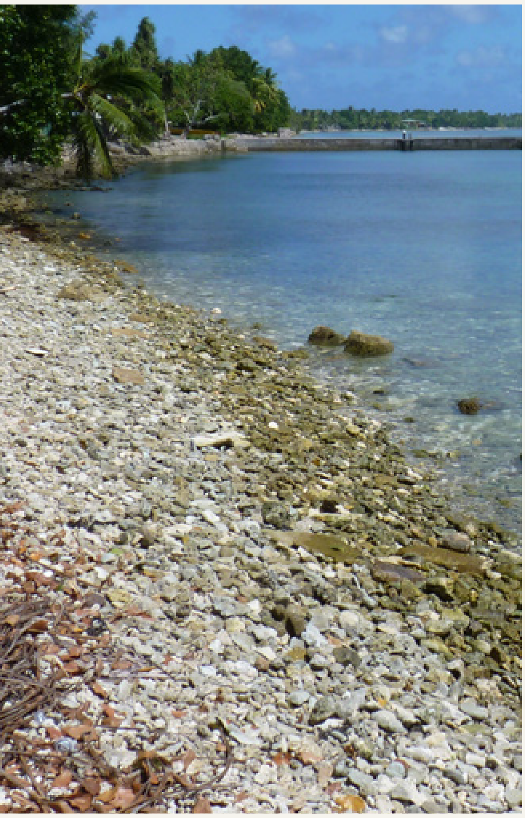
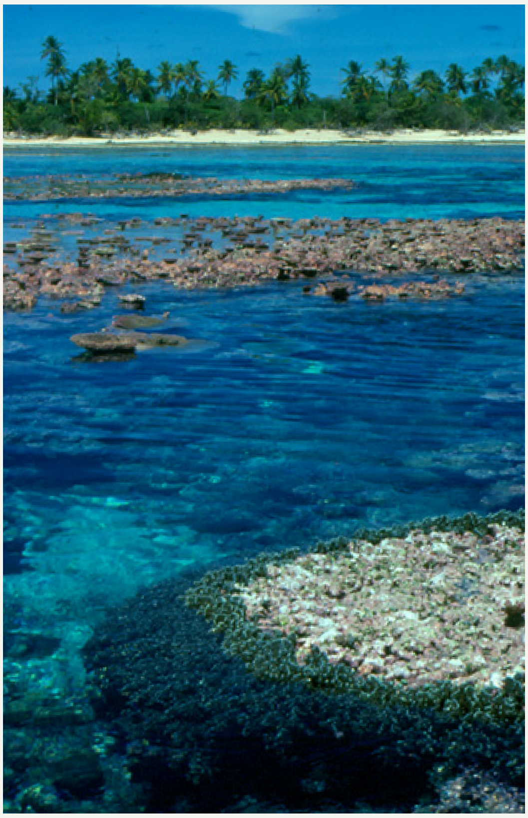
Regional coastal susceptibility assessment for the Pacific Islands: *Summary Report*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Regional coastal susceptibility assessment for the Pacific Islands: *Summary Report*

About the report

This Summary Report has been compiled from the Technical Report '*Regional Coastal Susceptibility Assessment for the Pacific Islands*' by P.D. Nunn, L. Kumar, I Eliot and R.F. McLean, January 2015.The project was undertaken as a desk-top study supported by the *Pacific Australia Climate Change Science and Adaptation Planning* (PACCSAP) program as part of the Australian Government's International Climate Change Adaptation Initiative administered by the Department of the Environment.

The PACCSAP program assists Pacific Island countries to better understand and respond to climate associated impacts now and in the future. The objectives of PACCSAP are to:

- Improve scientific understanding of climate change in the Pacific.
- Increase awareness of climate science, impacts and adaptation options.
- Improve adaptation planning to build resilience to climate change impacts.

There are four outputs of the project:

(1) A digital database of 1,532 islands across the 15 partner countries.

  a. The database was developed at the University of New England as part of the project.

  b. Details of the development of the database and source materials are provided in Chapter 2 of the Technical Report.

  c. Further information regarding the database is available from the authors of the Technical Report

(2) Three large scale annotated map sheets.

  a. Sheet 1 'Island types in the Pacific region'

  b. Sheet 2 'Indicative susceptibility of island types to climate change'

  c. Sheet 3 'Geomorphic sensitivity of Pacific Island coasts to future climate-ocean processes'.

(3) Technical report titled '*Regional Coastal Susceptibility Assessment for the Pacific Islands: Technical Report*' by P.D. Nunn, L. Kumar, I Eliot and R.F. McLean, Department of the Environment, January 2015

(4) Summary report titled: '*Regional Coastal Susceptibility Assessment for the Pacific Islands: Summary Report*'.

  a. This summary report, prepared by Roger McLean is based on the project's Technical Report which contains full details of the susceptibility assessment and the framework used in its development.

This report should be cited as:

'*Regional Coastal Susceptibility Assessment for the Pacific Islands: Summary Report*'. Department of the Environment, January 2015.

Contents

Chapter 1. Project Context and Objectives

Key Points

- Owing to their oceanic locations, Pacific Islands are highly exposed to external climate and ocean processes especially their coastal fringes.
- 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.
- A regional susceptibility assessment of coastal risk for Pacific islands considers the physical characteristics of islands and their susceptibility to present and projected changes in climate and ocean processes.
- The regional dimensions of this assessment will allow the rapid and informed identification of priority areas for intervention to reduce impacts of future climate-driven environmental changes.

1.1. Background

Pacific Island governments and communities are concerned about climate change and its implications. Island coasts are often seen as being particularly vulnerable, not only from sea-level rise, but also from changes in sea surface temperature, storm frequency and intensity, ocean acidification, and changes in wind, waves and rainfall regimes. Past studies of coastal vulnerability in the region have focussed on the potential response of low atoll islands to sea-level rise. In the present report all Pacific island coastal types are considered together with several climate change-related factors and not just sea-level rise. The objective is to develop a regional scale typology of island and coastal susceptibility based on geomorphological characteristics and relevant climate-ocean drivers.

In the past few decades 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 have occurred. The challenges facing Pacific Island nations and their peoples now and in the future are profound. It is clear that 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 deterioration and changes in patterns of extreme events like tropical cyclones and ENSO-linked droughts that may be exacerbated by the actions and aspirations of the people who inhabit the islands.

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 has occurred in the past. 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.

1.2 Project approach and objectives

Development of a regional understanding of Pacific island susceptibility to environmental changes was undertaken as a component of the Pacific-Australia Climate Change Science and Adaptation Planning (PACCSAP) program which is part of the Australian Government's *International Climate Change Adaptation Initiatitive* administered by the Department of the Environment. PACCSAP 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 to respond to climate-associated impacts. This assessment of susceptibility is intended to assist in understanding the dimensions of island and coastal-change for more efficient adaptive management and planning at a regional scale.

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.

Past vulnerability and adaptation studies in the Pacific Islands region have focused on individual islands or specific areas within islands. In contrast there have been few regional studies or studies spanning all islands in the region. This project differs from the local area or single-island assessments in two important respects. First, the assessment refers specifically to the inherent physical characteristics of islands and coast as a first step to a conventional vulnerability assessment. And second, people and infrastructure are not included in the broad scale analyses we present. What this means is that this is not a vulnerability assessment but is limited to identifying the inherent *susceptibility* of islands and island coasts to physical change and their *sensitivity* to present and projected climate and ocean processes

In this context **Susceptibility** is seen as a comparative estimate of the potential magnitude of physical change in island form and structure in response to a change in climate-ocean boundary conditions. Susceptibility can also be viewed as a comparative measure of an island's resistance to change. On the other hand **Sensitivity** refers to the degree to which an island coast may experience physical changes, such as erosion or accretion, as a result of changes in climate-ocean processes. An estimate of sensitivity is also a comparative measure based on geomorphic knowledge of coastal landform development.

As a desk-top study this project has sought publically available information such as that provided by Google Earth. Development of a typology for such an assessment also necessitates the rapid evaluation of available information describing the potential impacts of climate-ocean processes at a regional scale and achievement of the following objectives:

- Establishment of a database to provide a baseline against which future impacts can be identified for a range of island types at a regional scale.
- Identification and description of islands and their landforms at a broad regional scale.
- Comparison of the geologic composition and form of islands to establish their relative susceptibility to environmental change.
- Identification of key climate and ocean processes at a regional scale.
- Determination of regional and within-country variation in the geomorphic sensitivity of island coasts.

The development of a regional scale island typology comprises a series of nested scales with increasing spatial and temporal resolution at each step from all islands through a single island to the coast of an island and a segment of that coast. Three steps are illustrated on Figure 1.1 that also shows that the information requirements for environmental assessment and management are different for each scale change. The conceptual framework illustrated in Figure 1.1 underpins the approach used in the project.

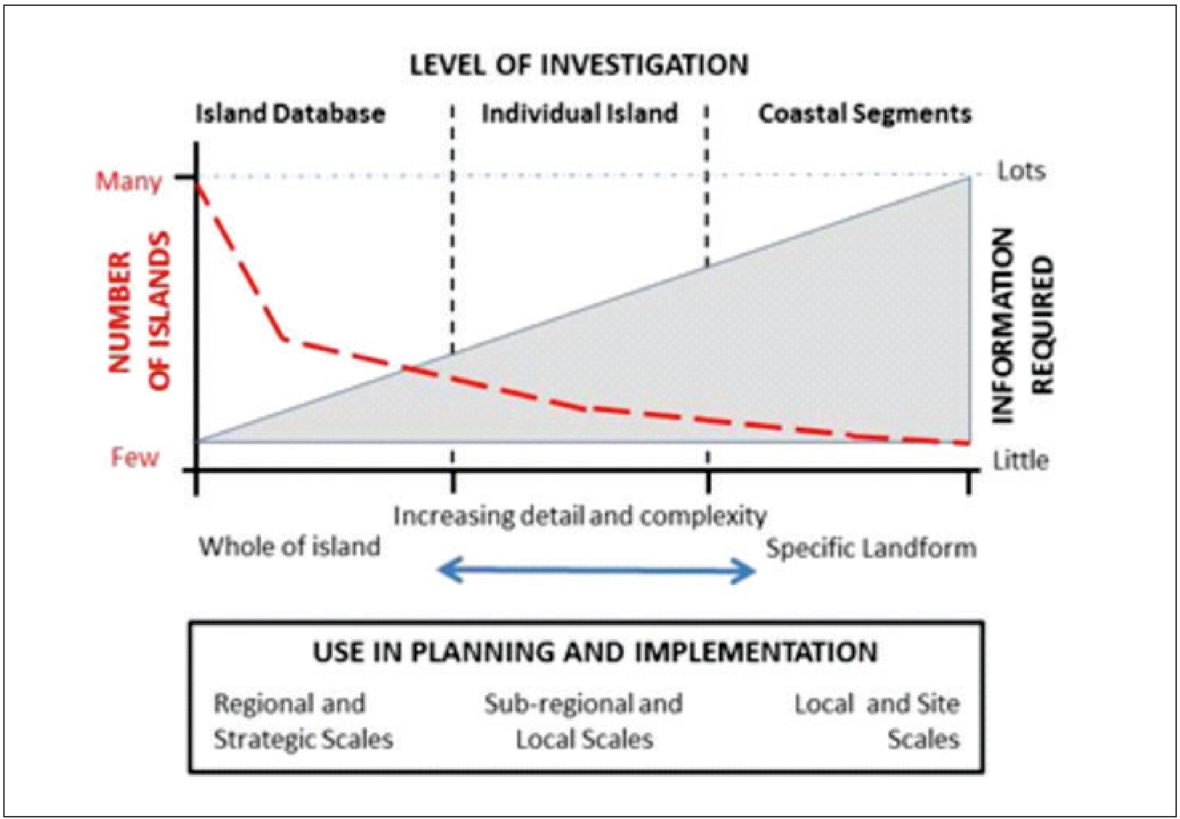


Figure 1.1 Conceptual framework for present study showing three levels of investigation: regional, single island and island coast and changes in information requirements at each level.

1.3 Structure of the report

This report incorporates a framework 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.

The first step was 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 were identified based on lithology and elevation: volcanic high, volcanic low, limestone high, limestone low, composite high, composite low, continental, and reef islands. The division between high and low islands was taken at 30 m.

Certain island types are inherently more susceptible to physical change than others. In **Chapter 3** four variables: lithology (as a surrogate for erodability; hard rock to unconsolidated sediment) maximum elevation, area and circularity (shape) were used to develop a measure of indicative susceptibility. A five-point scale susceptibility rating was derived for all 1,532 islands, with low to moderate susceptibility for volcanic islands and moderate to very high susceptibility for reef islands. Susceptibility ratings for the island types within each country in the region are also presented.

This methodology is also followed in **Chapter 4** where more variables are added to the diagnostic criteria including measures of insularity, proximity to other islands, and the cross-shore gradient from land to offshore. Indicative susceptibility ratings for the coasts of a number of sample islands are presented. Further downscaling from the coasts of whole islands to subdivisions or segments of the coast is also illustrated in Chapter 4 for a limited number of islands.

In **Chapter 5** the key climate and oceanographic drivers of coastal change in the Pacific islands region together with their likely future changes are described. An understanding of the geographical distribution of each driving process – tide, wind and waves, swell, ENSO, tropical cyclones and sea-level change—is critical to understanding future coastline behaviour in various parts of the region.

How these processes interact and will manifest in different regions of the Pacific are described in **Chapter 6** through the development of a measure of geomorphic sensitivity of coastal landforms to future change, based on an islands location and the projected changes expected in that part of the Pacific. Coastal geomorphic sensitivities are calculated for all islands in the database and the ways in which these vary between sub-regions and countries within the Pacific are illustrated.

