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FUTURE SEA-LEVEL RISE IN THE PACIFIC

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FUTURE SEA-LEVEL RISE IN THE PACIFIC: EFFECTS ON SELECTED PARTS OF COOK ISLANDS, FIJI, KIRIBATI, TONGA AND WESTERN SAMOA

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AUTHOR'S NOTE

This work arose from a preliminary report to the United Nations Environment Programme who funded an exploratory study on the topic named in the countries named by Dr. Patrick Nunn and other staff and students of the University of the South Pacific (USP). The work discussed is the result of investigations by the University of the South Pacific team in co-operation with governmental contacts in urban centres as follows; Suva, Labasa and Savusavu (Fiji), Apia (Western Samoa), Nuku'alofa and 'Ohonua (Tonga) and Tarawa (Kiribati).

Student researchers were funded under grant 0703-8701 from the University of the South Pacific and with funds from the United Nations Environment Programme (UNEP) administered through the Association of South Pacific Environmental Institutions (ASPEI), chaired by Dr. John Pernetta of the University of Papua New Guinea. Funds were also received from the latter source to assist in the preparation of reports, including this working paper.

It is a pleasure to acknowledge the help I have received from various colleagues at USP since this research commenced in November 1987. Responsibility for data analyses and unattributed opinions expressed in this working paper remains mine alone. It is emphasised that many results are preliminary, many sources of data as yet untapped and, consequently, some specific remarks may be in error. For these reasons, it is requested that this working paper is not quoted elsewhere without the author's written permission. I am grateful to Keresi Tabete for help in preparing the final draft.

Dr. Patrick D. Nunn
October 1988, Suva.

FUTURE CHANGES IN SEA LEVEL

The burning of fossil fuels, principally since the mid-nineteenth century, and certain synthetic materials has led to a 20-30% increase in the amount of carbon dioxide in the atmosphere (Keeling *et al.*, 1982) and an increase from negligible proportions of certain trace elements in the atmosphere (Ramanathan *et al.*, 1985). Principally through the operation of the 'greenhouse effect' (Figure 1), this has led to a global warming, discernible in meteorological records from at least the 1940s onwards (Jones *et al.*, 1986), although there is some dispute as to whether this has been a truly global phenomena (Mitchell, 1963).

This situation has been exacerbated by the clearance of vast areas of forest, which had previously been responsible for absorbing much atmospheric carbon and maintaining, it is thought, a state of equilibrium in the atmosphere between the amount of carbon dioxide relative to certain other gases (Bolin, 1977; Woodwell, 1978). The current release of carbon into the atmosphere from the combustion of fossil fuels is about 5×10^{15} grams annually. It is estimated that an additional $0.5\text{-}4.7 \times 10^{15}$ grams is contributed from deforestation (Woodwell, 1987).

There is no consensus as to the amount by which mean global temperature will increase; estimates vary between 1.5-5.5°C (34.7-41.9°F) by the year 2100 (National Academy of Sciences, 1977). The increase in atmospheric carbon dioxide between 1880 and 1975 should have increased the mean global temperature by 0.3°C (Manabe, 1971).

A clear possibility is that this global warming, be it occurring at present or likely to occur in the future, could cause some of the world's ice masses to melt and sea level to rise as a consequence with predictable effects on the world's coastlines (Hansen *et al.*, 1981). This possibility is given added credibility by the generally-accepted prediction that the temperature increase in polar regions is expected to be between three and five times greater than the average global increase (Schneider, 1975).

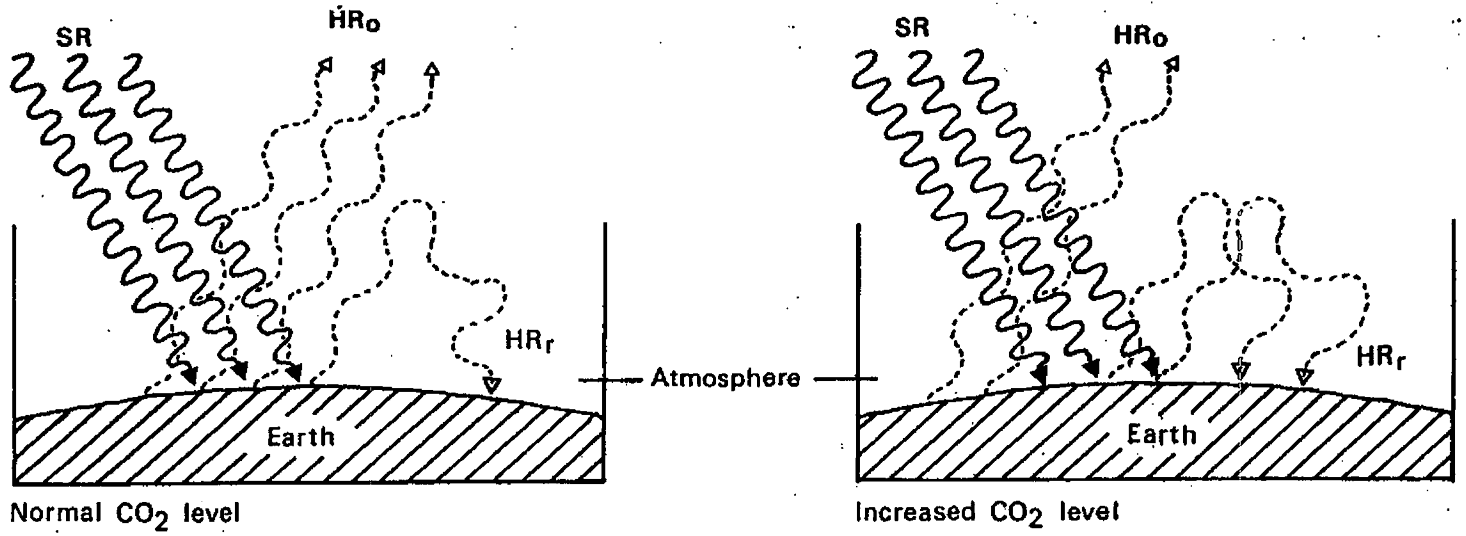

Figure 1. The "greenhouse effect", adapted from Miller (1980). Abbreviations: SR - incoming short-wave solar radiation, HR_o - outgoing long-wave heat radiation, HR_r - re-radiated long-wave heat radiation.

Some of the short-wave radiation which strikes the Earth's surface is eventually radiated back into the atmosphere as long-wave heat radiation. This is absorbed by carbon dioxide in the atmosphere and some is re-radiated back to the Earth's surface. An increase in atmospheric carbon dioxide has led to an increase in the amount of heat re-radiated back to the Earth's surface, and a consequent increase in Earth surface temperatures.

The amount by which sea level is predicted to rise is not agreed upon and Hoffman's (1984) range of estimates (Table 1) are representative of most. Estimates range from about half a metre to three and a half metres of sea-level rise by the year 2100. Although many people might dispute the magnitude of such estimates, the important point on which to focus is that there is almost certainly going to be a sea-level rise. This will affect vast areas of the world's coastline and must be addressed in advance if social and economic disruption is to be minimised. Such issues are much more important than arguments about the precise magnitude and timing of the sea-level rise.

Sea level will not rise only as the result of land-ice melting. An additional rise in sea level would result from the thermal expansion of ocean waters. A 2°C increase in mean global temperature would cause about a 1m rise in sea level due solely to thermal expansion (National Academy of Sciences, 1977).

If all the land ice on the Earth melted, sea level would rise by about 66-81m (Goudie, 1983; Gibb, 1988), but this is unlikely on the time-scale under consideration. The actual amount that sea level would rise as a consequence of the present global warming depends on the actual temperature increase, the time-scale over which this occurs and, critically, which ice bodies would be affected and which would not. In 1984, the United States National Research Council agreed on there being a rise in sea level of around 0.45m by the year 2100. Compared to other predictions, this is conservative indeed. Other authorities regard much greater increases in sea level as more probable (Mercer, 1978). The range of predictions is summarised in Table 1.

The considerable variation in predictions of future sea-level rise produced by increases in the amount of atmospheric carbon dioxide reflects variations in the parameters used in predictive models (National Academy of Sciences, 1977). Most of these models have been specific to North America and Western Europe and it is not possible to transfer their predictions uncritically to the Pacific islands.

Table 1. Estimates of sea-level rise, 2000-2100 (after Hoffman, 1984). All data are in centimetres

Year	Estimates			
	a	b	c	d
2000	4.8	8.8	13.2	17.1
2025	13.0	26.2	39.3	54.9
2050	23.8	52.3	78.6	116.7
2075	38.0	91.2	136.8	212.7
2100	56.2	144.4	216.6	345.0

a - conservative scenario
b, c - mid-range scenarios
d - "high" scenario

If a cup of water is added to a bucket of water, the water level will rise virtually instantaneously. Although, over about 200-600 years, this analogy is applicable to the effect of rapid partial polar ice melt on the level of the world's oceans, it is unrealistic in the shorter term owing to lags in the global system.

By way of example, one popular scenario for future ice melt involves the floating Arctic ice mass melting but the considerably larger Antarctic ice sheet remaining virtually intact (National Academy of Sciences, 1977). Were the Arctic ice to melt, there would be little direct change in sea level since it is floating already. The effect of melting of ice cubes on water level in a glass of water is an analogy. However, any attendant melting of the continental circum-Arctic ice masses, principally that in Greenland, would undoubtedly have an effect on sea level in the Arctic Ocean (Figure 2A). This is a fairly enclosed ocean and its narrowest and shallowest exit is that leading to the Pacific, known as the Bering Strait, which is bordered by high mountain ranges. Were sea level to rise rapidly in the Arctic, therefore, little of this would be able to enter the Pacific immediately. Most of it would enter the Atlantic and the greatest effects of the accompanying sea-level rise might not be felt on Pacific island coasts for many decades.

