• I •G• C•I

The University of Waikato
Te Whare Wānanga o Waikato

Climate Change
Vulnerability and Adaptation Assessment for Fiji

Supplementary Fiji Coastal Impacts Study

prepared for

The World Bank Group

by

International Global Change Institute (IGCI)
University of Waikato
Hamilton, *New* Zealand

in collaboration with

Pacific Islands Climate Change Assistance Programme (PICCAP), Fiji Country Team

30 June 2000

Coastal Impacts on Viti Levu:
Selected Case Studies

1.0 INTRODUCTION

This document presents extended case studies of the impacts of climate change on the Fiji coast. In particular the study evaluates:

- Coastal erosion at 3 representative sites on the coast of Viti Levu.
- Inundation at 3 representative sites on the coast of Viti Levu.

2.0 CASE STUDY SITES

The coast of Viti Levu is approximately 750 km long and possesses great variation in morphology. Using the 1:50 000 topographic map series the coast has been divided into 4 broad categories based on morphology, biological characteristics, population density and land-use. The categories include:

1. Mangrove fringed coast bordered by barrier reef (northwest and north). High density sugar cane growing.
2. Fringing reef coast (southern coast)
3. Urbanised coastal centres
4. Low-lying delta environments

These four types of coast comprise the majority of the Viti Levu coast and are the focus for the case study sites (Table 1 and Figure 1).

Table 1. Division of the Viti Levu coast into different coastal types used in this study

Coastal type	Length of coast	Proportion of coast	Example analysed in study
Narrow coastal plain overlying fringing reef	170 km	28%	Korotogo, south coast
Mangrove fringed shoreline fronted by barrier reef	281 km	47%	Tuvu, northwest coast
Urban Area (Suva, Lautoka, Lami)	37 km	5%	Suva Peninsula, southeast
Rewa River delta, low-lying delta with mangrove systems	78 km	10%	Western Rewa River delta, Southeast Viti Levu
Other sand spits and small deltas		10 °/0	

NB: divisions based on 1:250 000 and 1:50 000 topographic map series.

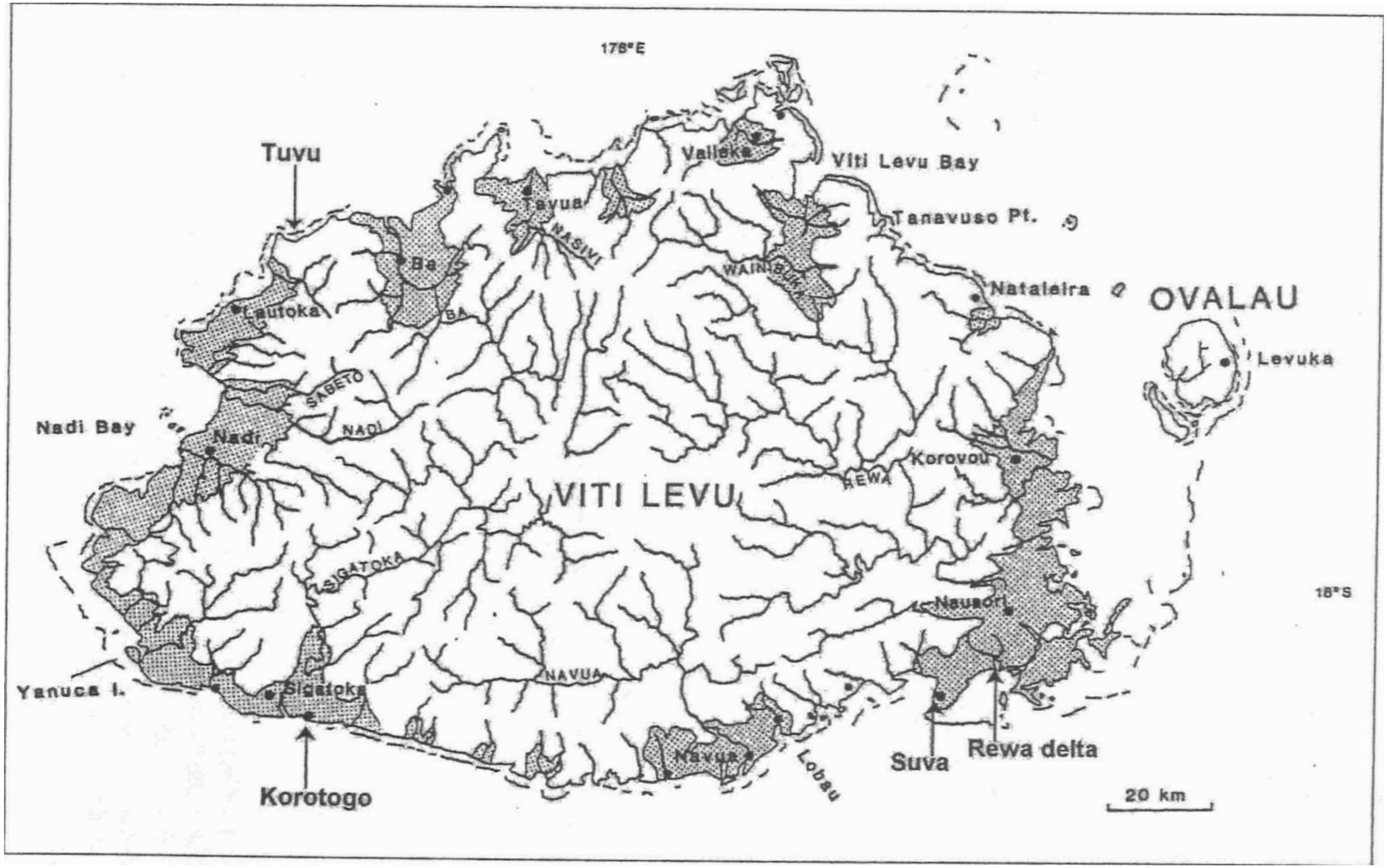


Figure 1. Viti Levu showing location of case study sites.