Chapter 7 summarises the implications of this regional analysis of whole-island vulnerability to climate and ocean change for 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.
- A database of 1,532 islands from 15 Pacific Island countries with a combined land area of 138,958 km^2 was developed; the island of New Guinea was excluded from analysis owing to its exceptionally large size.
- Rock type and elevation of each island allows its classification as one of eight types, each of which is uniquely susceptible to change in environmental processes.
- The most numerous island type is 'reef islands' which comprises 34% of all islands in the region, 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. Database creation and sources

A database comprising 1532 islands ≥ 1 ha (0.1 km^2) in area that covered the PACCSAP partner countries was identified from imagery in Google Earth. Most island locations (latitude and longitude) and maximum elevation (above or below 30 m) were determined from this source. Areas for islands were calculated directly from the polygon file created for the database and derived from the World Vector Shorelines File (WVF) that contains shorelines along the ocean-land interface at a nominal scale of 1:250,000. A number of sources were used to identify island lithology including regional and national geological survey maps, academic publications and online sources. The main reference for island names was '*Pacific Island Names: A Map and Name Guide to the New Pacific*' by L.S. Motteler Miscellaneous Publications 3, Bishop Museum Press, Honolulu, 2006.

2.2. Classification of island types

The classification of island-type 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 land-changing processes). Few islands comprise just one lithology. For this reason and in order to make the classification as simple as possible, we distinguish five types of lithology—volcanic (igneous), limestone (calcareous and non-volcanic sedimentary) composite (less than 80% volcanic and less than 80% limestone), reef (unconsolidated sediment) islands, 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) as well as 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.

A classification of islands in the Pacific region was produced based on the lithology and elevation of each island. The classification has eight categories:

1. *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.
2. *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
3. *Limestone high islands*: are those composed of at least 80% calcareous rock types and rise to a maximum elevation of at least 30 m above mean sea level.
4. *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.
5. *Reef islands*: are those which are composed of at least 80% unconsolidated sediments that have accumulated on a shallow platform commonly reefal in origin.
6. *Composite high islands:* are those 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.
7. *Composite low islands*: are those 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.
8. *Continental islands:* are those that are composed of at least 80% continental (not of oceanic origin) rocks.

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, and is used as a basis for the analyses in subsequent sections of the report.

2.3. Summary statistics for islands in the region: number and area

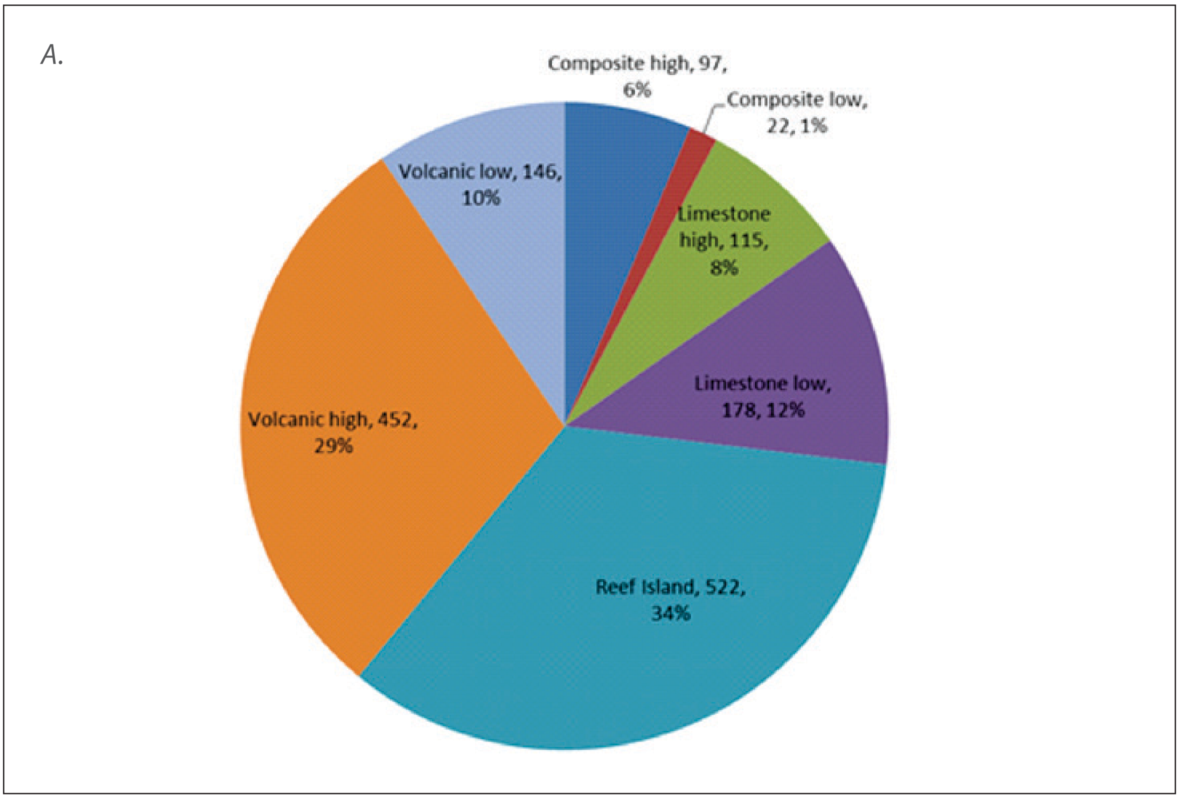
Of the 1532 islands, the largest number is in Papua New Guinea (439/29%), followed by Solomon Islands (413/27%) and Fiji (211/14%). The countries of Nauru and Niue have one island each. The total area of the 1532 islands is 138,958 km^2 the smallest is 0.013 km^2 the largest 35,780 km^2 and the mean area 90.7 km^2. The total number and area by country is given in Table 2.1. Large differences between countries are evident. For example, Vanuatu comes 4th in the area 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 that have many more islands but of a smaller size. Table 2.1 also shows average areas for islands within each country.

Table 2.1 Number and area of islands 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					

Nearly half of the islands in the region (745 islands) have an area less than 1 km^2 but collectively these small 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 only 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.

Figure 2.1 summarises the island types by number and by area. The most numerous island type is 'reef islands', with a total of 522 islands making up 34% of all islands in the region. 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.



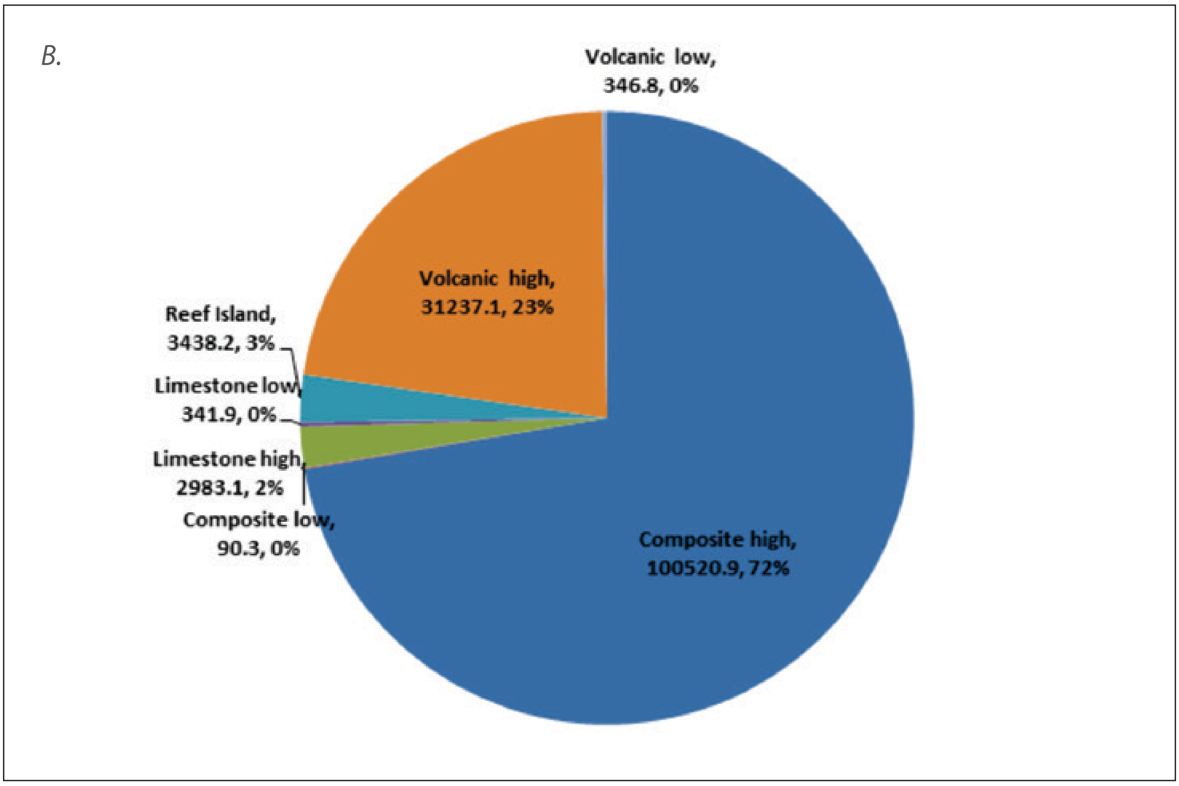


Figure 2.1 Island type (A) by number and (B) by area

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. Composite islands vary greatly in their nature and it is more difficult to generalise about them than for other island types. They comprise just 7% of islands in the region with 'composite high islands' being much more numerous than 'composite low islands' which reflects the dominance of volcanic components in the composite islands group.

In terms of area the results are quite different. While reef islands are the most common in the region, their total area is only 3,438 km^2, just 3% of total area. 29% of islands in the Pacific are 'volcanic high' but the total area of these (31,237 km^2) is 23% of the total area of islands. For instance In terms of area, composite high islands dominate the dataset, primarily 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.

2.4. Regional and country distribution of island types

The regional distribution of island types is mapped in Figure 2.2 which also shows bathymetry that allows the linkage between the major tectonic plate boundaries and island types to be seen. Many islands formed as a result of processes operating along convergent plate boundaries, marked by deep ocean trenches in darker blue. In the south the long Tonga-Kermadec Trench shows the islands of Tonga arranged along its western side in two linear groups, a limestone group closest to the trench, and a volcanic chain of islands farther away. On the eastern side of the trench is the uplifted high limestone island of Niue. At the northern end of the Tonga-Kermadec Trench lie the high volcanic islands of Samoa, an intra-plate hotspot chain. In contrast the Fiji islands occupy a 'micro-plate' that is buffeted by the Pacific Plate in the north and east, and the Indo-Australian Plate in the west and south resulting in a complex distribution of island types.

Another (dark blue) convergent plate boundary is visible to the west of Vanuatu. On the eastern side of the trench there are three sub-parallel lines of islands, two volcanic and one limestone. The Vanuatu Trench continues northwest along the southern side of the 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 and high composite islands in this area. In the northwest of the mapped area (Figure 2.2) is another ocean trench—the Marianas Trench—along which high volcanic and high limestone islands are clustered.

Almost all islands in the rest of the Pacific region 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. Islands close to the hotspot (as in Samoa) tend to be volcanic but, as they move farther away, they subside and frequently form atolls on which reef islands develop. This explains the existence of 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.

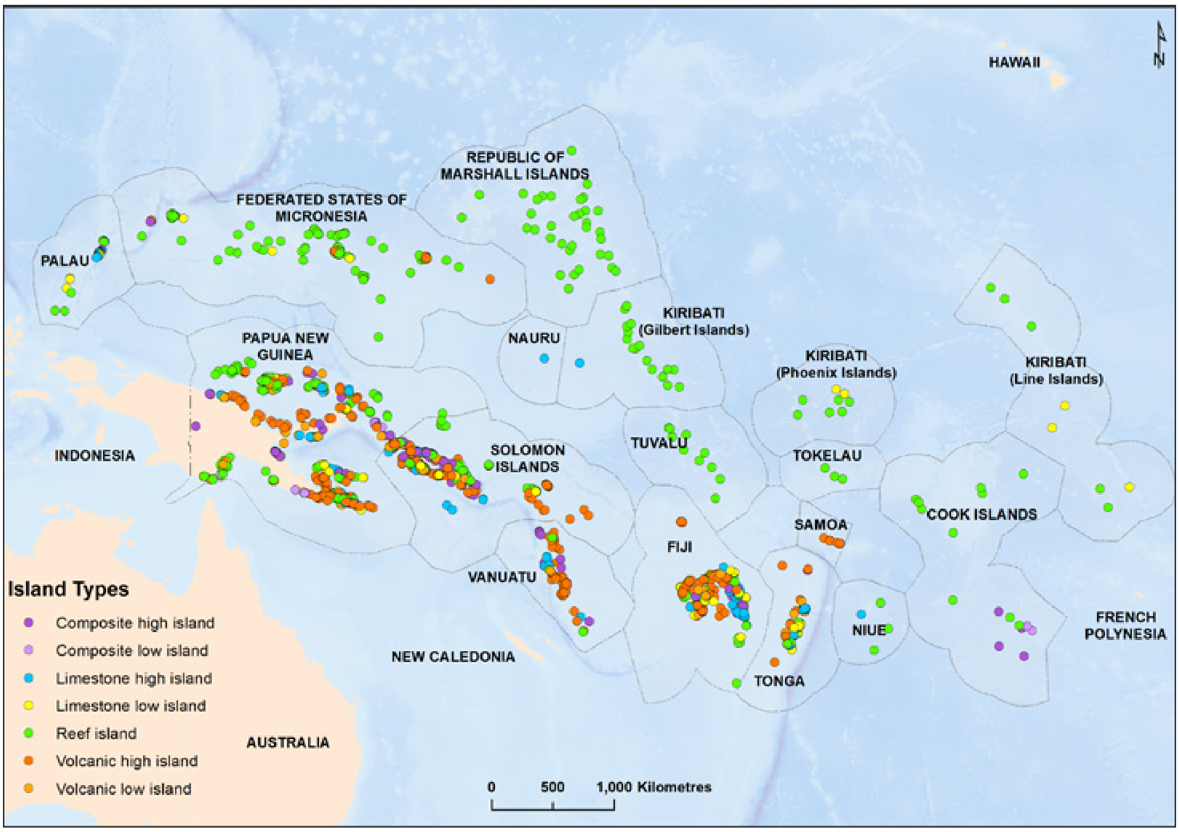


Figure 2.2 Geographical distribution of island types in the Pacific region.

