacific; a small reduction in wave height can be expected in the equatorial zone but this may be offset by an increase in distant-source swells from the southern ocean; the frequency of tropical cyclones may be reduced and intensity increased in the future.
- Geographical variations in these processes means that similar island types but located in different parts of the Pacific will be exposed to different climate-ocean regimes resulting in dissimilar coastal impacts.

5.1. Drivers of coastal change

The analysis thus far has been concerned with the inherent physical characteristics of islands—initially in Chapter 3 island geology, island area, maximum elevation and island shape—and our intuitive understanding of their potential to change. Such understanding has allowed the development of a coarse measure—*primary susceptibility*—at the whole island scale. It has also allowed downscaling to island coasts with the addition of several other physical and geographical variables to determine a finer scale *susceptibility*, in Chapter 4. Underlying and implicit in this analysis are the processes that have the potential to bring about island- and coastal-change. In this chapter those processes are made explicit and their temporal and geographical distributions across the Pacific now and in the future are identified. Here the processes of concern relate not to the whole island structure but to the islands' coastal zone.

Excluding the impact of people, the main drivers of coastal change in Pacific island countries comprise three groups of climate-ocean processes that operate over a range of time scales. The first are the ongoing day-to-day, week-to-week processes associated with fair-weather regimes such as trade winds and waves, tides and currents, some of which have a seasonal rhythm that is well recognised by islanders. Periodically these regular processes are interrupted by short-term episodic events including tropical cyclones, distant-source swells and king tides that provide a second group of processes, only the last of which is temporally predictable. Forming a backdrop to both fair- and stormy- weather variability is the third group, the interannual and long-term processes of which ENSO (El Niño Southern Oscillation) and its two phases El Niño and La Niña, together with gradual multi-decadal sea-level rise, are the best-known.

In this chapter the individual processes are discussed and their temporal and geographical patterns within the Pacific Basin explained in section 5.2. Rarely however do these processes operate alone. Rather major coastal impacts including erosion and flooding typically arise from a combination of drivers: an example is a tidal level on which wave conditions are superimposed with the eventual effect on the coast being influenced by the ENSO phase at the time. Thus section 5.3 is concerned with the integration of these processes. It is also important to acknowledge that some of these factors will be altered by future climate change which is discussed in section 5.4 based on the IPCC's Fifth Assessment as well as PACCSAP's science program.

5.2. Regional variations in key climate and ocean processes

5.2.1. Tidal type and tidal range

The daily rise and fall of the tide, its high and low levels, and its fortnightly 'spring' and 'neap' cycles are familiar to and anticipated by coastal dwellers throughout the Pacific Islands region. Less well known are the differences in tidal characteristics within the region and the role of the tide as a coastal-change variable.

Within the Pacific there are four different tidal types, the two most widespread being the semi-diurnal and mixed semi-diurnal tide with two highs and two lows within a 24 h 50 min day (Figure 5.1). Separating the eastern and western semi-diurnal regions is a narrow north-south zone of diurnal and mixed diurnal tide that passes through islands in the Federated States of Micronesia and northern Papua New Guinea before curving south-east to include much of Solomon Islands.

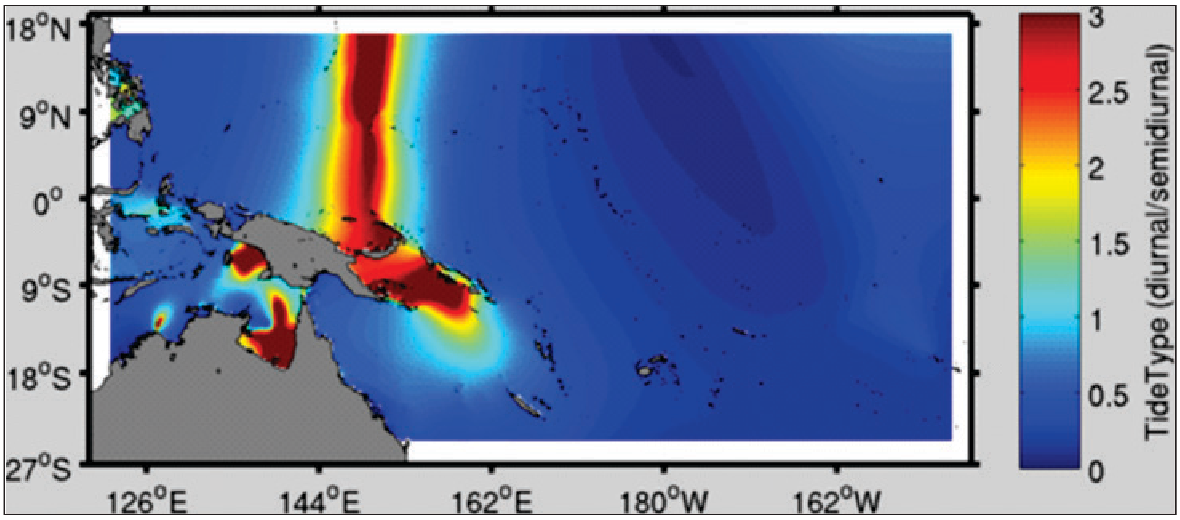


Figure 5.1 *Tidal types in the Pacific.*

The colour scale bar shows values of the tidal form factor (F), a ratio used as a measure of tide variation. By convention, when F= 0.0-0.25 the resultant tide is semidiurnal with two high waters and two low waters of approximately equal height in a tidal day. Mixed predominantly semi-diurnal tides (F=0.25-1.5) also produce two clearly-defined highs and lows per day but they are of unequal range (diurnal inequality). In mixed predominantly diurnal tides (F=1.5-3.0), the inequalities of range are larger and for part of the lunar cycle only one high tide a day is observed. In the diurnal tide (F=>3.0) the second tide disappears completely. From PACCSAP_Tidetype.png.

Whilst tidal type affects such variables as the length of exposure of particular parts of the shore to wave action, the duration of wet and dry periods in the intertidal zone, and the intensity and duration of tidal currents, differences in tidal range are also important in explaining variations in coastal geomorphology. Principal among these variations are the width of the wave wash zone and the changing depths at harbour and estuary entrances in the course of a single day. For example, island coasts that experience just one high and low tide daily may be affected by erosion-causing waves (at high tide) half as frequently as those coasts experiencing semi-diurnal tide types. Knowledge of tidal range is also important in the prediction of coastal flooding with king tides or when spring tides combine with storm surges, low atmospheric pressure or tsunami to achieve uncommonly high water levels.

Tides in the Pacific Basin do not have the large ranges of several metres that occur in some parts of the world including the central part of Australia's Great Barrier Reef. Generally in the Pacific region tidal range does not exceed 2.5 m (Table 5.1). In fact, mean high water spring tides (MHWS) range across the region from less than 0.6 m above mean sea level (MSL) in French Polynesia and the Cook Islands to a maximum of about 2.0 m in the westernmost Pacific. For example, three stations in Kiribati on the equator from east to west exhibit just such variations of spring-tide ranges: 0.64 m at Kiritimati in the Line Islands, 1.44 m at Kanton in the Phoenix Group, and 2.01 m at Tarawa in the Gilbert Islands.

Table 5.1 Tidal types and tidal range for a representative sample of islands in the Pacific

	Island	Type	Tide type	Tide range
1	*Aitutaki, Cook Islands*	Composite high island	SD	0.75-1.25
2	*Aniwa, Vanuatu*	Limestone high island	mSD	1.5-2.0
3	*Aore, Vanuatu*	Limestone high island	mSD	1.5-2.0
4	*Bellona, Solomon Islands*	Limestone high island	mD/mSD	1.0-1.5
5	*Emananus, Papua N. Guinea*	Composite high island	mD/mSD	0.5-1.0
6	*Lifuka, Tonga*	Limestone low island	mSD	1.5-2.0
7	*Loun, Solomon Islands*	Volcanic high island	mSD	1.0-1.5
8	*Manono, Samoa*	Volcanic high island	mSD	1.5-2.0
9	*Onotoa, Kiribati*	Reef island	mSD	2.0-2.5
10	*Oreor (Koror), Palau*	Composite high island	mSD	2.0-2.5
11	*Tonowas, FSM*	Volcanic high island	mSD	1.0-1.5
12	*Vaitupu, Tuvalu*	Reef island	mSD	2.0-2.5
13	*Vogali, Papua New Guinea*	Volcanic low island	mD	0.5-1.0

Tide type: m Mixed D Dirnal SD Semi-diurnal. Data extracted from NTC (BOM) 2014 tidal calenders
Tidal range in 0.5m classes.Data extracted from NTC (BOM) 2014 tidal calenders.

The regional map of tidal range (Figure 5.2) shows a broad central core with a tidal range of 1 to 1.5 m separating zones of lower tide range to the east and west. The north-south zone of lower ranges in the west is a notable feature and is coincident with the diurnal and mixed diurnal tidal types (see Figure 5.1) through the Federated States of Micronesia to Solomon Islands. Within this zone there is an area of 'zero' tide immediately to the north of Papua New Guinea associated with one of the Pacific's amphidromic points—or centres—around which the tide rotates.

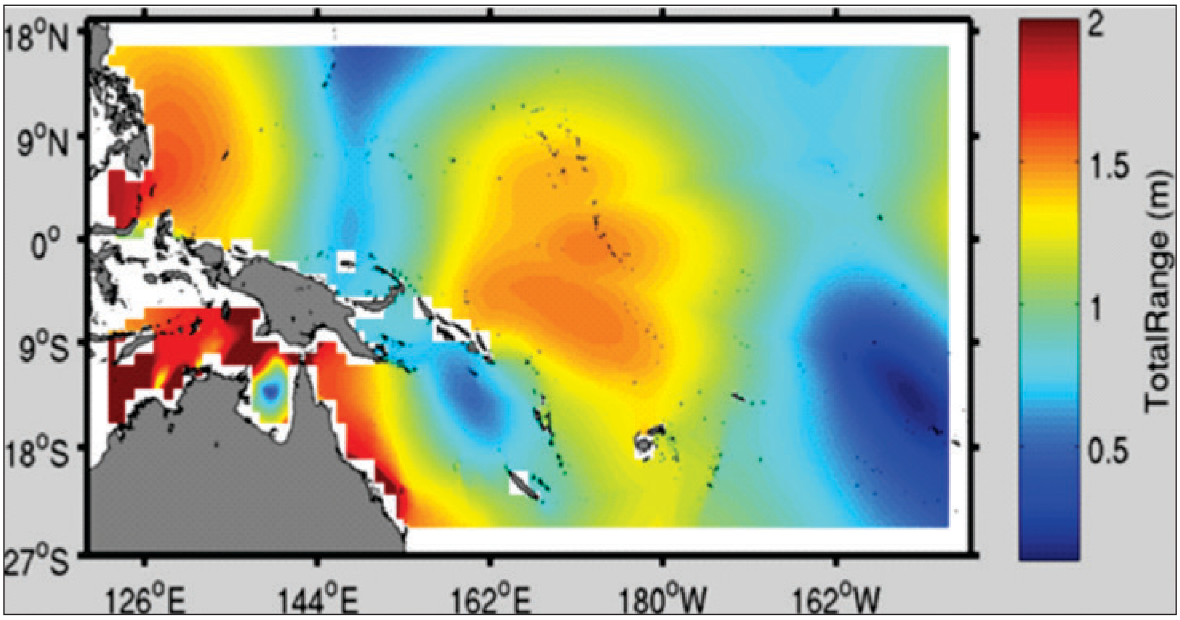


Figure 5.2 Distribution of tidal ranges in the Pacific. From: PACCSAP_TotalRange.png.

5.2.2. Waves

Details of the wave climate in the open Pacific away from continental margins are not well known, although in the last few years there have been several global and regional studies, including in the Pacific (Hemer et al., 2010; Qiu and Chen, 2006). Enough is now known about the pattern and nature of wave generation and propagation in the Pacific to describe the salient elements of the region's wave climate (Trenham et al., 2013).

Four major types of waves are present in tropical latitudes:

1. easterly trade waves;
2. westerly storm waves (associated with the monsoon);
3. distant-source swell waves generated from mid-high latitudes that include a persistent background swell from the south as well as less-frequent episodes of high damaging swell from the North Pacific and Southern Ocean; and
4. waves associated with tropical cyclones and storms (note that these are considered in section 5.2.3 separately).

Tsunamis should be included in the latter group although their incidence is clearly not associated with climate. The relative importance of these four wave types varies temporally, especially on a seasonal basis, as well as spatially from east to west and north to south in the tropical Pacific.

Of these four types, the **easterly trade waves** are the most persistent; they are usually present all year round and are strongest during the austral (southern hemisphere) winter months. Generated by the trade winds that blow over great distances from the east, the easterly trade waves have a strong windward-leeward effect on island shores, reefs and adjacent seas. Seasonal variations in the magnitude of trade-wind wave energy accompany seasonal shifts in the strength of the trade winds and the area of the Pacific they affect. Likewise, wave direction may vary with latitude in the Pacific Basin from north-east through east to south-east, moving southward along the dateline in the central Pacific paralleling variations with the wind direction. Nevertheless because much of the region is down-sea from the core of the trade wind belt, waves from the easterly quarter are likely to prevail during most of the year in the open seas surrounding the islands, though not in the Melanesian archipelagos where large elongate islands often shelter those in their lee.

Westerly storm waves occur infrequently during the southern hemisphere summer generally between November and March when the trade winds are weakest. These westerly waves are associated with local fronts and low-pressure cells in the summer monsoon and are often accompanied by strong winds and high rainfall. On occasions, westerly seas can be fierce for short periods and have been mistaken for hurricane (typhoon) generated waves.

In contrast to such locally produced storm waves are those **distant-source swell waves** developed far to the north or south of the tropics that move out of their area of generation and reach low latitudes as long-period swells. Sometimes northern swell reaches into the southern hemisphere from the northern Pacific and *vice versa*. Two types of distant-source swell waves can be recognised.

The first are the more regular and persistent southern swells generated by the strong westerly winds in the 'roaring forties' and 'fighting fifties' of the Southern Ocean. These waves often form a background swell along southern shores of many islands especially those not shielded by the Australian continent or larger islands in dense archipelagos. The second type is the high storm waves, generated by intensive and sometimes slow-moving low pressure systems in the mid-and high-latitudes of the North Pacific and the Southern Ocean. North Pacific storm swell commonly arrives during the northern hemisphere winter (October to May) approaching the low-latitude Pacific from either the northeast or northwest.

Coastal impacts of distant-source swell waves can be severe (Gardner et al., 2014; Hoeke et al., 2013). One example of heavy swell occurred in December 2008 and caused widespread flooding and displacement of people from coasts in the Marshall Islands, Kiribati, Papua New Guinea and the Solomon Islands. Comparable seas and swell come from the Southern Ocean, one notable recent event impacting the Coral Coast of Viti Levu Island (Fiji) in May 2011.

In addition to the direction from which waves reach the shore, a number of other wave variables are important in causing changes to coastlines and flooding, most notably the height of the wave. Waves tend to be defined in terms of their significant wave height (Hs) defined as the average level of the highest one-third of waves over a particular time interval. Contrasts in the pattern of Hs throughout the tropical Pacific show a clear distinction between those islands located in the open ocean, which are commonly exposed to waves of Hs 1.5 -2.5 m, and those either in the western doldrums or sheltered by surrounding islands that experience annual Hs <1.0 m (Izaguirre et al., 2011). These patterns are even more clearly seen in maximum wave heights (Hmax) which range from less than 3.0m to greater than 10 m (Table 5.2).

Table 5.2 Wave height, wave direction and tropical cyclone frequency for a sample of islands

	Island	Type	Wave Height (Hmax)[1]	Wave Height (Hs)[2]	Wave Direction (all months)[3]	TC Frequency[43]
1	Aitutaki, Cook Islands	Composite high	8.3	2.0-2.5	SSW	4.75
2	Aniwa, Vanuatu	Limestone high	8.5	1.5-2.0	SSW (SE)	5.25
3	Aore, Vanuatu	Limestone high	7.4	1.5-2.0	ESE	5.5
4	Bellona, Solomon Islands	Limestone high	9.2	1.0-1.5	E (N,NE)	3.25
5	Emananus, Papua N. Guinea	Composite high	3.2	0.5-1.0	NE	0
6	Lifuka, Tonga	Limestone low	9.9	2.0-2.5	E (NNW)	5.75
7	Loun, Solomon Islands	Volcanic high	2.8	1.0-1.5	N	1.25
8	Manono, Samoa	Volcanic high	11	2.0-2.5	NNW (ENE)	3.25
9	Onotoa, Kiribati	Reef island	3.5	1.5-2.0	ENE	0
10	Oreor (Koror), Palau	Composite high	7.9	1.0-1.5	NNE	<1
11	Tonowas, FSM	Volcanic high	5.5	1.0-1.5	ENE	<1
12	Vaitupu, Tuvalu	Reef island	5	1.5-2.0	SSW (E)	<1
13	Vogali, Papua New Guinea	Volcanic low	3.2	0.5-1.0	NE	0

1 Maximum wave height (Hmax) for nearest site to sample islands. Data extracted from *Climate Change in the Pacific: Scientific Assessment and New Research*. AustBOM and CSIRO, Volume 2: Country reports, 2011.

2 Annual significant wave height (Hs) for time slice representing present climate (1979-2009) From Hemer et al 2013 (Fig 2A)

3 Primary wave direction extracted from wave roses supplied by to project by BOM/CSIRO. Secondary direction in brackets.

4 Tropical storm frequency per decade based on data extracted from BOM Pacific Tropical Cyclone Data Portal for the 40 year period 1969/70–2009/10. Data for storm tracks reaching within 100km of the specific island.

5.2.3. Tropical cyclones and hurricanes (typhoons)

Tropical cyclones and hurricanes (typhoons) are the most important climate-associated catastrophic events to have a regular impact on many Pacific island coasts. In a very short time, they initiate temporary and sometimes permanent changes to the physical and biological environments - reefs, coasts, mangroves—as a result of exceptionally strong winds, waves and rainfall. While such extreme weather events are a significant component of the climate of much of the tropical world, it is important to recognise that tropical cyclones do not occur everywhere nor are they experienced with the same frequency or intensity in every part of the Pacific. Instead there are significant geographical variations as shown in Table 5.2 and Figure 5.3.

In Figure 5.3 it can be seen that the two bands of tropical-cyclone (TC) tracks in the northern and southern hemispheres are separated by an equatorial TC-free zone that extends about 5° north and south of the Equator. In the southeastern Pacific, there is a gradual reduction in the number of TC tracks, such that the region east of French Polynesia is TC-free. The map also shows that most TCs originate in the region between 10° and 15° north and south of the Equator, especially within the lower-latitude western Pacific where ocean-surface temperatures are mostly high enough (typically >27°C) to permit TC genesis. During El Niño events, another such 'warm pool' may develop in the eastern tropical South Pacific from which TCs may move out across islands in this region, particularly in French Polynesia, that normally experience few TCs.