2.1 Erosion Analysis: Case Study Sites

Three sites were selected for analysis of erosion with projected sea-level rise. The urban centre of Suva was not chosen for this analysis as the centre is almost entirely protected and the shoreline would not respond naturally to erosion processes.

Tuvu: is located in the northwest of Viti Levu (Fig. 1, 2). It represents sections of Viti Levu which are used for intensive sugar cane production. Narrow coastal plains abut mangrove systems, which are protected from the open ocean by the barrier reef.

Korotogo: is located on the southern coast where numerous tourist resorts are located in close proximity to the coast (Fig. 1, 3). Narrow coastal plains are situated directly upon fringing reef. Numerous villages are also located in the coastal margin.

Rewa Delta: The third case study site is the western margin of the Rewa River delta (Fig. 1, 4). This is a low-lying mangrove dominated system that has prograded into the adjacent barrier lagoon.

2.2 Inundation Analysis: Case Study Sites

Three sites were selected for analysis of inundation with projected sea-level rise including Tuvu (northwest) and Korotogo (south coast). The third site was the urban centre of Suva and in particular, the southern tip of Suva Peninsula.

3.0 METHODS

3.1 Sea-Level Rise Scenarios

Sea-Level rise scenarios for the study are contained in Table 2.

Table 2. Sea level rise scenarios

	2025	2050	2100
B2 (best guess)	11 cm	23 cm	50 cm
A2 (high)	21 cm	43 cm	103 cm

3.2 Erosion Analysis

Surveyed profiles across from the three case study sites were analysed using the Shoreface Translation Model (STM, Cowell et al., 1995). Bruun concepts underlie the model, which has been adapted for reef environments to account for horizontal and non-erodable coral reef substrates. The modified STM has recently been applied to examine shoreline change on islands in Tarawa atoll, Kiribati (Kench and Cowell, 1999) and is considered appropriate for use in reef settings. The STM incorporates elements of both the Standard and Generalised Bruun Rules, as well as hybrids of the two, but goes further in allowing for time-varying morphological dimensions (e.g., for the shoreface) and sediment gains and losses (such as those due to littoral sand transport).

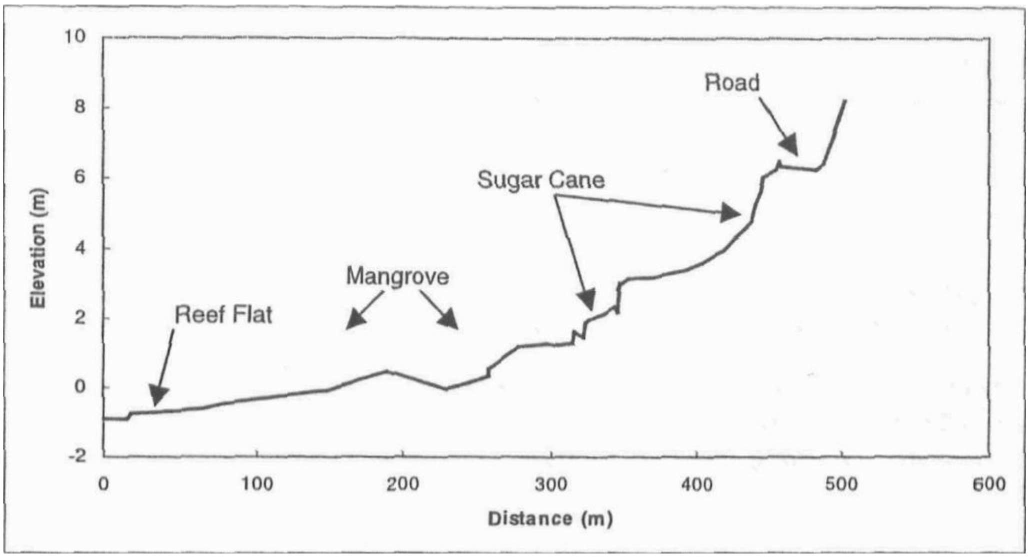


Figure 2. Coastal profile Tuvu, northern coast of Viti Levu. Location shown in Figure 1.

