ASSESSMENT OF THE VULNERABILITY OF BAIRIKI AND BIKENIBEU, SOUTH TARAWA, KIRIBATI, TO ACCELERATED SEA-LEVEL RISE

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Primary school boys in Kiribati

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1. EXECUTIVE SUMMARY

Under a United States Country Studies Program, The United States government committed a total of US$ 25 million to assist developing countries and those with economies in transition to meet their obligations under the United Nations Framework Convention on Climate Change, to carry out greenhouse-gas inventories and develop plans for responding to climate change. Under the umbrella of this program, SOPAC completed a study of vulnerability of Betio to Accelerating Sea-level Rise in 1997. Following the completion of the project, the government of Kiribati requested SOPAC to conduct another study, and extend the coverage to include the areas from Bairiki to Bonriki in Tarawa. This request was endorsed, and included in SOPAC's Work Program, Task Profile Number KI 99.03.

Vulnerability of South Tarawa to accelerating sea-level rise is fundamentally linked to the stability of the shoreline and the height of the beach crest. Because of data limitations and uncertainties, as well as the complexity and unpredictability of response of the whole natural system to accelerating sea-level rise in Tawara, the emphasis of this study was placed on the physical vulnerability of shorelines from Bairiki to Bonriki, South Tarawa, particularly focusing on overtopping and flooding, associated with analysis of possible response of shoreline and coast, coral reef, and humans to ASLR. Following Betio, Bairiki and Bikenbeu were chosen as two pilot areas for this study because of their high population density, development, logistics and availability of previous data.

Field reconnaissance surveys for this study were conducted from 26 July to 12 August 1999. During this time period, the elevation data of 485 points chosen on the coastal crest and coastal defense structures around Bairiki and Bikenibeu were acquired using a Sokkia Total Station. These data associated with the inland elevation collected from the contour line (with 1-m interval) of GIS Data Captured Digital Aerial Photography provided by Land Survey Department of Kiribati Government, constituted the basic three-dimensional landform of Bairiki and Bikenibeu in MapInfo GIS format to enable computation modeling.

At the same time, coastal erosion and coastal-protection structures around Bairiki and Bikenibeu were also examined. Ten beach profiles which were established around Bikenibeu by SOPAC in 1995 were resurveyed, by using the Sokkia Set 2C Total Station. This information, as a by-product of this project, was documented in SOPAC Preliminary Report 116: Re-survey of Bikenibeu Beach Profiles, South Tarawa, Kiribati.

Following conclusions and recommendations are derived from this study:

Conclusions

1. Elevations of the beach crest and coastal defense structures show that the average heights above 1974 - 1976 Mean Sea Level are as follows:

Bairiki	2.64 m
Bikenibeu	3.25 m at ocean side
	2.38 m at lagoon side

2. Computing results of overtopping coastline and flooding area under sea-level rises of three IPCC guess scenarios of 0.3 m, 0.5 m and 0.95 m above present sea level during a 14-year storm event (52-knot wind - Carter, 1983) which coincides with a spring tide for Bairiki and Bikenibeu are as following.

a. In Bairiki, When sea-level rises 0.3 m above present mean sea level during a 14-year storm event which coincides with a spring tide, 17% of the ocean-side shoreline will be overtopped, while 5.5% of the lagoon-side shoreline is undergoing overtopping. The total overtopped shoreline in Bairiki will be 640 m, accounting for 12.31% of total shoreline of the islet; the flooded land area in Bairiki is 80600 sq. m, 17% of total Bairiki land area. When the sea level continues to rise, vulnerability at the lagoon side can increase. The overtopped shoreline at the lagoon side will quickly increase to 1187 m at IPCC 0.5-m guess scenario, from 5.5% at 0.3 m rising to 58%, more faster than what is happening at the ocean side. Under the IPCC high-guess scenario, the whole islet will be over washed.

b. As a result of high elevations at the ocean side in Bikenibeu, the overtopping mainly occurs at the lagoon side of the islet. At the 0.3-m IPCC low-guess scenario during a 14-year storm event which coincides with a spring tide, 69% of the lagoon side-shoreline will undergo overtopping, while almost all of the ocean-side shoreline (97%) still keeps stable; the total overtopped shoreline is 3098 m, 37% of total Bikenibeu shoreline, and the flooded land area will be 54140 sq.m, accounting for 53% of total land area. With sea-level rise 0.5 m under the same meteorological condition, the overtopping shoreline increases to 51% at the lagoon side and 8.8% at the ocean side; and the flooded area reach 73050 sq.m, 71% of total land area. At the IPCC high guess scenario, almost the whole islet will be over washed.

3. It is still not known how the low-lying atoll coastal system will react to ASLR. At present sea level, the direction of sediment movement on North and South Tarawa is, to a large extent, dependent on the orientation of these two arms of the atoll rim with respect to the easterly trade winds and the ENSO-related westerly wind pattern. During a long ENSO period, the shoreline of South Tarawa, built up by the dynamic system dominated by easterly trade winds between ENSO periods, can be reshaped inversely. Analysis of beach profiles and dynamics shows that there is significant sand movement and transport around the island, causing erosion in some places and accretion in others under different meteorological conditions. Sand accretion at the beach near Tungaru Central Hospital was linked to unusual and persistent El Ni˜no conditions, in 1991-1995. This complicates the studies attempting to predict the change of the coastal system to ASLR in the future. Undoubtedly, ASLR will increase water depth, increase wave strength and accelerate coastal erosion.

4. The response of coral reefs to ASLR is another unclear factor. According to IPCC Special Report on “The Regional Impacts of Climate Change, An Assessment of Vulnerability”, current projected rates of sea-level rise per se are not expected to have widespread adverse effects on coral reefs. But indirectly, other adverse effects aggravated by ASLR will damage the health of coral reefs, such as coastal erosion and inappropriate human response to ASLR, as well as special events, like the ENSO phenomenon and cyclones.

5. Increasing anthropic stress caused by waste disposal (including sewage) is one of the major contributors to reef and lagoon degradation, causing death of coral species and a reduction of natural coastline protection provided by reef systems. This increases the vulnerability of coastal communities and infrastructure in the future.