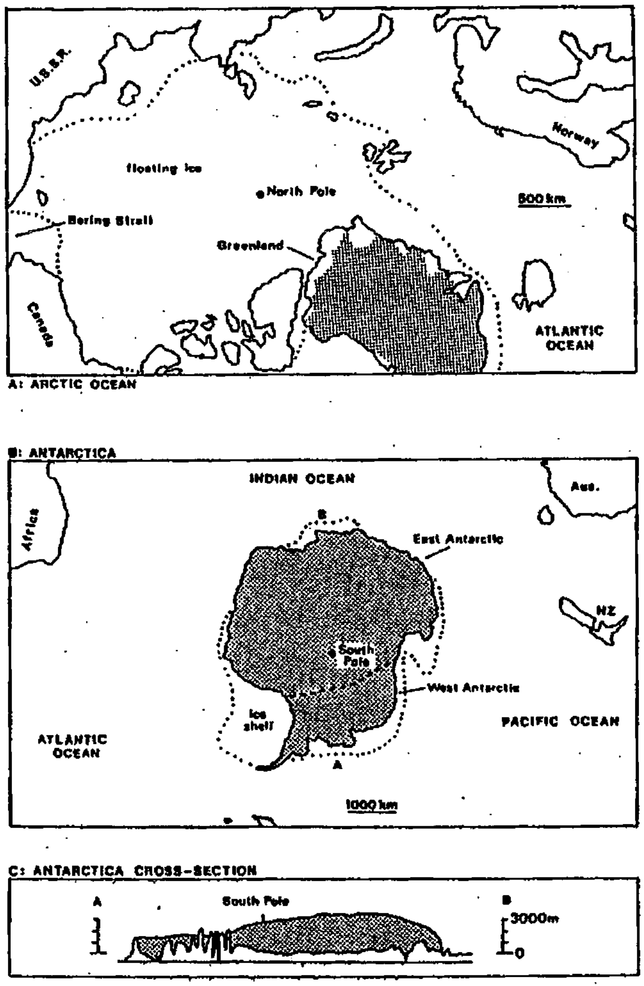

Figure 2. A: The Arctic, showing permanent ice (dot shading), principally in Greenland, and the southward limits (dotted line) of floating ice in the Arctic Ocean. About 10% of the world's ice (2.6×10^6 km^3) is in the Arctic (Denton et al., 1971).

B: The Antarctic, showing the continental ice sheets (dot shading) in East and West Antarctica and floating ice offshore. Just over 89% of the world's ice (24×10^6 km^3) is in the Antarctic. The ice sheet in West Antarctica has a volume of around 3.8×10^6 km^3, that in East Antarctica has a volume of 20.2×10^6 km^3. Volumes are from Denton et al. (1971).

C: Cross-section through the Antarctic ice sheet (after Bentley, 1965). Line of section shown in B.

Since around 90% of the world's ice is bound up in the Antarctic (Figure 2B, 2C), less favourable scenarios, particularly for the Pacific, involve the disintegration of the grounded West Antarctic ice sheet (Mercer, 1978) or even an Antarctic ice surge. Of the two possibilities, an ice surge involving the East Antarctic ice sheet, the largest on Earth, was first proposed by Wilson (1969) as responsible for having initiating ice ages over the last two million years or more. Although writers like Hollin (1972) presented much evidence in favour of Wilson's idea, it has not gained wide currency, although continues to gather support (e.g. Aharon *et al.*, 1980).

Both an Antarctic ice surge and the disintegration of the West Antarctic ice sheet would involve an essentially instantaneous input of a huge volume of ice into the southern oceans, perhaps causing the sea level to rise by as much as 10m above its present level over the following 300 years (National Academy of Sciences, 1977) or less (Hughes, 1983; Jacobs, 1987). Such scenarios are widely regarded as extreme for numerous reasons, an important one being that recent evidence from ice cores in the Antarctic has shown that the Antarctic ice sheets have withstood much greater fluctuations in the level of atmospheric carbon dioxide in the past than have been recorded in the last two hundred years.

It must be emphasised that our knowledge of the workings of the global climate system, although often impressive, is far from being complete and all predictions about future sea-level behaviour have a large element of uncertainty about them. A very few people working in this field still believe that no sea-level rise will result from the "greenhouse effect" (e.g. Bryant, 1987). It is more important perhaps to admit that our models of global climate are so comparatively deficient that "the effects of the rise in concentration of the greenhouse gases will come largely as surprises" (Broecker, 1987: 128).

RECENT CHANGES IN SEA LEVEL

It is widely believed that a major acceleration in sea-level rise as the consequence of the greenhouse effect has yet to begin. This is why, in many parts of the world, the gradual rise of sea level in the last hundred years or so has been and continues to be carefully monitored. Estimates for sea-level rise over the last century vary from 12cm (Gornitz *et al.*, 1982) to 30cm (Emery, 1980).

There is no reason to suppose that such 'global' estimates are all valid locally, and data specific to New Zealand are, in the absence of any from the island Pacific, the closest approximations. The work of Hannah (1988) revealed that mean sea level has been rising around New Zealand since about 1900 at a rate of 1.2mm/year, with well-marked variations from 0.8mm/year at Auckland to 1.6mm/year at Wellington. There is an urgent need for similar studies in the island Pacific in order that a clear relationship can be established between sea-level rise here and that in New Zealand and elsewhere.

AIMS OF THIS PROJECT

Most authorities believe that sea level will rise over the next hundred years, perhaps by as much as 3.5m. The consequences of this sea-level rise on Pacific islands will be substantial and should be the subject of some forward planning. The aim of the work reported below was to seek some indication of the nature of these effects. The most visible and probably the most immediate effect of the sea-level rise on Pacific island coasts will be in terms of land loss. This is also one of the easiest effects to predict accurately and thus formed a large part of the work carried out.

Following a brief account of the methods used and the sources of data available, the results are presented in the form of case studies, most of which are representative of a number of places in the island Pacific.

METHODS OF INVESTIGATION

Contoured maps of selected areas were sought. Linear interpolation between existing contours and map datum, supplemented by a particular investigator's knowledge of the area covered by the map, allowed the construction of four contours each representing a time-dependent scenario of future sea-level rise as follows. The following contours are those which were established by the United Nations Environment Programme as standard for this and similar projects elsewhere so that results from all projects would be quantitatively comparable.

(a) Contour at 20cm (0.2m) or 0.67 feet (8 inches); a medium scenario for the year 2025.

(b) Contour at 50cm (0.5m) or 1.5 feet (1 foot, 6 inches); a high scenario for the year 2025.

(c) Contour at 1.5m or 5 feet; the medium scenario for the year 2100.

(d) Contour at 3.5m or 11.5 feet (11 feet, 6 inches); the high scenario for the year 2100.

For this work, it was necessary to find maps with an existing contour interval equal to or less than 5m or 15 feet in order to allow linear interpolation to proceed and the contours named above (a-d) to be constructed. Once contours at these intervals had been constructed, it was possible to quantify impact in terms of the area of land loss. To do this, squares were counted on graph paper of specified size between each constructed contour and map datum; squares were converted to square kilometres or square metres using map scales. Each area was then divided on the basis of land-use types to enable the quantitative impact to be presented in terms which are readily convertible to measures of economic impact.

DATA SOURCES AND DATA ACQUISITION

The biggest problem encountered in this study was finding suitable maps. Ministries of Lands and Surveys in the various countries of the study region yielded little suitable material. Among the urban areas investigated, only Nuku'alofa and Suva apparently had map coverage at 1:1000 with suitable contour intervals. No maps of rural areas in any of the countries under study could be found at suitable scales, although unpublished geomorphological maps made for other purposes allowed some useful studies of small islands in Fiji to be made. Approaches to some of the large 'resorts' along the islands' coasts may be profitable in future in this context, as may contact with consulting architects and engineers, based both within and outside the region, who have worked on particular projects.

In many cases, the map datum and method of contour construction were not specified on the map so field checks were carried out to ensure that the contours were realistic. Where map datum was unspecified, it was assumed to be mean high water; on most islands in the region under study, this level is approximately 0.5m above mean sea level, the most common global map datum.

On few maps was it possible to calculate the 0.2m and 0.5m contours. In urban areas, the presence of sea walls commonly rendered these contours coincident with map datum.

The precision of data resulting from square counting within areas bounded by constructed contours and map datum is dependent in the final instance on the accuracy of the original map and the precision with which the existing contours were constructed. In many cases it is not possible to assess this meaningfully although an accuracy rating is given for all the results as a rough guide to data quality.

RESULTS

The results of the work on land loss and other impacts of sea-level rise are presented below as a series of separate case studies. The land-use categories used in Tables 2-14 are defined as follows.

(a) Agricultural (including grasslands).

(b) Forest (including areas of widely-spaced trees, such as coconut palms, not otherwise classifiable).

(c) Mangroves (including swampy areas not otherwise classifiable).

(d) Residential (including settlements with widely-spaced houses not otherwise classifiable).
(e) Industrial.

(f) Commercial.

(g) Others (as specified).

Most of the case studies described below were chosen because they are representative of a particular set of geographical conditions and the conclusions drawn concerning the impact of future sea-level rise may therefore be applied to similar situations. The case studies and the situations they typify are as follows.

Rarotonga - high volcanic island with extensive coastal plain fringed by a beach ridge, only a fringing reef offshore (similar to Moorea and Tahiti Nui, French Polynesia, Savai'i in Western Samoa, Kadavu in Fiji)

Beqa - small volcanic island with narrow coastal plain, highly variable offshore reef configuration (similar to many small islands in Vanuatu and Solomon Islands)

Cicia - small volcanic island with peripheral (*makatea*) limestone, only a fringing reef offshore (similar to Lakeba in Fiji, Rurutu in the Austral Islands, Mangaia and Aitutaki in the Cook Islands)

Moala - large volcanic island with narrow coastal plain and both fringing and barrier reef offshore (comparable to large volcanic Islands in the region such as Viti Levu, Fiji, and some of the Hawaii group)

Vatoa - moderate height limestone island with upland agriculture and variable offshore reef configuration (similar to Niuatoputapu, Tonga and the Loyalty Islands, New Caledonia)

Vatulele - low limestone island with lowland, often swampland, agriculture, variable offshore reef configuration (similar to many true atolls, also Vava'u and Tongatapu in Tonga)

Labasa - town at delta head threatened both by shoreline retreat and impounding of sediment in narrowly-constricted valleys (similar to many smaller settlements on Viti Levu and Vanua Levu in Fiji, and on Upolu in Western Samoa; and throughout Vanuatu and Solomon Islands)

Savusavu - town developed along narrow coastal plain threatened by impounding of steep narrow valleys at its rear as well as shoreline retreat (similar to many settlements on Viti Levu and Vanua Levu in Fiji, and in parts of Vanuatu and Solomon Islands)

Tarawa - ribbon atoll similar to most others in Tuvalu and Kiribati, the northern Cook Islands, and the island *motus* of French Polynesia and elsewhere

Nafanua - artificial harbour threatened from rear but considerable protection afforded already by naturally cliffy character of the shoreline (similar to cliffed limestone coasts elsewhere in Tonga, on Tongatapu and Vava'u for instance, in the southern Cook Islands and eastern Fiji)

Nuku'alofa - large urban centre to be considered a case by itself

Apia - large urban centre to be considered a case by itself

For each case study, an accuracy rating is stated. This is a general rating of data quality and intended to inform the reader how accurate the scenarios stated are and also to convey the urgency of gathering more precise data for particular case studies.

Cook Islands - Rarotonga

Suitable contour maps of the Cook Islands were not sufficiently detailed to allow anything other than the construction of the 1.5m contour (Figure 3, Table 2), and data quality is not high. Undoubtedly higher-quality data could be found on the island itself.

Rarotonga is a high volcanic island with a comparatively narrow, intensively-farmed and densely populated coastal plain. This is fringed by a beach ridge reaching 4-5m above sea level, which is important in preventing inundation of the inner parts of the coastal plain, where most development is located. Much of the area below 1.5m is agricultural, a large amount of staples being grown here in swampy areas.