This map also shows bathymetry which allows identification of ocean trenches (darker areas—marking convergent-plate boundaries) and the boundaries of the Exclusive Economic Zones of the 15 countries in the region.

In Figure 2.3 the percentage of island by number and by area of each island type in the 15 countries is presented. Five countries have only one island type: the two single island states (Nauru and Niue) are high limestone islands while the other three countries Marshal Islands, Tokelau and Tuvalu are made up solely of reef islands. On the other hand Papua New Guinea, Solomon Islands and Vanuatu have islands of every type.

A.

B.

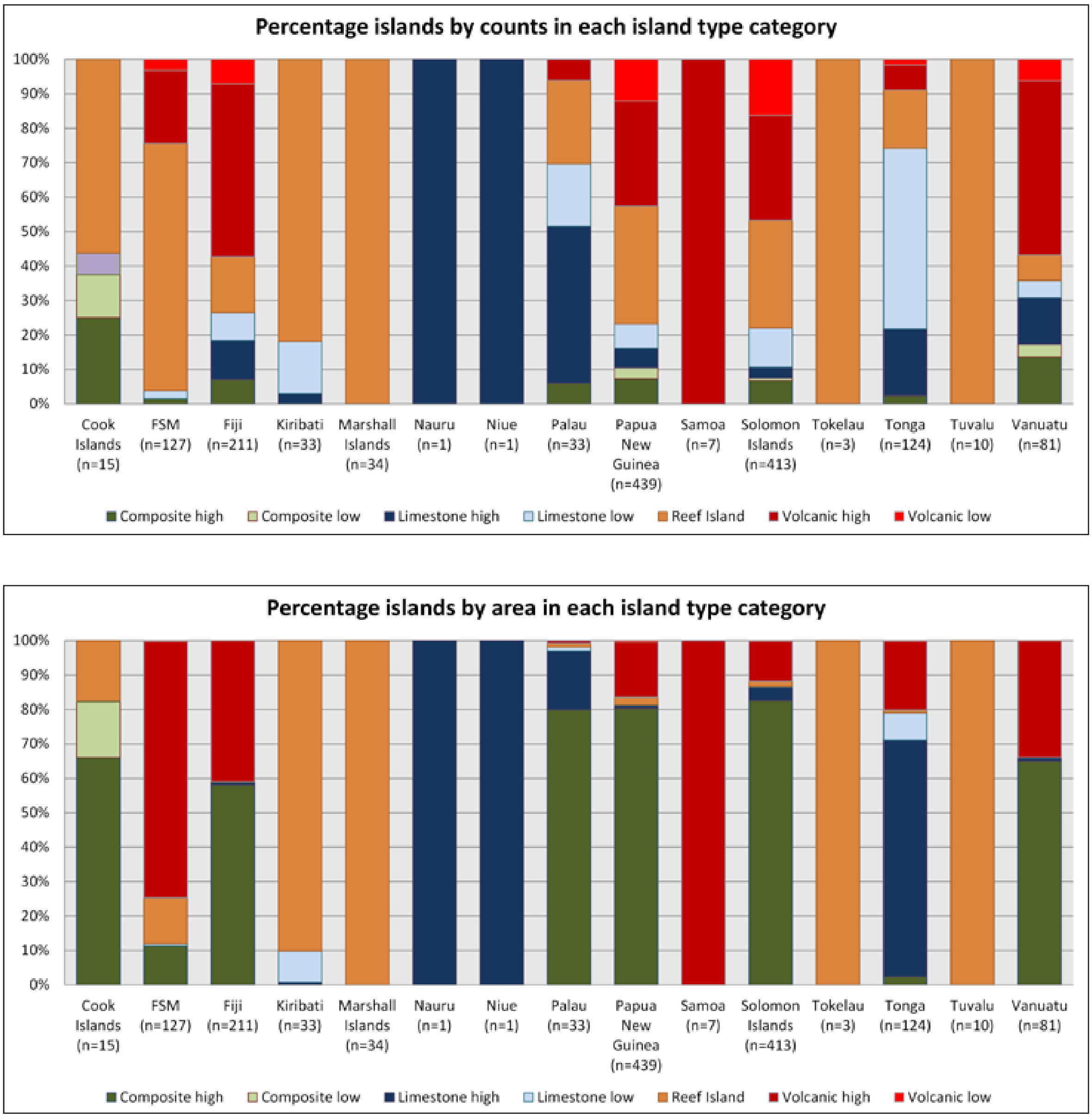


Figure 2.3 Distribution of island types by country. (A) Number of island types. (B) Area of island-types. Both (A) and (B) expressed as proportions of the total number and area within each country.

Figure 2.3 clearly shows that each country is dominated by one island type such that 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 country in terms of area. These data allow for effective regional evaluations and inter-nation comparisons. The data in Figure 2.3 also provides a snapshot of national island types that can be readily linked to particular issues including groundwater, soils, hazards and coastal susceptibility.

Chapter 3.
Regional Scale Assessment of Island Susceptibility

Key Points

- Susceptibility ratings were determined for each of the seven island types, with low to moderate susceptibility ratings for volcanic islands and moderate to very high ratings for reef islands.
- Six of the 15 countries in the Pacific region have islands in all five categories of susceptibility; 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. Indicators and estimates of island susceptibility

The relative susceptibility of islands at a broad regional-scale and the regional and within-country variation in the susceptibility of each island type is described. Certain island types are inherently more susceptible to long-term physical change than others. The measure of susceptibility developed here is based on four simple characteristics that every island has: lithology, maximum elevation, area and shape (circularity). Lithology refers to relative hardness or softness of the dominant rock type which provides a measure of erodability and/or resistance to change by climate-ocean processes. Maximum height provides a simple measure of susceptibility to marine inundation, for example the lower an island is the more susceptible it is to inundation. Similarly, island area is another simple measure such that a small island is likely to be relatively more unstable than a large island. Circularity is a shape term measured as roundness or conformity to a circle. A circular island is one with the smallest possible perimeter compared with an island that has embayments and promontories and has a longer perimeter.

Each variable was ranked on a four-point scale where rank 1 is the most resistant (or least susceptible) to changes and rank 4 the most susceptible (or least resistant). For instance islands made up of hard resistant volcanic rock are ranked 1 whilst reef islands made up of soft unconsolidated sands and gravels are ranked 4. Islands with a maximum elevation of less than 10 m are regarded as more susceptible to change from climate and ocean processes than islands with a maximum elevation greater than 100. These two examples also indicate the relative nature of the rankings of the four variables. The indicators and rankings are summarised in Table 3.1

Table 3.1 Criteria for primary assessment of susceptibility

(1) Lithology		(2) Circularity		(3) Height		(4) Area	
Material	Rank	Roundness	Rank	Maximum elevation (m)	Rank	Area (km^2)	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

In the analysis, all four criteria (lithology, circularity, elevation, area) were given equal weightings. Subsequently, rankings were summed and a susceptibility rating determined. The rating is referred to as the indicative *susceptibility* of each island because it provides an estimate of the long-term susceptibility of each island and island coast to possible physical change driven by climate and ocean processes. The coarse nature of the susceptibility estimates is stressed. This is a 'high-level' first-pass assessment intended to provide a basis for more detailed analyses.

3.2. Regional-scale susceptibility of islands

Indicative susceptibilities were calculated for all 1532 islands in the database and mapped in 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.

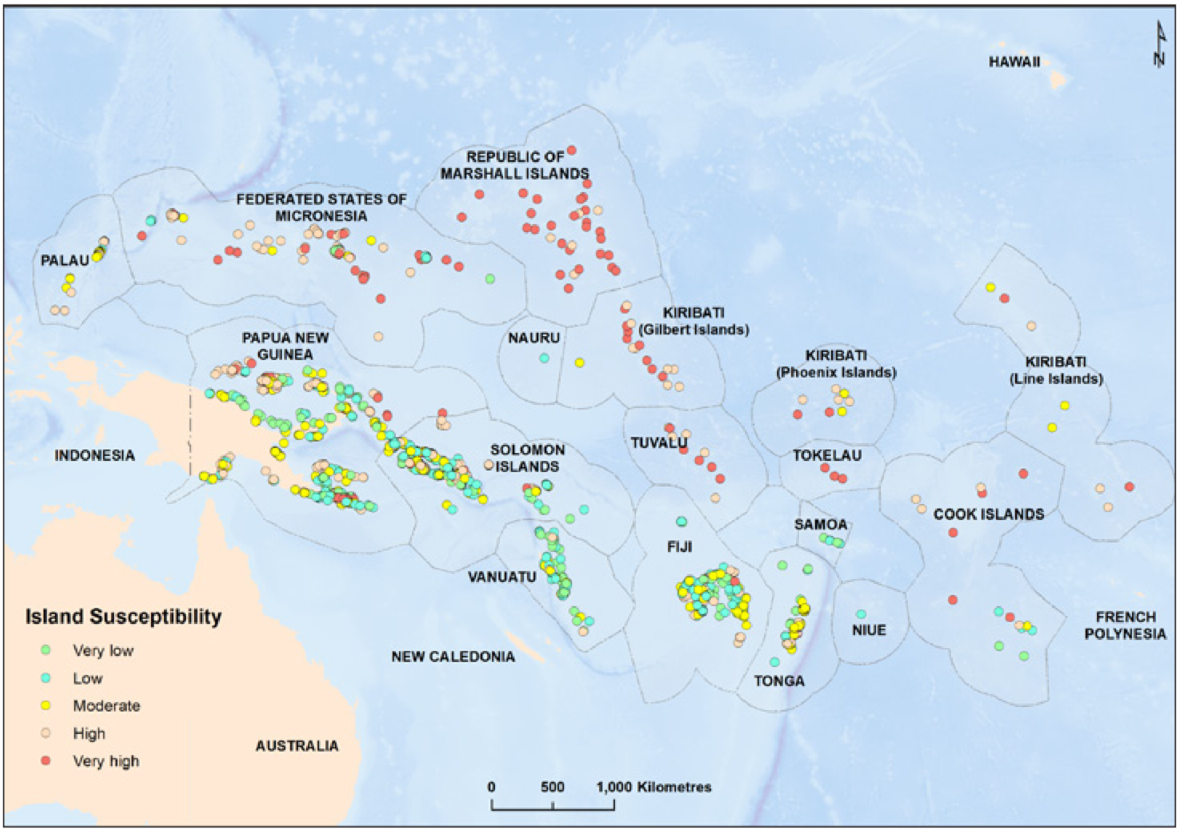


Figure 3.1 Island susceptibility in the Pacific region based on four criteria –island type, elevation, area and circularity (shape).

Certain island types are inherently more susceptible than others as indicated on Figure 3.2 which also shows that each of the seven island types includes more than one susceptibility class dependent on differences in the elevation, size and shape of a particular island. Higher-elevation islands (volcanic high, composite high and limestone high) tend to be least susceptible whilst, not surprisingly the most susceptible islands are the limestone low islands and reef islands.

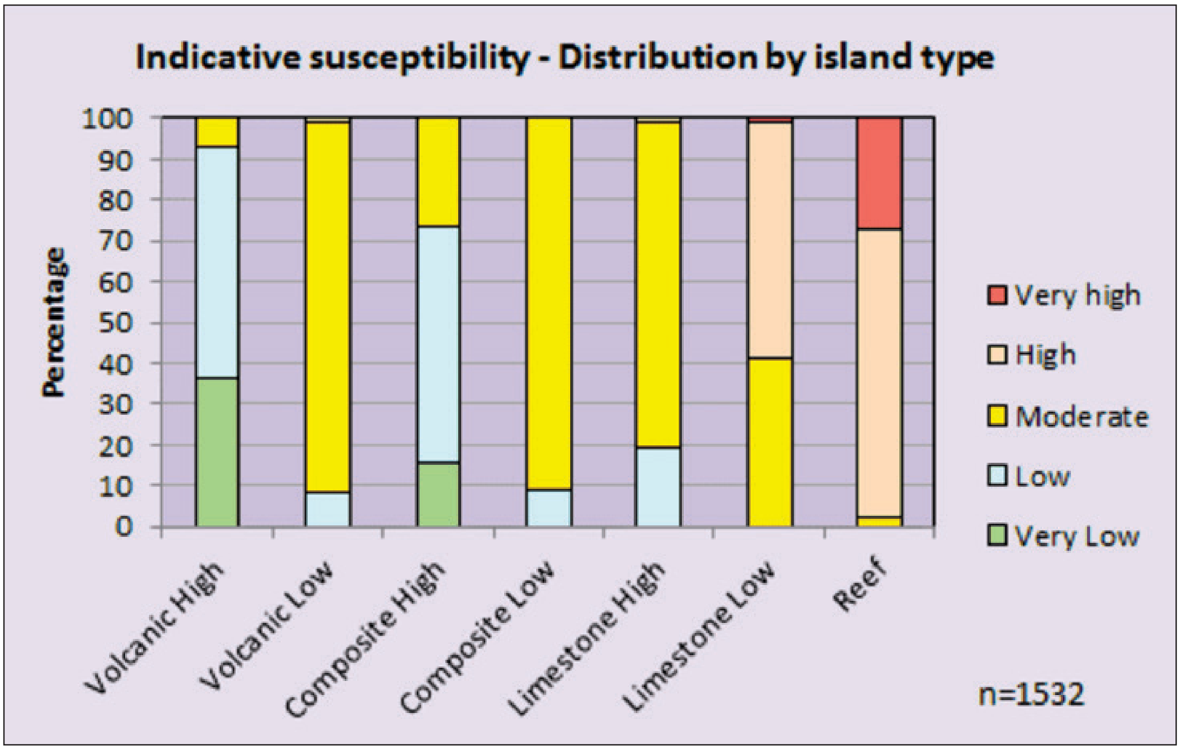


Figure 3.2 Indicative susceptibility by island type

3.3. Diversity of estimated susceptibility for each country

Susceptibility estimates for the 15 Pacific Island countries are portrayed in Figure 3.3. The geographic distribution of the values demonstrates significant variation in susceptibility between and within different countries with the exception of Nauru and Niue, which are single-island countries. The most common *susceptibility rating* for each country shows 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 ranging from very low to very high.