Recommendation:

In summary, there is no retreat to Tarawa when sea level rises, a small low-lying atoll with the elevation rarely higher than 4 m above mean sea level. In struggling for existence and pursuing a better life, it is wise to avoid overexploiting the natural resources. The equilibrium between economic development and environmental protection should be kept in a sustainable manner. Vulnerability can be minimized if consideration is given to:

, *Public awareness of preservation of reef environments;*
, *Waste disposal and pollution control;*
, *Establishment of building setback strategy;*
, *Reduction and control of sand and aggregate mining;*
, *Code of practice for coastal-structure design and engineering.*

As Tarawa geographically and ecologically is an ideal place for present and future monitoring of environmental change under global climate change, it has became one of the indicative coral atolls in case study in the South Pacific since global climate change came to attention. A continuous study of vulnerability assessment could be beneficial to both Kiribati people and scientific communities. At present, more and more scientific data on land use, population, vegetation coverage, coral reef, soil, water, land elevation, coastal mapping, natural dynamic of shoreline, as well as new economic data, are available for Kiribati. Availability of this information and new technological methodologies and tools in vulnerability assessment could fully facilitate and equip a new vulnerability study for the whole of Tarawa and the whole nation. This study and the previous study for Betio shall be combined into the vulnerability assessment for the whole of Tarawa. On the project-debriefing meeting at the Ministry of Environment and Social Development, the Kiribati Government put a request to extend the coverage of this study to the rest of South Tarawa. However, a recommendation from this study is that it is necessary and proper to consider Tarawa as a whole system to assess its vulnerability to climate change, not only to ASLR.

For long-term monitoring of shoreline stability, the present bi-annual beach-profile monitoring system should be extended to cover larger area around Tarawa, especially at the more dynamic areas. All the measurement data should be calibrated to the same datum system.

2. ACKNOWLEDGEMENTS

The funding for this project was provided by the Government of the People's Republic of China.

The work was carried out in collaboration with the Kiribati Government. Assistance was received from both Ministry of Natural Resource Development (MNRD) and Ministry of Environment and Social Development (MESD).

The coordination assistance and arrangement of logistic support from Ms Naomi Atauea of MNRD during the fieldwork period is highly appreciated;

Land Survey Department of Kiribati Government provided the GIS data obtained from aerial photography and elevation data of bench marks and ground control points.

Special thanks go to Mr Nakibae Teuatabo, PICCAP coordinator of Kiribati Government for useful discussion and information providing.

Review and useful comments on the draft of this report were given by Robert Smith, marine geophysics of SOPAC and Russell J. Maharai, CFTC expert.

Quan Chung from SOPAC, Tomwa from Ministry of Natural Resources Development and Augus from Ministry of Environment and Social Development provided field support for this project.

3. INTRODUCTION

3.1 Background and Objective

Under a United States Country Studies Program, The United States government committed a total of USD$ 25 million to assist developing countries and those with economies in transition to meet their obligations under the United Nations Framework Convention on Climate Change (UNFCCC), to carry out greenhouse gas inventories and develop plans for responding to climate change. Under the umbrella of this program, SOPAC completed the study of the Vulnerability of Betio to Accelerating Sea-level Rise in 1997. Following this, the government of Kiribati requested SOPAC to conduct another project, extending the coverage of this study to include the area from Bairiki to Bonriki, Tarawa Atoll.

The objective of this project is to quantitatively assess the physical vulnerability of chosen sites on Tarawa to accelerated sea-level rise in the range of 15-95 cm (using scenario IS92) by the year 2100, particularly focusing on overtopping and flooding.

3.2 The Study Area

The Republic of Kiribati, straddling the equator, consists of three island groups in the Pacific: Gilbert Islands, Line Islands, and Phoenix with a total land area of 717 sq. km. The Gilbert Islands group is at the westernmost of the country, with 16 atoll islands, and houses some 92 % of the total country population. Tarawa, the capital, is a triangular shape low-lying coral atoll located approximately midway in this north-south group of islands in the Western Pacific at 1°25’ N and 173°00’ E (Figure 1, Figure 2). The coral atolls are carbonate platforms built on top of sunken volcanic cones. The central part of Tarawa Atoll is a shallow lagoon with water depth less than 24 m, surrounded on the east and south sides by elongated islands and on the west side by a shallow, submerged reef (Solomon 1997). Sediments in the lagoon are mixtures of sand, gravel and mud (Richmond, 1990; Smith and Biribo, 1995). There is a series of islets on the east and south sides of the Tarawa Lagoon, which have mostly been linked by artificial causeways.

Bairiki and Bikenibeu are, administratively and economically, the two important, crowded islets, on which are based Central Government Office, Parliament Building, President’s Office and Residence, offices of other government departments, school, church, market and other facilities. They are located on the southern arm of the Tarawa Atoll, which extends some 35 km on the eastern and southern sides (Figure 2).

3.3 This Study

Following discussions with the Ministry of Environment and Social Development, especially with the national climate-change study team of Kiribati, this project was designed to assess the direct effects of future ASLR, with especially emphasis on overtopping and flooding. Mr Nakisae Teuatabo, the PICCAP coordinator of Kiribati Government put a request to assess the vulnerabilities under three different IPPC scenarios of 0.3 m, 0.5 m and 0.95 m during the discussion.

A set of guidelines has been provided for vulnerability and adaptation assessments under the US Country Studies Program. For coastal assessments, these follow closely the Common Methodology for assessing vulnerability to sea-level rise in coastal regions, set out by the IPCC Response Strategies Working Group (IPCC, 1992).