Although 17.11% of the lowland area on Rarotonga lies below 1.5m, far greater amounts of land would be lost were sea level to rise this much because of lateral erosion of the largely unconsolidated and/or permeable materials of which this coastal plain is composed. A rise in sea level causes shoreline disequilibrium. Equilibrium will be restored through lateral erosion which would be needed if the original (pre-sea level rise) equilibrium shoreline profile were to be established at a higher level.

The lowland fringe of Rarotonga will become increasingly uninhabitable as future sea-level rise progresses. It is suggested that increased utilisation of the upland volcanic areas be encouraged.

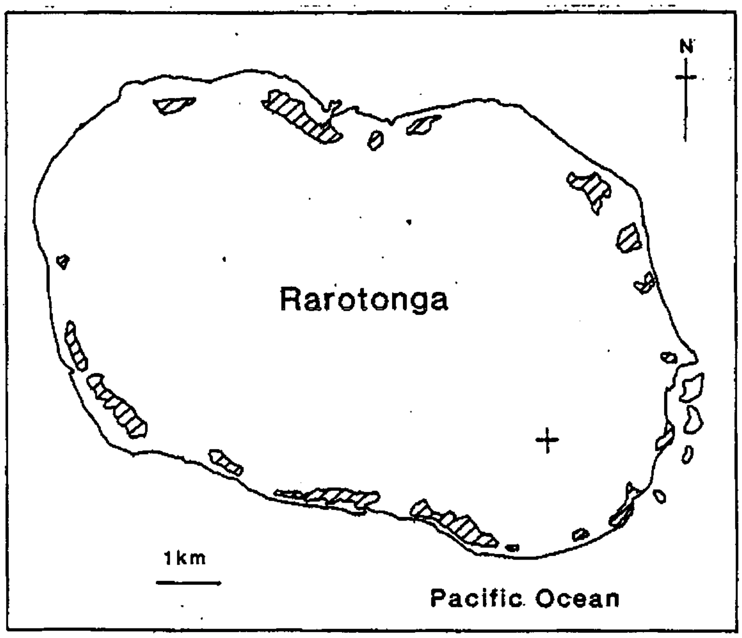

Figure 3. **Island of Rarotonga in the Cook Islands showing land below 1.5m (hatching). The cross marks the point 159°45'W, 21°15'S. The main population centre is Avarua in the centre of the north coast with the international airport just to its west. The island is surrounded by a fringing reef.**

Table 2. Impact of future sea-level rise on Rarotonga, Cook Islands, expressed as square kilometres of land loss for different scenarios identified by the sea level in metres above present. Total land area of Rarotonga is 66 sq.km (see Figure 3). The last column on the right refers to the 1.5m scenario only. Accuracy rating for Rarotonga data is medium to low.

Type of land loss	Scenario				% total in each category
	0.2	0.5	1.5	3.5	
Agricultural	?	?	0.83	?	?
Forest	?	?	0.31	?	?
Mangroves	?	?	0.20	?	?
Residential	?	?	0.58	?	?
Industrial	?	?	?	?	?
Commercial	?	?	?	?	?
Others	?	?	?	?	?
Total land loss	?	?	1.92	?	
% total land area		?	2.91	?	
% total lowland area		?	17.11	?	

Sources of data: Lands and Survey Department, Cook Islands, 1982, 1:15,840 topographic map of Rarotonga, 3rd edition

Fiji - Beqa island

Data sources for Beqa (Figure 4, Table 3) are reasonable and have been supplemented by direct field observation. Beqa is a small high volcanic island with a very narrow coastal plain in most places. The coincidence of villages with area of inundation indicates the critical shortage of low, flat land, which will obviously be exacerbated as sea level rises.

The low areas at the heads and along the sides of bays are mostly mangroves and not extensively used for agriculture at present. The amount of inundation shown in these areas for different scenarios is unlikely to be realised for most of the island's large rivers debouch into these bays and sea-level rise will greatly increase sedimentation therein, perhaps causing the bays to become (partly) infilled.

Villages on Beqa will all suffer from the effects of sea-level rise; 79.41% of their total would be inundated by a 3.5m rise. A substantial acreage of gardens and forest, mostly coconut palms, is also threatened. The solutions are obviously a gradual change from lowland to upland village sites and increased utilisation of the agricultural potential of upland areas.

Inundation of the offshore reef (not shown in Figure 4) will cause increased wave attack along the island's south and southeast coasts. Most of the Beqa lagoon lies off the island's northwest coast and changes in lagoon circulation caused by sea-level rise will have serious consequences for the fishing potential of nearshore areas. Diversification of agriculture and a decreased reliance on foods gathered from nearshore reefs is to be encouraged.

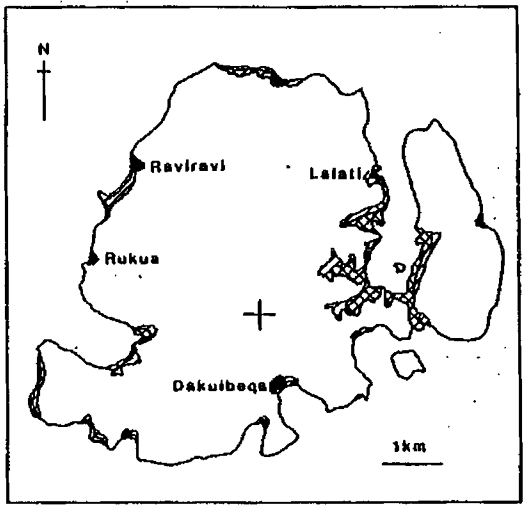

Figure 4. The island of Beqa (Mbengga) in Fiji showing the land below 3.5m (hatch), land below 1.5m (cross-hatch), and settlements (solid). The cross marks the point 178°08'E, 18°24'S. The island is surrounded by a fringing reef in the south and east, and a barrier reef in the north and west.

Table 3. Impact of future sea-level rise on Beqa island, Fiji, expressed as square kilometres of land loss for different scenarios identified by the sea level in metres above present. Total land area of Beqa is 36.26 sq.km (see Figure 4). The last column on the right refers to the 3.5m scenario only. Accuracy rating for Beqa data is medium.

Type of land loss	Scenario				% total in each category
	0.2	0.5	1.5	3.5	
Agricultural	?	?	0.04	0.40	?
Forest	?	?	0.15	0.29	?
Mangroves	?	?	0.82	0.82	100.0
Residential	?	?	0.13	0.27	79.41
Industrial	0	0	0	0	0
Commercial	0	0	0	0	0
Others - sand	?	?	0.15	0.42	80.0
Total land loss	?	?	1.29	2.20	
% total land area	?	?	3.56	6.07	

Sources of data: Department of Lands, Mines and Surveys, Fiji, 1961, 1:50,000 topographic map (Viti Levu sheet 22); field survey, P.D. Nunn (1988)

Fiji - Cicia island

Form-line maps of Cicia supplemented by field data were sufficient to allow construction of the 3.5m contour (Figure 5, Table 4), which is coincident in most places with that at 1.8-2.5m which represents the shoreline established 4-6,000 years ago when the sea first reached close to its present level after the long Holocene postglacial transgression (Nunn, 1987).

Over 75% of Cicia's settlements would be drowned in a 3.5m rise. Only the higher parts of Tarakua and Mabula, which are overflow settlements from the original sites on the crowded coastal plains, would be relatively untouched.

The central part of Cicia is volcanic but the island is fringed in places by uplifted reef limestone (the *makatea* of Polynesia), areas which would be undermined more than they are already by future sea-level rise. Increased sedimentation would be accommodated in what are presently the middle reaches of the main valleys, inland from the west coast and Lomati village. The major commercial copra plantation at Tokalau will be lost completely even if the sea rises only 1.5m.

Those parts of the coastal plain which are under greatest threat from compensatory lateral erosion associated with sea-level rise are southwest of Mabula, behind Naceva-Tokalau and between Lomati and Tarakua.

A movement of settlement away from the existing coastal plain into the foothills of the central mountains is recommended together with increased utilisation of inland areas for food rather than exclusively cash crops.

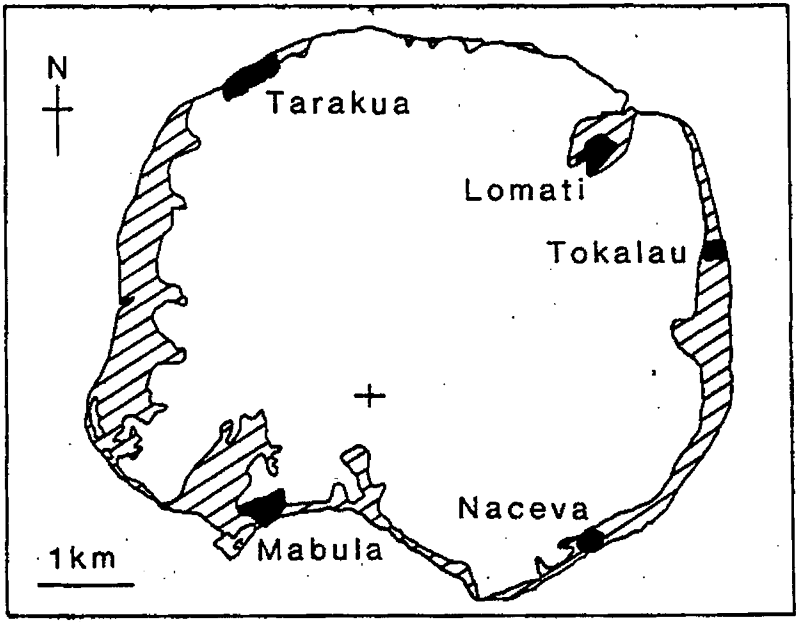

Figure 5. **The island of Cicia (Thithia) in eastern Fiji showing the land below 3.5m (hatch) and settlements (solid). The cross marks the point 179°20'W, 17°45'S. The airstrip is built on reclaimed land below 1.5m in the central part of the island's west coast.**

Table 4. Impact of future sea-level rise on Cicia island, Fiji, expressed as square kilometres of land loss for different scenarios identified by the sea level in metres above present. Total land area of Cicia is 34.6 sq.km (see Figure 5). The last column on the right refers to the 3.5m scenario only. Accuracy rating for Cicia data is medium.

Type of land loss	Scenario ----------------------------				% total in each category
	0.2	0.5	1.5	3.5	
Agricultural	?	?	0.2	0.6	8.0
Forest	?	?	0.35	1.71	30.0
Mangroves	?	?	0.95	0.95	100.0
Residential	?	?	0.2	0.5	76.6
Industrial	0	0	0	0	0
Commercial	0	0	0.05	0.3	80.0
Others - sand	?	?	0.12	0.77	?
Total land loss	?	?	1.87	4.83	
% total land area	?	?	5.40	13.96	

Sources of data: Department of Lands, Mines and Surveys, Fiji, 1958, 1:31,680 map (2 inch series); unpublished geomorphological maps and field notes by P.D. Nunn and S. Lutubula, 1986

Fiji - Moala island

Mapping of shorelines on Moala (Figure 6, Table 5) depended heavily on unpublished field notes and geomorphological maps, and data quality, although variable, is quite good. Moala is a large, high volcanic island with only a narrow coastal plain in most places, from which most villages have spilled over onto higher ground.