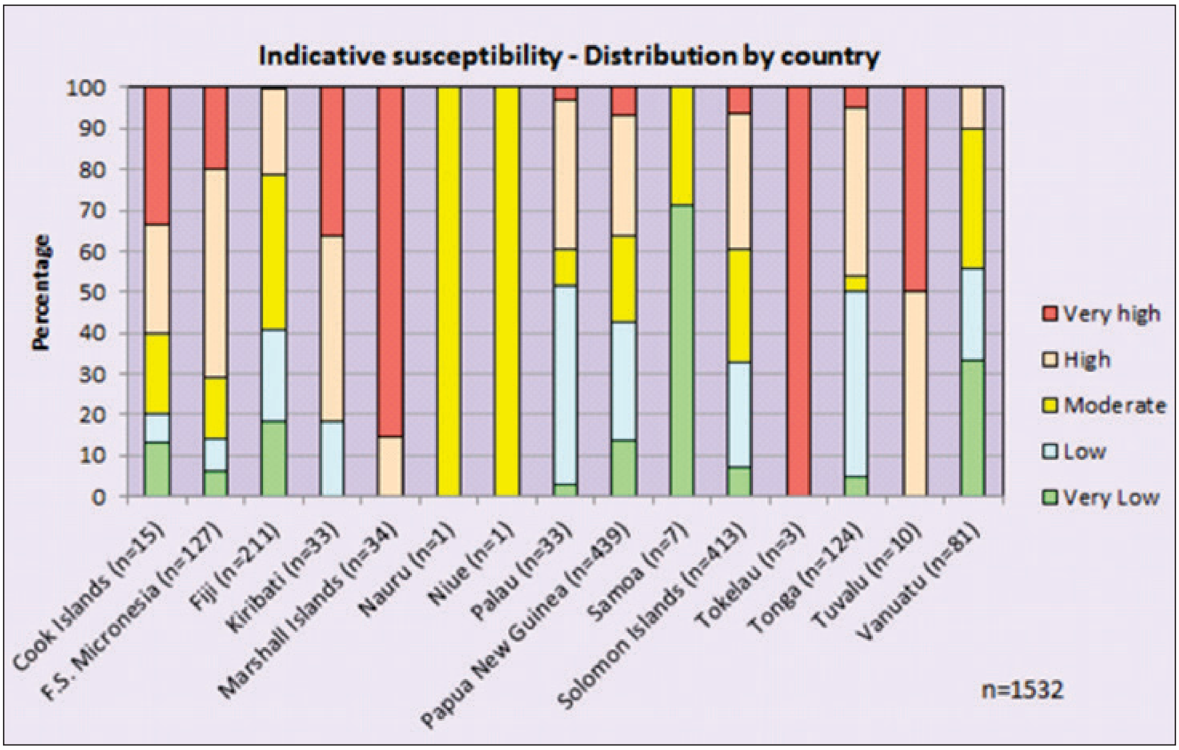


Figure 3.3 Range of indicative susceptibility of islands in each country.

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 territory with all (three) islands classified in the very high susceptibility category.

In this primary analysis, only four factors are used in determining island susceptibility. Clearly other physical attributes could be added such as the presence or absence of coral reefs or the effects arising from the proximity to adjacent islands. But despite the coarse nature of this primary assessment of susceptibility, the results provide a unique, comparative perspective of 1532 islands on the basis of consistent information across the entire Pacific region. By combining four simple measures—lithology, area, elevation and circularity—for each island it has been possible to provide a comparative assessment of the susceptibility of islands in the region. Whilst the broad character of this regional-scale assessment is stressed, the approach does provide a firm, consistent and defensible basis for more detailed, local-scale analyses in areas identified as having a high and very high susceptibility ratings.

There are three further points. (1) There is considerable similarity of island types between different countries and for which common problems may be defined and addressed. (2) It provides a strategic planning basis for countries and regional agencies to develop adaptation strategies to reduce the impacts of climate and ocean processes. And (3) some of the susceptibility ratings are expected to change as (i) more detailed information becomes available, or (ii) as other weightings are applied to criteria used here; or (iii) if further criteria are added to the assessment.

Chapter 4.
Downscaling from Island to Coastal Susceptibility

Key Points

- Estimates of susceptibility based on the physical features of islands can be downscaled from whole islands to coastal margins.
- In the downscaling process, additional physical and geographical attributes including insularity and proximity to other islands are added.
- Downscaling also requires increasingly detailed descriptions of the coast for the finer steps in the framework including subdivision of the whole-island coast into sectors.
- Full realisation depends on agreement in definition of coastal features and criteria describing relative state of the coast with respect to susceptibility.

4.1. Downscaling framework and steps

A regional examination of the physical character of 1532 islands based on their lithology and elevation ± 30 m was presented in Chapter 2 (island types). To lithology and elevation were added island area, island shape (circularity) and maximum elevation in Chapter 3 to provide a measure of island susceptibility to changes from climate and ocean processes over the long-term. A framework facilitating downscaling from this primary, regional-scale estimation of the susceptibility of a whole island to more detailed assessment of susceptibility of an island's coastal fringe is described in this chapter.

The framework comprises a series of four steps in which each step is a different scale in a management hierarchy ranging from regional, through country to local governance as illustrated in Figure 1.1. This framework continues to deal with the inherent physical characteristics of islands and coasts from which intuitive estimates of their *susceptibility* or resistance to change are developed.

Measures of indicative susceptibility described in Chapter 3 were based on the physical characteristics of whole islands that are valuable for regional and country-wide evaluation. However, they do not identify regional problems of relevance at a local level, either within a particular island subgroup or within an island itself. It is therefore desirable to downscale from the high-level primary assessment to more detailed levels. This involves:

- Extending the range of variables used to estimate indicative susceptibility (as in Chapter 3);
- Developing new criteria to estimate the relative stability of coastal sectors;
- Establishing a pathway for downscaling coastal assessments at a level suited to the use of sparse or coarse information; and
- Applying this 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 common characteristics

At all scales in the framework a similar procedure is used to estimate the susceptibility of coastal features. At each scale lithology and morphologic features are used as criteria to determine the stage of geomorphic development and to identify the likelihood of coastal change. The criteria vary from scale to scale as the degree of detail required in the estimates increases with downscaling.

4.2. Secondary assessment of island coasts

In addition to lithology (rock type), circularity (shape) and elevation (maximum) that were used in the initial susceptibility analysis (Chapter 3) other physical parameters for each island include an estimate of*: insularity, proximity, and shore gradient. Insularity* is defined as 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. 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 to assess the potential effects of sheltering of an island from meteorological and oceanographic processes. *Shore profile gradient* refers to the slope from the island's shore to the edge of any undersea platform or shelf. Wave and surge height are affected by seabed gradient.

The criteria used in the assessment of coastal susceptibility were all ranked on a five-point scale with 1 being the least susceptible (most resistant) and 5 being the most susceptible (least resistant) to coastal change over the long-term.

In addition to these six characteristics another series of shoreline attributes were added before the final coastal susceptibility measure was derived. Parameters used to estimate *Instability* describe coastal features of the backshore, intertidal zone, inshore and reef that were subdivided as follows:

1. *Backshore:* A. Elevation within 25 m of HWL; B. Sediment; C. Landform occupying >50% of coast.
2. *Intertidal*: A. Sediment type on >50% of coast; B. Landforms on >50% of coast.
3. *Inshore zone*: A. inshore morphology for > 50% of coast.
4. *Reef*: A. Seaward reef type; B. Seaward reef width; C. Reef coverage

Each of these criteria was ranked on a five-point scale. Both measures were combined to estimate coastal susceptibility to long-term change. As in Chapter 3, this more detailed secondary assessment of coastal susceptibility is still an indicative and relative measure. In the final phase of the secondary assessment, the separately ranked scores were rated as being low, moderate or high susceptibility and aggregated in a matrix to provide an estimate of the overall *susceptibility* of each of the 13 sample islands described in Table 4.1. Weightings were applied to ensure that the most important criteria have greater importance. These ranged from 35% for geology to 5% for seabed gradient in the initial susceptibility measure and from 20% for backshore slope to 5% for reef type, width and coverage in the instability measure.

Table 4.1 Secondary assessment of coastal susceptibility with weightings compared with primary assessment in the previous chapter.

Island and Country	Island Type	Primary Susceptibility (Chapter 3)	Secondary Susceptibility (This chapter)
Aitutaki Island, Cook Islands	Composite	Low	Moderate
Aniwa Island, Vanuatu	Composite	Moderate	High
Aore Island, Vanuatu	Limestone low	Moderate	Moderate
Bellona Id, Solomon Islands	Limestone low	Moderate	Moderate
Emananus I., Papua New Guinea	Composite low	Moderate	Moderate
Lifuka Island, Tonga	Limestone low	Moderate	Moderate
Loun Island, Solomon Islands	Volcanic high	Moderate	Low
Manono Island, Samoa	Volcanic high	Moderate	Very Low
Onotoa island, Kiribati	Reef	Moderate	Very High
Oreor (Koror), Palau	Composite high	Low	Low
Tonowas I, FSM	Volcanic high	Low	Low
Vaitupu Island, Tuvalu	Reef	High	Very High
Vogali I., Papua New Guinea	Volcanic low	Moderate	Moderate

4.3. Tertiary assessment of coastal sectors

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. Similarly, the finer-scale analysis is more directly applicable to policy, planning and management at a country and island scale.

In the Technical Report five islands—two volcanic (Loun and Pohnpei), one composite (Aitutaki), one limestone (Lifuka) and one reef island (Tarawa)—were selected to demonstrate how a susceptibility assessment could be undertaken at a coastal sector scale. The coastal fringe of each island was divided into sectors having common physical attributes. Ten criteria were used in this fine-scale assessment including: lithology (eg volcanic, limestone) coastal landforms (eg types, width, length, elevation) planform of shore (eg straight, embayed) inshore morphology (eg stepped, platform, beach) and reef (eg type, distance offshore, width) that were ranked on a five-point scale. Note this approach only incorporated natural features and did not include settlements, infrastructure, land use etc.

Sector susceptibility was then estimated by following the methodology outlined in the secondary assessment of susceptibility and comparing the most common landform comprising each sector with criteria identifying its relative instability. Criteria describing each variable used to estimate coastal susceptibility are ranked on a 5 point scale. The final ranking for susceptibility is a ranking of 1-3 (Low Susceptibility, Moderate Susceptibility, High Susceptibility).

Two contrasting examples of a high volcanic island Loun Island (Figure 4.1) and the composite island of Aitutaki (Figure 4.2) are illustrated here.

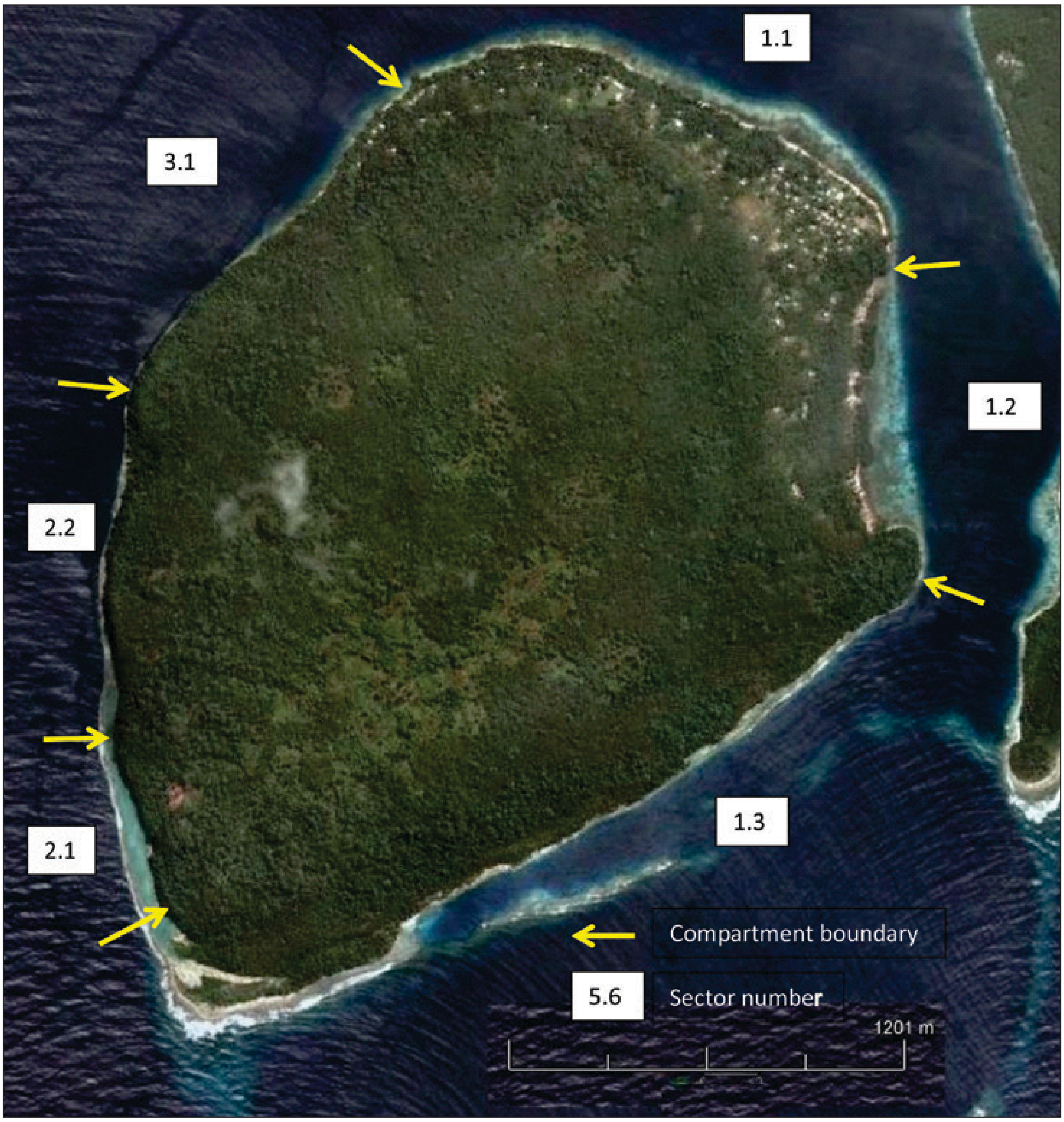


Figure 4.1. Coastal sectors recognised around a high volcanic island, Luon Solomon Islands.