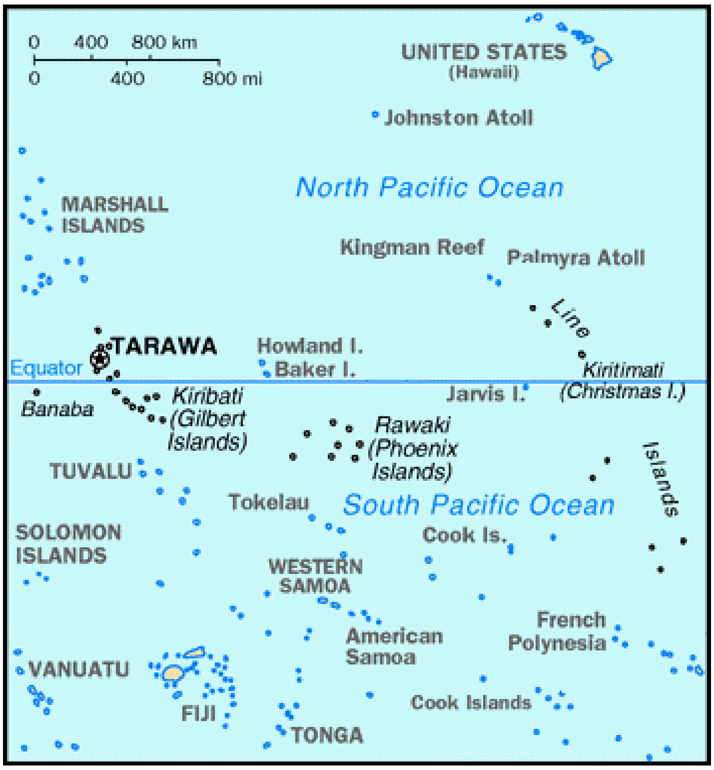

Figure 1. Pacific Ocean showing location of Tarawa, Republic of Kiribati.

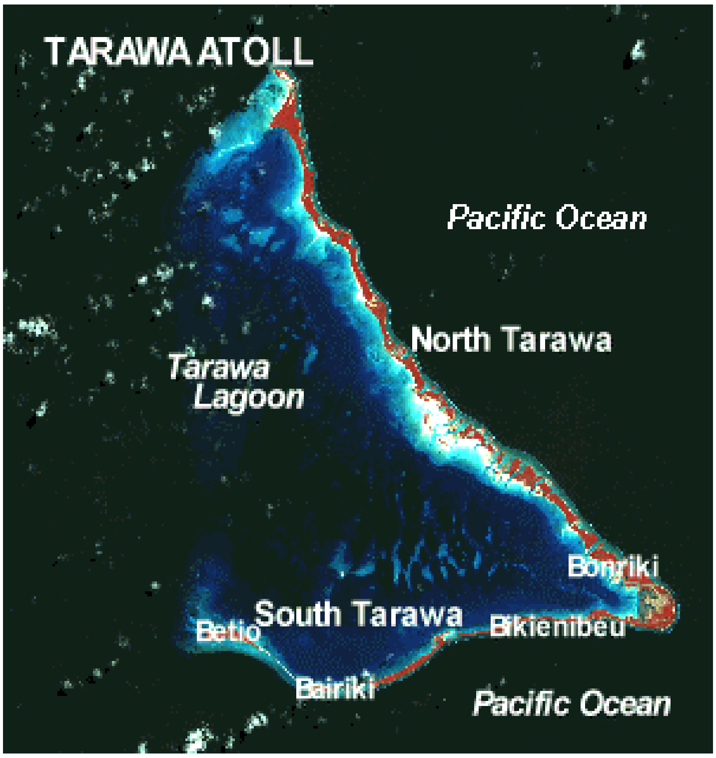

Figure 2. SPOT satellite image showing location of Bairiki and Bikenibeu.
Source: SOPAC Data

The IPCC Common Methodology and the US Country Studies Guidelines have limitations in their application to tropical reef coasts. Many studies in the South Pacific region have highlighted limitations of standard methodologies for vulnerability assessment in the Pacific Islands (Holthus et al., 1992; Nunn & Waddell, 1992; Kay et al., 1993; Yamada et al., 1995). Apart from the limitation of IPCC Common Methodology and the US Country Studies Guidelines, there is one constraint which prevents this project from fully adopting the IPCC Common Methodology; this is the small scale of study area. A small area is very sensitive to outside forces; even a small natural or human change in the system can be significant. For instance, when we assess the anthropological stress in a coastal ecosystem, if only the population and population density of a small area are given for consideration, this will distort the conclusion. In a small area, residents living outside and moving around the small study area might easily produce more-severe effects than those caused by the residents living in the area. Another example can be also given to explain the constraint: for identification of Development Factor, the step 3 in the seven steps of the IPCC Common Methodology for assessment of vulnerability to ASLR, it is impossible to split and detail properly the statistics of for either Kiribati or Tarawa as a whole to separate Bairiki and Bikenibeu, two small areas attached to a large background environment. There is therefore a need to develop new strategies and appropriate tool to assess independently the vulnerability of small areas closely linked to a large background environment, like Bairiki and Bikenibeu at South Tarawa.

Low-lying coral atolls in the South Pacific are very fragile to ASLR; especially those with elevations below 4 to 5 meters above mean sea level, like Tarawa, Kiribati. At its geographical setting on the equator, tropical cyclones are very rare, and the major environmental hazard brought by ASLR to Tarawa will be, in the future, overtopping, flooding and those adverse effects and deterioration caused by overtopping and flooding, such as seawater inundation, salination, coastal erosion, and contamination of ground-water. It is necessary to emphasize here that the scope of this study is only centered on physical vulnerability ASLR; global climate and regional change and their effects are beyond the scope of this study. This is another reason why this study cannot fully follow the IPCC Common Methodology and the US Country Study Guidelines, due to their limitations in scope.

Can ASLR be an independent subject applicable in VA on tropical reef coasts? This question was derived from analysis of the project data. The answer seems to be “no” as result of present science uncertainty. At present, the effects on coral reefs of sea-level rise are quite controversial. Actually, the rising global temperature driving sea-level rise is the major contributor to coral death and bleaching, which then exerts adverse effects on coral growth and its productivity. These will minimize the coral reef’s functions on reducing wave energy approaching the coast and producing sand supplied to the coast. Present vulnerability assessment of ASLR in tropical area is likely to have limitation and may lead to an opposite conclusion and obscure the real natural changes if those dominant factors controlling and behind ASLR can’t be included for consideration. In other words, the ASLR cannot be peeled off as an independent subject for the study in the tropical reef areas, and needs to be put into the topic of climate change as a whole for integrated consideration and study. This is why this study has to narrow its scope to overtopping and flooding.