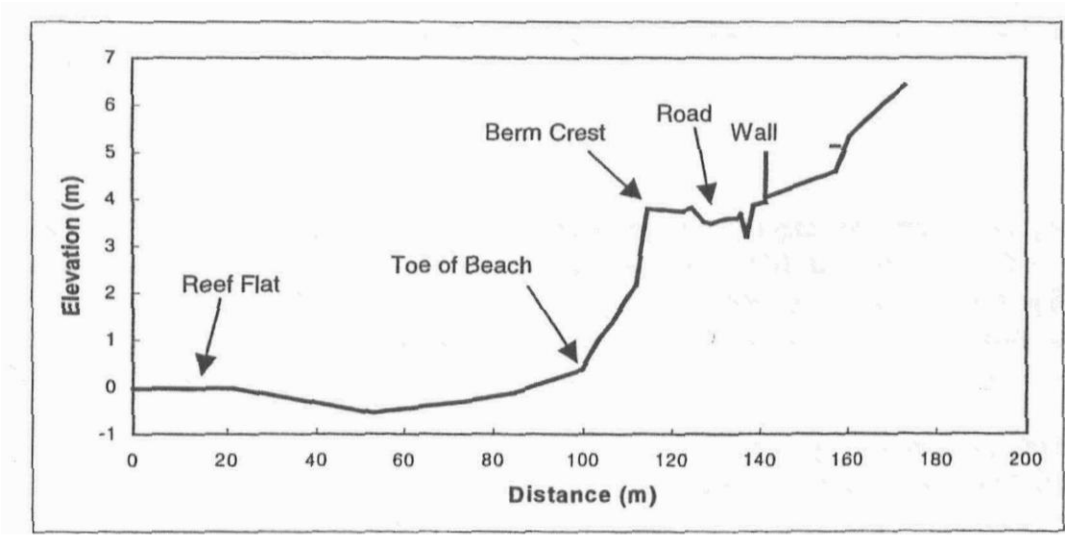


Figure 3. Coastal profile Korotogo, Southern coast of Viti Levu. Location shown in Figure 1.

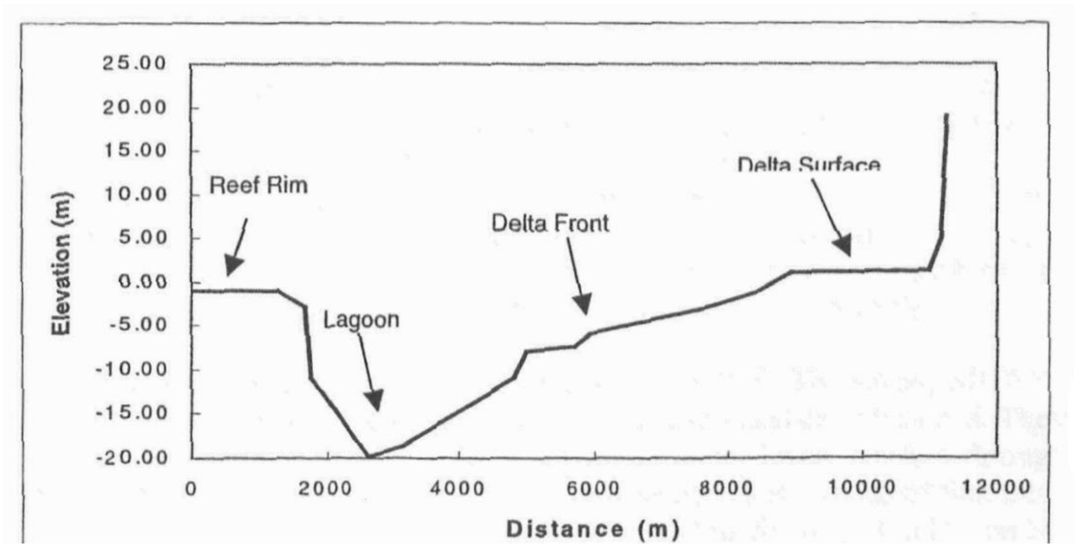


Figure 4. Coastal profile Rewa delta, southeast coast of Viti Levu. Location shown in Figure 1.

Simulations of morphological impacts on coastal types of Viti Levu using the STM were undertaken to predict shoreline recession and changes to shoreline morphology in response to sea-level rise. Surveyed profiles from the case study sites were used in the analysis. These profiles are considered to represent the morphology of the three case study areas.

In undertaking the analysis a number of assumptions were made. These assumptions must be carefully considered when interpreting the results: Assumptions include:

- A balanced sediment budget (no additional gains or losses). This assumption is unlikely to hold for the Rewa River delta. However, no data was available on sediment discharge rates or possible changes in sediment transport with sea-level rise.
- An increase in sea level of 0.1 m between each model step.
- Based on anecdotal evidence of storm inundation, washover of the coastal margin was allowed (up to 50 m), therefore, allowing deposition of sediment on the island surface.

3.3 Inundation Analysis

Analysis of island inundation was undertaken using a simple drowning concept. Topographic maps of Viti Levu are at too coarse a scale (20 m intervals) to be of value in this analysis. Therefore, field surveys of elevation and aerial photographs were used to construct contour maps with 1 m contours along specified sections of coast at each case study site.

Inundation analysis was performed by raising the MHWS level by different sea-level rise increments. In undertaking the inundation analysis a storm surge component was also added to the sea-level rise increment. The 1 in 50 year storm surge level was used as identified by Solomon and Kruger (1996) from the Suva tide gauge. This event promotes a surge of 0.98 m, which was added to the mean high water spring tide level (MHWS).

A number of raised water levels are analysed – 0.87, 1.0, 1.8 m, 2.0 m, 3.75 and 4.0 m (Table 3). The first 4 values approximate the sea-level rise scenarios for 2050 and 2100 together with the 1 in 50 year storm surge level as identified by Solomon and Kruger (1996) at the Suva tide gauge (Table 3). The fifth and sixth values incorporate anecdotal estimates of storm surge (but not measured). These scenarios were only used for the Tuvu and Korotogo sites as these levels were identified by members of the local community. No return period was able to be attached to these levels.

The raised water levels assume no change in level of MHWS. The altered MHWS mark was shifted under each scenario and the area of island inundated calculated. The MHWS level was chosen as it represents maximum water levels reached during spring tides, which occur several times in a fortnight period. It is considered that this frequency of water level, if inundating structures and causing flooding, would trigger an adaptation response from island inhabitants.