Luon Island (Figure 4.1) is sheltered by nearby islands to the N and E. It is surrounded by fringing reefs. Parts of the shore are rocky with bluffs and rock platforms especially along the W coast. Beaches are perched on rock platforms in the N and SW. Coastal lowlands form a cuspate foreland in the NE and a spit in the SW. The island is divided into 6 sectors with sectors 1 comprising 'coastal plain'; sectors 2 comprising 'rocky coast' and sector 3 'composite coast'. Application of the 11 detailed susceptibility criteria indicate all sectors in Luon Island are of *'moderate susceptibility'*.

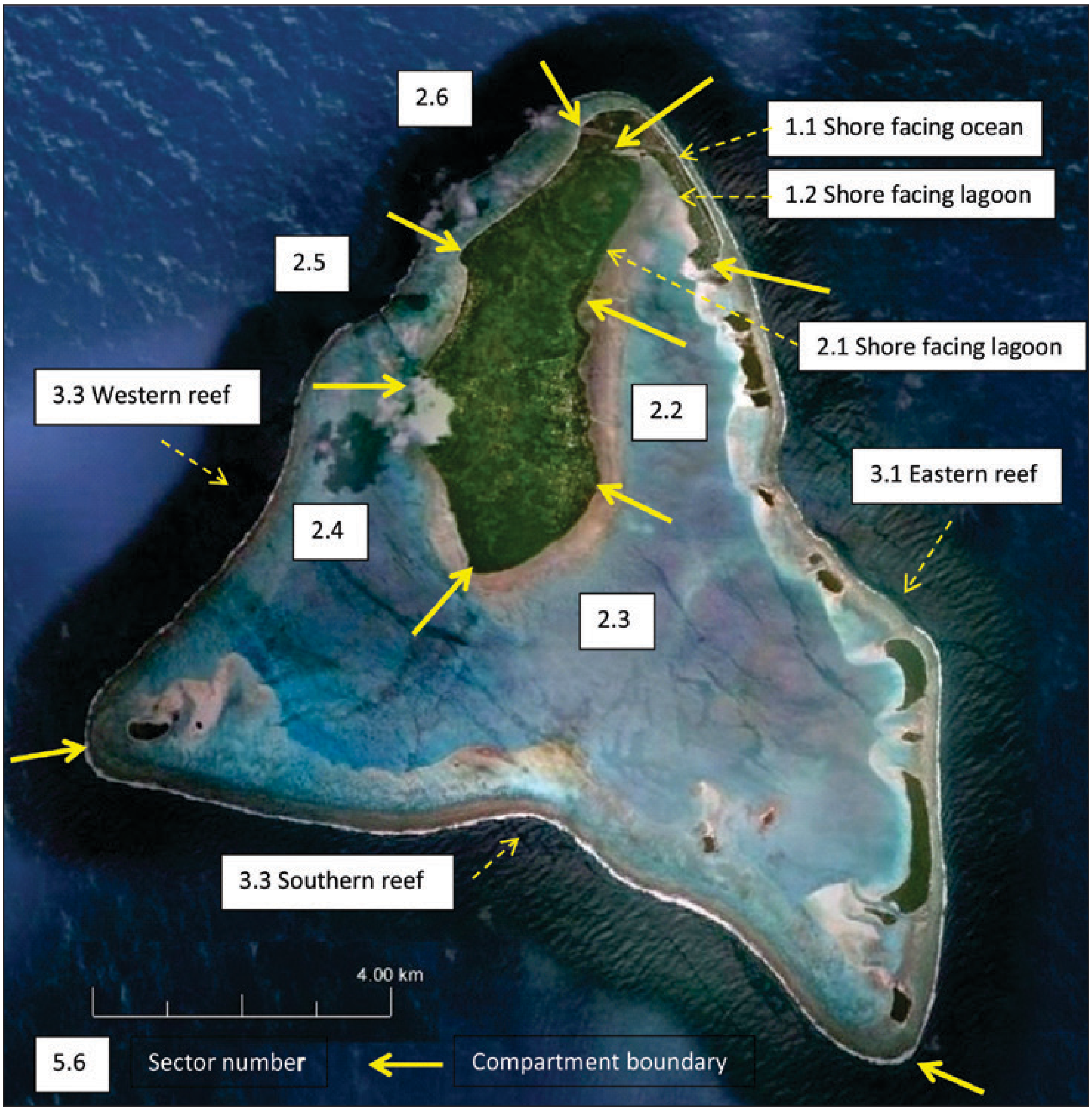


Figure 4.2 Coastal sectors around Aitutaki, Cook Islands.

Aitutaki (Figure 4.2) is a composite island comprising two contrasting island types an elongate volcanic island in the N surrounded by an increasingly wide lagoon and barrier reef to the W and S and to the E where the reef is surmounted by islands. Aitutaki has been called an 'almost atoll'. It can be divided into 11 coastal sectors from three main coastal types: (1) sandy forelands and spits; (2) volcanic terrain; and (3) barrier reef. Application of the 11 detailed susceptibility criteria indicate 'High susceptibility' for sector 1.1; 'Moderate susceptibility; for sectors 1.2 and 3; and 'Low susceptibility' for sector 2.

Note: (1) The basis for this measure of susceptibility is still an indicative or inherent measure based on the physical and geographical character of the coast; and (2) This is the assessment level at which there is opportunity to incorporate detailed land use, population, settlement, infrastructure information and to move from susceptibility analysis to vulnerability assessment. That move is flagged but is not progressed here.

The information for susceptibility analysis that has progressed from the simple primary level developed in Chapter 3 to the more detailed levels of island coasts and coastal sectors in this chapter is based on readily available Google Earth imagery and that requires interpretation. Whilst island elevations derived from this source are not always accurate, other measurements can be made from the imagery such as length of a shoreline segment, width of a landform etc. Although all islands have different suites of landforms, geological controls, reef structures and connectivity with adjacent islands some features are common to each of the island types described in this report.

Chapter 5.
Climate and Ocean Processes: Now and in the Future

Key Points

- Present day shorelines have been shaped by the geological setting and history as well as by the suite of physical and other processes that interact with island margins.
- Important climate-ocean processes that drive coastal change 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-ocean processes over the next few decades indicate that: tidal levels and ENSO range will shift upwards with rising sea-level but that will not be uniform across the Pacific; a small reduction in wave height in the equatorial zone 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.
- Geographical variations in these processes means that similar island types (eg reef islands) located in different parts of the Pacific will be exposed to different climate-ocean regimes resulting in dissimilar coastal impacts and the need for different adaptation strategies.

5.1. Drivers of coastal change

The analysis thus far has been concerned with the inherent physical characteristics of islands and our intuitive understanding of their potential to change. Such understanding allowed the development of a coarse indicative measure—*susceptibility*—based initially in Chapter 3 on island geology, area, elevation and shape. It has also allowed downscaling to island coasts with the addition of several other physical and geographical variables such as insularity, shore-face slope and proximity to other islands to develop a more detailed susceptibility measure in Chapter 4. Underlying these indicative measures and implicit in the analyses are the processes that bring about physical changes to island margins. In this chapter those processes are made explicit and their temporal and geographical distributions across the Pacific now and in the future identified.

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. 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.

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, and its fortnightly 'spring' and 'neap' cycles are familiar to coastal dwellers throughout the Pacific region. Less well known are the differences in tidal characteristics 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 southeast to include much of Solomon Islands.

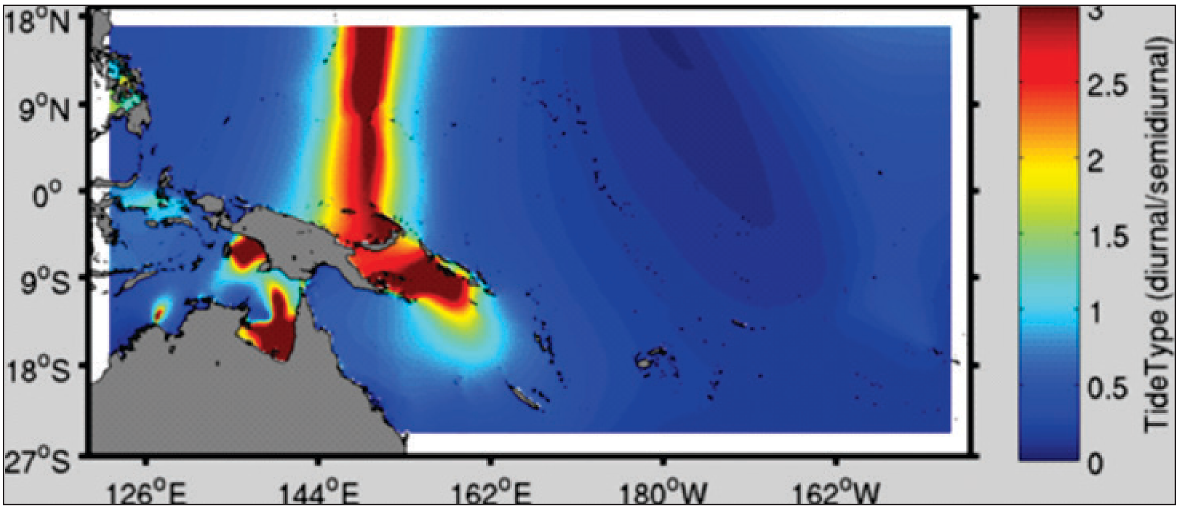


Figure 5.1 Tidal types in the Pacific. From PACCSAP_Tidetype.png.

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.

Differences in tidal type result in variations in the width of the wave-wash zone and 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.

Tides in the Pacific Basin do not have the large ranges of several metres that occur in some parts of the world. Generally tidal range does not exceed 2.5 m. In fact, mean tidal ranges across the region vary from less than 0.6 m in the Cook Islands to a maximum of about 2.0 m in the westernmost Pacific. Figure 5.2 also shows a broad central core with a tidal range of 1 to 1.5 m separating zones of lower range on either side. 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 through the Federated States of Micronesia to Solomon Islands.

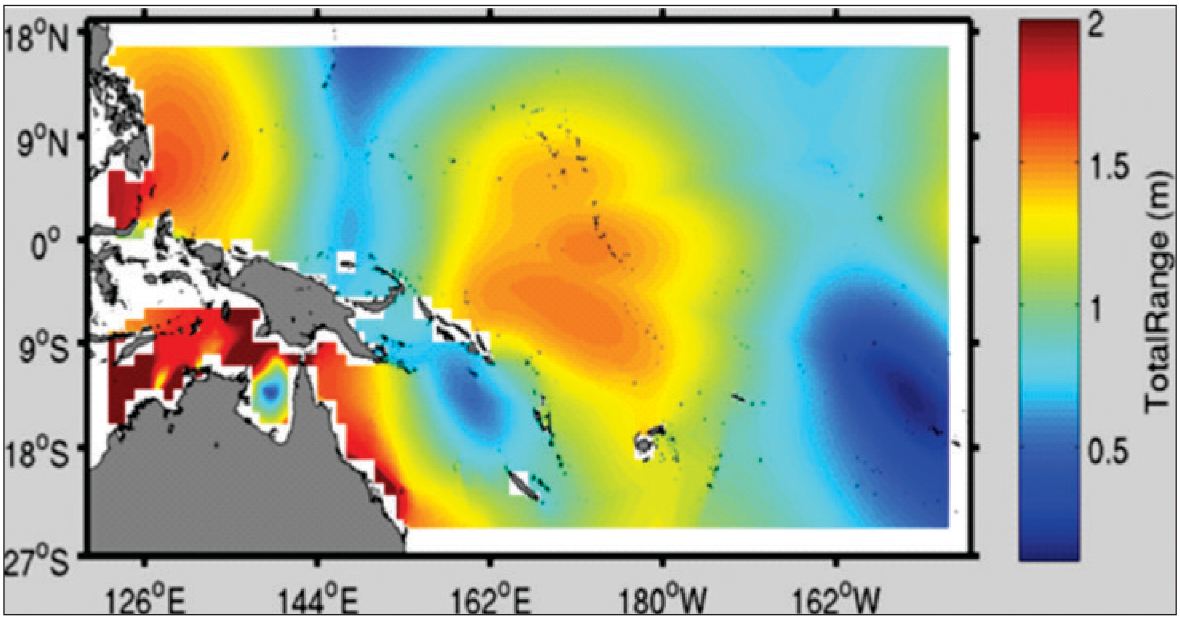


Figure 5.2 Distribution of tidal ranges in the Pacific. From: PACCSAP_TotalRange.png.