For a quantitative assessment of the effects of overtopping and flooding caused by ASLR, this project was designed to acquire the elevation data of pilot areas for computing overtopped coastline and areas of flooding under sea-level conditions of three IPCC scenarios of 0.3 m, 0.5 m and 0.95 m above present sea level. The elevation data of coastal crest and coastal defenses of Bairiki and Bikenibeu were measured using a Sokkia Total Station, and the inland elevation data of the study area were derived from contour line (with 1-m interval) of GIS data obtained from digital aerial photography provided by Land Survey Department of Kiribati Government. For consistency with the previous SOPAC VA study in Betio, South Tarawa, the same meteorological condition was chosen: a 14-year special event coinciding with a spring high tide.

4. BOUNDARY CONDITIONS

4.1 Tides and Water Levels

Tarawa tides are semi-diurnal. Mean high-water spring tide is 1.1 m above mean sea level and the spring tidal range is 2.1 m (UK Admiralty Tide Tables 1995).

At present, there are two organizations which operate tide gauges on Betio, the University of Hawaii (UH) (Figure 3) and the National Tidal Facility (NTF) at Flinders University in Australia (Figure 4). Tidal data from the UH and NTF indicate that the sea level at Tarawa fluctuates on a seasonal and an annual basis.

Figure 3. Tide gauges maintained by the University of Hawaii

Figure 4. Tide gauges maintained by the National Tidal Facility at Flinders University

The total range of tidal fluctuation is more than 42 cm, with a maximum of 19 cm above mean sea level and a minimum of 23 cm below mean sea level. There is a pronounced seasonal cycle which is characterized by a maximum in sea level during the months of September to January followed by a rapid drop of 10-15 cm over a period of less than one month. The seasonal change has been attributed to variation in the strength of the Equatorial current in the vicinity of Tarawa (Mclean, 1989). Interannual variability is attributed to the effect of the ENSO and decade scale variability can be caused by changes in the strength of the trade wind field (Inoue and O'Brien, 1987; as cited in Mclean, 1989). Mean water level during the first quarter of 1997 was unusually high, more than 15 cm above the 1992–1997 mean. In his report on assessment of the vulnerability of Betio to ASLR, Solomon (1997) concluded that the mean sea level at Tarawa exhibits highly complex periodic behavior, which has little to do with long term sea-level trends, but has comparable amplitude.

4.2 Datum

The land elevations measured during this study are based on a survey performed in 1998 by Land Survey Department of Kiribati Government. It extended the distribution of benchmarks throughout Tarawa based on the Cox Datum (0.107 m above the tide gauge zero). This datum was related to mean sea level using water-level information from the UH tide gauge during the period from August 1974 to July 1976. The mean sea level for that period was 1.18 m above the tide gauge datum and 1.073 m above Cox Datum.

4.3 Sea-Level Scenarios

According to Teuatabo and Teitiba (1996), IPCC sets boundary conditions for global accelerated sea-level rise of 0.3 m to 0.95 m, with an average best-guess scenario of 0.5 m by the year 2100 (Figure 5). It is clear that sea level is not expected to rise uniformly in the Earth's oceans. Regionally, the Pacific Ocean's water-level trends, reconstructed from tide gauge data and from large intertidal coral (microatolls) in Kiribati do not indicate a trend of rising sea level as rapid as the global average, and do not show any identifiable acceleration (Woodroffe and Mclean 1992). For the purpose of assessing physical vulnerability to ASLR by the year 2100, this study adopted the IPCC scenarios of low (30 cm), medium (50 cm) and High (90 cm) rise by 2100 (Figure 5).

In Tarawa, mean high-water spring (MHWS) tide in Tarawa is 1.1 m above mean sea level; the highest high tides (HHT) are at least 1.32 m above the mean sea level based on NTF tidal data for 1992-1997. The highest high tide above the monthly mean is about 1.22 m, based on the NTF's data as described by Teuatabo and Teitiba (1996). In his report on assessment of the vulnerability of Betio to ASLR, Solomon (1997) analyzed 10 maximum deviations from the predicted tidal level between 1992 and 28 February 1997 (provided by the NTF at Flinders), and concluded that the maximum anticipated still level is 1.22 m (the maximum high tide level) plus 0.27 m (the maximum observed residual water level) and chose 1.49 m for his study.

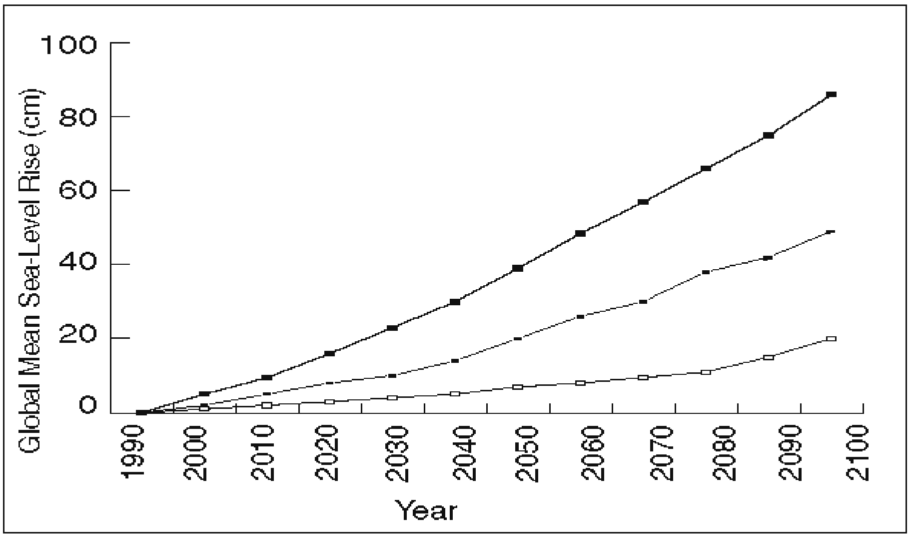

Figure 5. Projected Accelerated Sea-Level Rise for the period 1990-2100, using scenario IS92.

In this study, this still water level is rounded up to 1.5 m and scenarios are developed by adding the projected increase in sea level as suggested by the IPCC (Table 1). These water levels can be compared directly to land elevations which have be calculated relative to the UH 1974–1976 mean sea level.

Table 1. Scenario for sea-level rise and maximum water levels (HHT). The short-term meteorological effects are not included.