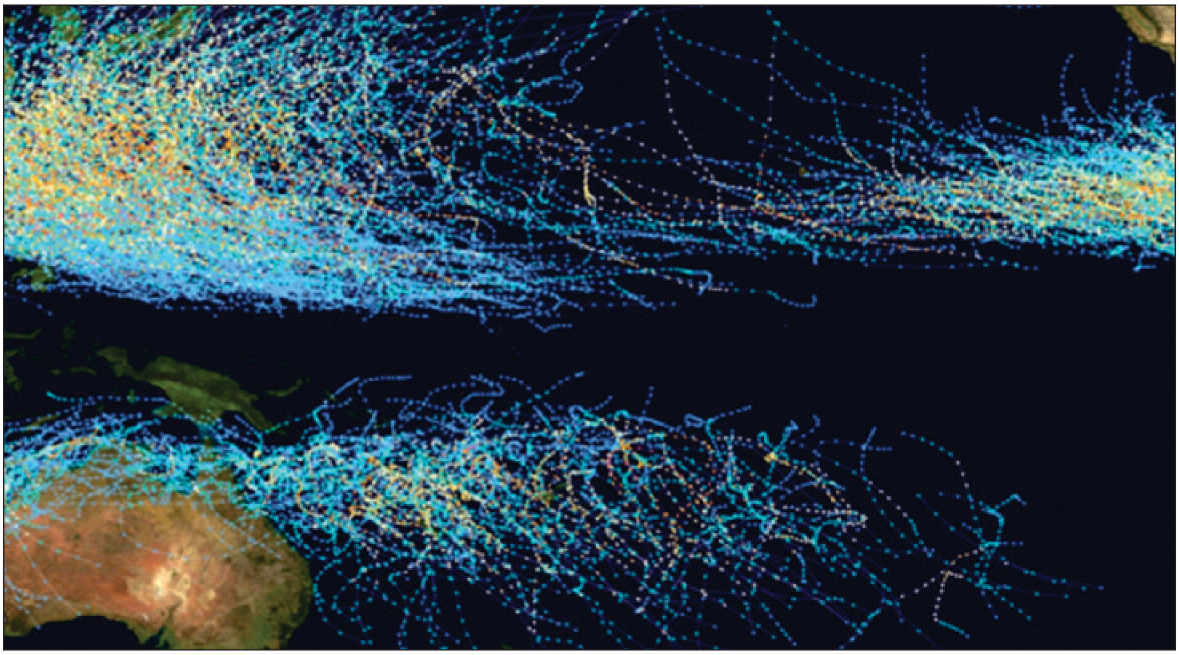


Figure 5.3 *Tropical-cyclone (hurricane or typhoon) tracks in the Pacific region 1985 to 2005.*

Track colours represent Safir-Simpson hurricane wind scale: Red category 5; Dark orange category 4; Light orange category 3; Dark yellow category 2; Light yellow category ; Aqua Tropical storm; Blue Tropical depression. From: Wikipedia- WkiProject Tropical cyclones/Tracks.

Notwithstanding the geographical pattern of TCs shown in Figure 5.3, TC-induced effects can extend well beyond a cyclone's path and affect areas where cyclones are generally rare or even absent. On low-latitude reef islands, high seas and gale-force winds generated by TCs several hundred kilometres away have occasionally swept across the islands with destructive effect (Terry and Chui, 2012). The radius of gale-force winds associated with some TCs can be as much as 800 kilometres. Such large storms passing to the south or north of the TC-free belt, particularly those that are slow-moving and have a strong sustained west-to-east direction in the southern hemisphere and east-to-west direction in the northern hemisphere are those most likely to funnel high seas into the TC-free areas of Papua New Guinea, Federated States of Micronesia, the southern Marshall Islands and Kiribati. In these regions, island geomorphology and ecosystems differ from islands exposed to a high frequency of cyclones so that the effects of these occasional high ocean-water levels may be disproportionately severe, even though independent contrasts in island types from low reef islands to high limestone and volcanic islands make it difficult to adequately test this hypothesis.

In addition to the obvious geographical differences in TC frequency in the Pacific (Figure 5.3), there is also immense spatial variation in the coastal impact of a single storm depending on its size, intensity, track, duration and timing relative to tide levels. In general, the degree of impact decreases away from the storm centre and is at a maximum in the front left quadrant (looking in the direction of movement) in the southern hemisphere and front right quadrant in the northern hemisphere where the strongest wind velocities occur. Given the overall pattern of cyclone tracks (Figure 5.3), it is likely that the north and west coasts of islands in the southern hemisphere and south and east coasts in the northern hemisphere will experience the greatest associated impacts. This pattern has been confirmed in a study of storm-surge impacts that showed the northwestern coastlines of both Viti Levu and Vanua Levu islands in Fiji are most vulnerable to high storm surges (McInnes et al., 2011). Yet it should be noted that the unpredictable movement of TCs and the fact that they are revolving does make all sides of an island potentially vulnerable to their impacts.

In addition to geographical variations in TC incidence, there are also temporal variations, the most obvious being at the seasonal level. In the southern hemisphere, the hurricane season extends over six months from November through April although there are increasing instances of events outside the traditional 'season'. For instance, a particularly severe TC named *Bebe* passed through southern Tuvalu, Rotuma and the Fiji Islands in October 1972 prior to the start of the hurricane season (Yamano et al., 2007).

In contrast, interannual variation in TC frequency is large and the establishment of any periodicity longer than the seasonal rhythm is more speculative, though there may be some clustering in cyclone activity both spatially and temporally especially in areas of low TC frequency. For instance, it is clear that in the South Pacific, TCs are more frequent during El Niño events; often successive events will occur in a single cyclone season at such times compared to few during ENSO-neutral or La Niña times.

When considering the potential impact of storms and at the same time attempting to develop a risk ranking, it is important to recognise two points. First, the low frequency of storm events in low latitudes does not mean that the geomorphological or ecological effects on particular island coasts are any less severe than in areas of higher frequency. Indeed it can be argued that the massive changes to reef and island landforms and biota in Funafuti during Hurricane *Bebe* were not only the result of the intensity of that particular event but also a result of the long time-lag between it and any predecessor (McLean and Hosking, 1991). In areas of more frequent storm activity, where time lags between events are shorter, island geomorphic and ecologic systems may well be better adjusted to periodic high-magnitude perturbations. Thus it is likely that the on-island effects of a single storm of equal magnitude experienced on similar island types, but one in an area of high storm frequency and one in an area of low storm frequency, would be quite different.

Secondly, terms like 'hurricane absence', 'low frequency' and 'high frequency' used to delimit regions of TC activity are all relative to the time scale considered. For instance, if the patterns of hurricane incidence over the past several decades (see Table 5.2) are representative of those during the last 5,000 years since sea level attained roughly its present level, then Aitutaki (18°S) in the Cook Islands and Aniwa (19°S) in Vanuatu in the 'high frequency' zone may have experienced some 2500 storms within 100 km of the island while even 'low frequency' low-latitude islands such as Vaitupu (7°S) in Tuvalu and Oreor (Koror) (7°N) in Palau may have experienced some 250 storms.

5.2.4. Sea level

In the Pacific, there is good evidence to indicate that sea level attained its approximate present position (+/- 2 m) quite recently, in the last four or five millennia (Grossman et al., 1998)1998. For the present project, this is particularly relevant for two reasons.

First, this 4 - 5,000 year period is probably the longest time that sea level has been relatively constant (at least within the last 20,000 years). This stability has enabled some sort of equilibria to be achieved between the geomorphic and ecologic characteristics of island shores and external climate-ocean drivers, including short-period sea-level changes.

Second, in that time most of the morphological detail of island coasts has been shaped. Indeed virtually all of the reef islands in the region are of recent sedimentary origin formed by incremental accumulation of biogenic sands and coral rubble sourced from the surrounding reef and lagoon and delivered to reef surfaces by wave action in the last 4–5,000 years. On the limestone and volcanic islands, the low sandy strips of flat coastal land that vary in width and lateral extent have developed by similar processes. The materials of these flats are in many cases derived from the adjacent reef rather than from the island itself, although on the volcanic and composite islands mud and rocks from hillslope wash and streams have contributed to the development of flat coastal lands and deltas. These natural processes are continuing to this day, often resulting in shifts of the shoreline and subtle changes in island configuration and topography.

In the past, as at present, the level of the sea at any particular time and place is made up of a minimum of three components in the Pacific: the underlying eustatic sea level, the astronomical tide level and the ENSO phase. The last two usually have the biggest effect on the observed level of the sea while the former can generally only be recognised after the effects of tidal fluctuations and ENSO variability have been removed. Also other climate-ocean factors can add or subtract from that level including wave conditions, ocean currents, storm surges, sea-surface salinity and atmospheric pressure as—for entirely unrelated reasons - can vertical (tectonic) movements of the land.

Superimposed on these recent trends of mostly rising sea level in the Pacific are the transient interannual variations in sea-surface elevation driven primarily by phase changes in ENSO. Hence the pattern of sea-level variability over the last few decades has not been uniform across the Pacific (See Table 5.3).

Table 5.3 Recent rates of sea level rise and ENSO range for a sample of 13 islands in the Pacific

	Island	Island type	Recent sea-level rise (mm/yr)[1]	Sea-level change rate to Jan 2014 (mm/yr)[2]	Inter-annual ENSO range (+/- mm)[3]	Sea-level projection to 2030 (mm/yr)	Sea -level projection to 2090 (mm/yr)
1	Aitutaki, Cook Islands	Composite high	4	5	190	2.5	3.8
2	Aniwa, Vanuatu	Limestone high	6	4.3	180	2.5	4
3	Aore, Vanuatu	Limestone high	6	4.3	180	2.5	4
4	Bellona, Solomon Islands	Limestone high	8	7.3	310	2.25	3.8
5	Emananus, Papua N. Guinea	Composite high	7	8.1	230	2.5	3.9
6	Lifuka, Tonga	Limestone low	6	9.7	180	2.5	3.9
7	Loun, Solomon Islands	Volcanic high	8	7.3	310	2.25	3.8
8	Manono, Samoa	Volcanic high	4	7.8	200	2.5	3.8
9	Onotoa, Kiribati	Reef island	4	3.3	260	2.25	3.8
10	Oreor (Koror), Palau	Composite high	9	n/a	360	2.25	3.8
11	Tonowas, FSM	Volcanic high	10	15.6	260	2.25	3.9
12	Vaitupu, Tuvalu	Reef island	5	3.8	260	2.25	3.9
13	Vogali, Papua New Guinea	Volcanic low	7	8.1	230	2.25	3.7

1 Sea-level rise since 1993 based on data from *Climate Change in the Pacific: Scientific Assessment and New Research*. AustBOM and CSIRO, Volume 2: Country Reports, 2011 (data from nearest tide gauge to site)

2 Sea level change rate based on BOM/NTC Seaframe tide gauges from *Monthly Data Report - January 2014, Pacific Sea Level Monitoring Project*, BOM, Table 1.

3 Data from *Climate Change in the Pacific: Scientific Assessment and New Research*, Aust BOM and CSIRO Volume 2: Country reports, 2011.

Figure 5.4 shows a reconstruction of the changes in sea level over the 60-year period between 1950 and 2009. During this time the greatest positive changes in sea level took place within about 15° of the equator in Palau, the Federated States of Micronesia, southern Marshall Islands and the Gilbert Islands (western Kiribati). This region is also where sea level has the largest interannual variability with peak-to-peak amplitudes as large as 45 cm associated with ENSO (particularly El Niño) events. For countries in higher tropical latitudes such as Vanuatu, Fiji, Tonga and Samoa, the ENSO signal is of reduced amplitude, partly as a result of large-scale trade-wind variability in forcing sea-level perturbations in these latitudes.

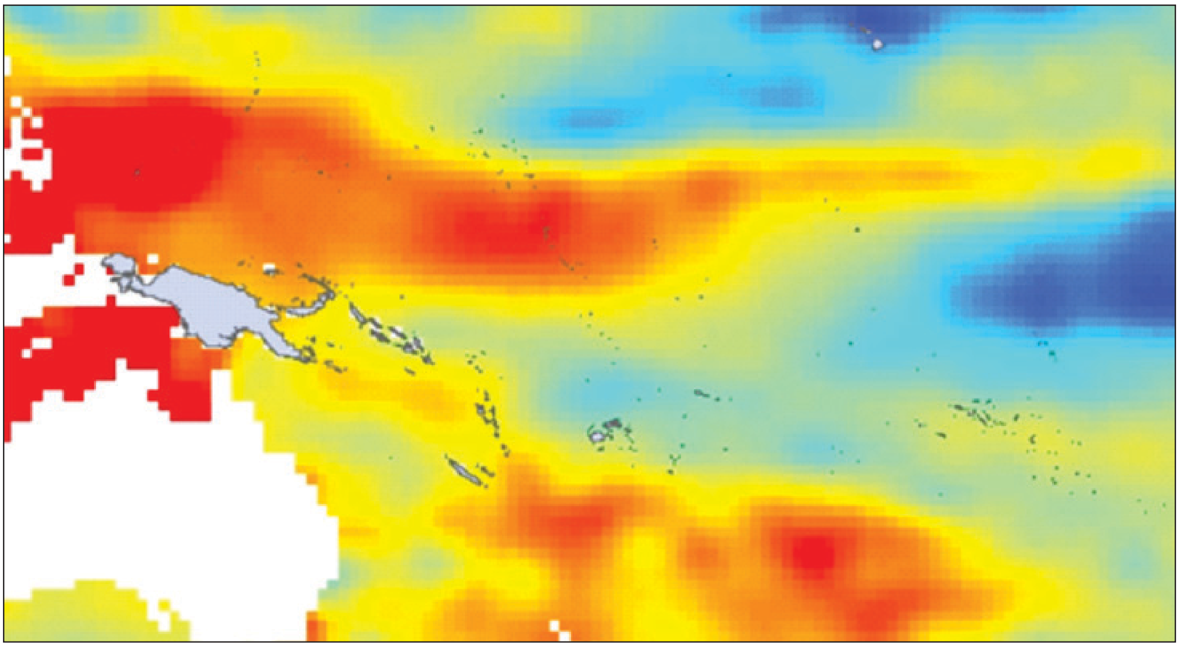


Figure 5.4 *Sea-level reconstruction for the Pacific 1950-2009.*
In this figure red represents +3.5 to +5.0 mm per year; orange +2.0 to +3.5 mm per year; yellow +0.5 to +2.0 mm per year; green –1.0 to +0.5 per year; blue –1.0 to –2.5 mm per year

Cross-Pacific shifts in high and low sea levels linked to ENSO phases are quite clear (Figure 5.5) though these are modulated by the tendency for an overall low sea level during El Niño events and high sea level during La Niña events (Chang et al., 2013). These changes are not seasonal and therefore conflict with many natural and human cycles of coastal change/interaction. In particular, note the low sea levels in the western low-latitude Pacific that can endure for months during El Niño events resulting in the emergence of shorelines and near-shore coastal ecosystems (Gierach et al., 2013).

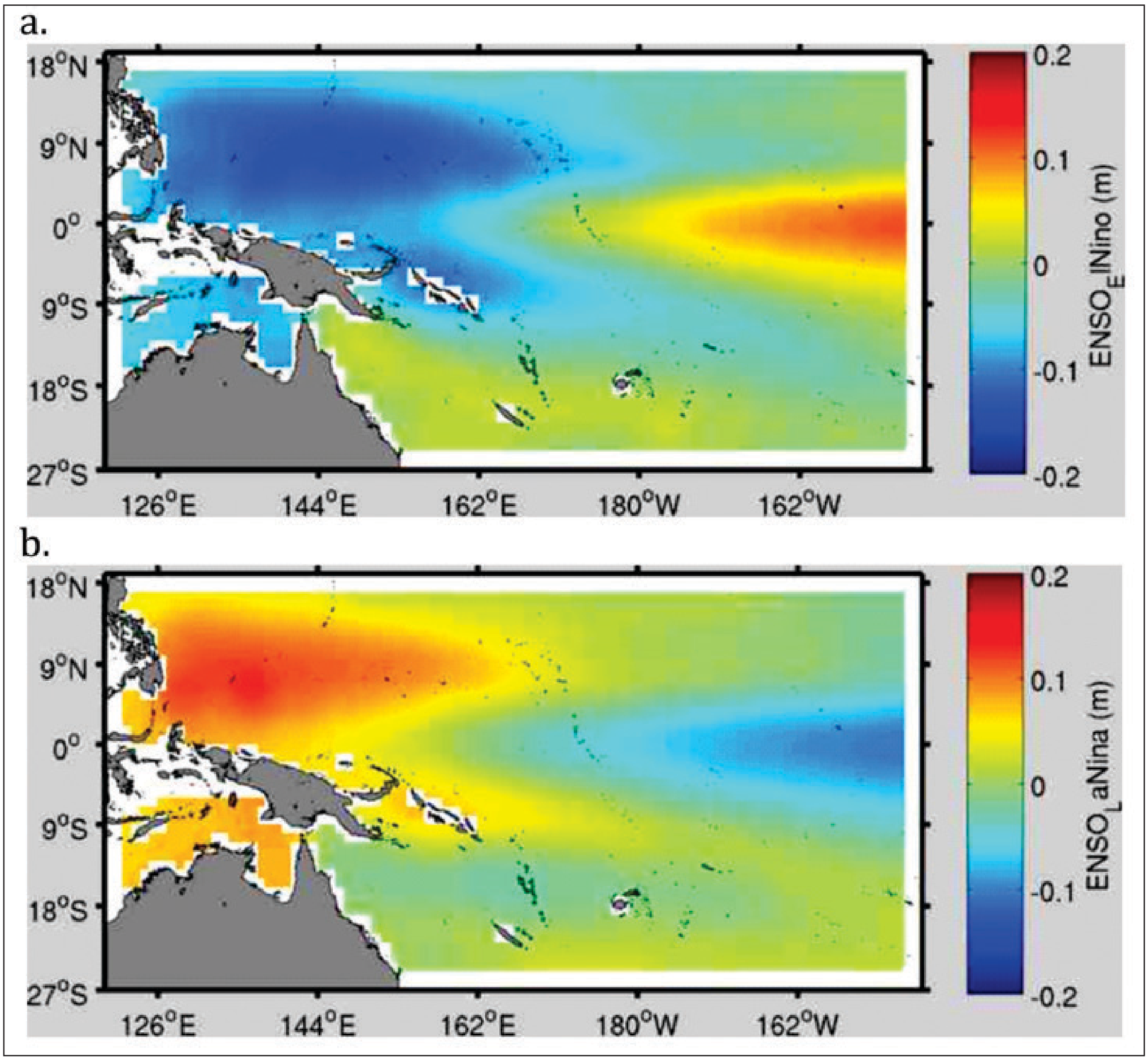


Figure 5.5 Average sea level in the Pacific associated with ENSO phases. a. El Niño, b. La Niña.