Table 3. Projected changes in super-elevation of water level for the 1 in 50 year storm surge at Suva (from Solomon and Kruger 1996) for each sea-level rise scenario

Sea-Level Rise Scenario	Present MHWS	Present MHWS + Storm Surge	2025 MHWS + SLR+ Storm Surge	2050 MHWS + SLR+ Storm Surge	2100 MHWS + SLR+ Storm Surge
B2 (best guess))	0.64	1.62 [3.5]	1.73	1.85 [3.73]	2.12 [4.00]
A2 (high)	0.64	1.62 [3.5]	1.83	2.05 [3.93]	2.65 [4.53]

NB: MHWS = Mean High Water Spring tide level; 1:50 year storm surge level in brackets after Solomon and Kruger (1996) 0.98 m; Anecdotal surge levels in square brackets; SLR sea-level rise projection for time period.

4.0 RESULTS: EROSION ANALYSIS

4.4.1 Tuvu simulations

Simulations of the shoreline response to increments of sea-level rise are presented in Figure 5 and Table 4. The shoreline is displaced between 13.0 and 29.0 m for the maximum best guess and high sea-level rise estimates respectively. Overwash processes imply the upward and landward movement of sediment across the narrow coastal plain. Of note, the profile tracks across the horizontal reef surface and sediment is supplied from the shoreface to the backshore.

4.4.2 Korotogo simulations

Korotogo simulations indicate that rates of shoreline recession are much lower than Tuvu (Fig. 6, Table 5). Recession estimates range between 4.0 m and 8.5 m for the maximum best guess and high sea-level rise estimates respectively. Overtopping of the coastal margin also allows sediment transfer landward which allows the seaward margin to keep pace with sea-level rise.

4.4.3 Rewa river delta simulations

Simulations of the Rewa river delta shows large rates of shoreline recession (Fig. 7, Table 6). Using the maximum best-guess and high sea-level rise estimates the delta is shown to recede by 320 and 650 m respectively. The large rates of delta recession are directly related to the low elevation of the delta surface. As the delta has a large surface area, sediment is excavated from the delta front to cover and maintain the elevation of the delta surface with respect to sea level. It is important to note that this analysis assumes no change in sediment supply.

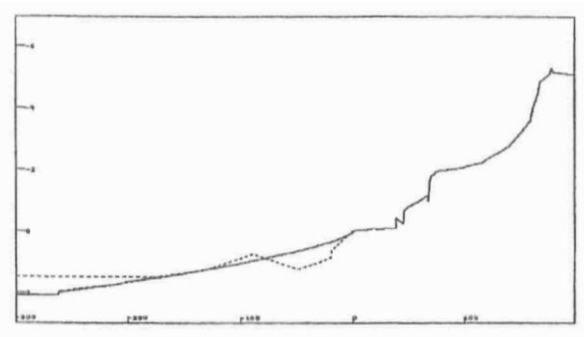
4.4.4 Summary of erosion results

Simulations at all sites analysed indicate the shoreline of Viti Levu will undergo erosion with increased sea-level rise. The magnitude of retreat varies depending on the initial morphology of the coastline. Low-lying delta environments will undergo greatest amounts of recession. In contrast the southern coast is relatively more stable with recession rates <10 m for the maximum sea-level rise scenario.

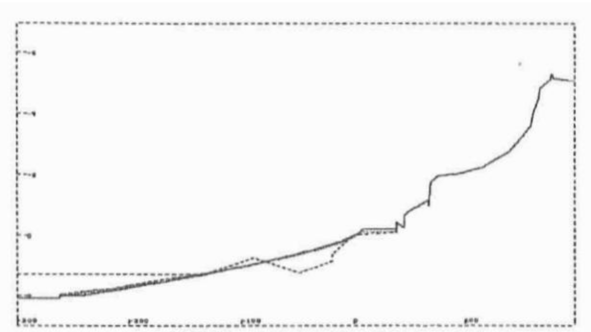
All simulations indicate that sediment will not simply be eroded from the shoreface and deposited seaward. Rather sediment will be redistributed from the shoreface on top of the coastal margin and will, therefore be able to contribute to vertical building of the coastal plain to keep pace with sea-level rise.

Simulations of shoreline response were all undertaken under the assumption there will he no change in sediment supply. At coastal sites composed predominantly of terrigenous sediment (from highland catchments) changes in sediment supply will be determined by changes in the rate of delivery from rivers to the coast. Tentative evidence would indicate that increasing sea level may cause a reduction in sediment supply to the coast, which would promote greater amounts of erosion than simulated in Figures 5, 6 and 7.

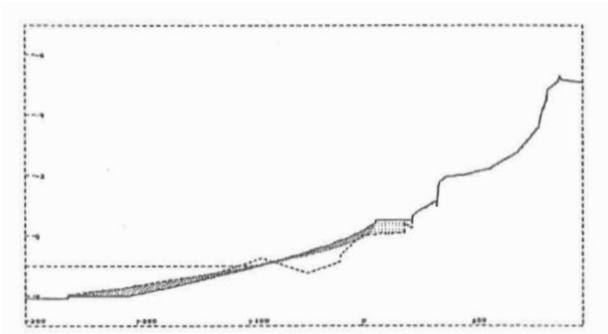
At coastal sites composed of carbonate sediments (derived from the adjacent reef environment) changes in sediment supply are linked to the response of the reef to increased water levels and water temperatures. Such changes are poorly understood. Where sediment supplies increase the shoreline may he able to offset the erosive effects. However, where sediment supplies decline the magnitude of erosion is likely to increase.