Outside the villages, most of the narrow strip of coastal lowland is used intensively for agriculture and a significant amount of copra would be lost were sea level to rise 1.5m. Many villages depend on copra plantations located outside villages, such as southeast of Vadra, for their cash income.

Much of the rest of the island's cash income comes from *yaqona* (*Piper methysticum*) and staples such as yam (*uvi*) which are grown in the island's cooler, higher parts. These are the usual growing areas for these important crops on other small Pacific islands and their availability could be seriously curtailed by the rise in temperature of 1.5°-5.5°C which is a primary predicted consequence of the "greenhouse effect".

The presence of both a barrier and fringing reef around Moala means that the coastline is well protected at present from aggressive coastal erosion. The effects of the removal of this protection would be analogous to those where there are presently gaps in the reef, such as west of Naroi, where much sand is brought onshore during storms. Diversification of food crops, especially those suited to higher ground, is recommended, as is the gradual resettlement of people from low to higher ground. This process has already begun at Naroi, Maloku and Nasoki.

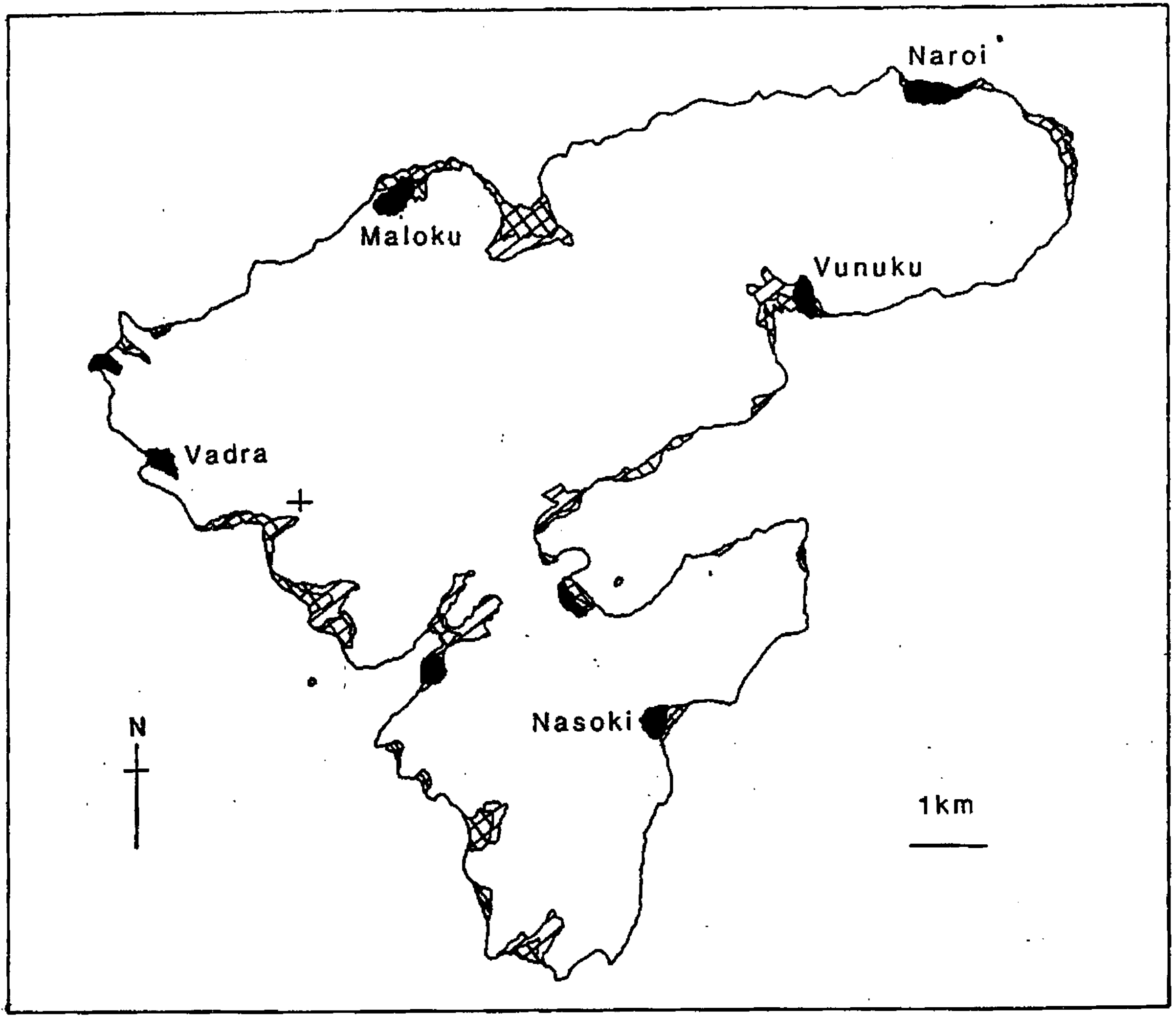

Figure 6. The island of Moala in Fiji showing the land below 3.5m (hatch), the land below 1.5m (cross-hatch) and the villages (solid). The cross marks the point 179°52'E, 18°36'S. The airstrip is on the eastern-most extremity of the island, all below 3.5m. A fringing reef and barrier reef are continuous around most of the island.

Table 5. Impact of future sea-level rise on Moala island, Fiji, expressed as square kilometres of land loss for different scenarios identified by the sea level in metres above present. Total land area of Moala is 62.12 sq.km (see Figure 6). The last column on the right refers to the 3.5m scenario only. Accuracy rating for Moala data is medium to high.

Type of land loss	Scenario				% total in each category
	0.2	0.5	1.5	3.5	
Agricultural	?	?	0.17	0.29	15.0
Forest	?	?	0.25	0.58	9.0
Mangroves	?	?	1.92	1.92	100.0
Residential	?	?	0.20	0.34	39.53
Industrial	0	0	0	0	0
Commercial	0	0	0.04	0.04	90.0
Others - sand and rock	?	?	0.20	0.71	?
Total land loss	?	?	2.78	3.88	
% total land area	?	?	4.48	6.25	

Sources of data: Mineral Resources Division, Fiji, 1976, Geology of Moala, Matuku and Totoya; unpublished geomorphological maps and field notes, P.D. Nunn, 1986-1987.

Fiji - Vatoa island

Very few maps exist of Vatoa (Figure 7) but a reasonable picture has been built up from sources cited (Table 6). The island is presently well protected by reef which lies close to its southeast-facing coasts and fringes a lagoon off Raviravi.

Vatoa is composed wholly of limestone and reaches a maximum height of around 45m. Most of the direct land loss resulting from sea-level rise will be in the main copra-growing areas, which will affect the island's cash economy. Although a little upland agriculture is practised at present, this must clearly be increased to counter the effect of land loss, although the lithology is not conducive to intensive cultivation.

Erosion on the island's limestone (southeast-facing) coasts will increase greatly as sea level rises. On the (northwest-facing) sandy coasts, this will be preceded by removal or redistribution of existing beaches.

It appears possible that Vatoa is one kind of island where permanent settlement may have to be abandoned as sea level rises. In summary, there are several reasons for this, namely: most of the productive agricultural land is low-lying; most of the upland is unproductive and infertile; and most of the groundwater is found in lowland wells.

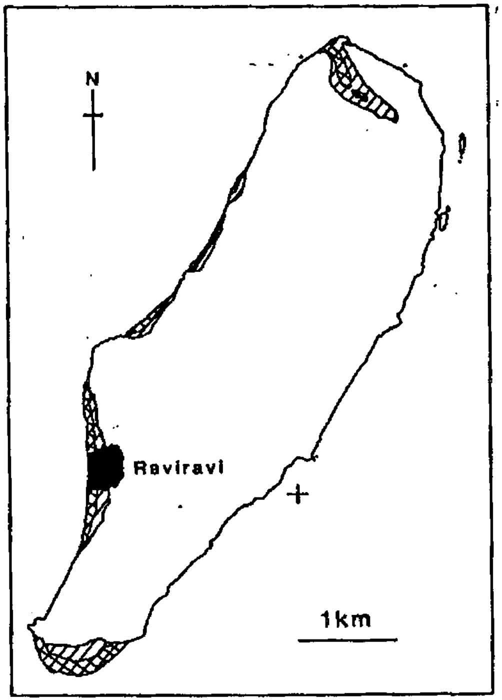

Figure 7. The island of Vatoa in southeast Fiji showing the land below 3.5m (hatch), the land below 1.5m (cross-hatch), and the villages (solid). The cross marks the point 178°13'W, 19°50'S.

Table 6. Impact of future sea-level rise on Vatoa island, Fiji, expressed as square kilometres of land loss for different scenarios identified by the sea level in metres above present. Total land area of Vatoa is 4.45 sq.km (see Figure 7). The last column on the right refers to the 3.5m scenario only. Accuracy rating for Vatoa data is medium to low.

Type of land loss	Scenario				% total in each category
	0.2	0.5	1.5	3.5	
Agricultural	0	0	0	0	0
Forest	?	?	0.39	0.61	?
Mangroves	0	0	0	0	0
Residential	?	?	0.04	0.09	64.29
Industrial	0	0	0	0	0
Commercial	0	0	0	0	0
Others					
- sand	?	?	0.02	0.04	?
- bare rock	?	?	?	0.18	?
Total land loss	?	?	0.45	0.92	
% total land area	?	?	10.11	20.67	

Sources of data: L.E.A. Patterson, 1967, Topographical Survey of Vatoa Island, Sth Lau Group (1:4,800).

Fiji - Vatulele island

Unpublished geomorphological maps of Vatulele (Nunn, in press) were of great assistance in constructing the 1.5m and 3.5m contours (Figure 8 and Table 7). Vatulele is a low (maximum height 36m) limestone island with a fringing reef close to the cliffed west coast and a barrier reef some 2-3km off the low east-facing coast.

A 1.5m sea-level rise would not produce substantial land loss directly owing to the presence of a coastal dune ridge parallel to and adjoining the east coast. Those areas which would be affected directly would be the marshy flats inland where *taro* (*dalo*) and other staples are grown in comparative abundance. Most of the island's worked copra resources lie atop the dune ridge which would be unaffected directly although would be seriously undermined by shoreline retreat accompanying sea-level rise.

The picture is obviously more severe for a 3.5m sea-level rise which would inundate the dune ridge, the island's main settlements and most of its presently agriculturally-productive area. As with Vatoa, this might result in permanent settlement on Vatulele having to be abandoned.