5.3. Interaction of key climate and ocean processes

The effects on coastal landforms of the above processes invariably result from the interactions between tides, waves, storms, ENSO and sea level, which makes it difficult to both hindcast and forecast those effects accurately.

Earlier it was noted that the local sea level or tide level experienced by residents in the Pacific comprised at least three components: a long-term eustatic component, an astronomical component and an interannual (ENSO) component. In addition to the effect of ENSO cycles that may last for several months or years, predicted tide levels can be elevated or lowered by a number of other factors including both longer-term interdecadal oscillations and short-term forcings such as storm surges and wave set-up. Storm surges result in a temporary increase in sea level over a few hours or days as a result of low atmospheric pressure and the influence of wind on the sea surface, something typically associated with tropical storms, hurricanes or typhoons. Coastal water levels can also be raised by large ocean swell events such as those generated by distant-source storms in the mid- and high-latitudes or from local depressions where large waves breaking on the seaward edge of a reef can impact adjacent shorelines more than under 'normal' wave conditions.

If elevated water levels are a primary cause of flooding in low-lying coastal areas and strong wave action is the primary cause of shoreline change, the two processes in combination are clearly implicated in some of the Pacific's most damaging coastal impacts. Such combinations typically occur during local TCs and storms, from high seas fanning out from slow tracking storms and from long-period swells propagated far beyond the tropics that are particularly damaging to exposed open ocean coasts. In more sheltered locations, enclosed seas and atoll lagoons where swell waves are excluded, strong locally generated wind waves and choppy seas can also damage coastal sites, especially during king tides and high ENSO-negative (El Niño) sea levels. ENSO also has a large-scale influence on regional wave conditions through its effect on the trade-wind field. For example, prolonged El Niño events result in a weakening of the easterly trade winds and an increase in wind and wave strength and frequency from the west. Such conditions also result in a slight shift in wave direction to a more southerly wave approach.

5.4. Future conditions of climate and ocean processes during the 21st century

The most recent reports comprising the 5th Assessment Report of the IPCC (Church et al 2013; Nurse et al 2014) assess recent research on climate and ocean processes with a focus on how these are likely to change as a result of temperature forcing between now and the end of the 21st century. Projected changes based on sources from the IPCC reports are summarised in Table 5.4 and discussed separately below in sections 5.4.1–5.4.5.

Table 5.4 Projected future condition of climate and ocean processes in the Pacific

Tides
Tide characteristics around oceanic islands are unlikely to change as a result of climate change and sea-level rise.
Small range changes are expected in enclosed seas, lagoons, harbours and estuaries.
The effect of sea-level rise will be felt most in areas of low tidal range where the base of the mean tidal envelope could be raised above present mean sea level or even high water level.
Waves
Wave period may increase in the eastern Pacific
Decrease in significant wave height of about 7% (0.1m) along the equator is expected.
A poleward shift in the extra-tropical cyclone belts may reduce the effects of potentially damaging distant-source swells on low latitude islands.
A projected increase in South Pacific trade winds associated with the strengthening of trade winds in the austral subtropics.
Projected changes in wave direction include a subtle clockwise rotation with more southerly waves in the southern equatorial region and easterly wind waves in the North Pacific.
Decrease in significant wave height over most of the world's oceans but an increase in significant wave height in the Southern Ocean.
Southern Ocean generated background swells that propagate northwards may be more persistent on southern coasts of islands in the central and eastern Pacific.
Tropical cyclones and storms
Global frequency is expected to either decrease or remain unchanged.
Likely global increase in both maximum wind speed and rain rates including in tropical cyclones affecting many Pacific islands.
In the Pacific expect future increase in relative frequency of tropical depressions, tropical storms, and category 5 storms, and a general decrease in the number of storms in other categories.
Slight equatorward movement of tropical cyclone tracks in the northern hemisphere and poleward movement in the southern hemisphere.
El Nino Southern Oscillation (ENSO)
ENSO will remain the dominant driver of natural (interannual) climate variability in the region.
Natural variability in the size and location of ENSO are so large that confidence in any projected change is low.
Sea Level
Global sea level will continue to rise and will likely accelerate above the observed 1971-2010 rate within the next few decades.
Future projections of global sea-level rise for 2081-2100 (relative to 1986-2005) range from 0.26-0.55 m (RCP 2.6) and 0.45-0.82 m (RCP 8.5).
Strong regional deviations from these global projections of 10-20 % can be expected in countries near the equator, such as Nauru and parts of Kiribati,

5.4.1. Projected future changes in tides in the Pacific and their effects

Available research suggests that there will be no effects on tide characteristics within the rest of the 21st century as a result of climate change and sea-level rise. It is envisaged that the same types of tidal regime that exist at the moment will continue to do so. Exceptions are likely in small semi-enclosed bodies of ocean water where changes in the rates at which water enters when the tide is rising and exits when it is ebbing may occur.

It is clear that tidal levels will shift upwards with sea-level rise. In areas where today the tidal range is higher than average, the effects of this on coastal geomorphology and processes is unlikely to be severe, at least for the next few decades. This is because much the same vertical area of coast will be alternately exposed and submerged during a tidal cycle as it is today.

A difference is likely to be noticed in areas where tidal range is today comparatively low, for it is possible that within a few decades the base of the mean tidal envelope will be raised above present mean sea level. This would result in coastal landforms that are currently exposed (emergent) at low-tide level becoming permanently submerged, with all the consequent changes in form and process this might entail. For example, in such situations it is likely that subsea erosion (tidal scour) will affect permanently submerged areas of the shoreline causing loose sediments to be mobilised and perhaps re-deposited offshore. Such processes would have effects on the entire coastline, contributing to shoreline recession through sediment erosion. It is therefore clear that those Pacific Island coasts where today the tidal range is comparatively low (see Figure 5.2) will likely experience an additional risk of future shoreline erosion associated with sea-level rise.

5.4.2. Projected future changes in waves in the Pacific and their effects

Changes in the periodicity of waves, particularly in the eastern Pacific (which is mostly beyond the study area of this project) have been projected for the next few decades as a result of a steeper meridional pressure gradient (Hemer et al., 2010; Hemer et al., 2013a). Yet the same models also project a decrease in significant wave height (Hs) of about 7%, or about 10 cm on average, along the Equator.

Several models have suggested that for the next few decades, the tracks of tropical cyclones (TCs) in the Pacific will move polewards (Knutson et al., 2010; Lowe et al., 2010), something that may already be happening. This is good news for many low-latitude Pacific islands because it means they are less likely to be affected by potentially damaging TC-generated swells and winds. Yet the benefits of this may be offset by an increase in long-range swells generated in the Southern Ocean (see below).

Models also project that trade-winds are likely to strengthen in the southern hemisphere sub-tropics over the next few decades (Timmermann et al., 2010) which will mean a consequent increase in the wind strengths that affect many islands in the study area. In addition to the direct impacts of stronger winds, the effects of these on wave set-up, particularly in semi-enclosed lagoons, may result in significantly higher rates of shoreline erosion than at present along exposed coasts. Small changes in wave direction are also projected (Hemer et al., 2010) but are unlikely to be significant for most island coasts.

Models of significant wave height (Hs) project a fall in this over most of the world's oceans yet a rise in the Southern Ocean well south of the Pacific islands on which this project focuses (Hemer et al., 2013a; Hemer et al., 2013b). Yet related to this is that increased higher-latitude wave activity in the Southern Ocean is likely to lead to increased persistence of the northward-propagating swells that affect islands in the southern low-latitude Pacific, particularly the eastern and central parts of the study area.

5.4.3. Projected future changes in tropical cyclones and storms in the Pacific and their effects

Observations of tropical-cyclone (TC) frequency and intensity over the past decade seem to agree with projections that suggest the number of TCs will decrease but that the intensity of those that do occur will be at the higher end of the intensity scale (Knutson et al., 2010). The combined effects of this reduced frequency and higher intensity are difficult to predict for island coasts because so much depends on the precise conditions of particular TCs. In general, it seems reasonable to assume that the situation will see more coasts 'recovering' between successive TCs allowing both their biophysical and human systems to revert to 'normal'. But when a TC does occur, it is likely to have more severe effects than most past TCs on coasts in its direct path and that its effects will extend further outwards.

A shift in TC tracks towards the South Pole in the southern hemisphere may see islands experience either fewer or more TCs; models suggest that the TC belt in the northern Pacific may shift towards the Equator with comparable effects.

5.4.4. Projected future changes in ENSO in the Pacific and its effects

No models are known that suggest ENSO will not remain the dominant driver of interannual climate variability in the Pacific Islands region. In fact, because natural variability in the size, location and even the precise expressions of ENSO (particularly El Niño events) is so great, it would be meaningless given the present state of knowledge to project particular impacts on particular areas of the region as a result of future changes in ENSO.

It is perhaps important to note that ENSO will continue to affect the region in the next few decades much as it does now but that its multifarious effects will be progressively imposed on a different climate and sea level. The latter is worth considering for the known variations in Pacific sea level during contrasting ENSO phases (see Figure 5.5). Therefore, compared to today, the degree of inundation during La Niña (ENSO-positive) phases in the future is likely to be greater along island coasts in the northwest Pacific. Conversely, the effects of low sea levels on offshore island ecosystems in this same area during El Niño events is likely to be less in the future because the mean sea level will be higher.

5.4.5. Projected future changes in sea level in the Pacific and its effects

Almost all models suggest that global sea-level will rise in the next few decades (Church et al., 2013), exacerbating associated effects along all coastlines. In many low-lying coastal parts of the Pacific, these effects have been felt for several decades, and in almost all Pacific island coasts for at least the last decade (Barnett and Campbell, 2010). By the end of the 21st century, sea level is likely to be at least 82 cm higher than 1986–2005, resulting in widespread disruption of both the physical and social fabric of many Pacific islands (Nunn, 2013).

Models also show that, just as sea-level rise across the Pacific has been spatially variable over the past few decades (Becker et al., 2012), so the rate of future sea-level rise is also likely to vary substantially. Some models suggest that central Pacific islands like Nauru and many in Kiribati will be affected by sea-level rise accelerating above the global average, while it is possible that some of the islands in the Federated States of Micronesia and Solomon Islands that experienced some of the highest rates of sea-level rise over the past few decades will in fact experience rates below the global average later on this century (Timmermann et al., 2010).

Figure 5.6 shows a map of projected future sea-level change in the year 2055 relative to the present (assuming an emissions scenario SRESA1B). It can be seen that the highest rates of sea-level rise in the region will continue to be in the western Pacific, particularly in Palau and the western Federated States of Micronesia, where sea-level rise over the past few decades has been above the global average. Far lower rates of sea-level rise will have occurred in parts of Papua New Guinea and Solomon Islands, as well as in the central Federated States of Micronesia. Comparatively high rates of sea-level rise will also have affected much of the central part of the study area from the Marshall Islands in the north to Fiji in the south, and from the eastern/central Solomon Islands in the west to Tuvalu in the east. Farther east, countries like Tokelau, Samoa, Niue, the Cook Islands and eastern Kiribati will have experienced lower-than-average rates of sea-level rise.

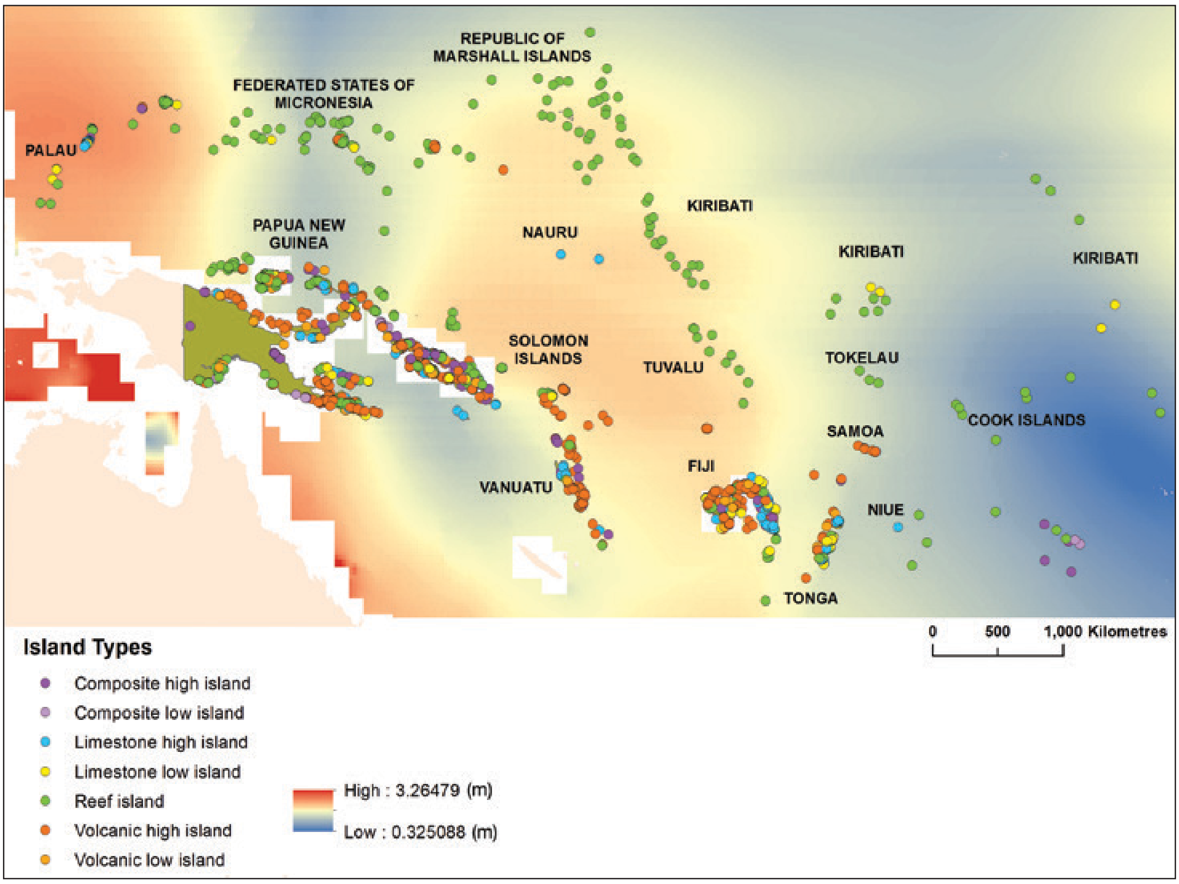


Figure 5.6 *Projected sea level in the year 2055 relative to present sea level (upper range tide in m).*

This is the projected change in mean sea level relative to 'modelled current' sea level for 2055 (upper tidal range) based on the SRESA1B emissions scenario (between RCP 4.5 and RCP 8.5 emissions scenarios). Source: Australian Bureau of Meteorology and CSIRO (2014).

The implications of these different patterns of sea-level rise bring into focus the fact that on islands of similar type the potential impact of sea-level rise could be quite different. For instance reef islands in the Federated States of Micronesia, western Kiribati and Marshall islands are likely to be affected by above-average sea-level rise over the next few decades, though this is not projected to be the case for reef islands in the northern Cook Islands or eastern Kiribati for example.

Chapter 6.
Coastal responses to a changing climate

Key points

- While coastal change has historically been a fact of life for many communities in the Pacific, climate and ocean processes together with increasing population and development on island coasts are likely to become increasing sensitive to climate change and sea-level rise.
- This chapter combines the geophysical characteristics of islands (Chapter 3) with selected climate-ocean processes and projections (Chapter 5) to understand the sensitivity of Pacific island coasts.
- The measure of island susceptibility and sensitivity to climate and ocean processes developed here is known as *geomorphic sensitivity* and is a measure of the sensitivity of island coastal areas to projected future climate conditions.
- Geomorphic sensitivity for all 1532 islands in the database show that most islands are either highly (28%) or very highly (25%) sensitive to future climate-ocean processes including sea-level rise.
- Profiles of coastal geomorphic sensitivity for individual countries in the Pacific Islands region vary considerably and provide a valuable tool for regional and national planning. States with the highest coastal geomorphic sensitivity include Tokelau, Marshall Islands, Federated States of Micronesia, Tuvalu and Tonga.

6.1. Simplifying key processes at a regional scale

To develop a coastal sensitivity index for Pacific islands, climate and ocean processes (Chapter 5) were combined in a single ranking with island susceptibility (from Chapter 3) to provide a final ranking for the overall sensitivity of coastal landforms to change from climate and ocean conditions. It is referred to here as *geomorphic sensitivity* though the first step was to develop a *process sensitivity.*

Selection of climate and ocean processes for use in the measure of process sensitivity was based on whether

- The process was meaningful for coastal response at an island scale;
- The process had variability across the Pacific;
- A regional dataset was available.

Climate and ocean processes initially considered were tides, waves, storms, inter-annual variations in mean sea level, tropical cyclones, rainfall and winds. The three processes finally selected were a measure of water-level variability (tide and ENSO), waves and tropical cyclones. They were selected to indicate the vertical range of water level and wave activity, together with the influence of tropical cyclones on coastal dynamics. A range of parameters was available for each process, with only one parameter selected per process to allow a ranking to be developed. For example, frequency, intensity, duration and approach direction are all relevant for wave activity and tropical cyclones, but only average annual significant wave height and tropical cyclone frequency respectively were selected. Each parameter is separated into five categories to ensure sufficient spatial variation across the Pacific for development into the final process rank (Table 6.1).