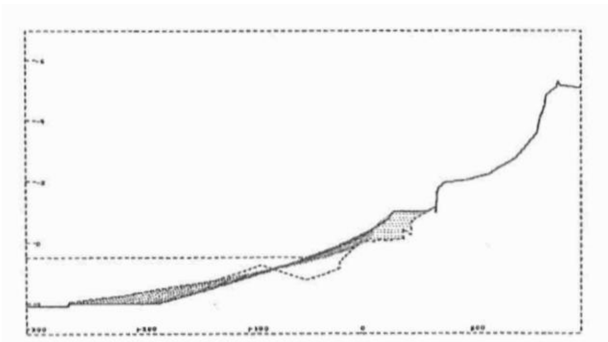
Tuvu — initial conditions



Tuvu — 0.2 m sea-level rise



Tuvu — 0.5 in sea-level rise



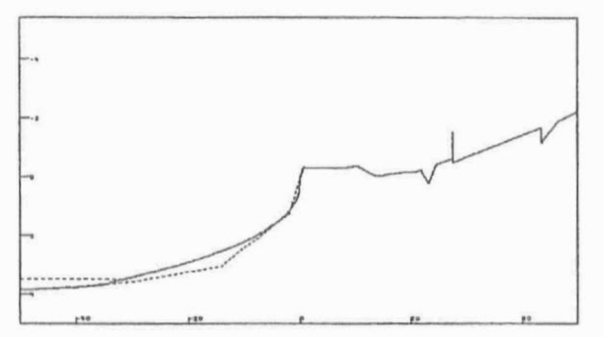
Tuvu — 1.0 m sea-level rise

Figure 5 Tuvu coastal profile STM simulations. A, Initial condition. B - D simulation of shoreline retreat after varying rates of sea-level rise.

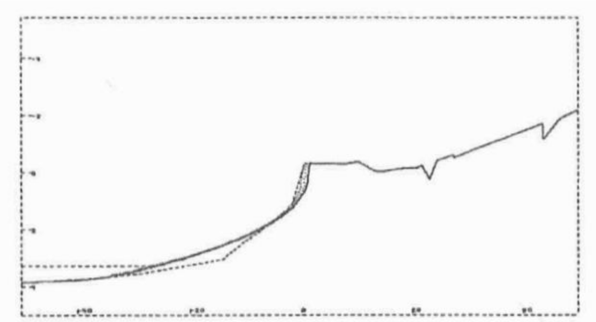
Table 4 Shoreline recession distance with projected rising sea level.

Sea Level (m above present)	Recession distance (m relative to present shoreline)
0.0	0.0
0.0	0.7
0.1	6.7
0.2	9.0
0.3	10.6
0.4	11.5
0.5	12.9
0.6	15.9
0.7	18.2
0.8	21.4
0.9	25.5
1.0	29.1

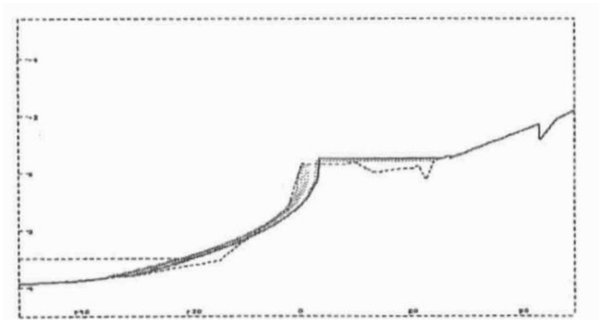
Figure 6 Korotogo coastal profile STM simulations. A, Initial condition. B - D simulation of shoreline retreat after varying rates of sea-level rise.



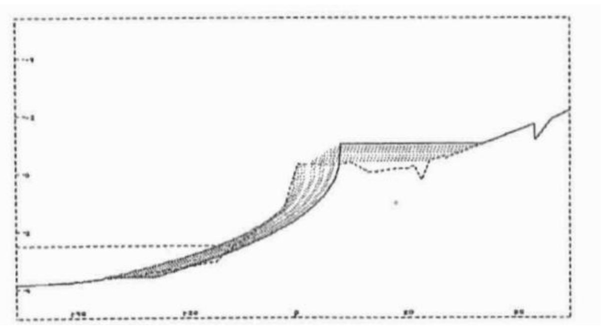
Korotogo — initial profile



Korotogo — 0.2 m sea level rise



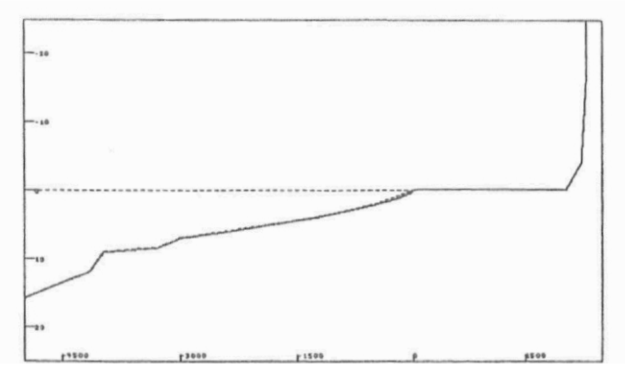
Korotogo — 0.5 m sea-level rise



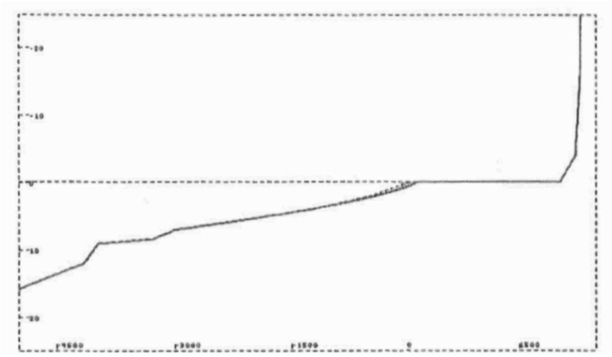
Korotogo — 1.0 m sea-level rise

Table 5 Shoreline recession distances with projected rising sea level.