The effective removal of reef barriers would amplify the already high-energy erosional regime of the island's west coasts and would cause accelerated retreat of the east coast. For these reasons, the shorelines shown in Figure 8 should be regarded as conservatively drawn; they represent the theoretical starting point of a rapidly adjusting (retreating) shoreline profile.

After decades of getting drinking water from shallow wells, often contaminated with sea water, each village on Vatulele has recently switched to rainwater roof-catchments, which is clearly the type of move similarly-situated island communities should make to counter not only existing water shortages but also those which will arise in the future as the result of a different set of factors.

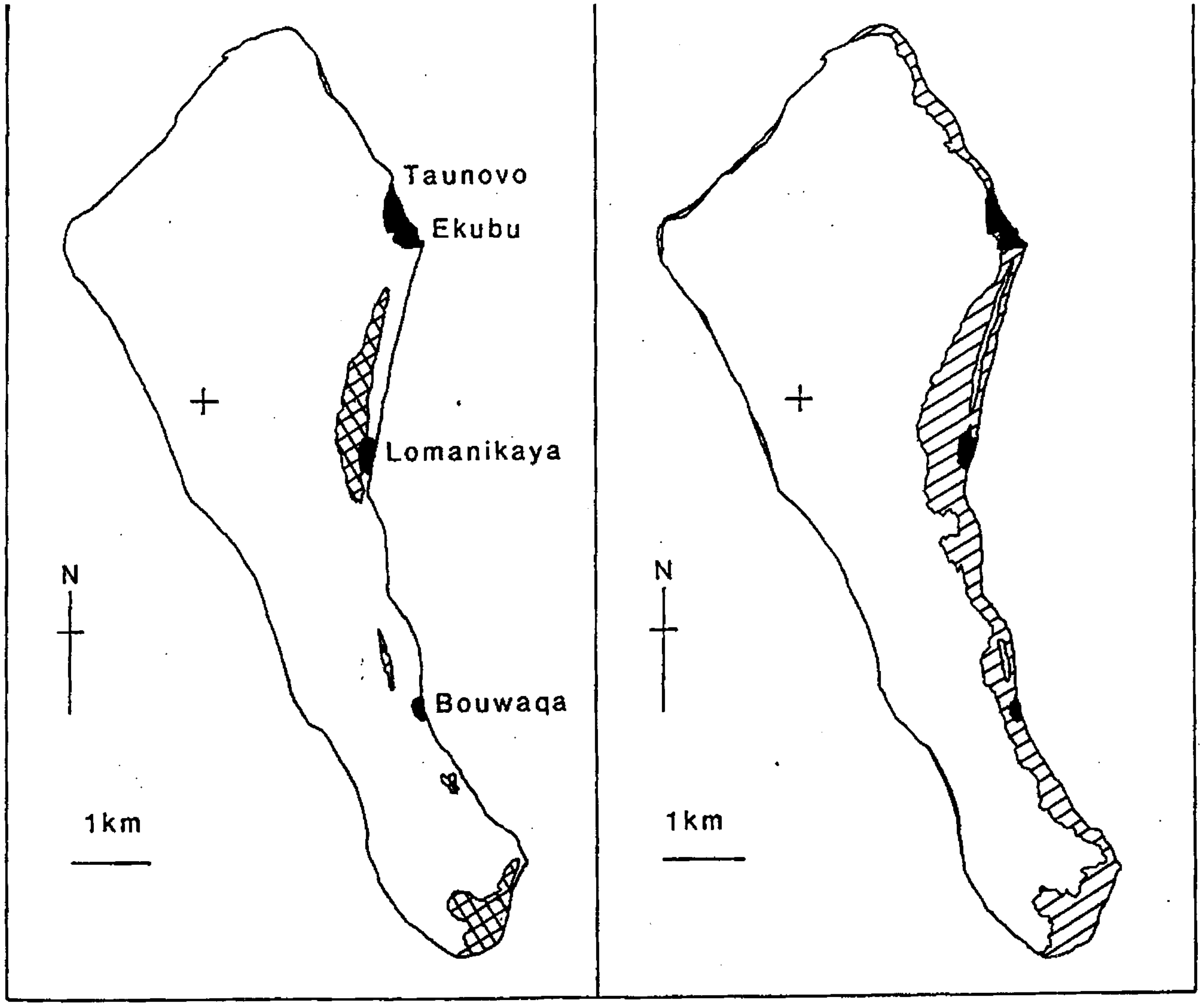

Figure 8. The island of Vatulele in Fiji showing the land below 1.5m (cross-hatch in left-hand diagram) and the land below 3.5m (hatch in right-hand diagram). Villages are shown as solid shading. The cross in both diagrams represents the point 177°37'E, 18°32'S.

Table 7. Impact of future sea-level rise on Vatulele island, Fiji, expressed as square kilometres of land loss for different scenarios identified by the sea level in metres above present. Total land area of Vatulele is 31.57 sq.km (see Figure 8). The last column on the right refers to the 3.5m scenario only. Accuracy rating for Vatulele data is medium to high.

Type of land loss	Scenario 0.2	0.5	1.5	3.5	% total in each category
Agricultural	?	?	0.19	0.95	31.1
Forest	?	?	0.52	1.65	26.77
Mangroves	?	?	0.01	0.03	100.0
Residential	?	?	0.03	0.34	96.0
Industrial	0	0	0	0	0
Commercial	0	0	0	0	0
Others - sand and bare rock	?	?	0.33	0.73	c40.0
Total land loss	?	?	1.08	3.70	
% total land area	?	?	3.42	11.72	

Sources of data: Government of Fiji, 1986, 1:50,000 topographic map, FMS 31 M 30, Government Printer, Suva; unpublished maps (Nunn, in press) and field notes, P.D. Nunn, 1985-1987

Fiji - Labasa town

Labasa is the largest urban centre on Vanua Levu island in Fiji and has important functions as a port, primarily for export of cash crops, especially sugar cane. Labasa (Figure 9) is located close to the head of a large delta, the productive parts of which are protected by a number of sea walls. Three large river systems - the Wailevu, Labasa and Qawa - empty into this delta and in their alluvial valleys, bounded by the lowest break of slope in Figure 9, most of the sugar cane in the immediate area is grown. Figure 9 shows the 1.5m and 3.5m contours reconstructed as permitted by map coverage of the area.

The Wailevu, Labasa and Qawa have been contributing sufficient sediment to the Labasa coast to enable it to prograde (extend) over the last few millennia. Were sea level to rise, the main effect in terms of land loss would be the landward movement of the present shoreline. This would also cause river sediment and water to become impounded in the Wailevu, Labasa and Qawa valleys, an effect which would leave the site of Labasa itself virtually uninhabitable. It would also adversely affect the productivity of the valleys which, like so many along Viti Levu's north coast, provide the main element in the island's cash economy. As sea level began rising in the area, the first noticeable effect would be an increase in large-magnitude flood frequency in the valleys, which would cause increased annual failure of the sugar cane and short-term enrichment and build-up of the alluvial carpet.

The impact in terms of land loss on Labasa town itself (Figure 10, Table 8) was determined from detailed land-use mapping on good quality base maps. Nearly 90% of the town would be inundated in the 3.5m scenario, but the site would undoubtedly be abandoned long before the sea level reached that height, for reasons stated above. With such a large coastal frontage, abandonment of the site appears the only feasible option in the long term. The high ground immediately to the north of the present town would be suitable for relocation.

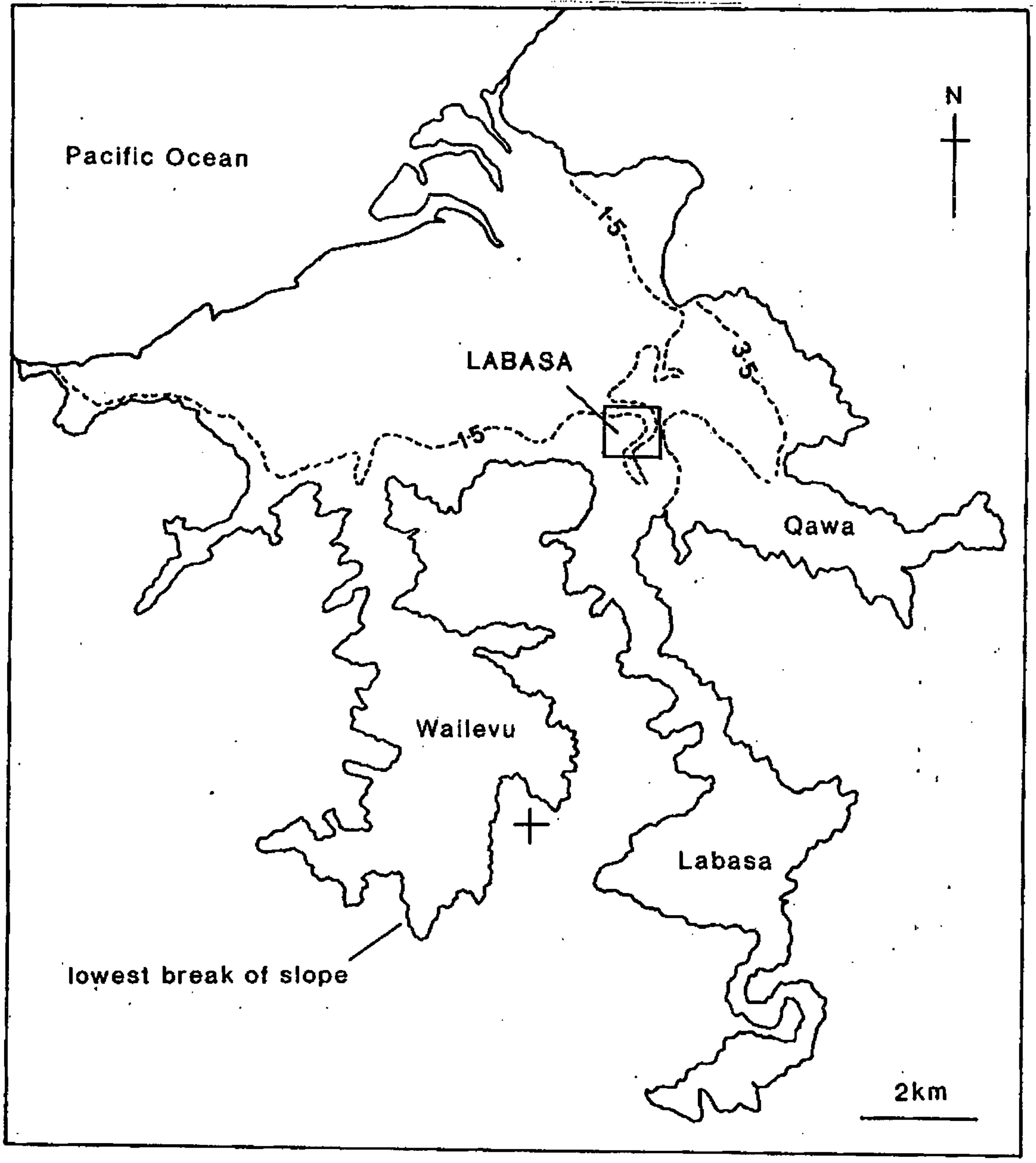

Figure 9. The Labasa area, northern Vanua Levu, Fiji, showing the 1.5m and 3.5m shorelines, and the three main valleys feeding the delta, bounded by the lowest slope break, which represents the approximate upper limit of alluvium and intensive commercial cultivation. For details of Labasa town, see Figure 10. The cross represents the point 179°21'30"E, 16°30'S.