Table 6.1 Three parameters used for the process ranking in sensitivity

		Parameter		
		1. Composite Water Level Ranging	**2. Annual Average H_s**	**3. Tropical Cyclone Frequency**
	Description	Composite WL = (HAT-LAT) + 2 x (ENSO Ranging)	Annual Average Significant Wave Height	Based on number of tropical cyclone tracks in longest dataset available.
	Rationale for Breakpoints	Values selected to have gradation across the area	Values selected to have physical meaning for sheltering provided by island chains and ridges, as well as to correlate with rounded H_s^2 (wave energy) breaks.	Values selected based on being able to describe resilience and disturbance. Actual values to be determined later once we have actual data
RANK	Very Low	<1.0m	<1.0m	None in available dataset
	Low	1.0-1.49m	1.0–1.49m	1 (less frequent than 1 in 20 years)
	Moderate	1.5–1.99m	1.5–1.74m	2-8
	High	2.0–2.49m	1.75–1.99m	9–15
	Very High	>2.5m	>2.0m	>15 (more frequent than 1 in 3 years)

6.1.1. Composite water level

A composite water level parameter was developed to incorporate the vertical range of frequent (tide) and inter-annual (ENSO) variations in ocean water level (see Table 5.1 and 5.3). Emphasis is placed on the vertical range of water-level fluctuations to demonstrate the significance of potential sea-level rise. As mentioned previously, the effect of sea-level rise will be felt most in areas of low water-level range. The parameter selected for total tidal range was a numerical model output of Lowest Astronomical Tide to Highest Astronomical Tide (LAT to HAT), as this is a measure that indicates the maximum likely tidal excursion. However, tidal range is not the sole consideration in the Pacific because of variations in water-level attributable to ENSO, particularly in areas with a low tidal range. The absolute magnitude of water-level range due to ENSO is included when considering future effects of potential sea-level rise as it provides an indication of interannual water-level ranging as well as longer-term variations in mean sea level. To ensure the ENSO signal is incorporated appropriately in the ranking, it has been added at twice its value. This is particularly important as ENSO phases sustain higher or lower mean sea level for months or years as opposed to more frequent tidal movements. Thus the composite water-level parameter is a sum of the tidal range and twice the ENSO range. The parameter is split into five categories from very low (<1 m) to very high (>2.5 m) according to the values in Table 6.1.

The geographical variation in composite water level rankings is shown in Figure 6.1.

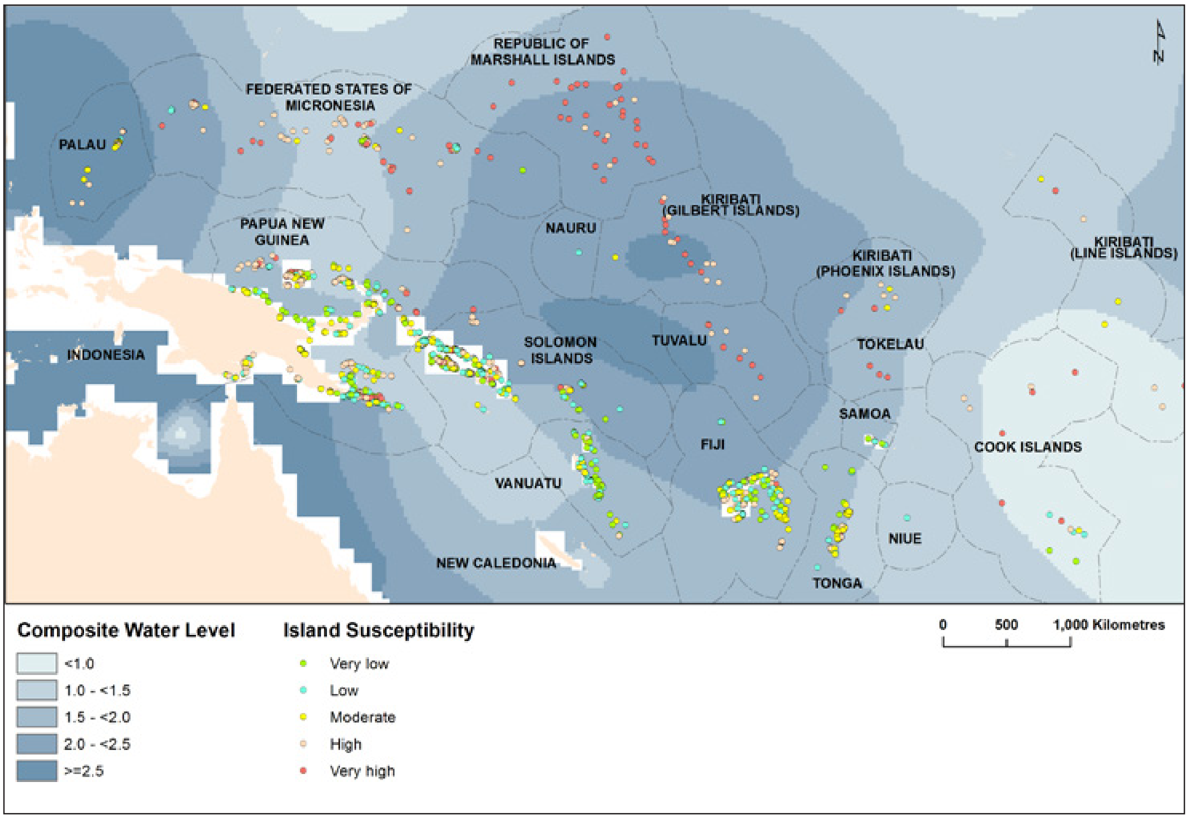


Figure 6.1 Map of composite water-level ranking in the Pacific Island region.

6.1.2. Wave height

Annual average significant wave height (Hs) was selected as the parameter for representing wave energy (see Chapter 5.2.2). The wave parameter is considered in conjunction with tropical cyclones to compare ambient and extreme conditions, as well as for consideration of potential sea-level rise.

The parameter is split into five categories from very low (<1 m) to very high (>2 m) according to the values in Table 6.1. Values for rankings were selected to incorporate physical meaning for sheltering provided by island chains and ridges, as well as to correlate with wave energy (Hs^2). The geographical variation in rankings in Figure 6.2 clearly shows an east to west decline in wave height as well as a zonal decline towards the equator in both hemispheres.

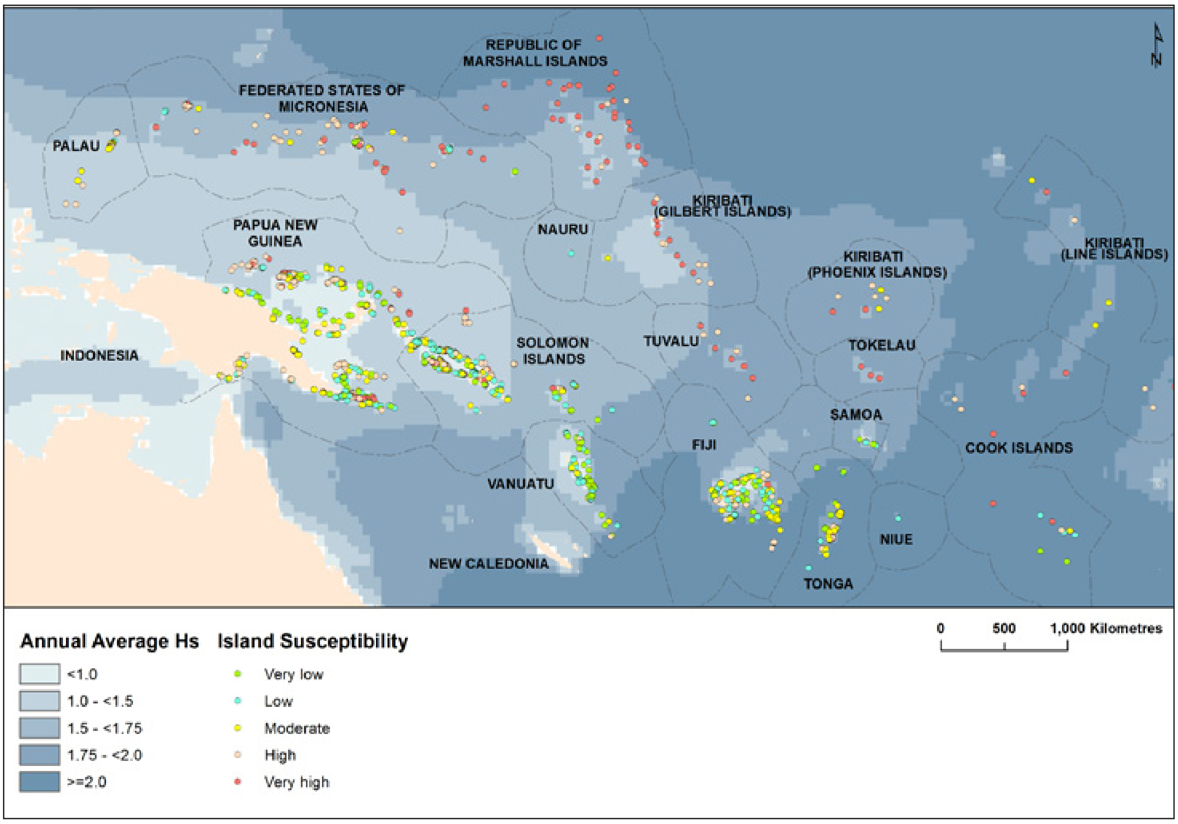


Figure 6.2 Map of annual significant wave height (Hs) ranking in the Pacific islands region.

6.1.3. Tropical cyclone frequency

Tropical-cyclone frequency was selected as the parameter for representing extreme weather events. Frequency indicates whether an area experiences tropical cyclones, and may be used to consider whether coastal landforms are resilient to extreme events. Here it is used to provide an indication of potential landform response based on the estimates of resilience and likelihood of disturbance. The map of tropical cyclone tracks (Figure 5.3) was annotated to separate the Pacific into five categories of tropical-cyclone frequency. The very low category represents no tropical cyclones in the available dataset, with very high representing areas where tropical cyclones occur more frequently than one in three years. Geographical variation in the rankings is shown in Figure 6.3, with two cores of high frequency, one covering Vanuatu and west of Fiji, the other extending to the north of the Federated States of Micronesia.

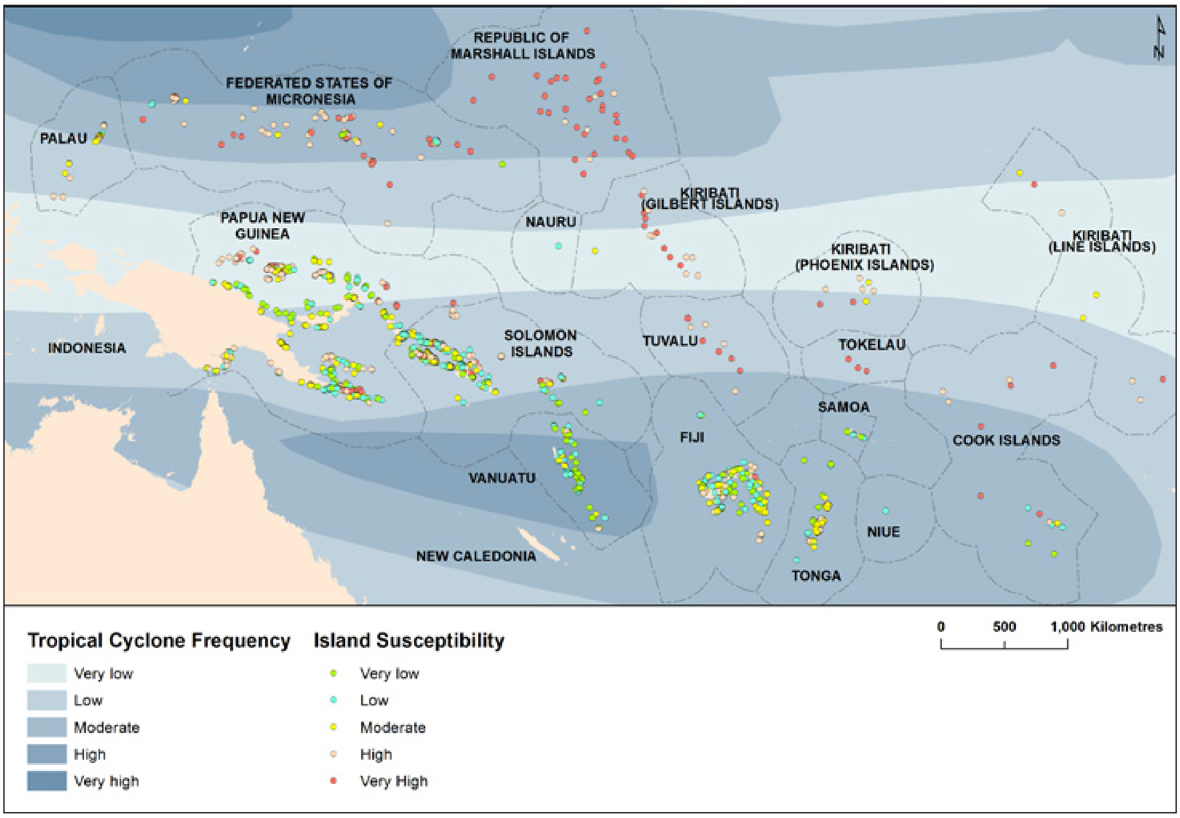


Figure 6.3 Map of tropical cyclone frequency ranking in the Pacific Islands region.

6.2. Process sensitivity

The three parameters—composite water level, significant wave height and tropical cyclone frequency—were combined to yield a single value (see Appendix 3.1 for the methodology used) to obtain a climate-ocean process sensitivity as a measure of potential island-coast change to future conditions. Results of this assessment for the 1532 islands in the database are presented in Figure 6.4 and Figure 6.5.

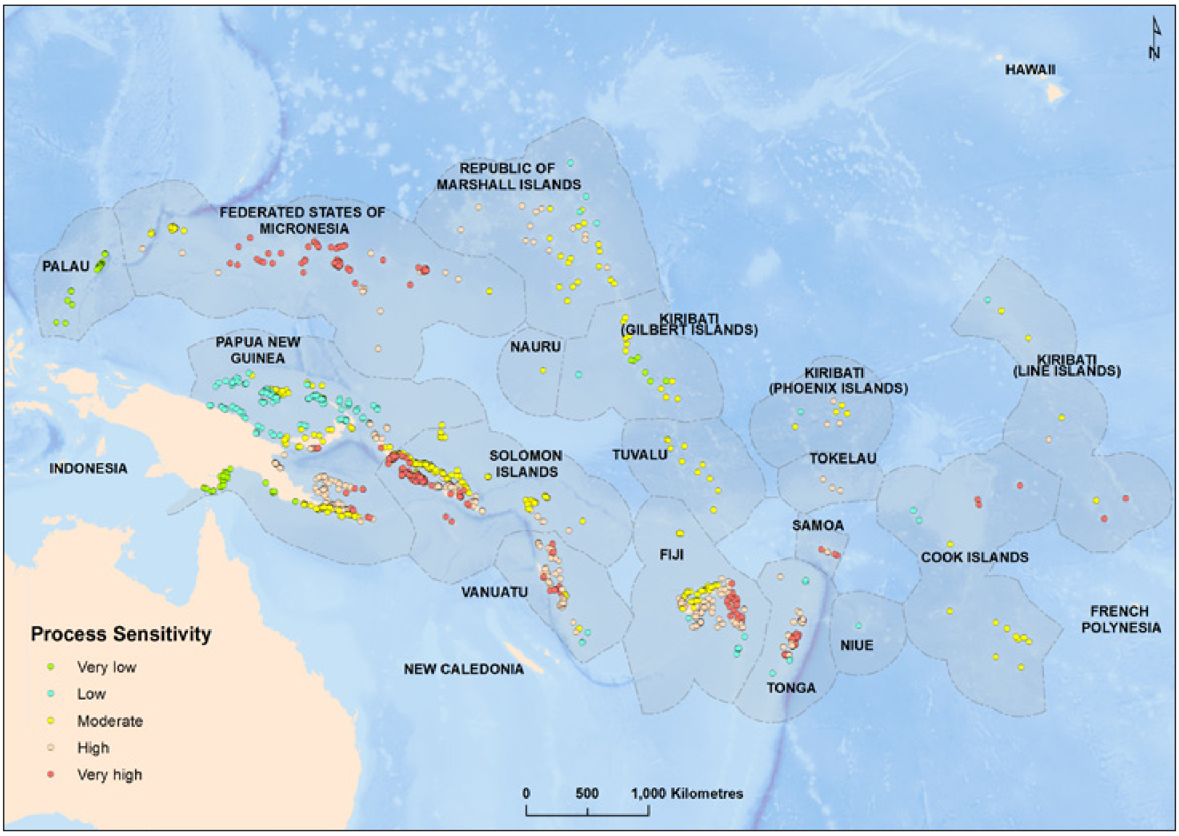


Figure 6.4 Process sensitivity for all 1532 islands in the data base.

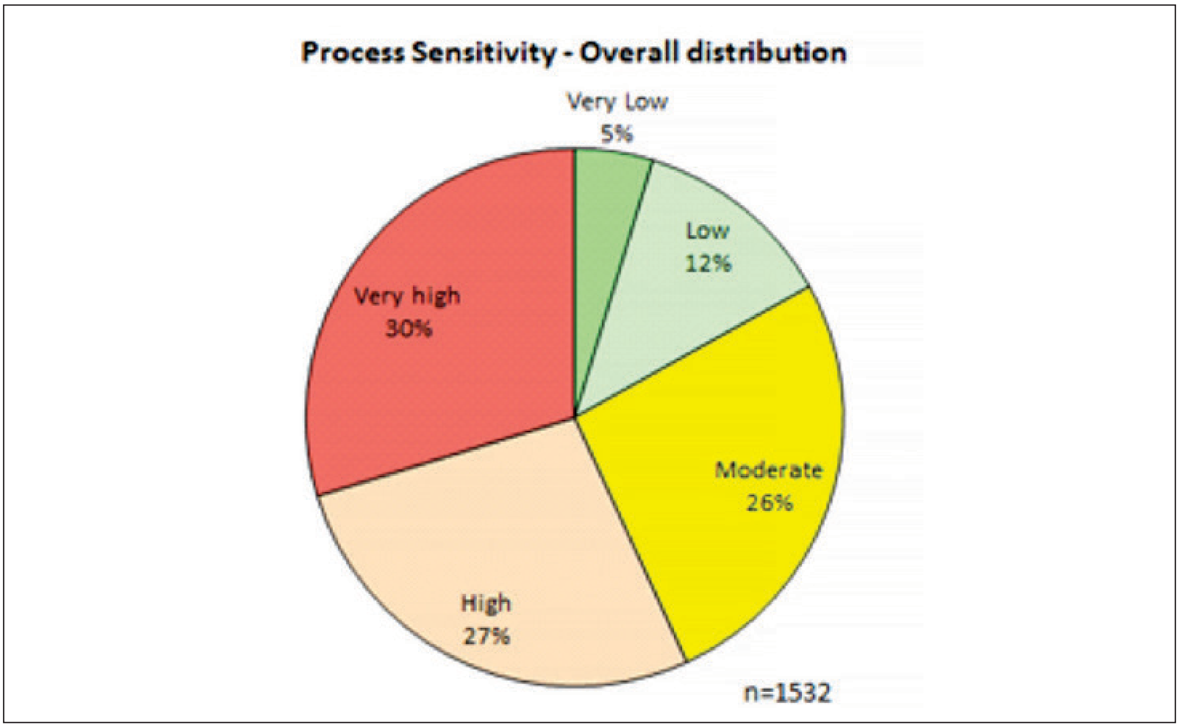


Figure 6.5 Distribution of process sensitivity for all 1532 islands in the database.