Tidal level	Present	2100 Low	2100 Medium	2100 High
MSL (1974-76) (Cox datum)	0 (1.073 m)	0.3 (1.373 m)	0.5 (1.573 m)	0.95 (2.023 m)
HHT	1.5	1.8	2.0	2.45

4.4 Climate and Oceanography

Kiribati weather is influenced by the seasonal movement of the Intertropical Convergence Zone (ITCZ) and the Equatorial Doldrums Belt (EDB). June to November is drier and Southeasterly Tradewinds dominate. December to May is wetter and winds from the north and east quadrants are prevalent. Winds are usually light. Strong winds are associated with Westerly squalls. Wind roses for Tarawa indicate that the Westerlies are more common during the months of June to November. The frequency of easterly winds varies directly with the Southern Oscillation Index (SOI), being more frequent when the SOI is positive. Westerly winds are more prominent during times of negative SOI. Easterly and southeasterly winds are generally around 4–10 knots (7.4-18.5 km/hour), and the strongest wind recorded between 1979 and 1986 was 52 knots (96 km/hour), from 280^0 west.

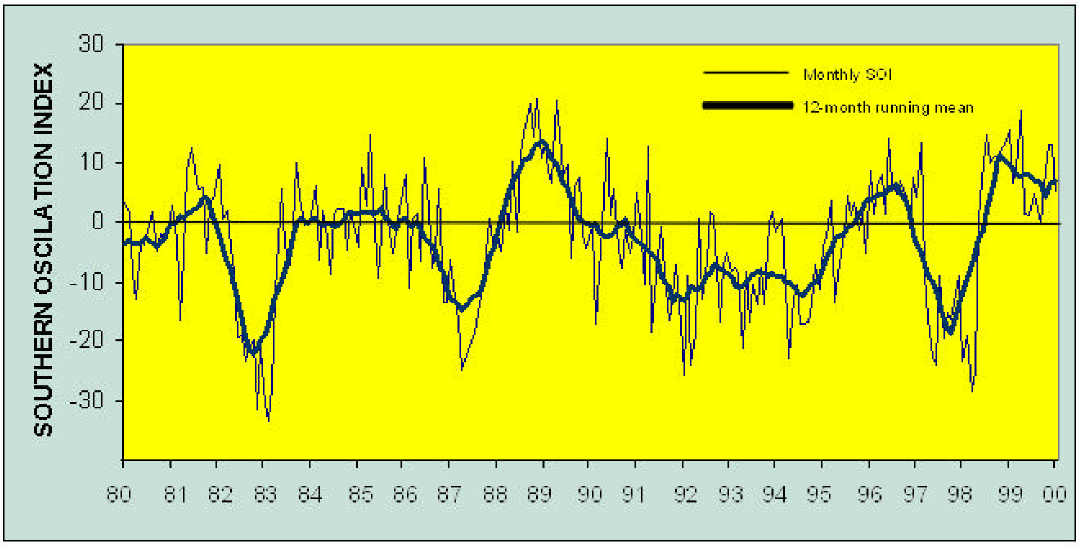

Figure 6. Southern Oscillation Index (SOI) from 1980 to 2000, showing monthly values and 12-month running mean. Data form Southern Oscillation Index [SOI] value website: http://nic.f64.gov/data/cddb/. Plotted by writer of this report for this project.

Cyclones are very rare this close to the Equator, but they have been known to occur. Gale force winds (32.9 knots) may occur when cyclones develop to the south of Tarawa (Gilmour and Coleman, as cited in Forbes and Hosoi, 1995)

In line with Solomon's report (SOPAC Technical Report 251), using Carter's 1983 estimate of wind of 52 knots (27 m/s) with a return period of 14 years, a fetch of 0.6 km (the average width of the fringing reef), and water depth of 2 m at high tide, a wind setup of about 0.08 m was calculated. Wave setup on the ocean side, based on a transmitted wave (after Carter, 1983) of H_s=1.37 m and Tp=3 s, causes an addition 0.10 m of setup. On the lagoon side, waves with a period of 3 s and H_s of 0.75 m produce only 0.02 m of setup. Run-up on the 7^0 beach slope (average beach slop around Bairiki and Bikenibeu) beach slope under the same wave conditions is about 0.7 m. Thus, under stormy conditions, the still water level might increase by 0.08–0.18 m over the predicted maximum tide (i.e. from 1.5 m to a maximum of 1.64 m). Run-up would increase the maximum water-level elevation to 2.34 m.

5. RESULTS

For this study, elevations were measured at 485 chosen points on the coastal crest and coastal defense structures around Bairiki and Bikenibeu were measured. This information shows that average height of Bairiki is 2.64 m above 1974-1976 mean sea level, the average height of the ocean side of Bikenibeu is 3.25 m and that of the lagoon side is 2.38 m above 1974–76 mean sea level.

Based on Carter's estimate of meteorological effects, computations were made to model the real situation of overtopping and flooding. A 14-year storm event with a 52-knot wind was chosen for computation. The result is presented in the following sections.

5.1 Projection Under Sea-Level Condition of IPCC Low-Guess Scenario: 0.3 m above Present Mean Sea Level

1. Bairiki assessment

Under the sea-level condition of IPCC low-guess scenario of 0.3 m above present sea level during a 14–year storm event (52-knot wind – Carter, 1983) which coincides with a spring tide, there will be four parts of coastline subjected to overtop and their adjacent land areas to flooding. These are Section A and at Section B at ocean side and Section C and Section D at lagoon side (Figure 7). The seawater overtopping Section B will inundate a large area (highlighted by blue color on Figure 7) at the west of Bairiki.

Under the above assumption of rising sea level and meteorological conditions, the length of shoreline subjected to overtopping is 528 m at the ocean side, 17% of total the ocean side shoreline, and a 112 m of shoreline at the lagoon side will be overtopped, accounting for 5.5% of total lagoon shoreline. The total coastline which will be overtopped in Bairiki, will be 640 m, which accounts for 12.31% of total length of coastline for Bairiki; and the total flooded area is 80600 m^2, which accounts for 17% of total land area of Bairiki.