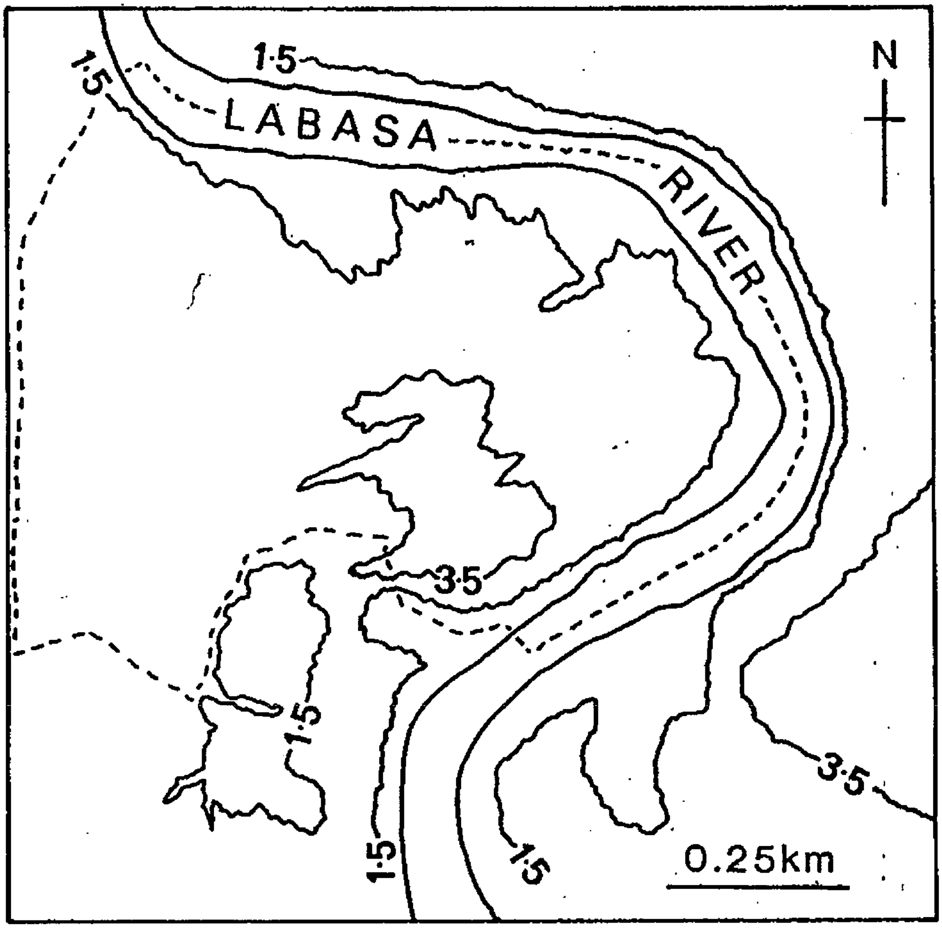

Figure 10. Labasa town, Fiji (see also Figure 9) showing the 1.5m and 3.5m contours. The river flows northwards, the broken line represents the town boundary.

Table 8. Impact of future sea-level rise on Labasa town, Vanua Levu, Fiji, expressed as square kilometres of land loss for different scenarios identified by the sea level in metres above present. Total land area of Labasa is approximately 0.28 sq.km (see Figures 9 and 10). The last column on the right refers to the 3.5m scenario only. Accuracy rating for Labasa data is high.

Type of land loss	Scenario 0.2	0.5	1.5	3.5	% total in each category
Agricultural	0	0	0	0	-
Forest	0	0	0	0	-
Mangroves	0	0	0	0	-
Residential	?	?	0.015	0.054	-
Industrial	?	?	0.002	0.006	-
- port-related	?	?	0.031	0.048	-
Commercial	?	?	0.010	0.104	-
Others - services	?	0.002	0.019	?	-
- open space		?	0.004	0.006	-
- education		?	0.008	0.014	-
Total land loss	?	?	0.072	0.251	
% total land area	?	?	25.71	89.64	

Sources of data: Ministry of Lands, Fiji, 1968, Plans of Labasa and surrounding area (1:1,584); supplementary information by B. Masianini.

Fiji - Savusavu town

Savusavu is located on the southern side of Vanua Levu island, across from Labasa (see above). It is smaller than Labasa, although of proportional importance to its hinterland, and stretched along a narrow coastal plain. As such it is typical of many settlements on islands where there are no extensive coastal flats available for settlement. It should be noted that data in Table 9 referring to Figure 11 are in square metres, not square kilometres as with the other tables.

Although nearly half the town would theoretically be inundated were sea level to rise 3.5m (Table 9), the impounding of sediment behind the landwards-retreating shoreline would cause greater problems to the town area presently lying above 3.5m. These would be manifested as an increase in the extent and frequency of large-magnitude floods and mass movements (landslides etc.). It is suggested that a site like this would become economically impractical to occupy within 30-50 years and that a suitable site for the relocation of essential services in the area is sought.

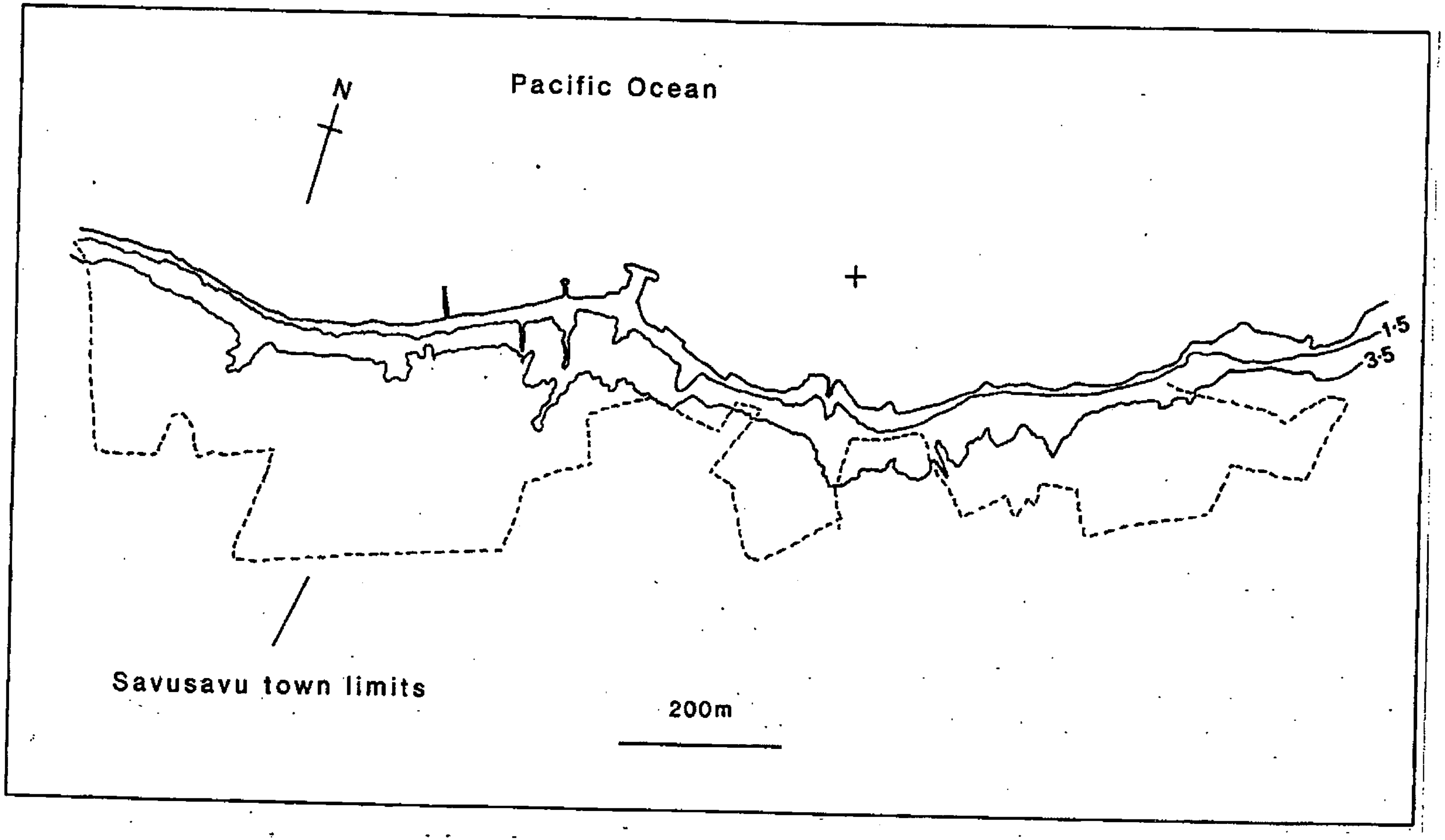

Figure 11. Savusavu town, Vanua Levu, Fiji, showing the 1.5m and 3.5m contours and the town limits (broken line). The cross represents a point 179°20'E, 16°46'30"S.

Table 9. Impact of future sea-level rise on Savusavu town, Vanua Levu, Fiji, expressed as square metres of land loss for different scenarios identified by the sea level in metres above present. Total town area of Savusavu is approximately 0.1 sq.km (see Figure 11). The last column on the right refers to the 3.5m scenario only. Accuracy rating for Savusavu data is high.

Type of land loss	Scenario				% total in each category
	0.2	0.5	1.5	3.5	
Agricultural	0	0	0	1200	-
Forest	0	0	0	0	-
Mangroves	0	0	0	0	-
Residential	0	0	0	4688	
Industrial	0	0	0	6720	
Commercial	0	60	3120	16640	
- mall	0	0	0	1120	
Others					
- civic	0	416	1856	5568	
- open space	0	5968	9136	10400	
Total land loss	0	6444	14112	46336	
% total town area	0	5.95	13.03	42.79	

Sources of data: Ministry of Lands, Suva, 1967-1970, Topography of Nasavusavu (2 chains to an inch); local information by B. Masianini.

Kiribati - Tarawa atoll

Although no direct original information about the impact of future sea-level rise in Kiribati could be obtained, owing to a lack of primary sources, it is clear that Tarawa atoll, where the capital of the same name is situated, exemplifies the island type.