Process sensitivity for whole islands was mainly moderate (26%), high (27%) or very high (30%) with fewer falling into the lower ranks of very low (5%) and low (12%) (Figure 6.5). This skewness towards moderate and higher rankings is attributed to the location of islands in areas of some combination of lower composite water-level range, moderate wave heights, and some tropical-cyclone activity.

6.3. Variations in process sensitivity between countries

The distribution of process sensitivities for different countries is also of interest (Figure 6.6 and Table A3.4). The figure and table demonstrate a different range of process sensitivities for all but single island countries.

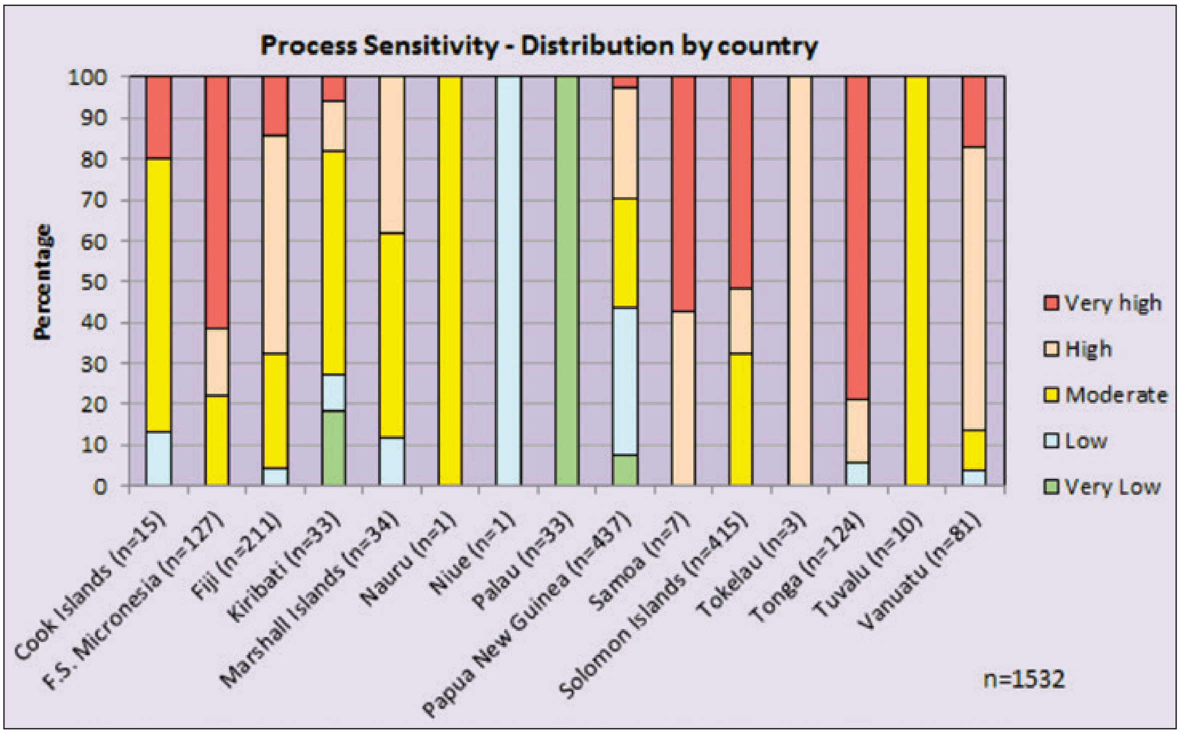


Figure 6.6 Process sensitivity by country (single island countries excluded).

The modal process sensitivity for each country is shown in Table A3.4. All of Palau's islands have a process sensitivity of very low because the area has a high level of energetic coastal processes (high tidal range, high wave heights and high tropical cyclones). This suggests the area is not likely to be sensitive to small changes in mean sea level, waves or tropical-cyclone activity. Niue has one island, with a low sensitivity to potential changes in environmental forcing. The mode of Papua New Guinea is also low, with islands ranging from very low to very high due to the influence of the large land mass of New Guinea on ocean processes. Nauru has one island, categorised as moderately sensitive to changes in environmental forcing. Other countries with a mode of moderate process sensitivity are the Cook Islands, Kiribati, Marshall Islands and Tuvalu. The mode of Fiji, Tokelau and Vanuatu is high, with islands ranging from low to very high except in Tokelau. The Federated States of Micronesia, Samoa, Solomon Islands and Tonga each have a mode of very high, with most islands ranging from moderate to very high.

6.4. Geomorphic sensitivity of island coasts

The term *geomorphic sensitivity* is applied to the combination of island susceptibility (Chapter 4) and process sensitivity. This is a means of considering the sensitivity of the coastal landforms of whole islands to potential changes in climate-ocean processes. To do this both the drivers (process sensitivity) and receptors (island susceptibility) are integrated. The methodology used to derive the geomorphic sensitivity of islands is detailed in Appendix 4.

Process sensitivity and geomorphic sensitivity were calculated for all 1532 islands in the database (Table A4.1). As an example, the susceptibility, process sensitivity and geomorphic sensitivity are shown for a sample of islands in Table A4.2.

The ten volcanic islands ranged from low to moderate (mode low) geomorphic sensitivity, compared with very low to moderate (mode very low) susceptibility. The approach of combining susceptibility and processes raised the modal sensitivity of the volcanic islands. The weighted secondary assessment of indicative vulnerability ranged from low to high for these islands.

Only one of the seven composite islands changed ranking by applying the combined susceptibility and process sensitivity, with Oreor changing from low susceptibility to very low geomorphic sensitivity. This was because Oreor is located in an area of very low process sensitivity and the other example composite islands had a low or moderate process sensitivity, similar to the ranks of island susceptibility.

The derivation of geomorphic sensitivity for the eight limestone islands changed four of the islands with moderate susceptibility to a high geomorphic sensitivity, with the remaining four islands rank remaining unchanged. The four islands that changed rank were in areas of high or very high process sensitivity, with the increased rank not represented in the secondary assessment of indicative vulnerability.

The 11 reef islands ranged from high to very high susceptibility, with two of the high ranked islands changing to very high geomorphic sensitivity when the process sensitivity was applied.

6.5. Broad-scale geomorphic sensitivity of island coasts

Geomorphic sensitivity is presented for the 1532 islands in the database as a combined measure of island susceptibility and potential sensitivity to changes in climate-ocean processes (Figure 6.7). The geomorphic sensitivities for whole islands were mainly moderate (23%), high (28%) and very high (25%) with fewer falling into the lower ranks of very low (5%) and low (19%) (Figure 6.8). This skewness towards the moderate to higher geomorphic sensitivities is attributed to many of the islands with lower susceptibility occurring in areas with higher process sensitivities. Applying the process sensitivity changed the susceptibility ranks to different geomorphic sensitivities for 882 (58%) of the islands in the database.

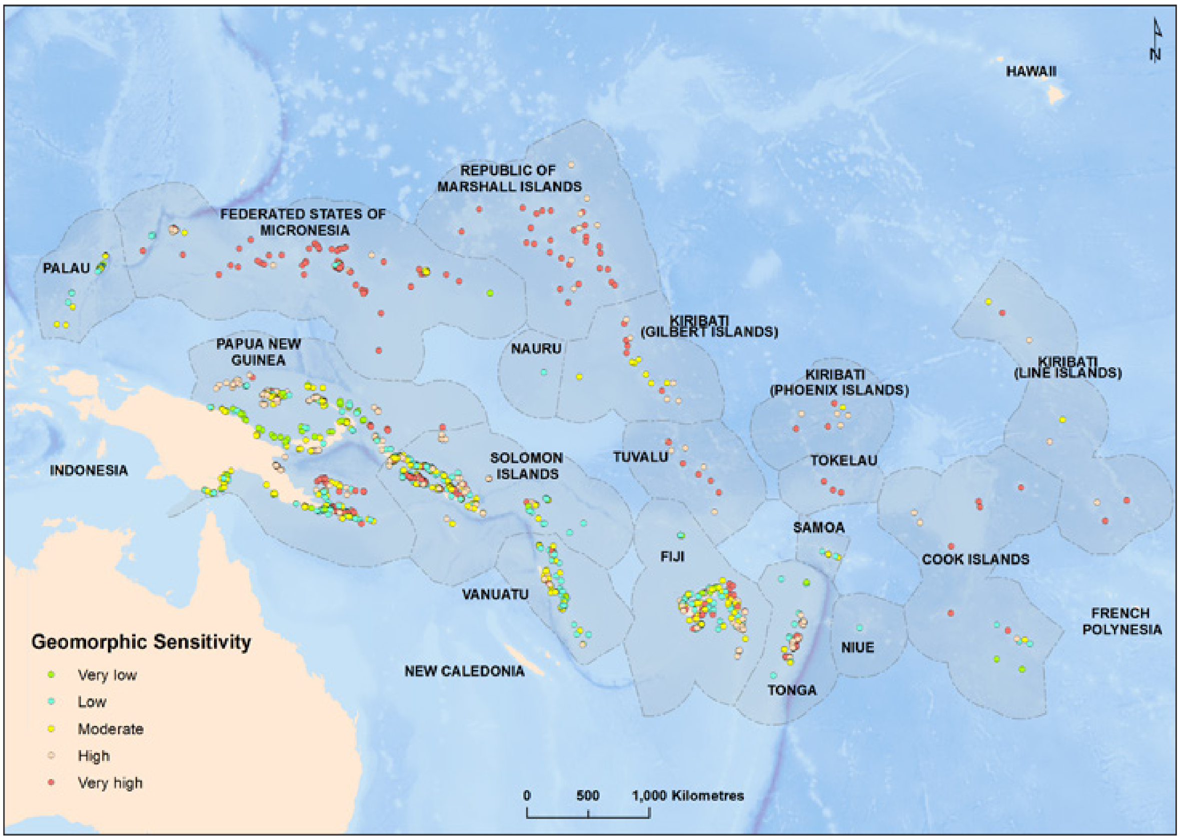


Figure 6.7 *Geomorphic sensitivity for the 1532 in the database.*

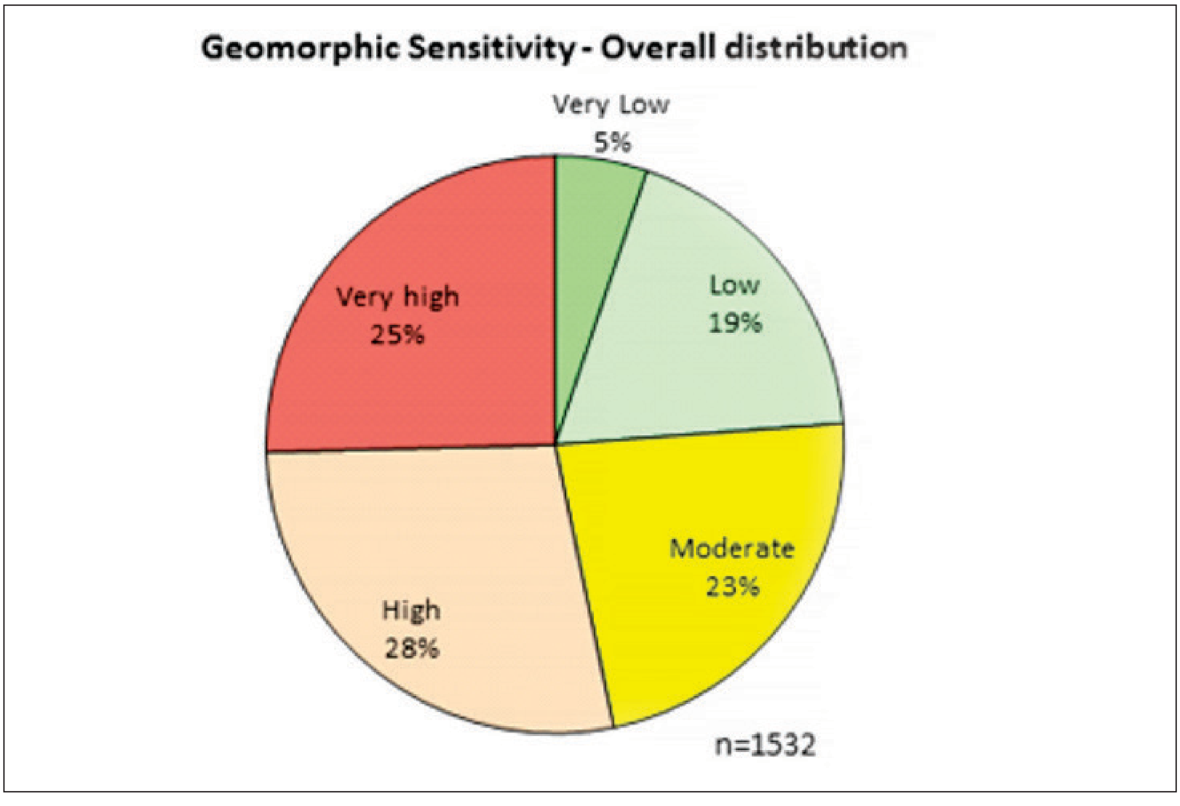


Figure 6.8 *Geomorphic sensitivity for all islands in the database.*

6.6. Geomorphic sensitivity by country and island type

Variations in geomorphic sensitivities are found for different countries (Figure 6.9 and Table A4.3). The figure and appendix table demonstrate a different range of geomorphic sensitivities for all but single-island countries. The countries with some islands in the very high category are Cook Islands, Fiji, Kiribati, Papua New Guinea, Tonga and Vanuatu. The countries with the modal category of very high geomorphic sensitivity are the Federated States of Micronesia, Marshall Islands, Solomon Islands, Tokelau (all three islands) and Tuvalu.

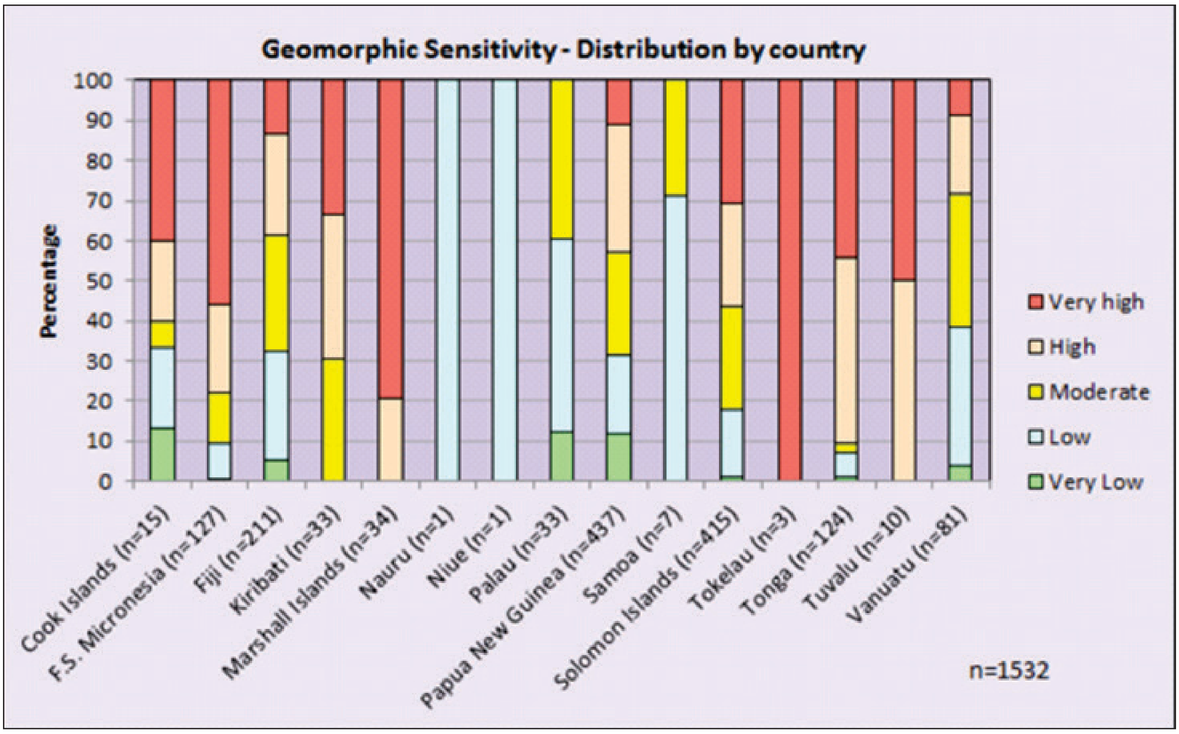


Figure 6.9 Geomorphic sensitivity by country.

Certain island types are more geomorphically sensitive than others (Figure 6.10 and Table A4.4).

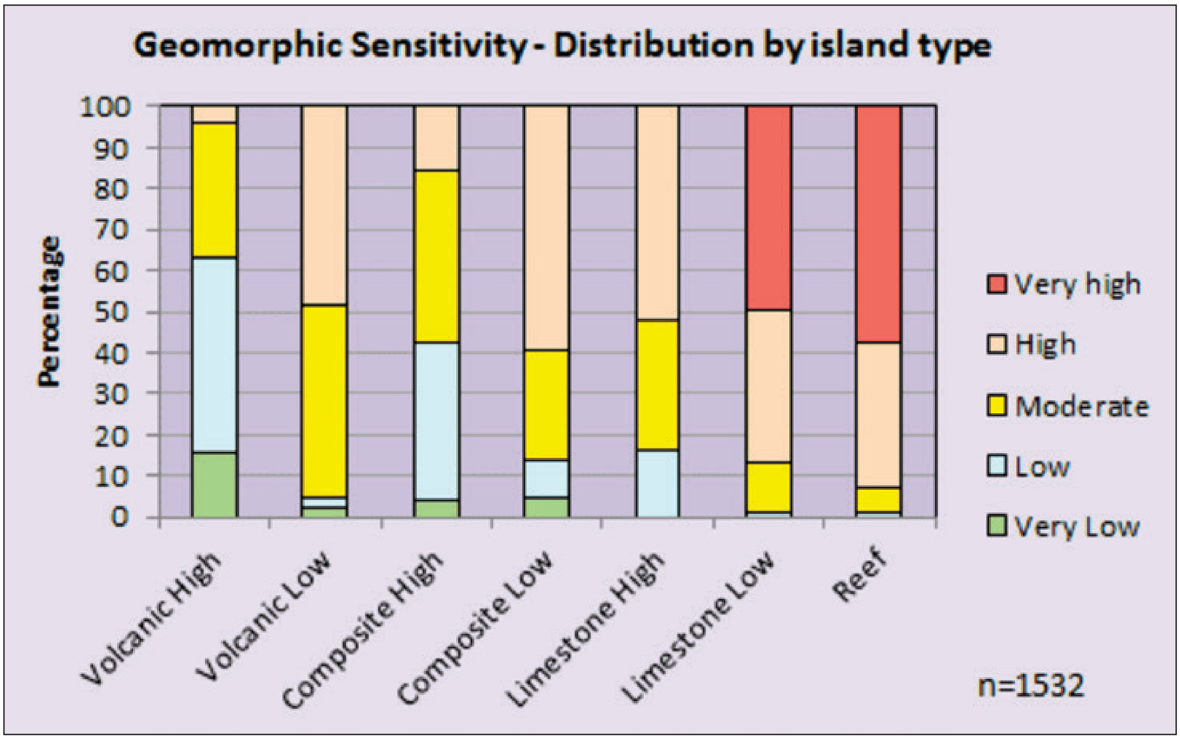


Figure 6.10 Geomorphic sensitivity by island type.