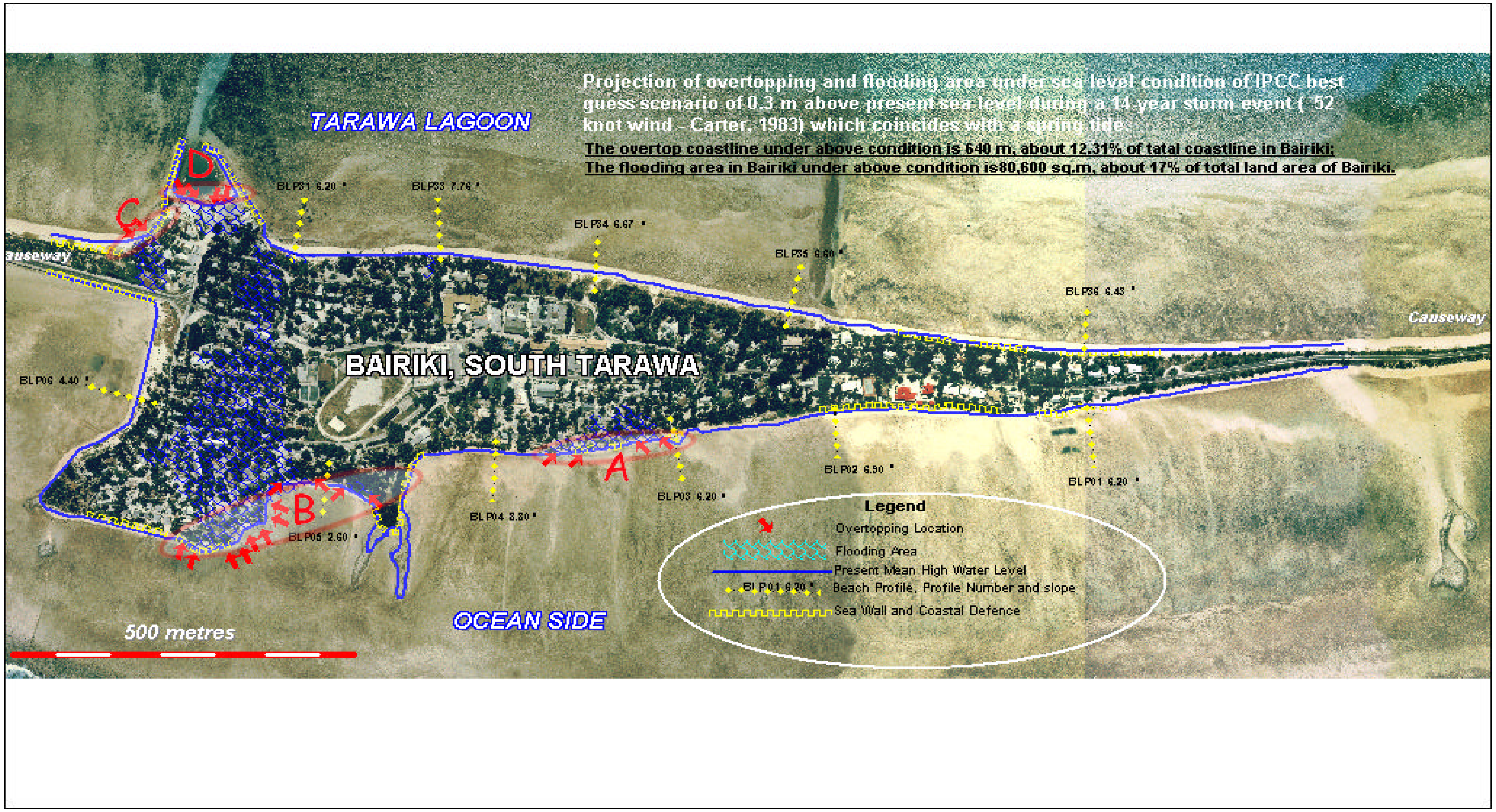

Figure 7. Projection of overtopping and flooding associated with a 0.3 m sea-level rise above present sea level during a 14-year storm event (52-knot wind – Carter, 1983) coinciding with a spring tide.

2. Bikenibeu assessment

Figure 8 shows the overtopping and flooding in Bikenibeu, under a 0.3-m rise in sea level during a 14-year storm event (52-knot wind – Carter, 1983) which coincides with a spring tide. As a result of high elevation at the ocean side, overtopping mainly occurs at the lagoon side of Bikenibeu. Under the above sea-level and meteorological condition, 69% (3012 m) of the shoreline at the lagoon side will be overtopped, while only 2.2 % (86 m) shoreline at the ocean side will be overtopped. The total overtopped shoreline will be 54140 m^2, 53% of total land area.

5.2 Projection under Sea-Level Condition of IPCC Medium-Guess Scenario: 0.5 m above Present Mean Sea Level

1. Bairiki assessment

Under the sea level condition of IPCC medium guess scenario of 0.5 m above present sea level during a 14-year storm event (52-knot wind – Carter, 1983) which coincides with a spring tide, seven sections of shoreline will be overtopped and their adjacent land areas are inundated and flooded; these are Sections A, B, C, D, E, F and G (Figure 9). Sections A, B, C, D and E are at the ocean side, with total length of coastline of 1093 m, accounting for 35% of total shoreline at the ocean side. Sections G and G are at the lagoon side with total length of coastline 1187 m, accounting for 58% shoreline at the lagoon side (Figure 9). The total overtopped shoreline will be 2280 m in Bairiki, or 43% of total shoreline on this islet.

Under the above assumpted conditions, the area adjacent to the overtopped areas will be flooded. The seawater overtopping Section C at the ocean side can meet the water overtopping Section F, then inundate most of the land area of the west part of Bairiki. The water overtopping Section A from the ocean side and Section G from the Lagoon side join together to split the east part of Bairiki (Figure 7). The total land area subjected to flooding will be 16 1715 m^2, 35% of total land area.

The total length of coastline which will be overtopped under this sea-level condition will be 2280 m, which accounts for 43.85% of total coastline in Bairiki; and the total flooded land area is 16 1715 m^2, 35% of the total land area of Bairiki.

2. Bikenibeu assessment

For Bikenibeu, a sea-level rise of 0.5 m will cause almost all the shoreline at the lagoon side to be overtopped, while only a small part of the ocean shoreline will be overtopped. Computing shows that 90% of shoreline at the lagoon side, and 8.8% of shoreline at the ocean side will be under threat of overtopping. The total length of overtopped shoreline is 3448 m, 51% of total shoreline around Bikenibeu and the flooded land area is 72 050 m^2, 71% of total land area of Bikenibeu (Figure 10).