Since most mid-ocean (oceanic) atolls do not rise much above 3.5m, the impact of a sea-level rise of that magnitude on total land area will clearly be greater than for any other case study presented in this report. The small size of the *motus*, or sand-reef islets, will render artificial shoreline protection prohibitively expensive.

Connections between *motus*, such as the Betio-Bairiki causeway on Tarawa, will be increasingly subject to severe erosion and periodic inundation as sea level begins rising and may quickly be rendered unusable.

The inundation of the atoll reefs offshore will result in greater wave energy on the shoreline and a reduction in the supply of reef-rock debris to the shoreline; both effects will cause a sharp increase in the erosion of the ocean-facing sides of *motus*.

The high reliance of atoll communities on groundwater for drinking and for agriculture, especially in pits dug down into the freshwater lens, must be lessened if future sea-level rise is not to necessitate abandonment of the atolls within the next 30-50 years because a sea-level rise will cause the boundary between salt and fresh water in the groundwater lens to rise, which will reduce the size of the fresh water part of the lens.

The scenarios of impact on atolls are the most severe discussed and it is recommended that plans for resettlement are drawn up by the appropriate authorities.

Tonga - Nafanua harbour

The harbour here (Figure 12) is largely artificial and was constructed to serve the needs of the island of 'Eua, of which 'Ohonua is the largest settlement. The design of the harbour with a wharf 2m in height appears able to accommodate future sea-level rise with less problems than elsewhere (Table 10), a conclusion which applies elsewhere on 'Eua on account of its generally cliffed coast.

Flooding along the river valley to the southeast of the wharf is already a problem and one which would be excerbated by the sea-level rise (see section on Labasa town above). The commercial centre of 'Ohonua would be largely untouched by a 3.5m sea-level rise.

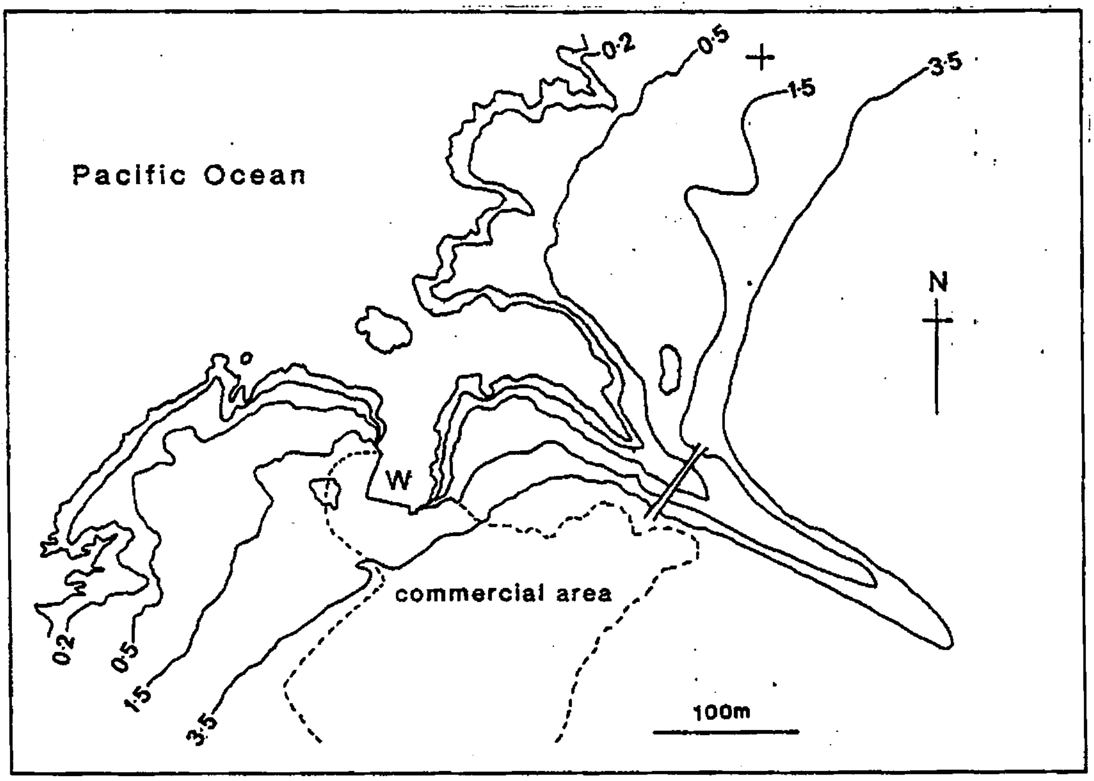

Figure 12. Nafanua harbour, 'Ohonua, 'Eua island, Tonga, showing contours at 0.2m, 0.5m, 1.5m and 3.5m. W marks the wharf which rises to around to around 2m above sea level. The cross marks the point 174°57'W, 21°20'S.

Table 10. Impact of future sea-level rise for Nafanua Harbour, 'Ohonua, 'Eua island, Tonga, expressed as square kilometres of land loss for different scenarios identified by the sea level in metres above present. Total land area of the map is 0.245 sq.km (see Figure 12). The last column on the right refers to the 3.5m scenario only. Accuracy rating for Nafanua data is high.

Type of land loss	Scenario ------ 0.2	0.5	1.5	3.5	% total in each category
Agricultural	0	0	0	0	
Forest	0	0	0	0	
Mangroves	0	0	0	0	
Residential	0	0	0	0	
Industrial	0	0	0	0	
Commercial	0	0	0	0.003	
Others - sand and bare rock	0.009	0.015	0.07	0.094	
Total land loss	0.009	0.015	0.07	0.097	
% total land area	3.67	6.12	28.57	39.59	

Sources of data: Central Planning Department, Tonga, 1981, Nafanua Harbour (1:1,000); additional information by S. Afeaki.

Tonga - Nuku'alofa

Owing to the availability of suitable maps, the study of Nuku'alofa is one of the most detailed case studies in this report. Nuku'alofa (Figure 13) is the capital city of the Kingdom of Tonga and is situated on the low-lying northern side of Tongatapu island, which is composed entirely of limestone and superficial deposits.

As can be seen from diagram N1 (Figure 13, Table 11), most of the 0.2m and 0.5m sea-level rise scenarios would not cause substantial inundation of the central part of Nuku'alofa on account of existing sea walls, although once these have been overtopped, severe effects in terms of land loss on the commercial district and one of the most important cultural areas in Tonga will ensue. Work in preparation (Spennemann, 1988, personal communication) suggests that large parts of Nuku'alofa would be rendered uninhabitable by a 0.2m or 0.5m sea-level rise because of the effect this would have on raising the surface of the water table.

The major port area of Nuku'alofa (Figure 13, diagram N2, and Table 12) is also bordered by a seawall, but this will not prove as effective a barrier to inundation and most of the map area would be inundated if sea level rose 3.5m. This area includes many hydrocarbon storage facilities and is responsible for the manufacture of many light industrial and other products.

A representative area of suburbs in Nuku'alofa (Figure 13, diagram N3, and Table 13) was also examined. The coastline here is not seawall-protected and the 0.2m and 0.5m shorelines have been traced through the mangroves and debris which comprise most of it. As with area N2, nearly half this area would be inundated by a 1.5m sea-level rise, nearly all by a rise of 3.5m. The effect of moating in the lagoon (Spennemann, 1988, personal communication) will amplify the actual sea-level rise along this coastline: the effect at present produces a difference of +0.15m on lagoonal coasts compared to those facing the open sea on Tongatapu.

The highest parts of Tongatapu lie in the island's south and southwest and, it seems likely that relocation of Nuku'alofa in these directions will have to take place. Owing to the low-lying and exposed character of Tongatapu's north coast, its preservation in its present condition will become increasingly expensive and probably increasingly ineffective.

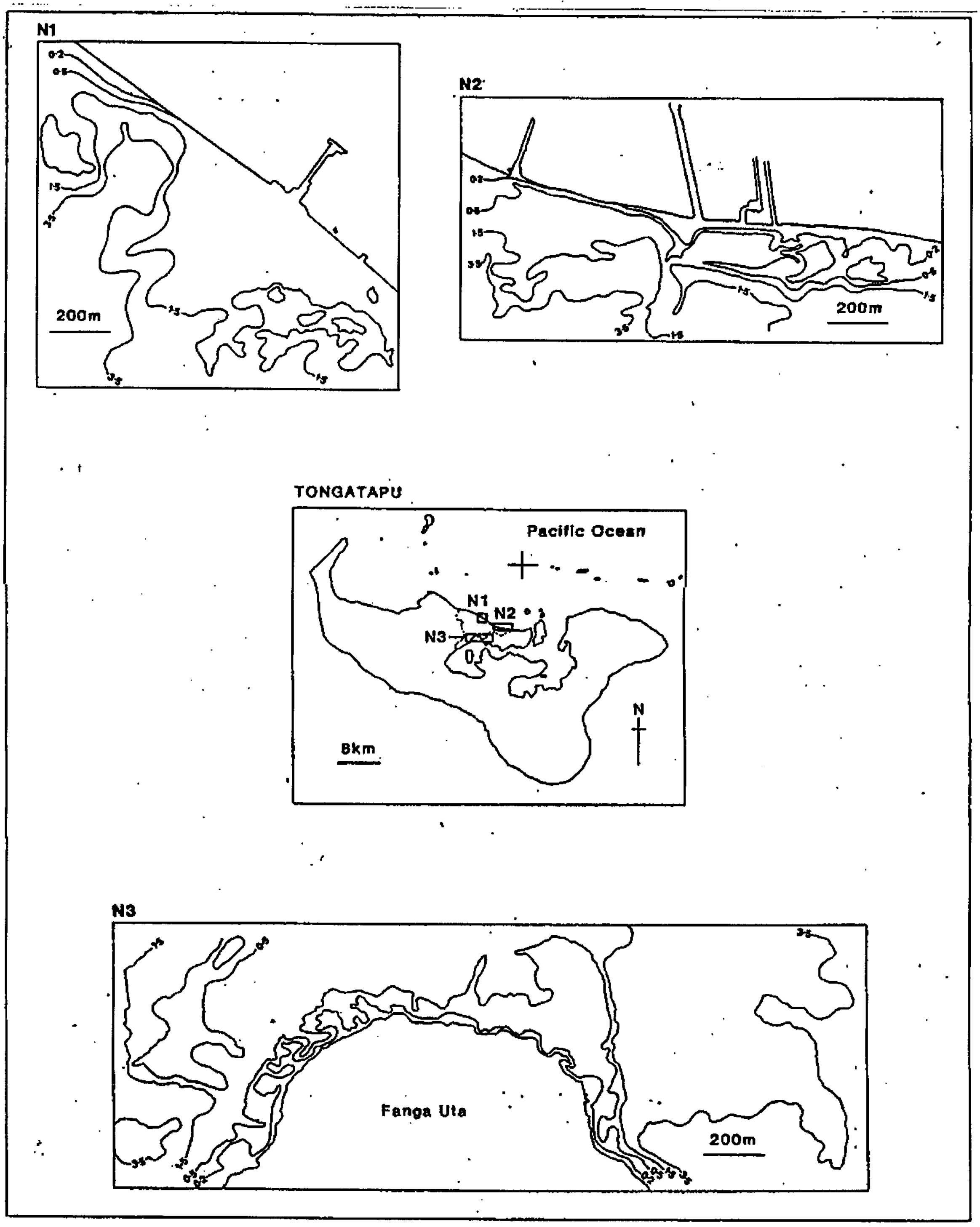

Figure 13. Nuku'alofa, Tongatapu island, Tonga. The location of Nuku'alofa is on the central diagram, showing the island of Tongatapu; Nuku'alofa is bounded by the broken line, the cross represents the point 175°10'W, 21°05'S. The three squares (N1, N2 and N3) located in the diagram represent case studies of Nuku'alofa as follows:

N1: central Nuku'alofa
N2: port area
N3: representative suburb

Table 11. Impact of future sea-level rise on central Nuku'alofa, Tongatapu island, Tonga, expressed as square kilometres of land loss for different scenarios identified by the sea level in metres above present. Total land area of the map (N1) is 0.81 sq.km (see Figure 13). The last column on the right refers to the 3.5m scenario only. Accuracy rating for Nuku'alofa (N1) data is high.