Volcanic high and composite high islands are the least sensitive, with reef islands and limestone low islands the most sensitive. The modal geomorphic sensitivity for each island type is highlighted in Table A4.4. If an island is a volcanic high island, it is most likely to be in the low geomorphic sensitivity category, ranging from very low to high. If an island is composite high, it is most likely to be moderate, ranging from very low to high geomorphic sensitivities. If an island is a volcanic low, composite low or limestone high island, it is most likely to be in the high geomorphic sensitivity category, ranging from very low (or low) to high. If an island is limestone high or a reef island, it is most likely to be in the very high geomorphic sensitivity category, ranging from low to very high. Applying the process sensitivity to susceptibility to generate the geomorphic sensitivity has increased the modal sensitivity to changing environmental variables by one level for all island types other than volcanic high islands.

Chapter 7.
Key Findings and Implications for Planning and Management

Key points

- This analysis provides the first regional assessment of potential coastal response to climate change in the Pacific region.
- Coastal change will drive movement of people inland from the coast or to another island, which means land-use planning approaches become involved, or to another country when migration settings become more of a focus.
- This analysis identifies a science-based assessment process that can guide decision makers through identifying sensitive areas at local scale through to regional.
- Further analysis will enable well-informed assessments of coastal risk and encourage the development of robust adaptation responses.

7.1. Introduction

This chapter briefly reviews the main implications of the findings of this report for both donors, like Australian Aid, and in-country partners, ranging from Pacific Island governments and regional organisations to communities confronted by coastal-environmental changes attributable to climate change. The degree to which particular islands are exposed to such changes is discussed in Chapter 3 at a whole-island scale using the measure of susceptibility. Islands are each assigned a measure of susceptibility that can be used to identify areas at a regional scale of various degrees of sensitivity to coastal landform change. Susceptibilities should also be of value for regional planning, especially by regional agencies, for the purpose of identifying areas of comparative need both at present and in the future.

The assessment described in Chapters 2-6 of this report allows a comparative analysis of susceptibility to change between islands in the Pacific Islands region as well as within particular islands.

7.2. Whole-island susceptibility

This section provides an overview of whole-island susceptibility (i) across the entire Pacific Islands region and (ii) for each constituent country; this analysis is not comprehensive but is intended to show the potential of the methodology that has been developed for the objective data-informed assessment of island susceptibility. The most useful application of this will to help regional decision-makers determine where 'hotspots' of potential change/impact exist, both now and in the future, in order to target interventions to appropriate places.

7.2.a. Regional overview

The type of island most susceptible to change based on lithology and elevation (see Chapter 2) is the 'reef island', which is found throughout the Pacific Islands region yet occurring only rarely in its southern part (Vanuatu-Fiji-Tonga-Samoa-southern Cook Islands) (see Figure 2.4). In terms of understanding region-wide responses to possible diminishing habitability of reef islands, as is likely as sea-level rise accelerates this century (Dickinson, 2009), it is important to note that reef islands are generally the sole island type found in much of the central Pacific meaning that, unlike other places where they are also numerous, there are no nearby islands with lower vulnerability to which displaced people might relocate (see Figure 2.4).

Reef islands, although comprising all/most islands in countries like Kiribati, Marshall Islands, Tokelau and Tuvalu, are actually more numerous in countries like Papua New Guinea, Solomon Islands and the Federated States of Micronesia (see Figure 2.5). The total area of reef islands in Papua New Guinea (1533 km^2) and Solomon Islands (455 km^2) is also significantly greater than in most 'atoll nations', the largest of these being Kiribati with a total 897 km^2 of reef islands (see Figure 2.6). It is envisaged that the graphs in Figure 2.7 and Figure 2.8, which show the same data by constituent country in the Pacific Islands region could be useful as tools for determining relative national susceptibility for different purposes.

For example, water conservation might be considered more critical on limestone islands which comprise all Nauru and Niue and more than half the islands in Palau and Tonga, something readily seen on Figure 2.7. Subtle differences emerge when considering the area of limestone islands within particular countries (in Figure 2.8) where the situation in Palau is actually somewhat less critical than might be supposed from looking at Figure 2.7; only a small area of limestone islands are found in this island group (Figure 2.8).

When drivers of change—recent and projected (future)—are factored in, whole-island susceptibility to change was mapped (see Figure 3.1). This map shows that the islands most susceptible to change are in the northern part of the region, from the Federated States of Micronesia in the northwest through to the northern Cook Islands in the southeast. Those islands least susceptible to change have a parallel distribution, from Papua New Guinea in the northwest to the southern Cook Islands in the southeast. Within this broad picture, there are some interesting sub-regional observations, including the following.

In some parts of the atoll area, there are islands with moderate susceptibility close to those with high to very high susceptibility, opening up the possibility of the relocation of threatened populations from the latter to the former. Examples are found in parts of central and eastern Kiribati as well as in the Federated States of Micronesia. The reverse situation is found in parts of western Melanesia (Papua New Guinea and Solomon Islands) where there are concentrations of highly susceptible islands, often peripheral to the main groups, that are nevertheless close to islands with much lower susceptibility.

The distribution of susceptibility within each country in the region was shown graphically in Figure 3.4 in a way that allows decision-makers to make a rapid assessment of each country's susceptibility profile. Thus countries with many islands like Papua New Guinea and Solomon Islands have a fairly uniform distribution of island susceptibilities, raising the possibility that issues around displaced peoples, for example, might all be resolved internally. A contrasting situation is found in countries like the Marshall Islands and Tuvalu where all islands have either high or very high susceptibility. Interesting observations can also be made about island countries that fall between these extremes. In the Cook Islands, for instance, more than half of the 15 islands have high or very high susceptibility, suggesting that internal migration from outer islands to Rarotonga might continue as well as continued out-migration to New Zealand. In contrast, Vanuatu has a profile that is generally far less susceptible implying that few island populations might need to relocate internally in the future.

In terms of future susceptibility to change that is different from the present nature of change (process sensitivity), based on projections of key drivers of coastal change, it is also possible to look at the regional distribution by islands (see Figure 6.4). This map shows a distribution that can be interpreted as what is likely to happen in the next few decades. Large swathes of the islands in the region are not likely to see much change in the nature of the processes that have affected them in the recent past; such islands are found in Palau and northern Papua New Guinea with moderate change being predicted for the Marshall Islands, Tuvalu, much of Kiribati and the southern Cook Islands. More concern might be felt about the future of island coasts in parts of Solomon Islands, Vanuatu, Fiji, Tonga and Samoa which are dominated by high or very high process sensitivities.

The country-by-country distribution of process sensitivity (see Figure 6.6) is also instructive, with countries like Vanuatu, Samoa and Tonga showing a high sensitivity to process change while others like Kiribati, the Marshall Islands and even Papua New Guinea showing much lower sensitivities. This information is important for planning purposes, countries with lower sensitivity being able to plan with more certainty for future change while others with greater sensitivity needing to be more aware of projections of future change.

This picture can be viewed alongside the distribution of geomorphic sensitivity (see Figure 6.7) that expresses the degree to which coastal landforms on particular islands are likely to be affected by future climate-linked processes. Most higher islands are understandably less liable to change while most lower islands are more so. There are interesting sub-regional patterns, particularly in western Melanesia and western Kiribati that could be noted in regional planning.

Geomorphic sensitivity by country (see Figure 6.9) allows planners insights that complement those of process sensitivity, discussed above. Very high geomorphic sensitivities understandably occur in atoll countries, where coasts are formed mostly from unconsolidated materials, but there are also interesting profiles for other countries. There is a fairly even distribution of geomorphic sensitivities in the Cook Islands, Fiji and Vanuatu, for example, that reflects the diverse nature of island coasts therein, something that could be used as a proxy measure of coastal resilience.

7.2.b. National susceptibility

There is considerable variation in susceptibility to externally-driven change within the Pacific Islands region by country. This section gives an overview of this variation and explains how the data presented in earlier chapters can be used to provide more specific information.

Most of the islands in the **Cook Islands** are reef islands with around 25% being composite high in type (Figure 2.7). Yet when the land area of these islands is used, it is seen that more than 65% of the Cook Islands are high with composite lithologies (Figure 2.8). This allows the latter island type to be recognised as the dominant one. As shown in Figure 3.3, composite high islands are moderate to very low in terms of their susceptibility that allows the interpretation that the largest area of land in the Cook Islands is not unduly susceptible to extraneous change even though a majority of its constituent islands are more susceptible (Figure 3.4). Process sensitivity gives a more mixed picture (Figure 6.8). The geomorphic sensitivity of Cook Island coasts to future changes in process is a cause for greater concern, with 60% of coasts calculated as having either high or very high landform sensitivity (Figure 6.9).

Most of the islands in the **Federated States of Micronesia** are reef islands with around 20% being volcanic high in type (Figure 2.7). Yet when the land area of these islands is used, it is seen that around 75% of islands in the Federated States of Micronesia are high with volcanic lithologies (Figure 2.8). This allows the latter island type to be recognised as the dominant one. As shown in Figure 3.3, volcanic high islands are moderate to very low in terms of their susceptibility that allows the interpretation that the largest area of land in the Federated States of Micronesia is not unduly susceptible to extraneous change even though a majority of its constituent islands are more susceptible (Figure 3.4). Process sensitivity shows that process changes in the future are a major concern (very high process sensitivity) for a majority of islands in the Federated States of Micronesia (Figure 6.6).

The geomorphic sensitivity of coasts in the Federated States of Micronesia to future changes in process is a cause for some concern, with nearly 60% of coasts calculated as having very high landform sensitivity (Figure 6.9).

Most of the islands in **Fiji** are volcanic with significant numbers of other types (Figure 2.7). Yet when the land area of these islands is used, it is seen that nearly 60% of Fiji is high with composite lithologies, followed closely by volcanic high islands (Figure 2.9). In planning terms, there seems a good case for looking only at these two types. As shown in Figure 3.3, both these island types are moderate to very low in terms of their susceptibility that allows the interpretation that the largest area of land in Fiji is not unduly susceptible to extraneous change; only around 22% of the islands in Fiji have a high susceptibility to change, the rest being more resilient (Figure 3.4). Process sensitivity gives a more mixed picture (Figure 6.6). The geomorphic sensitivity of Cook Island coasts to future changes in process is of interest, with an almost uniform distribution (Figure 6.9).

Most of the islands (>80%) in **Kiribati** are reef islands with a few classified as limestone low and one (Banaba) as limestone high in type (Figure 2.7). Yet when the land area of these islands is used, it is seen that more than 90% of Kiribati are reef islands (Figure 2.8). This allows the latter island type to be recognised as the dominant one. As shown in Figure 3.3, reef islands are high to very high in terms of their susceptibility that allows the interpretation that the largest area of land in Kiribati is extremely susceptible to extraneous change even though almost 20% of its islands are rated as having low susceptibility (Figure 3.4). Process sensitivity gives a more mixed picture with all categories well represented and 'moderate' susceptibility dominating (Figure 6.6). The geomorphic sensitivity of Kiribati coasts to future changes in process is a cause for greater concern, with almost 70% of coasts calculated as having either high or very high landform sensitivity (Figure 6.9).

All islands in the **Marshall Islands** are reef islands (Figure 2.7). As shown in Figure 3.3, reef islands are high to very high in terms of their susceptibility that allows the interpretation that the largest area of land in the Marshall Islands is extremely susceptible to extraneous change with around 85% of its islands exhibiting very high susceptibility (Figure 3.4). Process sensitivity gives a more mixed picture with the three middle categories well represented and 'moderate' susceptibility dominating (Figure 6.6). The geomorphic sensitivity of Marshall Island coasts to future changes in process is a cause for greater concern, with almost 80% of coasts calculated as having very high landform sensitivity, a reflection of the almost total dominance of soft-sediment coasts in this island group (Figure 6.9).

The only island in **Nauru** is a limestone high island (Figure 2.7). As shown in Figure 3.3, such islands have mostly a moderate susceptibility (Figure 3.4). Process sensitivity is also calculated as moderate (Figure 6.6). The geomorphic sensitivity of Nauru's coasts to future changes in process is low, implying that there will be few physical climate-associated changes to the island's coast within the next few decades (Figure 6.9).

The only island in **Niue** is also a limestone high island (Figure 2.7). As shown in Figure 3.3, such islands have mostly a moderate susceptibility (Figure 3.4). Process sensitivity is calculated as low, a reflection of the different region of the Pacific in which this island lies compared to Nauru (Figure 6.6). The geomorphic sensitivity of Niue's coasts to future changes in process is low, implying that there will be few physical climate-associated changes to the island's coast within the next few decades (Figure 6.9).

Most of the islands in **Palau** are limestone high islands with slightly more than 20% being reef islands (Figure 2.7). Yet when the land area of these islands is used, it is seen that around 80% of Palau is high with composite lithologies, a reflection of the comparatively great size of Babeldaob Island and the smallness of the others (Figure 2.8). This allows the composite high island type to be recognised as the dominant one. As shown in Figure 3.3, such islands are mostly low in terms of their susceptibility that allows the interpretation that the largest area of land in Palau is not unduly susceptible to extraneous change even though some 40% of its constituent islands have either high or very high susceptibility (Figure 3.4). Process sensitivity shows that process changes in the future are of little concern, all of Palau showing a very low process sensitivity (Figure 6.6). The geomorphic sensitivity of coasts in Palau to future changes in process is likewise a cause of comparatively little concern, with all coasts calculated as having moderate to very low landform sensitivity (Figure 6.9).

The islands in **Papua New Guinea** are numerous and because they are found in a range of geotectonic contexts exhibit a range of island types dominated by reef islands and volcanic high islands (Figure 2.7). Yet when the land area of these islands is used (excluding the island of New Guinea itself), it is seen that around 75% of islands in Papua New Guinea are high with composite lithologies, the outcome of the large land areas of islands like New Britain and New Ireland (Figure 2.8). This allows the latter island type to be recognised as the dominant one. As shown in Figure 3.3, composite high islands are moderate to very low in terms of their susceptibility that allows the interpretation that the largest area of land in Papua New Guinea is not unduly susceptible to extraneous change even though just over 35% of its constituent islands have high or very high susceptibility (Figure 3.4). Process sensitivity is likewise variable within this extensive island group yet quite different from adjoining Solomon Islands (see below), islands with low process sensitivity slightly dominant (Figure 6.6). The geomorphic sensitivity of coasts in Papua New Guinea to future changes in process also shows a somewhat uniform spread (Figure 6.9).

All seven islands in **Samoa** are volcanic high islands (Figure 2.7). As shown in Figure 3.3, volcanic high islands are moderate to very low in terms of their susceptibility that allows the interpretation that the largest area of land in Samoa is not unduly susceptible to extraneous change even though just under 30% of its constituent islands have moderate susceptibility (Figure 3.4). Process sensitivity is more a cause for concern with all islands having either high or vary high process sensitivity (Figure 6.6). The geomorphic sensitivity of coasts in Samoa to future changes in process is either moderate or low (Figure 6.9).

The islands in **Solomon Islands** are numerous and because they are found in a range of geotectonic contexts exhibit a range of island types dominated by reef islands and volcanic high islands (Figure 2.7). Yet when the land area of these islands is used, it is seen that >80% of islands in Solomon Islands are high with composite lithologies, the outcome of the large land areas of islands like Choiseul, Guadalcanal and Malaita (Figure 2.8). This allows the latter island type to be recognised as the dominant one. As shown in Figure 3.3, composite high islands are moderate to very low in terms of their susceptibility that allows the interpretation that the largest area of land in Solomon Islands is not unduly susceptible to extraneous change even though 40% of its constituent islands have high or very high susceptibility (Figure 3.4). Process sensitivity is likewise variable within this extensive island group yet quite different from adjoining Papua New Guinea (see above), islands with very high process sensitivity comprising more than 50% of the total number of islands (Figure 6.6). The geomorphic sensitivity of coasts in Solomon Islands to future changes in process is also dominated by islands with high or very high sensitivity (Figure 6.9).

All three islands in **Tokelau** are reef islands (Figure 2.7). As shown in Figure 3.3, reef islands are high to very high in terms of their susceptibility that allows the interpretation that the largest area of land in Tokelau is extremely susceptible to extraneous change with all islands exhibiting very high susceptibility (Figure 3.4). Process sensitivity shows that all islands have a high sensitivity (Figure 6.6). The geomorphic sensitivity of Tokelau coasts to future changes in process is a cause for greater concern, with all coasts calculated as having very high landform sensitivity, a reflection of the total dominance of soft-sediment coasts in this island group (Figure 6.9).

The islands of **Tonga** are comparatively numerous and are dominated by limestone islands, the low variety slightly outnumbering the high variety (Figure 2.7). Yet when the land area of these islands is used, it is seen that >70% of islands in Tonga are limestone high islands, the outcome of the large land areas of islands like Tongatapu and Vava'u (Figure 2.8). This allows the latter island type to be recognised as the dominant one. As shown in Figure 3.3, limestone high islands are moderate to low in terms of their susceptibility that allows the interpretation that the largest area of land in Tonga has an average susceptibility to extraneous change even though nearly 40% of its constituent islands have high susceptibility (Figure 3.4). Process sensitivity gives a different picture, islands with very high process sensitivity comprising nearly 80% of the total number of islands (Figure 6.6). The geomorphic sensitivity of coasts in Solomon Islands to future changes in process is also dominated by islands with high or very high sensitivity (Figure 6.9).

All ten islands in **Tuvalu** are reef islands (Figure 2.7). As shown in Figure 3.3, reef islands are high to very high in terms of their susceptibility that allows the interpretation that the largest area of land in Tuvalu is extremely susceptible to extraneous change with all islands exhibiting very high susceptibility (Figure 3.4). Process sensitivity shows that all islands have a moderate sensitivity (Figure 6.6). The geomorphic sensitivity of Tokelau coasts to future changes in process is a cause for greater concern, with all coasts calculated as having either high or very high landform sensitivity, a reflection of the near-total dominance of soft-sediment coasts in this island group (Figure 6.9).