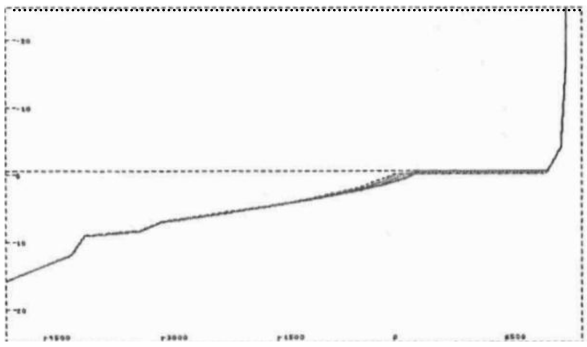
Sea Level (m above present)	Recession distance (m relative to present beach)
0.0	0.0
0.1	0.6
0.2	1.3
0.3	1.9
0.4	3.1
0.5	3.7
0.6	4.9
0.7	5.5
0.8	6.7
0.9	7.3
1.0	8.5



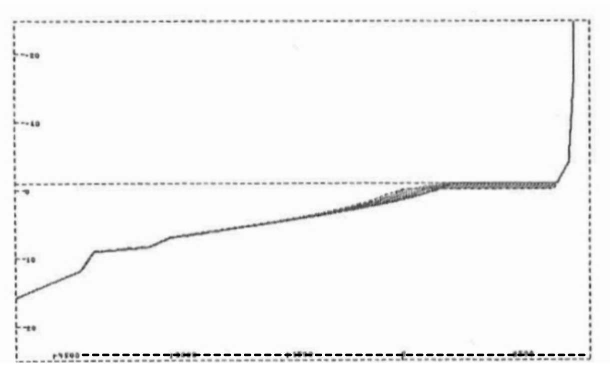
A. Initial Profile.



B. 0.2 m sea-level rise



C. 0.5 m sea level rise



D. 1.0 m sea level rise

Figure 7 Rewa river delta STM simulations. A, Initial condition. B - D simulation of shoreline retreat after varying rates of sea-level rise.

Table 6 Shoreline recession distances with projected rising sea level.

Sea Level (m above	Recession distance (m relative to present
0.1	50.0
0.2	112.2
0.3	181.7
0.4	250.7
0.5	318.6
0.6	385.5
0.7	451.8
0.8	517.1
0.9	581.9
1.0	645.6

Table 7 presents results of simulations of potential shoreline change at each coastal site using the shoreface translation model and extrapolations of these results to representative sections of coast.

Table 7. Potential shoreline retreat at each case study site using the shoreface translation model (STM).

Sea Level Rise (m)	**Korotogo** **Potential Retreat (m)**	Extrapolated area for coastal type (m^2)	**Tuvu** **Potential Retreat (m)**	Extrapolated area for coastal type (m2)	**Rewa** **Potential Retreat (m)**	Extrapolated area for news Delta (m2)
0.1	**0.6**	102 000	**6.7**	1 882 700	**50.0**	3 900 000
0.2	**1.3**	221 000	**9.0**	2 529 000	**112.2**	8 751 600
0.3	**1.9**	323 000	**10.6**	2 978 600	**181.7**	14 172 600
0.4	**3.1**	527 000	**11.5**	3 231 500	**250.7**	19 554 600
0.5	**3.7**	629 000	**12.9**	3 624 900	**318.6**	24 850 800
0.6	**4.9**	833 000	**15.9**	4 467 900	**385.5**	30 069 000
0.7	**5.5**	935 000	**18.2**	5 114 200	**451.8**	35 240 400
0.8	**6.7**	1 139 000	**21.4**	6 013 400	**517.1**	40 333 800
0.9	**7.3**	1 241 000	**25.5**	7 165 500	**581.9**	45 388 200
1.0	**8.5**	1 445 000	**29.1**	8 177 100	**645.6**	50 356 800

NB:

- The table provides potential erosion estimates using the surveyed profiles. While the profiles were selected to represent a large section of coast, extrapolation of these values across a broad spatial scale should be undertaken with extreme caution as topography varies greatly.
- Extrapolated values (erosion rate x length of coast the profile represents) at best provide an order of magnitude estimate of potential changes on each coastal sector. *See* Table 1 for length of coastline represented by each profile. This length is used as the basis to extrapolate erosion.
- Diagrams showing translation for each profile will be provided in the complete report.

4.2 Inundation Analysis

Potential inundation for the range of raised water levels analysed are presented in Table 8 for each case study site. Results indicate that significant areas of low-lying coastal land are susceptible to inundation under the raised water levels examined.

Table 8. Potential inundation using selected increased water levels at each case study site.