Type of land loss	Scenario				% total in each category
	0.2	0.5	1.5	3.5	
Agricultural	0	0	0	0	
Forest	0	0	0	0	
Mangroves	0	0	0	0	
Residential	0.011	0.011	0.011	0.011	
Industrial	0	0	0	0	
Commercial	0.009	0.019	0.129	0.421	
Others					
- Royal Palace		0	0	0.052	
- Royal Tombs		0	0	0.043	
- park		0	0	0.03	
Total land loss	0.02	0.03	0.14	0.557	
% total land area on map	2.47	3.70	17.28	68.77	

Sources of data: World Health Organisation, 1:1,000 map of Nuku'alofa, Tongatapu, Tonga 1981; local detail by S. Afeaki and V. Tiseli

Table 12. Impact of future sea-level rise on the main port area of Nuku'alofa, Tongatapu island, Tonga, expressed as square kilometres of land loss for different scenarios identified by the sea level in metres above present. Total land area of the map (N2) is 0.78 sq.km (see Figure 13). The last column on the right refers to the 3.5m scenario only. Accuracy rating for Nuku'alofa (N2) data is high.

Type of land loss	Scenario ----------------------------				% total in each category
	0.2	0.5	1.5	3.5	
Agricultural	0	0	0.002	0.113	
Forest	0	0	0	0	
Mangroves	0.008	0.008	0.008	0.008	
Residential	0.008	0.035	0.130	0.288	
Industrial	0.004	0.061	0.064	0.080	
Commercial	0.005	0.019	0.053	0.055	
Others - school and church	0.018	0.051	0.073	0.166	
Total land loss	0.043	0.174	0.330	0.710	
% total land area on map	5.51	22.31	42.31	91.03	

Sources of data: World Health Organisation, 1:1,000 map of Nuku'alofa, Tongatapu, Tonga 1981; local detail by S. Afeaki and V. Tiseli

Table 13. Impact of future sea-level rise on the Fanga - Havelu-Loto-Mataika suburb of southern Nuku'alofa, Tongatapu island, Tonga, expressed as square kilometres of land loss for different scenarios identified by the sea level in metres above present. Total land area of the map (N3) is 2.12 sq.km (see Figure 13). The last column on the right refers to the 3.5m scenario only. Accuracy rating for Nuku'alofa (N3) data is high.

Type of land loss	Scenario				% total in each category
	0.2	0.5	1.5	3.5	
Agricultural	0	0	0	0.01	100.0
Forest	0	0	0	0	
Mangroves	0.020	0.048	0.048	0.048	100.0
Residential	0.045	0.285	0.890	1.828	
Industrial	0	0	0	0	
Commercial	0	0.003	0.003	0.003	
Others - school and community centre		0	0	0.011	
Total land loss	0.065	0.336	0.941	1.90	
% total land area on map	3.07	15.85	44.39	89.62	

Sources of data: World Health Organisation, 1:1,000 map of Nuku'alofa, Tongatapu, Tonga 1981; local information by S. Afeaki and V. Tiseli

Western Samoa - Apia

Apia (Figure 14, Table 14), the capital of Western Samoa, occupies a narrow coastal plain fringed partly with mangroves, around a harbour which lies opposite a prominent break in the reef. Most of the mangroves would be inundated were sea level to rise slightly, but if this increased to 1.5m, then most of the commercial centre of Apia would be inundated, including the peninsula leading to Mulinu'u Point, where the government buildings and many large hotels are situated. A 3.5m sea-level rise would not add much to this picture although the dispersal of sediment and water coming down the steep, narrow valleys of the Gasegase, Mulivai and Vaisigano rivers behind the town would become increasingly problematical. The solution to the latter is to pipe the discharge of these rivers away from the town but this is not a long-term solution to problems which will probably render lowland Apia uninhabitable within the next 40-60 years.

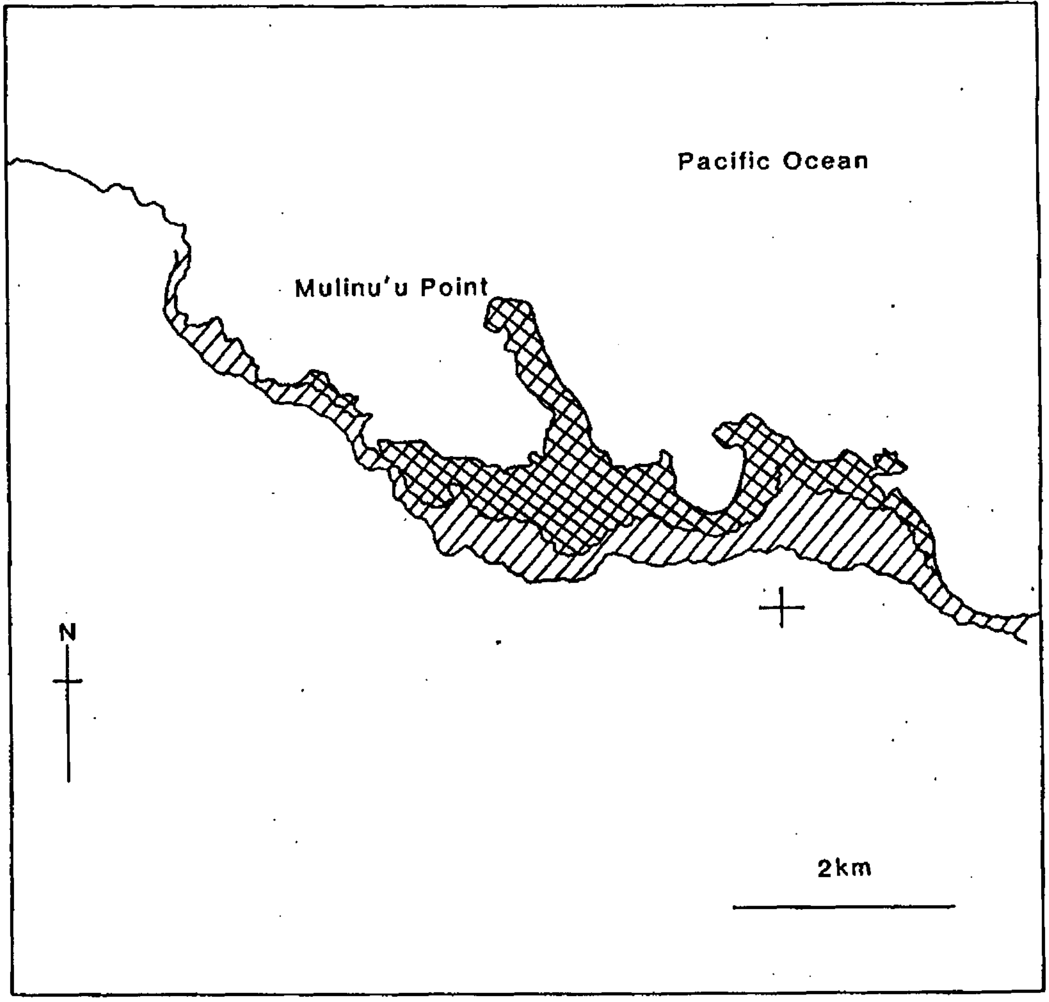

Figure 14. The coast of Apia, Upolu Island, Western Samoa, showing the area below 3.5m (hatch) and the area below 1.5m (cross-hatch). The central parts of Apia are located in the central third (in an east-west sense) of the shaded areas, most residential area lie to the south. The cross marks the point 171°45'W, 13°50'S.

Table 14. Impact of future sea-level rise on Apia, Upolu Island, Western Samoa, expressed as square kilometres of land loss for different scenarios identified by the sea level in metres above present. Total land area of Apia is 7.8 sq.km (see Figure 14). The last column on the right refers to the 3.5m scenario only. Accuracy rating for Apia data is medium to low.

Type of land loss	Scenario				% total in each category
	0.2	0.5	1.5	3.5	
Agricultural	0	0	0	0	
Forest	0	0	0	0	
Mangroves	?	?	0.570	0.570	
Residential	?	?	0.481	0.730	
Industrial	?	?	0.160	0.231	
Commercial	?	?	1.406	1.994	
Others	?	?	?	?	
Total land loss	?	?	2.617	3.525	
% total land area	?	?	33.55	45.19	

Sources of data: Department of Lands and Survey, Western Samoa, 1983, Topographical map of Western Samoa (Upolu Sheet 19), 1:20,000; supplementary information by R. Lafaele

CONCLUSIONS AND RECOMMENDATIONS

It is clear that, if the sea level rises in the next 50-100 years as predicted, the economic and social consequences for Pacific island nations will be enormous. However, in many cases, forward planning would offset the enormity of the impact, although in other cases, primarily those of presently-inhabited atolls, there appears to be no feasible way of lessening the impact of future sea-level rise.

In all cases, advance knowledge is not enough; farsighted and unpopular decisions need to be taken soon.

Some specific recommendations are given below.

(a) It is recommended that a more in-depth study of the potential impact of future sea-level rise on Pacific islands be carried out as a priority. Few data used to compile the above results were gathered specifically for this study and can therefore indicate the impact of future sea-level rise only in very general terms. Among studies which need to be undertaken are those looking at the effect of future sea-level rise *and* temperature rise on Pacific island agriculture and fisheries.

(b) It is recommended that quantitative data on sediment and water discharge of major rivers close to important settlements are gathered and input into models which are able to predict landscape response to both sea-level rise and temperature rise.

(c) It is recommended that plans be drawn up for the movement or relocation of major Pacific island settlements to areas where they will not be affected by future sea-level rise.

(d) It is recommended that Pacific island governments form a joint consultative body to reach and implement decisions based on available data.

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