The islands in **Vanuatu** are found in a range of geotectonic contexts exhibit a range of island types dominated by volcanic high islands (Figure 2.7). Yet when the land area of these islands is used, it is seen that >60% of islands in Vanuatu are high with composite lithologies, the outcome of the large land areas of islands like Espiritu Santo and Efate (Figure 2.8). This allows the latter island type to be recognised as the dominant one. As shown in Figure 3.3, composite high islands are moderate to very low in terms of their susceptibility that allows the interpretation that the largest area of land in Solomon Islands is not unduly susceptible to extraneous change with nearly 90% of its constituent islands having moderate to very low susceptibility (Figure 3.4). Process sensitivity presents a quite different picture, islands with very high or high process sensitivity comprising more than 85% of the total number of islands (Figure 6.6). The geomorphic sensitivity of coasts in Solomon Islands to future changes in process is more mixed, being dominated by islands with low or moderate sensitivity (Figure 6.9).

The next steps in dealing with these results at country level would be to overlay information about other factors such as island population densities, economic value/potential, and even community/district resilience in order to identify 'hotspots' where severe impacts on particular island populations might occur. These are likeliest to be in areas where there is elevated levels of process sensitivity as well as high geomorphic sensitivity.

7.3. Future directions

In terms of overall susceptibility, it is clear that there are hotspots within the region where all measures developed point to an above-average exposure to external change, both now and in the future. It is no surprise that reef islands, particularly those that are comparatively isolated, are among the most susceptible but there are numerous subtleties that would be revealed by applying the secondary and tertiary analyses to the entire dataset.

This project has developed a methodology that could be applied to other areas of islands, tweaked for different purposes, and could eventually become a standard for the assessment of susceptibility to change. In a future world where change becomes more rapid at the same time as funds to assist poorer countries to cope with that change become inevitably more scarce, the development of tools of this kind is a priority.

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Appendices

Appendix 1.
Estimates of susceptibility and instability

A.1.1 Weighted and non-weighted estimates of susceptibility

Susceptibility levels estimated for the 36 islands are shown for the six criteria together with the final susceptibility ranking in Table A2.1, for both non-weighted and weighted (as in Table 4.6) criteria. Eight islands had a high susceptibility; four had low susceptibility, and the majority (24) show moderate susceptibility. For the weighted criteria this shifted to 14 with high susceptibility, 19 with moderate susceptibility, and three with low susceptibility.

Table A1.1 Susceptibility rankings for 36 illustrative islands

	Island Name	Rank							Susceptibility	Weighted Susceptibility (see Table 4.6 for weightings)
		Geology	Roundness	Perimeter to Square root Area Ratio	Maximum Elevation	Proximity	Shore gradient	Susceptibility Score		
1	Aitutaki Island, Southern Group, Cook Islands	3	3	3	1	5	5	20	Moderate Susceptibility	Moderate Susceptibility
2	Aniwa Island, Vanuatu	4	2	4	2	5	4	21	Moderate Susceptibility	High Susceptibility
3	Aore Island, Vanuatu	4	2	4	2	2	2	16	Moderate Susceptibility	Moderate Susceptibility
4	Atafu Island, Tokelau	5	4	1	5	5	5	25	High Susceptibility	High Susceptibility
5	Atiu, Cook Islands	3	1	5	2	5	5	21	Moderate Susceptibility	High Susceptibility
6	Banaba (Ocean), Kiribati	4	1	4	2	5	4	20	Moderate Susceptibility	High Susceptibility
7	Bellona Island, Solomon Islands	4	2	4	2	5	4	21	Moderate Susceptibility	High Susceptibility
8	Eluvuka, Fiji	5	1	5	5	3	2	21	Moderate Susceptibility	High Susceptibility
9	Emananus Island, Saint Matthias (Mussau) Group, Papua New Guinea	3	3	3	2	4	4	19	Moderate Susceptibility	Moderate Susceptibility
10	Kiritimati (Christmas Island), Line Islands Group, Kiribati	5	4	1	5	5	4	24	High Susceptibility	Moderate Susceptibility
11	Lifuka Island, Ha'apai Group, Tonga	4	3	4	4	3	4	22	Moderate Susceptibility	Moderate Susceptibility
12	Loun Island, Russell Group, Solomon Islands	2	1	4	2	2	4	15	Moderate Susceptibility	Moderate Susceptibility
13	Mangaia, Cook Islands	3	1	4	1	5	5	19	Moderate Susceptibility	Moderate Susceptibility
14	Manihiki, Cook Islands	5	5	1	5	5	5	26	High Susceptibility	High Susceptibility
15	Manono Island, Samoa	2	2	4	1	3	2	14	Low Susceptibility	Moderate Susceptibility

	Island Name	Rank: Geology	Roundness	Perimeter to Square root Area Ratio	Maximum Elevation	Proximity	Shore gradient	Susceptibility Score	Susceptibility	Weighted Susceptibility (see Table 4.6 for weightings)
16	Manuae (Scilly) Island, French Polynesia	5	4	2	4	5	5	25	High Susceptibility	High Susceptibility
17	Mauke, Cook Islands	3	1	4	3	5	5	21	Moderate Susceptibility	Moderate Susceptibility
18	Nauru	4	1	5	2	5	5	22	Moderate Susceptibility	High Susceptibility
19	Niuafo'ou Island, Tonga	2	1	5	1	5	5	19	Moderate Susceptibility	Moderate Susceptibility
20	Niue	4	1	4	2	5	5	21	Moderate Susceptibility	High Susceptibility
21	Onotoa island, Gilbert Group, Kiribati	5	4	1	5	5	2	22	Moderate Susceptibility	Moderate Susceptibility
22	Oreor (Koror), Palau	3	4	3	1	1	1	13	Low Susceptibility	Low Susceptibility
23	Ovalau, Fiji	2	2	4	1	4	1	14	Low Susceptibility	Moderate Susceptibility
24	Penrhyn, Cook Islands	5	5	1	5	5	4	25	High Susceptibility	High Susceptibility
25	Pohnpei, FSM	2	1	5	1	4	2	15	Moderate Susceptibility	Moderate Susceptibility
26	Pukapuka, Cook Islands	5	2	4	5	5	4	25	High Susceptibility	High Susceptibility
27	Rakahanga, Cook Islands	5	2	4	5	5	4	25	High Susceptibility	High Susceptibility
28	Rarotonga, Cook Isands	3	1	4	1	5	4	18	Moderate Susceptibility	Moderate Susceptibility
29	Savai'i, Samoa	2	2	4	1	2	4	15	Moderate Susceptibility	Moderate Susceptibility
30	Tarawa, Kiribati	5	5	1	5	3	4	23	High Susceptibility	Moderate Susceptibility
31	Tongatapu, Tonga	4	4	2	2	2	4	18	Moderate Susceptibility	Moderate Susceptibility
32	Tonowas (Tonoas) Island, Chuuk Group, Federated States of Micronesia	2	3	3	1	1	1	11	Low Susceptibility	Low Susceptibility
33	Upolu, Samoa	2	3	3	1	3	4	16	Moderate Susceptibility	Moderate Susceptibility

	Island Name	Rank							Susceptibility	Weighted Susceptibility (see Table 4.6 for weightings)
		Geology	Roundness	Perimeter to Square root Area Ratio	Maximum Elevation	Proximity	Shore gradient	Susceptibility Score		
34	Utupua Island, Eastern outer Solomon Islands	2	4	2	1	3	4	16	Moderate Susceptibility	Moderate Susceptibility
35	Vaitupu Island, Tuvalu	5	2	4	5	4	2	22	Moderate Susceptibility	High Susceptibility
36	Vogali (Mbuke; Wogali) Island, Manus Group, Papua New Guinea	2	2	4	3	2	1	14	Low Susceptibility	Low Susceptibility

Instability scores for the 36 islands are shown for the nine criteria that contribute to Susceptibility together with the final susceptibility ranking in Table A1.2 for both non-weighted and weighted (as in Table 4.6) criteria. The rationale behind each of the rankings is included for each of the nine criteria in Table 4.2. Two islands had a high instability, 12 had low instability, and the majority (22) showed moderate instability. For the weighted criteria, this shifted to 12 with high instability, 17 with moderate instability and seven with low instability.

Table A1.2 Instability rankings for 36 illustrative islands

	Island Name	Rank									Instability Score	Instability	Weighted Instability (see Table 4.6 for weightings)
		Backshore Slope	Backshore Sediment	Backshore Landforms	Intertidal Shore—Sediment Type	Intertidal Shore—Landforms	Inshore—morphology	Reef—Type	Reef—Width	Reef—Cover			
1	Aitutaki Island, Southern Group, Cook Islands	3	2	3	4	5	2	4	1	1	25	Moderate Instability	Moderate Instability
2	Aniwa Island, Vanuatu	3	2	3	3	5	2	2	4	1	25	Moderate Instability	Moderate Instability
3	Aore Island, Vanuatu	3	1	1	4	4	2	2	4	3	24	Moderate Instability	Moderate Instability
4	Atafu Island, Tokelau	4	3	4	4	4	1	5	3	1	29	Moderate Instability	Moderate Instability
5	Atiu, Cook Islands	4	1	2	3	3	2	2	4	1	22	Moderate Instability	Moderate Instability
6	Banaba (Ocean), Kiribati	3	1	1	3	2	1	2	4	1	18	Low Instability	Low Instability
7	Bellona Island, Solomon Islands	3	1	2	2	1	2	2	4	2	19	Low Instability	Low Instability
8	Eluvuka, Fiji	5	5	4	4	4	1	5	1	1	30	Moderate Instability	High Instability
9	Emananus Island, Saint Matthias (Mussau) Group, Papua New Guinea	4	2	4	5	1	2	2	1	2	23	Moderate Instability	Moderate Instability
10	Kiritimati (Christmas Island), Line Islands Group, Kiribati	5	5	4	4	4	2	5	4	3	36	High Instability	High Instability
11	Lifuka Island, Ha'apai Group, Tonga	4	1	3	4	4	1	2	1	2	22	Moderate Instability	Moderate Instability
12	Loun Island, Russell Group, Solomon Islands	3	2	3	4	3	2	2	4	2	25	Moderate Instability	Moderate Instability
13	Mangaia, Cook Islands	3	1	1	1	3	1	2	3	1	16	Low Instability	Low Instability
14	Manihiki, Cook Islands	4	3	4	4	4	1	5	4	1	30	Moderate Instability	High Instability
15	Manono Island, Samoa	4	1	2	4	3	1	3	1	2	21	Low Instability	Moderate Instability
16	Manuae (Scilly) Island, French Polynesia	5	4	4	4	4	3	5	4	1	34	High Instability	High Instability
17	Mauke, Cook Islands	3	1	1	3	2	1	2	4	1	18	Low Instability	Low Instability
18	Nauru	3	1	2	4	4	1	2	2	1	20	Low Instability	Moderate Instability

	Island Name	Rank									Instability Score	Instability	Weighted Instability (see Table 4.6 for weightings)
		Backshore Slope	Backshore Sediment	Backshore Landforms	Intertidal Shore—Sediment Type	Intertidal Shore—Landforms	Inshore—morphology	Reef—Type	Reef—Width	Reef—Cover			
19	Niuafo'ou Island, Tonga	2	1	1	1	3	2	1	5	5	21	Low Instability	Low Instability
20	Niue	2	1	1	1	3	2	2	4	4	20	Low Instability	Low Instability
21	Onotoa island, Gilbert Group, Kiribati	4	3	4	4	4	1	5	1	3	29	Moderate Instability	Moderate Instability
22	Oreor (Koror), Palau	3	1	1	1	5	3	2	1	2	19	Low Instability	Moderate Instability
23	Ovalau, Fiji	4	2	4	5	2	2	4	4	3	30	Moderate Instability	High Instability
24	Penrhyn, Cook Islands	4	3	4	4	4	1	5	4	1	30	Moderate Instability	High Instability
25	Pohnpei, FSM	5	2	4	5	5	2	4	1	3	31	Moderate Instability	High Instability
26	Pukapuka, Cook Islands	5	3	4	4	4	3	5	1	1	30	Moderate Instability	High Instability
27	Rakahanga, Cook Islands	4	3	4	4	4	3	5	3	2	32	Moderate Instability	High Instability
28	Rarotonga, Cook Isands	4	2	3	3	4	3	2	1	2	24	Moderate Instability	Moderate Instability
29	Savai'i, Samoa	3	1	1	1	2	1	2	5	4	20	Low Instability	Low Instability
30	Tarawa, Kiribati	4	4	4	4	4	1	5	3	2	31	Moderate Instability	High Instability
31	Tongatapu, Tonga	3	1	1	1	3	3	2	4	3	21	Low Instability	Moderate Instability
32	Tonowas (Tonoas) Island, Chuuk Group, Fed. States of Micronesia	4	2	4	5	2	2	3	1	1	24	Moderate Instability	Moderate Instability
33	Upolu, Samoa	3	1	3	3	2	3	2	1	2	20	Low Instability	Moderate Instability
34	Utupua Island, Eastern outer Solomon Islands	5	1	4	5	2	2	4	1	2	26	Moderate Instability	Moderate Instability
35	Vaitupu Island, Tuvalu	4	3	4	4	4	5	5	1	2	32	Moderate Instability	High Instability
36	Vogali (Mbuke; Wogali) Island, Manus Group, Papua New Guinea	5	2	4	5	4	2	2	1	2	27	Moderate Instability	High Instability

Appendix 2.
Tertiary criteria and weightings for susceptibility assessment

Table A.2.1 Tertiary assessment criteria for susceptibility

	LITHOLOGY	LANDFORMS				SHORELINE PLANFORM	INSHORE MORPHOLOGY	REEF		
Rank	**Coastal lithology**	**Landform element for >50% of coastal sector**	**Maximum width of landform (m)**	**Length of shore along landform (km)**	**Mid-landform elevation (m)**	**Shoreline planform of the coastal sector**	**Inshore morphology for >50% of coastal sector**	**Reef type directly offshore**	**Distance offshore (km)**	**Width of reef (m)**
5	Unconsolidated sediment of marine or terrestrial origin	Coastal flats, including washover fans and low (<5m) inundation plains; OR	<50	<1	<5	Irregular shoreline with the depth of embayments being less than the distance (chord length) between the headlands containing them.	Stepped subtidal sandy terrace formed of unconsolidated sediments grading to beach.	Fringing reef abutting an island on a reef flat; OR	< 0.01	<50
		Reef flats						Platform or reef along lagoonal shore		
4	Limestone	Embayments partly or wholly infilled with marine sediments and without stream discharge; OR	50 - 99.99	0.99 - 4.99	5 to 9	Convex coast or salient facing ocean or lagoon. The salient may be a broad headland, singular rocky headland or cuspate foreland	Discontinuous subtidal platform or pavement	Merging of fringing and barrier reef along the sector	0.01 - 0.099	50 - 99.99

	LITHOLOGY	LANDFORMS				SHORELINE PLANFORM	INSHORE MORPHOLOGY	REEF		
Rank	Coastal lithology	Landform element for >50% of coastal sector	Maximum width of landform (m)	Length of shore along landform (km)	Mid-landform elevation (m)	Shoreline planform of the coastal sector	Inshore morphology for >50% of coastal sector	Reef type directly offshore	Distance offshore (km)	Width of reef (m)
		Forelands (including beach ridge plains) or spits with elevations <10m.								
3	Composite	Coastal plains >10m elevation; OR	100 - 499.99	5 - 9.99	10 to 15	Highly irregular shoreline with the length of inlets being greater than the distance between the headlands containing them.	Inshore lagoon with patch reef and sand sheets; OR	Barrier reef; OR	0.1 - 0.999	100 - 499.99
		Embayments partly or wholly infilled by stream deposition of deltas, alluvial fans and terrestrial outwash.					Beach overlying beachrock exposed on upper beach face.	Attached reef; OR		
								Fringing reef, without attachment and merging with other reef types.		
2	Volcanic	Raised rock platform or sediments on rocky terrace >10m elevation with low gradient to landward	500 -1000	10 - 19.99	15 to 19	Concave coastline, embayment or estuary facing ocean or lagoon. The depth of the embayment is >> than the distance between the headlands containing it.	Inshore lagoon with reef pavement and sand sheets; OR	Composite fringing and barrier reef - including reef platform in an atoll lagoon; OR	1.0 - 10.0	500 - 1000
							Sandy beach overlying reef pavement or rock platform.	fringing reef attached to a rocky island		
1	Continental	Terrace or coastal plain with a steep upward gradient to landward	>1000	>20.0	>19	Straight or slightly rhythmic shoreline for >80% of sector	Continuous subtidal platform or boulder ramp	No reef, includes plunging cliffs or boulder ramps	>10	>1000

A2.2 Weightings

Table A2.2 Weightings for tertiary assessment criteria for susceptibility

Susceptibility Criteria	Weighting
Lithology	20%
Landform element	15%
Max width of landform	5%
Landform length	5%
Mid-landform elevation	5%
Shoreline planform	5%
Inshore morphology	10%
Reef type	15%
Distance offshore	10%
Width of reef	10%
Total	**100%**

Appendix 3. Developing the process sensitivity measure

A3.1. Developing the process sensitivity measure

Composite water level (tide range + 2x ENSO range) wave height and tropical cyclone frequency were combined to yield a single value for ranking of potential sensitivity of the coast to a change in mean sea level across the region. When attributed to individual islands this measure is referred to as a *process sensitivity*. The measure focuses on future sensitivity to changes in mean sea level, with less emphasis on present levels of risk.

Following preparation of the three parameter rasters, the process ranking was calculated in three steps. The first step was to combine the rankings of tropical-cyclone frequency and annual average significant wave heights into a matrix to obtain a score (Table A3.1) because the tropical-cyclone influence is integrated with wave response. These parameters are linked in terms of the island landform resilience and likely disturbance as a result of potential sea-level rise. This table may be used as a look-up table to obtain a value based on the ranking of the two parameters. The results of applying this matrix to the Pacific is demonstrated at a conceptual level in Figure A3.1.