Water Level (m)	Tuvu Potential inundation (m^2)	Korotogo Potential inundation (m^2)	Suva Potential inundation (m2)
0.87 m	10066	1570	38705
1.00 m	120793	2457	60581
1.80 m	266051	5397	572035
2.00 m	267535	6132	668628
3.75 m	316046	48745	-
4.00 m	321243	50540	-

Note linear coastal length for each case study site is: Tuvu = 1 000 m, Korotogo = 440 m, Suva = 5 575 m around the peninsula.

4.2.1 Impacts of inundation: Suva Peninsula case study

The following tables present the impacts of sea-level rise and storm surge at Suva for specified time horizons. In many instances differences between 'best guess' and 'high estimates' are too small to allow precise differentiation of impacts. Values calculated provide an order of magnitude estimate of impacts.

Table 9. Potential inundation of land area, buildings and roads at Suva peninsula with increase in sea level only.

Time	**Potential Inundation**			
	Water Level	**Land** (m^2)	**Buildings (number)**	**Roads (m)**
2025 BG	0.75	*15 000	0	0
2025 HE	0.85	38 705	0	0
2050 BG	0.87	38 705	0	0
2050HE	1.07	60 581	0	0
2100 BG	1.10	60 581	0	0
2100 HE	1.67	475 441	87	5 943

NB: * is estimate only. BG = best guess, HE = high estimate. Length of Study site is 5 575 m.

Table 10. Potential inundation of land area, buildings and roads at Suva peninsula with increase in sea level and storm surge

Time		Potential inundation		
	Water Level	Land (m²)	Buildings (number)	Roads (m)
2025 BG	1.73	475 441	87	5 943
2025 HE	1.83	572 035	112	6 126
2050 BG	1.85	572 035	112	6 126
2050 HE	2.05	668 628	137	6 310
2100 BG	2.12	"	"	"

NB: Water level difference is too small between some value to be able to confidently determine changes in potential inundation and impacts on structures etc.

4.2.2 Impacts of inundation: Korotogo case study

The following tables present the impacts of sea-level rise and storm surge at the Korotogo site for specified time horizons. In many instances differences between `best guess' and 'high estimates' are too small to allow precise differentiation of impacts. Values calculated provide an order of magnitude estimate of impacts.

Table 11. Potential inundation of land area, buildings and roads at Korotogo with increase in sea level only.

Time		Potential inundation		Roads (m)
	Water Level	Land (m²)	Buildings (number)	
2025 BG	0.75	-	0	0
2025 HE	0.85	1 570		
2050 BG	0.87	1 570	0	0
2050HE	1.07	2 457		
2100 BG	1.10	2 457	0	0
2100 HE	1.67	4 662	0	0

NB: BG = best guess, HE = high estimate. Length of coast in study area is 440 m.

Table 12. Potential inundation of land area, buildings and roads at Korotogo with increase in sea level and storm surge after Solomon and Kruger (1996).

Time	Potential Inundation			
	Water Level	Land (m^2)	Buildings (number)	Roads (m)
2025 BG	1.73	4 662	0	0
2025 HE	1.83	5 397	0	0
2050 BG	1.85	5 397	0	0
2050 HE	2.05	6 132		
2100 BG	2.12	6 132	0	0

NB: 1 in 50 year storm surge is 0.98 m as calculated by Solomon and Kruger (1996).

Table 13. Potential inundation of land area, buildings and roads at Korotogo with increase in sea level and anecdotal storm surge level (2.86 m).

Time	Potential Inundation			**Roads** (m)
	Water Level	Land (m^2)	Buildings (number)	
Present	3.50	46 950	23	1 000
2025 BG	3.61	*47 000	23	1 000
2025 HE	3,71	48 745	23	1 000
2050 BG	3.73	48 745	23	1 000
2050 HE	3.93	50 540	24	1 000
2100 BG	4.00	50 540	24	1 000

NB: Anecdotal storm surge is 3.5 m above mean sea level (MSL). Note simulation of this storm surge under present sea level.

4.2.3 Impacts of inundation: Tuvu case study

The following tables present the impacts of sea-level rise and storm surge at the Tuvu site for specified time horizons. In many instances differences between 'best guess' and 'high estimates' are too small to allow precise differentiation of impacts. Values calculated provide an order of magnitude estimate of impacts.

Table 14. Potential inundation of land, mangrove, sugar cane, buildings and railway at Tuvu with increase in sea level only.

Time	Potential Inundation					
	Water Level	Land (m^2)	Mangrove (m^2)	Sugar Cane (m^2)	Buildings (number)	Railway (m)
2025 BG	0.75	*5000	* 5 000	0	0	0
2025HE	0.85	10 066	10 066	0	0	0
2050 BG	0.87	10 066	10 066	0	0	0
2050 HE	1.07	120 793	120 7 3	0	0	0
2100 BG	1.10	>120 793	120 793	0	0	0
2100 HE	1.67	264 568	192 310	0	0	0

NB: BG = best guess, HE = high estimate, *=estimate only. Length of coast analysed = 1 km. No sugar Cane inundated.

Table 15. Potential inundation of land, mangrove, sugar cane, buildings and railway at Tuvu with increase in sea level and storm surge after Solomon and Kruger (1996).

Time	Potential Inundation					
	Water Level	Land (m^2)	Mangrove (m^2)	Sugar Cane(m^2)	Buildings (number)	Railway (m)
2025 BG	1.73	264 568	192 310	0	0	0
2025HE	1.83	266 051	192 310	0	0	0
2050 BG	1.85	266 051	192 310	0	0	0
2050 H E	2.05	267 535	192 310	1 854	0	1 000
2100 BG	2.12	267 535	192 310	1 845		

NB: 1 in 50 year storm surge is 0.98 m as calculated by Solomon and Kruger (1996).