5.2.2. Ocean waves and swell

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. Enough is now known about the pattern and nature of wave propagation to describe the salient elements of the region's wave climate.

Four major types of waves are present in tropical latitudes:

1. Easterly trade waves are the most persistent being present all year round and 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 lagoons.
2. Westerly storm waves occur infrequently during the summer months when the trade winds are weakest. These westerly waves are associated with local fronts and low-pressure cells in the monsoon and are often accompanied by strong winds and high rainfall.
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.
4. Waves associated with tropical cyclones and storms.

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. But it is important to recognise that tropical cyclones do not occur everywhere in the Pacific. Instead there are significant geographical variations as shown in Figure 5.3. 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. The map also shows that most TCs originate in the region between 10° and 15° north and south of the Equator.

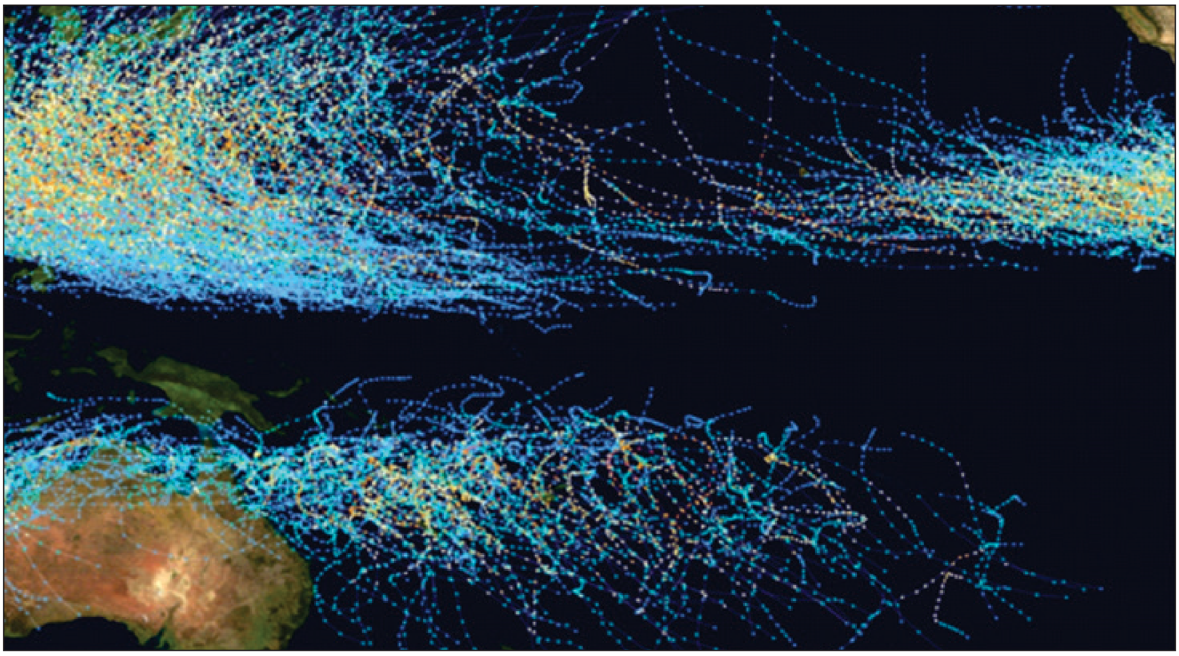


Figure 5.3 Tropical-cyclone (hurricane or typhoon) tracks in the Pacific region 1985 to 2005.

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 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. In these regions, island geomorphology and ecosystems differ from islands exposed to a high frequency of cyclones such that the effects of occasional high ocean-water levels may be disproportionately severe. In addition to the obvious geographical differences in TC frequency in the Pacific, there is also immense spatial and temporal variation in the coastal impact of a single storm depending on its size, intensity, track, duration and timing relative to tide levels.

5.2.4. Sea level and ENSO

In the Pacific, there is good evidence to indicate that sea level attained its approximate present position (+/- 2 m) in recent geological times, in the last four or five millennia. This is 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 which has enabled some sort of equilibria to be achieved between the geomorphic characteristics of island shores and the 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 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. 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. 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. Cross-Pacific shifts in high and low sea levels linked to ENSO phases are also quite clear (Figure 5.4) 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 that can endure for several months.

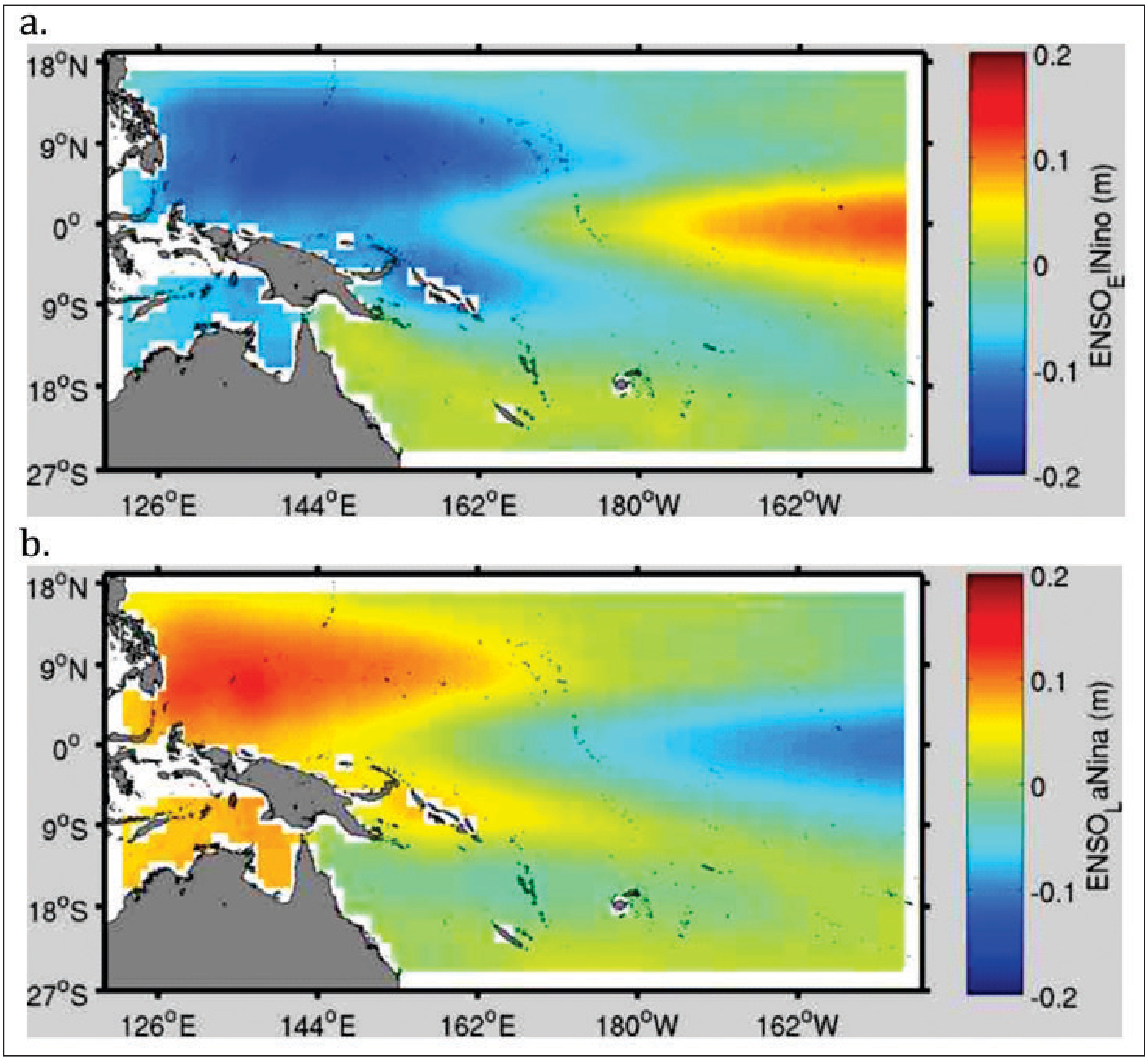


Figure 5.4 Average sea level in the Pacific associated with ENSO phases. a. El Niño, b. La Niña.

5.3. Interaction of key climate and ocean processes

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

5.4. Future conditions: climate and ocean processes in the 21st century

The most recent reports of the IPCCs Fifth Assessment evaluated 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 in the Pacific based on the IPCC reports are summarised in Table 5.1.

5.4.1. Projected future tides, waves and tropical cyclones

Available research suggests that there will be no effects on tide characteristics within the rest of the 21st century though 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. But in areas where tidal range is today comparatively low, it is possible the base of the mean tidal envelope will be raised above present mean sea level which would result in coastal landforms that are currently exposed (emergent) at low-tide level becoming permanently submerged.

Trade-winds are likely to strengthen in the southern hemisphere sub-tropics over the next few decades which will mean an increase in the wind strengths—and waves—that affect many islands in the region. 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. Wave height (Hs) is projected to fall over most of the world's oceans yet rise in the Southern Ocean which is likely to lead to increased persistence of the northward-propagating swells that affect islands in the low-latitude Pacific, particularly in its eastern and central parts.

Several models have suggested that for the next few decades, the tracks of tropical cyclones (TCs) in the Pacific will move polewards. The number of TCs is expected to decrease but the intensity of those that do occur will be at the higher end of the intensity scale. The combined effects of this reduced frequency and higher intensity are difficult to predict for island coasts. In general, it seems reasonable to assume that the situation will see more coasts 'recovering' between successive TCs. But when a TC does occur, it is likely to have more severe effects than most past TCs.

Table 5.1 Projected future conditions of climate and ocean processes in the Pacific by 2100

Process	Projected future conditions
Tides	• Tide characteristics around oceanic islands are unlikely to change as a result of climate change and sea-level rise. • 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. • Small range changes are expected in enclosed seas, lagoons, harbours and estuaries.
Waves	• 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. • 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.
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

5.4.2. Projected future sea level

Global sea-level is projected to continue to rise in the next few decades exacerbating associated effects along all coastlines. In many low-lying coasts these effects have been felt for several decades, and in almost all Pacific islands for at least the last decade. By the end of the 21st century, sea level is likely to be at least 82 cm higher than 1986–2005.

Models also show that, just as sea-level rise across the Pacific has been spatially variable over the past few decades, so the rate of future sea-level rise is also likely to vary substantially. Figure 5.5 shows a map of projected future sea-level change in the year 2055 relative to the present. The highest rates of sea-level rise in the region are expected to be in the western Pacific, particularly in Palau and the western Federated States of Micronesia. Lower rates are anticipated in parts of Papua New Guinea and Solomon Islands, as well as in the central Federated States of Micronesia with higher rates in the central Pacific from the Marshall Islands to Fiji, and from the Solomon Islands in the west to Tuvalu in the east. Farther east, countries like Tokelau, Samoa, Niue, the Cook Islands and eastern Kiribati can expect lower-than-average rates of sea-level rise.

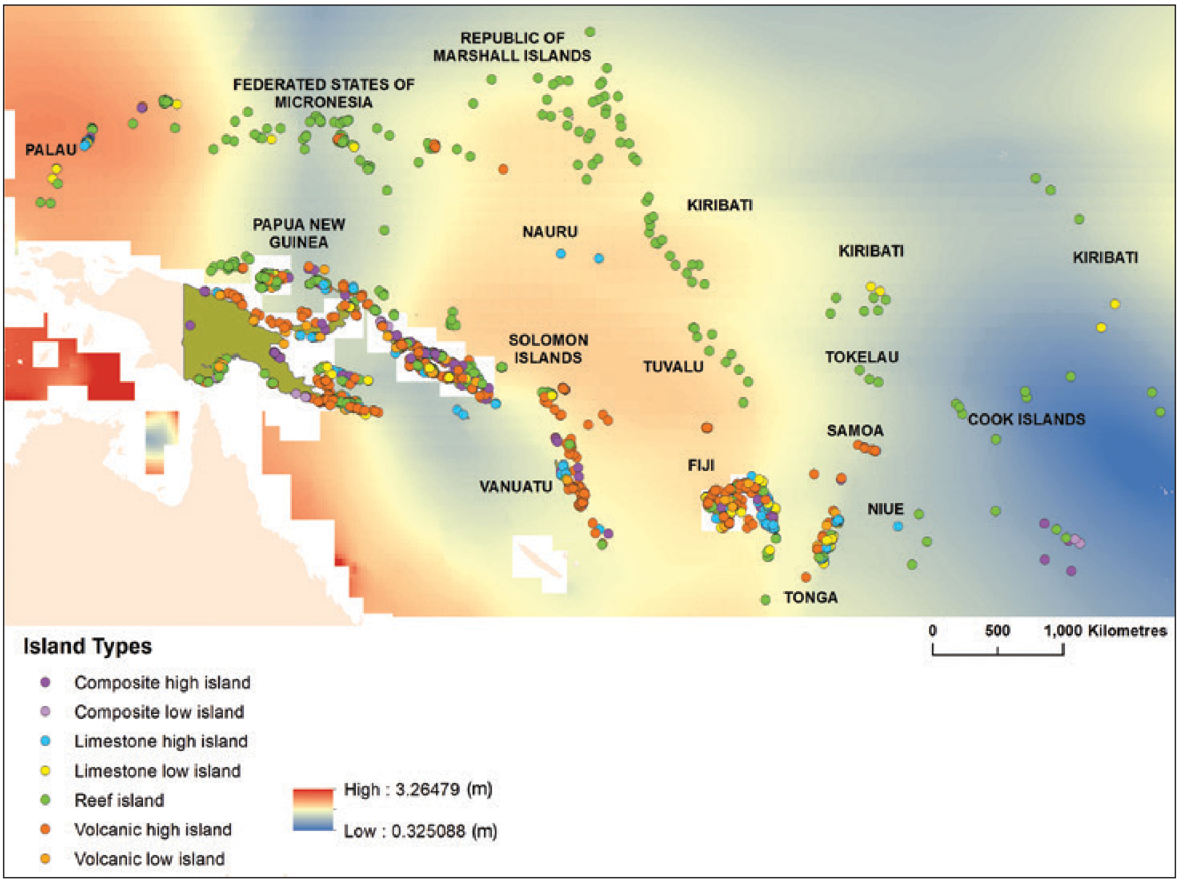


Figure 5.5 Projected sea level in the year 2055 relative to present sea level (upper range tide in m).
This is the projected change in mean sea level relative to 'modelled current' sea level for 2055 (upper tidal range) based on the SRESA1B emissions scenario (between RCP 4.5 and RCP 8.5 emissions scenarios). Source: Australian Bureau of Meteorology and CSIRO.