5.3 Projection under Sea-Level Condition of IPCC High-Guess Scenario: 0.95 m above Present Mean Sea Level

1. Bairiki assessment

Figure 11 shows the still waterline during a spring high tide after a 0.95-m rise in sea level. Under this condition, the west part of Bairiki will be flooded by still water. If an extreme event occur, the wave set up will wash over the whole islet.

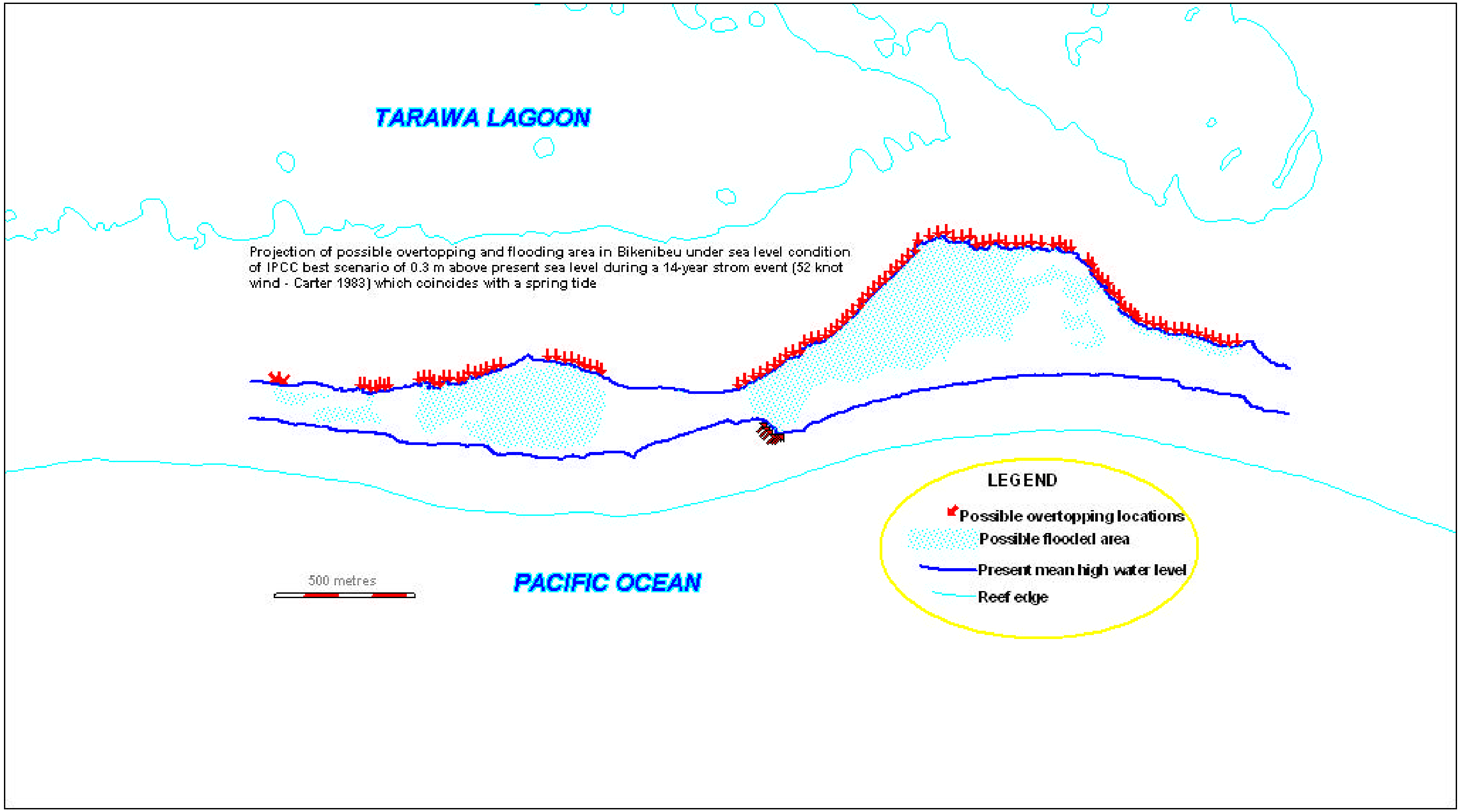

Figure 8. Projection of overtopping and flooding associated with a 0.3-m rise in sea level in Bikenibeu during a 14 -year storm event (52- knot wind – Carter,1983), which coincides with a spring tide.