Table A3.1 Combining annual average significant wave height and tropical-cyclone frequency parameters

		TC				
		Very Low	Low	Moderate	High	Very High
Hs	Very Low	1	3.5	5	7	8
	Low	1.75	5.5	6.75	6.75	6.75
	Moderate	4	7.25	8	6.5	5
	High	2	5	5.5	3.5	2.5
	Very High	1	1.25	1.25	1	1

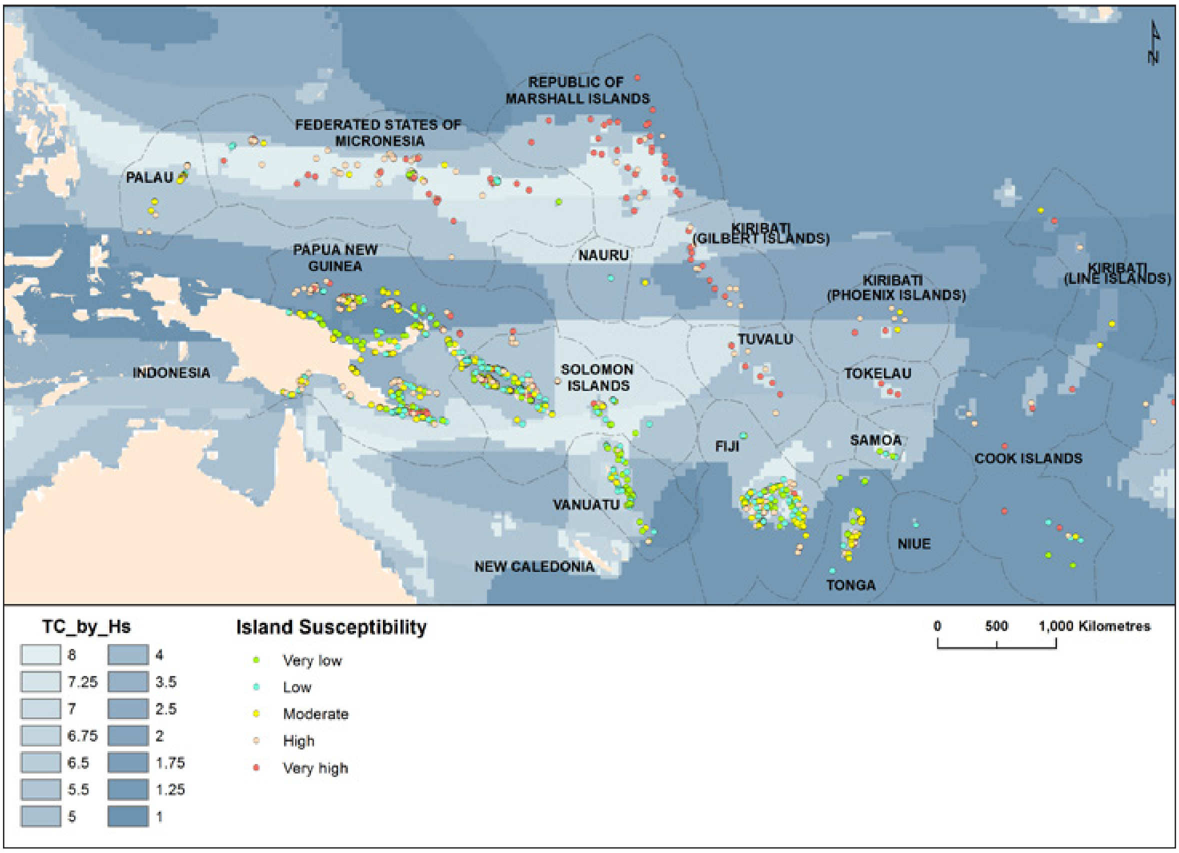

Figure A3.1 Map of combined annual average significant wave height (Hs) and tropical-cyclone frequency in the Pacific Islands region (see also Table A3.1).

Areas with exposure to frequent tropical cyclones are highly likely to have a high resilience to changing environmental parameters while an area with exposure to 'no record of tropical cyclones' will respond to waves alone. Areas with low wave heights and high tropical-cyclone frequency are sensitive to changes in mean sea level as the coastal landforms have a limited capacity to rebuild when they are eroded or deflated during extreme events. Areas with high wave heights and low tropical-cyclone frequency already have a large hydraulic zone with capacity for rebuilding. Yet such areas are most susceptible to human modification of the coastal landforms and reef structures.

The second step determined the relationship of water level and sensitivity to changing environmental variables. The result is monotonic and inverse to the water-level range. A very low water-level range is most sensitive to changing environmental variables. A composite water-level multiplier (Table A3.2) was applied to the combined wave height and tropical cyclone matrix (as in Table A3.1).

Table A3.2 Composite water-level multiplier

		Multiplier
Composite Water Level	Very Low	2
	Low	1.5
	Moderate	1
	High	0.5
	Very High	0.05

The values in Step 1 (see Table A3.1 and Figure A3.1) and Step 2 (Table A3.2) were multiplied to generate values from 0.05 to 16 for the 125 unique combinations of the three parameters. Cut-off values were applied to this score to obtain the 5-point process ranking (Table A3.3). The cut-off values were selected to generate a physically meaningful process ranking according to the authors' understanding of dynamics in the Pacific Ocean (see Chapter 5). The process rank is presented in Figure A3.2 as a five-class raster against the country boundaries and primary indicative susceptibility for the 1532 islands in the database (Chapter 4).

Table A3.3 Cutoff values for Process Ranking

		Range
5-Point Combined Process Rank	Very Low	0 to 0.625
	Low	0.63 to 2
	Moderate	2.1 to 4
	High	4.1 to 8
	Very High	8.1 to 16

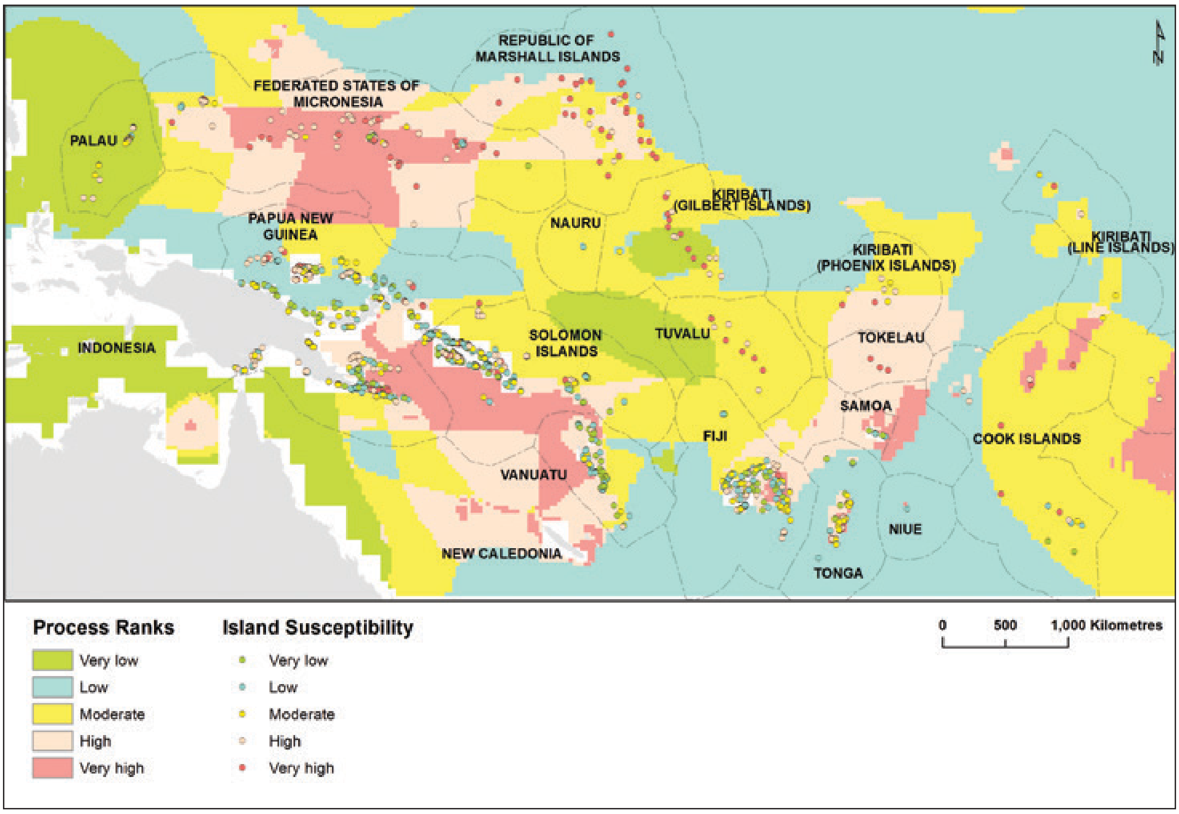

Figure A3.2 Map of process ranking in the Pacific Islands region (see also Table A3.4).

The process ranking and indicative susceptibility can be combined in a final geomorphic sensitivity only if a process ranking value is attributed to each of the islands ('process sensitivity'), thereby converting a raster to a point. For each of the islands in the database, the process ranking value that was the closest to that island in terms of Euclidean distance was selected and attributed as a process sensitivity. For many of the smaller islands, the island polygon sat within the larger process ranking pixel so that pixel was extracted (30-km grid). For the larger islands, where there are gaps in the process ranking (white areas in Figure A3.2), the value of the closest cell was selected as the process sensitivity.

Table A3.4 Process sensitivity by country

	Process Sensitivity										Total	
	Very Low		Low		Moderate		High		Very High			
Country	Count	% of Country	Count	% of Country	Count	% of Country	Count	% of Country	Count	% of Country	Number of Islands	% of Islands
Cook Islands	0	0%	2	13%	**10**	**67%**	0	0%	3	20%	15	1%
F.S. Micronesia	0	0%	0	0%	28	22%	21	17%	**78**	**61%**	127	8%
Fiji	0	0%	9	4%	59	28%	**113**	**54%**	30	14%	211	14%
Kiribati	6	18%	3	9%	**18**	**55%**	4	12%	2	6%	33	2%
Marshall Islands	0	0%	4	12%	**17**	**50%**	13	38%	0	0%	34	2%
Nauru	0	0%	0	0%	**1**	**100%**	0	0%	0	0%	1	0.10%
Niue	0	0%	**1**	**100%**	0	0%	0	0%	0	0%	1	0.10%
Palau	**33**	**100%**	0	0%	0	0%	0	0%	0	0%	33	2%
Papua New Guinea	33	8%	**158**	**36%**	116	27%	118	27%	12	3%	437	29%
Samoa	0	0%	0	0%	0	0%	3	43%	**4**	**57%**	7	0.50%
Solomon Islands	0	0%	0	0%	135	33%	66	16%	**214**	**52%**	415	27%
Tokelau	0	0%	0	0%	0	0%	**3**	**100%**	0	0%	3	0.20%
Tonga	0	0%	7	6%	0	0%	19	15%	**98**	**79%**	124	8%
Tuvalu	0	0%	0	0%	**10**	**100%**	0	0%	0	0%	10	1%
Vanuatu	0	0%	3	4%	8	10%	**56**	**69%**	14	17%	81	5%
TOTAL	**72 (5%)**		**187 (12%)**		**402 (26%)**		**416 (27%)**		**455 (30%)**		**1532**	

Appendix 4.
Development of a measure of coastal geomorphic sensitivity

The five-point rankings of indicative susceptibility were combined with the five-point process sensitivity with a non-linear skewness for indicative susceptibility (Table A4.1). An inverse logarithmic trend is applied to the resulting measure of island susceptibility in order to have a higher importance in the geomorphic sensitivity ranking, given that it is the notional 'response' variable. This results in islands with very low indicative susceptibility only having very low or low geomorphic sensitivity rankings. Islands with very high indicative susceptibility rankings are weighted to have a higher likelihood of a very high geomorphic sensitivity ranking.

Table A4.1 Combining Susceptibility and Process Sensitivity to obtain Geomorphic Sensitivity

		Process Sensitivity				
		Very Low	**Low**	**Moderate**	**High**	**Very High**
Indicative Susceptibility	**Very Low**	Very Low	Very Low	Very Low	Low	Low
	Low	Very Low	Low	Low	Moderate	Moderate
	Moderate	Low	Moderate	Moderate	High	High
	High	Moderate	High	High	Very High	Very High
	Very High	Moderate	High	Very High	Very High	Very High

Process sensitivity and geomorphic sensitivity were calculated for all 1532 islands in the database. As an example, the indicative susceptibility, process sensitivity and geomorphic sensitivity are shown in Table A4.2 for a sample of 36 islands.

Table A4.2 Processes and Geomorphic Sensitivity for 36 Islands considered in Secondary Assessment

	Island	Primary Assessment Indicative Susceptibility	Process Sensitivity	Geomorphic Sensitivity	Secondary Assessment Indicative Sensitivity	
					Non-weighted	Weighted
1	Aitutaki Island, Cook Islands	Low	Moderate	Low	Moderate	Moderate
2	Aniwa Island, Vanuatu	Moderate	Moderate	Moderate	Moderate	High
3	Aore Island, Vanuatu	Moderate	High	High	Moderate	Moderate
4	Atafu Island, Tokelau	Very High	High	Very High	High	High
5	Atiu, Cook Islands	Low	Moderate	Low	Moderate	High
6	Banaba (Ocean), Kiribati	Moderate	Low	Moderate	Low	Moderate
7	Bellona Island, Solomon Islands	Moderate	Very High	High	Low	Moderate
8	Eluvuka, Fiji	High	High	Very High	Moderate	Very High
9	Emananus I., Papua N. Guinea	Moderate	Low	Moderate	Moderate	Moderate
10	Kiritimati, Kiribati	High	Moderate	High	Very High	High
11	Lifuka Island, Tonga	Moderate	Very High	High	Moderate	Moderate
12	Loun Island, Solomon Islands	Low	High	Moderate	Moderate	Moderate
13	Mangaia, Cook Islands	Very Low	Moderate	Very Low	Low	Low
14	Manihiki, Cook Islands	Very High	Very High	Very High	High	Very High
15	Manono Island, Samoa	Very Low	High	Low	Very Low	Moderate
16	Manuae Island, French Polynesia	Very High	Moderate	Very High	Very High	Very High
17	Mauke, Cook Islands	Low	Moderate	Low	Low	Low
18	Nauru	Low	Moderate	Low	Low	High
19	Niuafo'ou Island, Tonga	Very Low	High	Low	Low	Low
20	Niue	Low	Low	Low	Low	Moderate
21	Onotoa island, Kiribati	Very High	Moderate	Very High	Moderate	Moderate
22	Oreor (Koror), Palau	Low	Very Low	Very Low	Very Low	Low
23	Ovalau, Fiji	Very Low	High	Low	Low	High
24	Penrhyn, Cook Islands	Very High	Very High	Very High	High	Very High
25	Pohnpei, FSM	Very Low	Very High	Low	Moderate	High

	Island	Primary Assessment Indicative Susceptibility	Process Sensitivity	Geomorphic Sensitivity	Secondary Assessment Indicative Sensitivity	
					Non-weighted	Weighted
26	Pukapuka, Cook Islands	High	Low	High	High	Very High
27	Rakahanga, Cook Islands	High	Very High	Very High	High	Very High
28	Rarotonga, Cook Isands	Very Low	Moderate	Very Low	Moderate	Moderate
29	Savai'i, Samoa	Very Low	Very High	Low	Low	Low
30	Tarawa, Kiribati	Very High	Moderate	Very High	High	High
31	Tongatapu, Tonga	Moderate	Very High	High	Low	Moderate
32	Tonowas I, Fed. St. of Micronesia	Low	Very High	Moderate	Low	Low
33	Upolu, Samoa	Very Low	Very High	Low	Low	Moderate
34	Utupua I., Solomon Islands	Low	High	Moderate	Moderate	Moderate
35	Vaitupu Island, Tuvalu	High	Moderate	High	Moderate	Very High
36	Vogali I., Papua New Guinea	Moderate	Low	Moderate	Low	Moderate

The geomorphic sensitivity of islands coasts for a sample of countries is shown in Table A4.3 and for the island types Table A4.4.

Table A4.3 Geomorphic sensitivity by country

	Driver Index										Total	
	Very Low		Low		Moderate		High		Very High			
Country	Count	% of Country	Count	% of Country	Count	% of Country	Count	% of Country	Count	% of Country	Number of Islands	% of Islands
Cook Islands	2	13%	3	20%	**1**	**7%**	3	20%	6	40%	15	1%
F.S. Micronesia	1	1%	11	9%	16	13%	28	22%	**71**	**56%**	127	8%
Fiji	11	5%	57	27%	**62**	**29%**	53	25%	28	13%	211	14%
Kiribati	0	0%	0	0%	10	30%	**12**	**36%**	11	33%	33	2%
Marshall Islands	0	0%	0	0%	0	0%	7	21%	**27**	**79%**	34	2%
Nauru	0	0%	**1**	**100%**	0	0%	0	0%	0	0%	1	0.10%
Niue	0	0%	**1**	**100%**	0	0%	0	0%	0	0%	1	0.10%
Palau	4	12%	**16**	**48%**	13	39%	0	0%	0	0%	33	2%
Papua New Guinea	52	12%	86	20%	111	25%	**139**	**32%**	49	11%	437	29%
Samoa	0	0%	**5**	**71%**	2	29%	0	0%	0	0%	7	0.50%
Solomon Islands	5	1%	70	17%	106	26%	107	26%	**###**	**31%**	415	27%
Tokelau	0	0%	0	0%	0	0%	0	0%	**3**	**####**	3	0.20%
Tonga	1	1%	8	6%	3	2%	**57**	**46%**	55	44%	124	8%
Tuvalu	0	0%	0	0%	0	0%	**5**	**50%**	**5**	**50%**	10	1%
Vanuatu	3	4%	**28**	**35%**	27	33%	16	20%	7	9%	81	5%
TOTAL	79 (5%)		286 (19%)		351 (23%)		427 (28%)		389 (25%)		1532	

Table A4.4 Geomorphic sensitivity by island type

	Driver Index											
	Very Low		Low		Moderate		High		Very High		Total	
Country	Count	% of Country	Count	% of Country	Count	% of Country	Count	% of Country	Count	% of Country	Number of Islands	% of Islands
Volcanic High	71	16%	**215**	**47%**	148	33%	19	4%	0	0%	453	30%
Volcanic Low	3	2%	4	3%	68	47%	**70**	**48%**	0	0%	145	9%
Composite High	4	4%	37	38%	**41**	**42%**	15	15%	0	0%	97	6%
Composite Low	1	5%	2	9%	6	27%	**13**	**59%**	0	0%	22	1%
Limestone High	0	0%	19	17%	36	31%	**60**	**52%**	0	0%	115	8%
Limestone Low	0	0%	2	1%	22	12%	66	37%	**88**	**49%**	178	12%
Reef	0	0%	7	1%	30	6%	184	35%	**301**	**58%**	522	34%
TOTAL	**79 (5%)**		**286 (19%)**		**351 (23%)**		**427 (28%)**		**389 (25%)**		**1532**	

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