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 Sensitivity to a Changing Climate: A Framework

Key Points

- Coastal change has been a fact of life for many communities in the Pacific but with increasing population and development, island coasts are likely to become increasing sensitive to climate change and sea-level rise.
- 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 conditions.
- Coastal geomorphic sensitivity 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 sensitivity for individual countries in the Pacific 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 and 4) to provide a ranking for the overall sensitivity of island coasts to climate-ocean conditions. This is referred to here as *geomorphic sensitivity* though the first step was to develop a measure of *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; and, a regional dataset was available.

Climate and ocean processes initially considered were tides, waves, storms, inter-annual (ENSO) variations in mean sea level, tropical cyclones, rainfall and winds. The three processes finally selected were 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. As indicated in the preceding chapter 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 geographical 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 6.1). Emphasis is placed on the vertical range of water-level fluctuations to demonstrate the significance of potential sea-level rise that 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. 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 mapped in Figure 6.1.

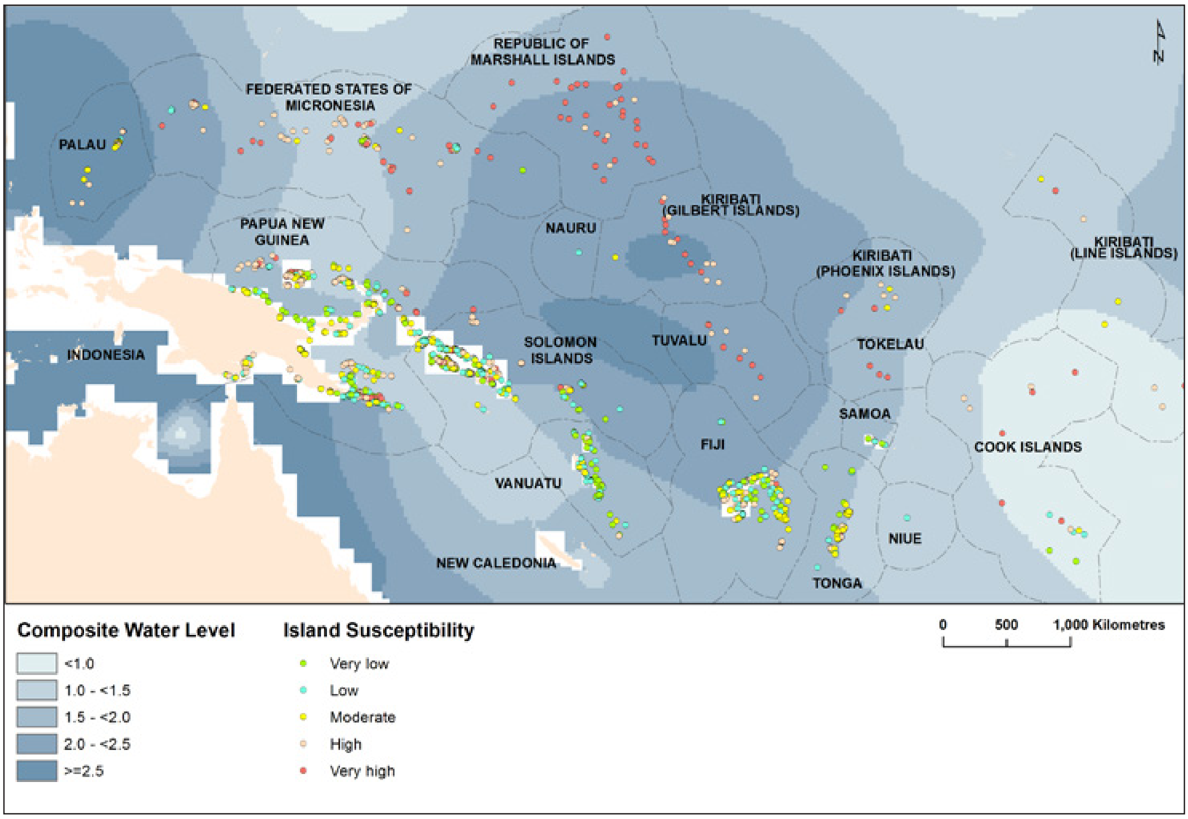


Figure 6.1 Map of composite water-level ranking in the Pacific Island region.

6.1.2. Wave height and tropical cyclone frequency

Annual average significant wave height (Hs) was selected as the parameter for representing wave energy (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. Hs 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). It incorporates the east to west decline in wave height as well as a zonal decline towards the equator in both hemispheres.

Tropical-cyclone (TC) 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 TC tracks (Figure 5.3) was annotated to separate the Pacific into five categories of TC frequency. The very low category represents no TC in the available dataset, with very high representing areas where tropical cyclones occur more frequently than one in three years.

To develop the process ranking the individual rankings of TCs and wave height were combined (Figure 6.2). Areas with exposure to frequent tropical cyclones are likely to have high resilience to several changing environmental processes while an area with 'no record of tropical cyclones' will respond to waves alone. Areas with low wave heights and high TC frequency are sensitive to changes in mean sea level as the coastal land forms have a limited capacity to rebuild when they are impacted by extreme events. Areas with high wave heights and low TC frequency have a high capacity for rebuilding.

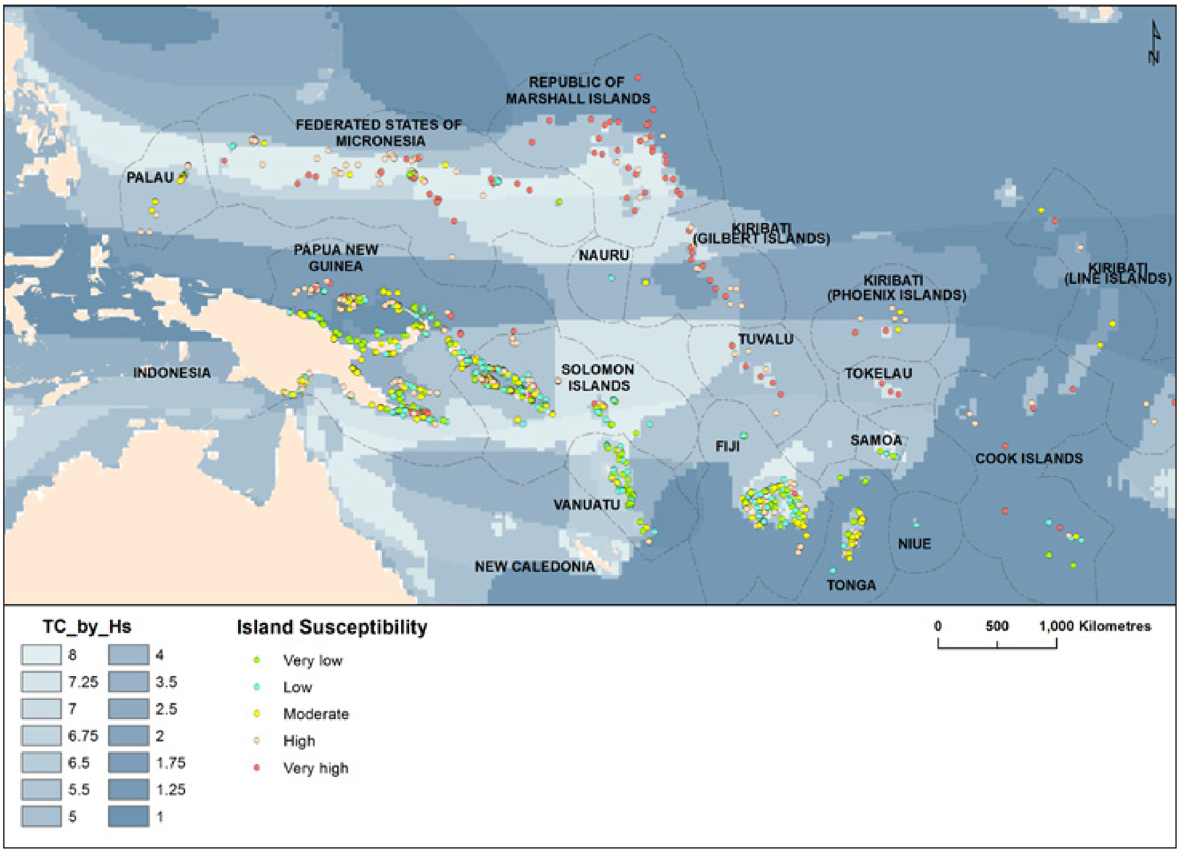


Figure 6.2 Map of combined average significant wave height (Hs) and tropical cyclone frequency.

6.2. Process sensitivity

The three parameters—composite water level, significant wave height and tropical cyclone frequency—were combined to yield a single value to obtain a climate-ocean process sensitivity as a measure of potential island-coast change to future conditions. 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%). 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. The distribution of process sensitivities for different countries demonstrates a different range of process sensitivities for all but single island countries (Figure 6.3).

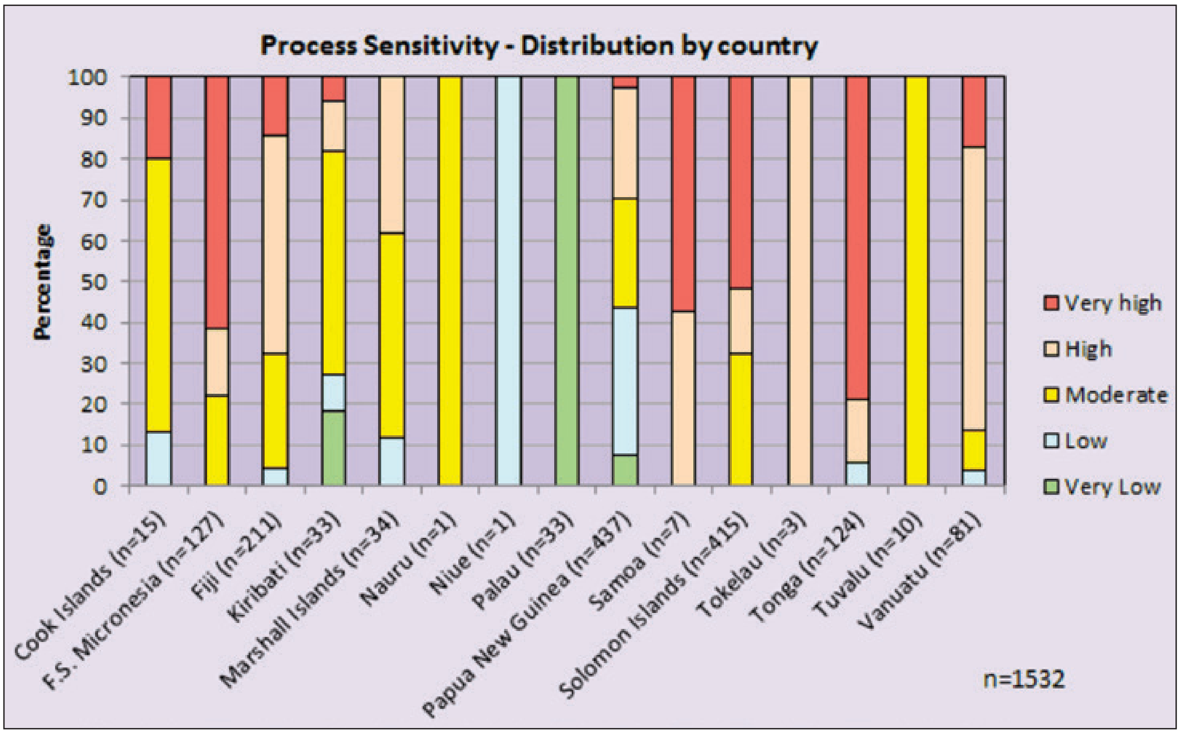


Figure 6.3 Process sensitivity by country.

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's one island is of low sensitivity while Nauru is classed as moderately sensitive to potential changes in environmental forcing. Papua New Guinea on the other hand includes all categories with islands ranging from very low to very high. Other countries with a range of values but a mode of moderate sensitivity are the Cook Islands, Kiribati, Marshall Islands and Tuvalu. The modal values 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.

6.3. Geomorphic sensitivity of island coasts

The term *geomorphic sensitivity* is applied to the combination of island susceptibility (Chapters 3 and 4) and process sensitivity (this Chapter). This is a means of considering the sensitivity of the coastal landforms of whole islands to potential changes in climate-ocean processes and involves both the drivers (process sensitivity) and receptors (island susceptibility) being integrated.

The geomorphic sensitivities for all islands in the database is mapped in Figure 6.4. Mainly islands were of moderate (23%), high (28%) and very high (25%) geomorphic sensitivity with fewer falling into the lower ranks of very low (5%) and low (19%). This skewness towards the moderate to higher geomorphic sensitivities is attributed to the islands with lower susceptibility occurring in areas with higher process sensitivities.