Table 16. Potential inundation of land, mangrove, sugarcane, buildings and railway at Tuvu with increase in sea level and anecdotal storm surge level (2.86 m).

Time				**Potential Inundation**		
	Water Level	**Land (m^2)**	**Mangrove (m^2)**	**Sugar Cane (m^2)**	**Buildings (number)**	**Railway (m)**
Present	3.50	310 849	192 310	42 275	1	1 000
2025 BG	3.61	*313 000	192 310	42 275	1	1 000
2025 HE	3.71	316 046	192 310	46 952		1 000
2050 BG	3.73	316 046	192 310	46 952	1	1 000
2050 HE	3.93	321 243	192 310	51 629	1	1000
2100 BG	4.00	321 243	192 310	51 629	9	1 000

NB: Anecdotal storm surge is 3.5 m above mean sea level (MSL). Note simulation of this storm surge under present sea level conditions.

Tables 9 - 16 show that the impacts to be expected from inundation will vary greatly depending on topography, land use and level of infrastructure development. For example, at Tuvu inundation impacts most prominently on areas of mangrove, sugar cane and rail track with little impact on buildings. In contrast, at Suva Peninsula inundation levels will have significant impacts on buildings and the road system.

Of note, areas predicted to be inundated under maximum sea-level rise scenarios are currently inundated during the 1 in 50 year storm event. The results highlight the importance of storms in promoting inundation. These storm impacts will be exacerbated with increases in sea level.

REFERENCES

Cowell P.J., Roy P.S., and Jones R.A., 1995. Simulation of large-scale coastal change using a morphological behaviour model: Amsterdam, Marine Geology, 126: 45-61.

Kench P.S. and Cowell P.J., 1999. Impacts of sea-level rise and climate change on Pacific coasts. Proceedings of the PACCLIM Workshop: Modelling climate change and sea-level change effects in Pacific Island Countries, Auckland, 2327 August, 1999.

ANNEX 1.

Extended Water Resources Analysis for Kiribati

T o n y   F a l k l a n d

EcoWise

Additional groundwater modelling of the Bonriki freshwater lens, Tarawa, Kiribati using the SUTRA groundwater model

May 2000

Introduction

The SUTRA groundwater model (Voss, 1984; Voss et al., 1997) was applied to a selected cross section through the Bonriki freshwater lens to analyse the impacts of 8 climate change and sea level rise scenarios on the freshwater thickness. These scenarios were chosen by IGCl/World Bank project to better reflect possible future climate conditions in the year 2050, than the scenarios used in a previous study of the impacts on the Bonriki freshwater lens (Alam & Falkland, 1997).

Summary of results

Comparisons between the freshwater lens thickness at a selected critical time step were made between each scenario and a baseline scenario, which was also used in the 1997 study. The critical time step selected for comparisons between the simulated freshwater lens thicknesses was that occurring in November 1985 at the end of a long drought. This this time step was selected on the basis of previous modelling (Alam & Falkland, 1997), as it produced the thinnest freshwater lens condition.

The impact of the 8 scenarios of climate change (rainfall change), sea level rise and potential loss of island width on the Bonriki freshwater lens are summarised in the table below. The average change in freshwater thickness relative to the baseline scenario, in absolute and percentage terms (to 2 significant figures), are listed in the table.

Scenario	Average change in freshwater thickness compared with baseline scenario (m)	(%)
Baseline scenario (current MSL & rainfall): average freshwater thickness = 12.1 m	-	-
1. Current MSL, 7% increased rainfall	+0.66	+5.5
2. Current MSL, 10% reduced rainfall	-1.7	-14
3. 0.2 m MSL rise, current rainfall	-0.10	-0.9
4. 0.4 m MSL rise, current rainfall	+0.25	+2.0
5. 0.4 m MSL rise, 10% reduced rainfall	-1.4	-12
6. 0.4 m MSL rise, current rainfall, reduced island width	-3.5	-29
7. 0.4 m MSL rise, 7% increased rainfall, reduced island width	-2.3	-19
8. 0.4 m MSL rise, 10% reduced rainfall, reduced island width	-4.7	-38

Notes:

- The reduction in island width used in scenarios 6, 7 and 8 is 230 m. This reduces the effective width of the island from 1,230 m to 1,000 m.
- All scenarios have been run with a pumping rate over the lens of 1,000 m3/day (equal to the current pumping rate).
- The recharge to the lens was based on the same vegetation and soil conditions as used in the 1997 study.

References

Alam K. &Falkland A.C. (1997). Vulnerability to Climate Change of the Bonriki Freshwater Lens, Tarawa. Report No HWR97/11, ECOWISE Environmental, ACTEW Corporation, prepared for Ministry of Environment and Social Development, Republic of Kiribati, April 1997.

Voss C.I. (1984). SUTRA, A finite-element simulation model for saturated-unsaturated, fluid-density-dependent ground-water flow with energy transport or chemically-reactive single- species solute transport. USGS Water-Resour. Invest. Report 844389, 409 pp.

Voss C I, Bo1dt D & Shapiro A M (1997). A Graphical-User Interface for the US Geological Survey's SUTRA Code using Argus ONE (for Simulation of Variable –Density Saturated-Unsaturated Ground-Water Flow with Solute or Energy Transport), U S Geological Survey, Open-File Report 97-421, Reston, Virginia.