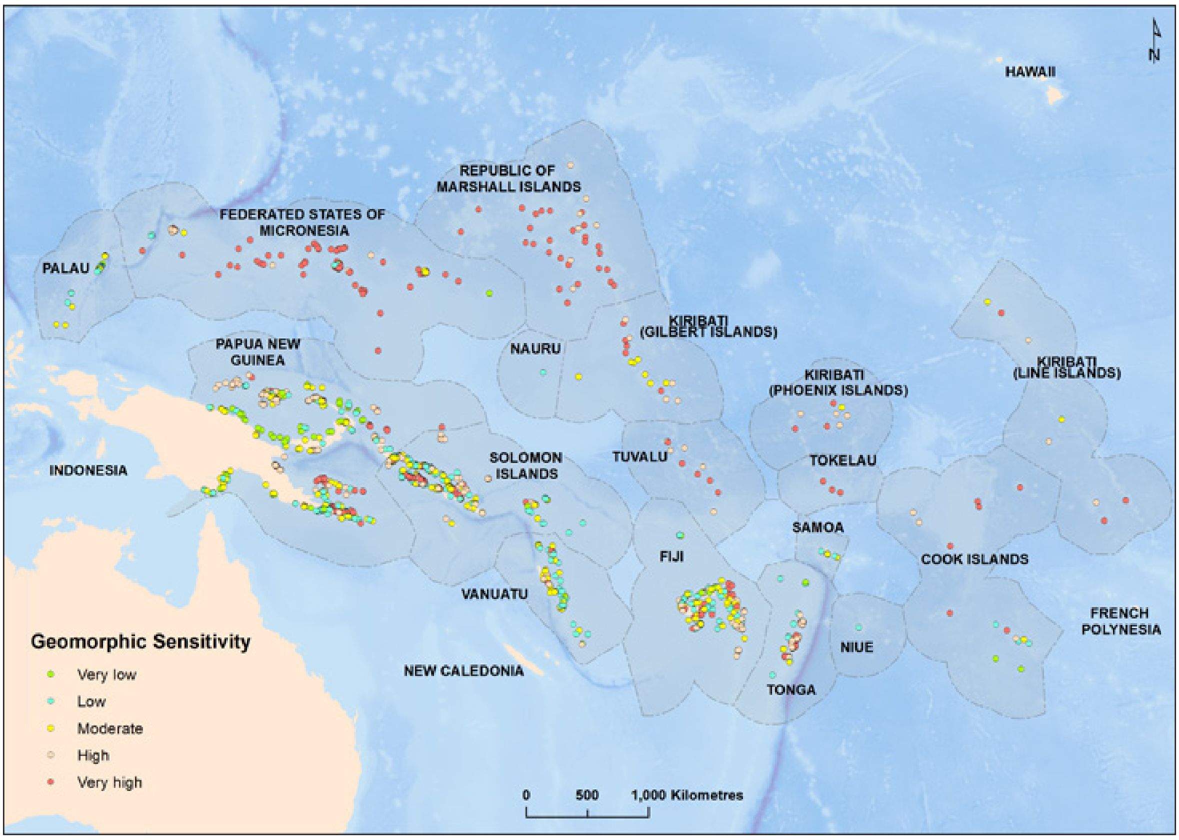


Figure 6.4 Geomorphic sensitivity for the 1532 islands in the database.

6.4. Geomorphic sensitivity by island type and country

Certain island types are more geomorphically sensitive than others (Figure 6.5). 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 indicates that if an island is a volcanic high island, it is most likely to be in the low geomorphic sensitivity category, though the range is 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, though 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.

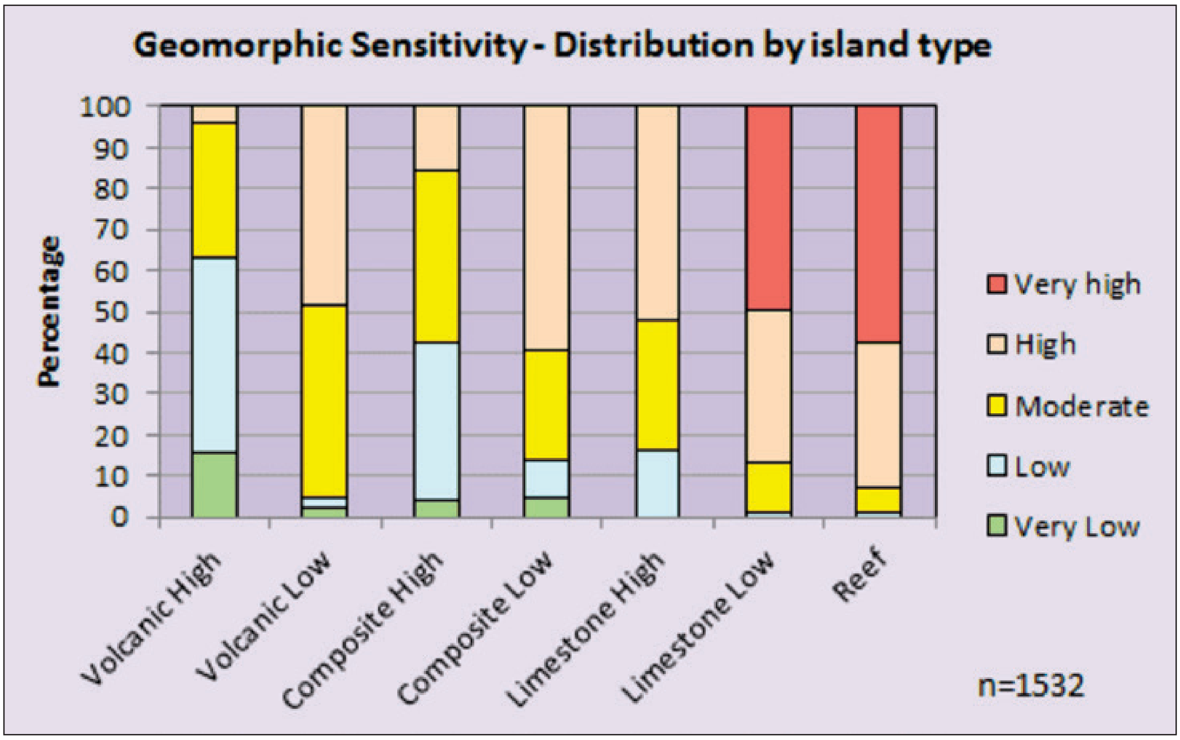


Figure 6.5. Geomorphic sensitivity of island types

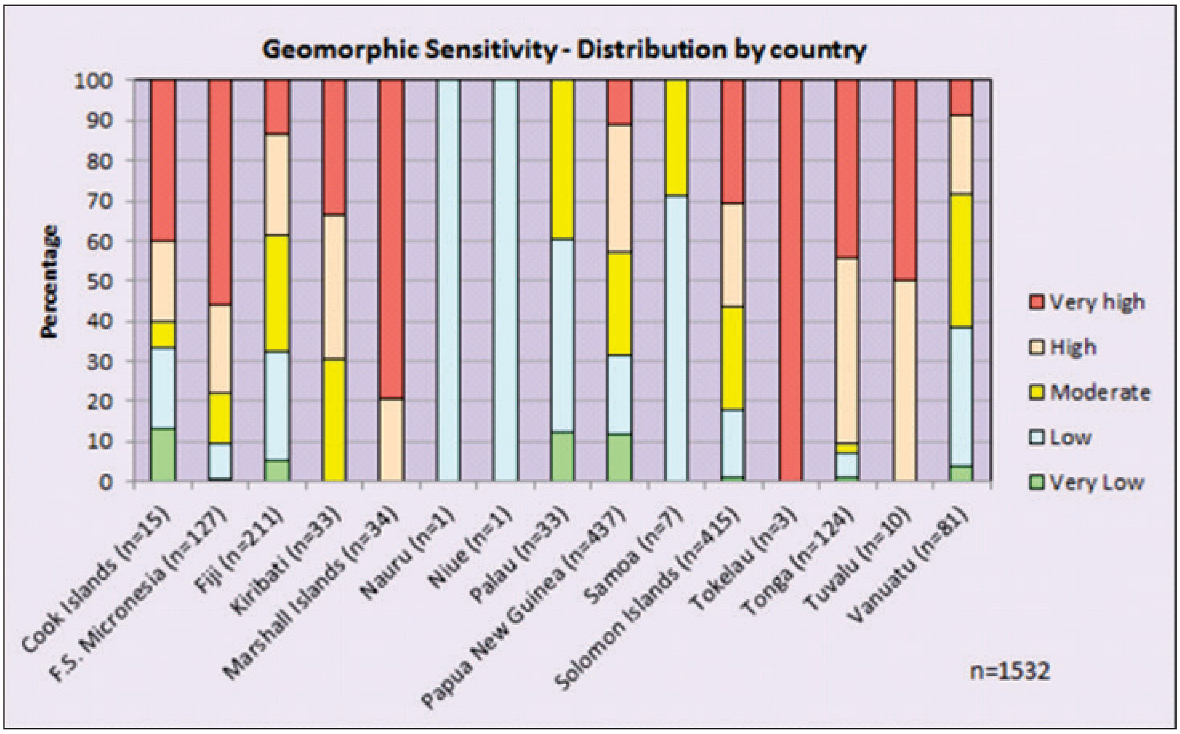


Figure 6.6 Geomorphic sensitivity by country

Variations in geomorphic sensitivities are found for different countries (Figure 6.6). The figure demonstrates a different range of geomorphic sensitivities for all but single-island countries (Nauru and Nuie). 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.

Chapter 7.
Key Findings and Implications for Planning and Management

Key Points

- This analysis provides a regional assessment of potential coastal response to climate –ocean change across the Pacific.
- This report provides a science-based framework for assessing the susceptibility and sensitivity of island coasts to climate and ocean processes both now and in the future.
- The process presented involves a series of steps where the physical and geographical criteria used initially in assessing susceptibility are incrementally expanded to finally develop a measure of geomorphic sensitivity that also includes climate and ocean processes that result in coastal change.
- Whilst this analysis can guide decision makers through identifying sensitive coastal areas at regional through to local scale, it is not of itself a coastal vulnerability assessment. Rather it provides a consistent and systematic process that can readily incorporate vulnerability studies.
- Further analysis will enable well-informed assessments of coastal vulnerability and risk and encourage the development of robust adaptation responses.

7.1. Synopsis

This chapter briefly reviews the main implications of the findings of this report for both the Australian Government and in-country partners, ranging from Pacific Island governments and regional organisations to communities confronted by coastal-environmental problems attributable to climate-ocean variability and change.

The degree to which particular islands are exposed to such changes is initially discussed in Chapter 3 at a whole-island scale using a simple measure of susceptibility based on four inherent physical characteristics that every island has: rock type (lithology) height, area and shape (circularity). Everyone of the 1,532 islands in the database are assigned an indicative measure, from very low to very high susceptibility, that can be used to identify areas at a regional scale of various degrees of susceptibility to coastal landform change. Added to the four primary variables are two further groups of physical and geographical attributes in Chapter 4 the first of which includes insularity, proximity of other islands and seabed slope, and the second includes a further nine characteristics of the backshore, intertidal, inshore and reef zones of the coast. These attributes are combined to derive a more detailed secondary assessment of susceptibility which is still an indicative and relative measure. The chapter concludes with an even finer scale subdivision of island coasts into coastal sectors. Two examples are illustrated: the first by the high volcanic island of Luon (Solomon Islands) where all sectors have similar susceptibility; and the second by the composite island of Aitutaki (Cook Islands) which has characteristics of both volcanic and reef islands with sectors ranging from low to high susceptibility.

Following on from Chapter 5 which deals with the present and future climate-ocean processes, the penultimate chapter (Chapter 6) takes the results from the susceptibility and climate-ocean chapters to develop a process sensitivity and ultimately coastal geomorphic sensitivity to change. The results of this analysis clearly demonstrate that islands of similar type do not have the same sensitivity to change. For instance all reef islands do not have 'very high sensitivity' but range over three sensitivity classes from moderate to very high because of the different climate-ocean settings of the islands. Similarly all countries in the region (apart from single-island Nauru and Nuie and the three atolls of Tokelau) have islands with different sensitivity values. Both of these factors serve to emphasise the conclusion that adaptation strategies need to be flexible enough to cover the range of susceptibility and sensitivity identified here.

Thus the assessment described in the foregoing chapters allows a comparative analysis of susceptibility and sensitivity to change between islands in the Pacific region as well as within particular islands. The results should 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.

7.2. Regional coastal susceptibility assessment

This section provides an overview of whole-island susceptibility across the entire Pacific Islands region and 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 be 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.

The type of island most susceptible to change based on lithology and elevation is the 'reef island', which is found throughout the Pacific Islands region yet occurring much less in its southern part (Vanuatu-Fiji-Tonga-Samoa-southern Cook Islands). 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. 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. It is envisaged that the graphs in Figure 2.3 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 2.3. Subtle differences emerge when considering the area of limestone islands within particular countries in Figure 2.3 where the situation in Palau is actually somewhat less critical than might be supposed from looking at Figure 2.3; only a small area of limestone islands are found in this island group.

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. 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 3.3 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. 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. In contrast, Vanuatu has a profile that is generally far less susceptible.

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, that can be interpreted as what is likely to happen in the next few decades (Comparing Figure 3.3 and 6.3). 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 6.3) 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 6.4 and 6.5) 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 6.6) allows planners insights that complement those of process sensitivity, discussed above. Very high geomorphic sensitivities understandably occur in atoll (reef island) 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.

The next steps in dealing with the sensitivity 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, modified for different purposes, and could eventually become a standard for the assessment of susceptibility to change. It could also serve as a template for future vulnerability assessment studies by providing a consistent and justifiable regional context for such work. 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 expansion of tools of this kind become ever more important.