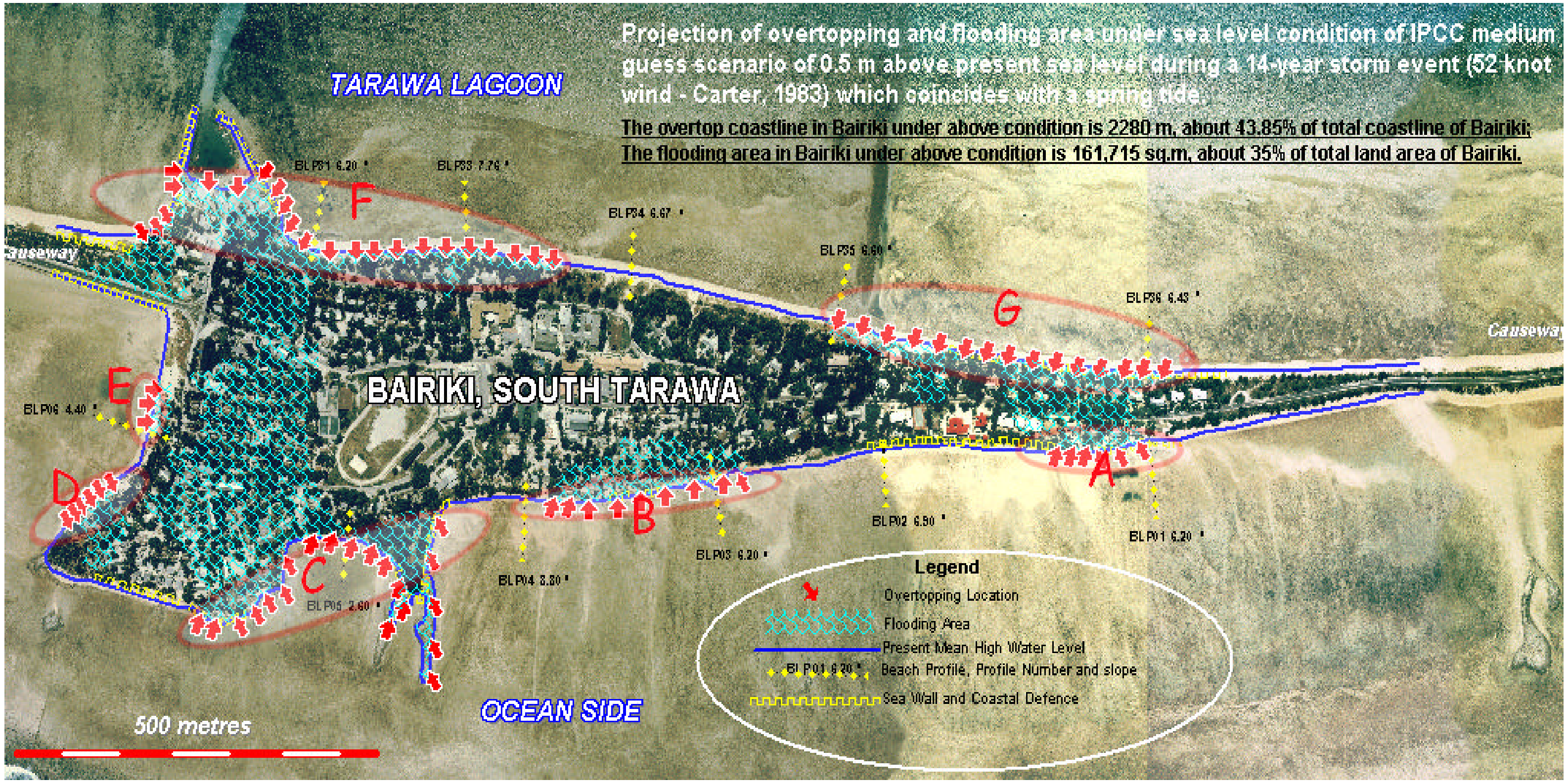

Figure 9. Projection of overtopping and flooding associated with a 0.5-m rise in sea level in Bairiki during a 14-year storm event (5-knot wind – Carter, 1983) which coincides with a spring tide.

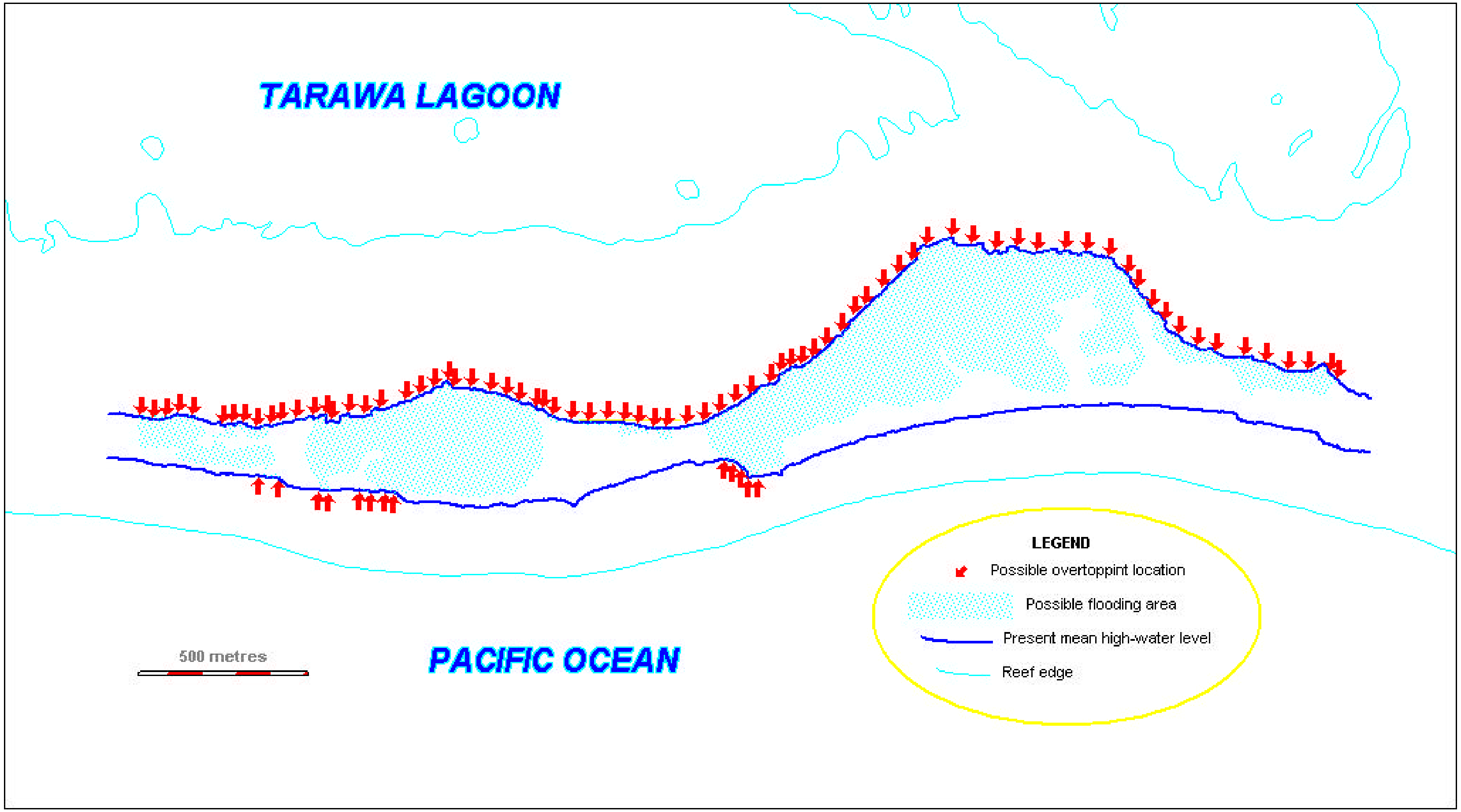

Figure 10. Projection of overtopping and flooding associated with a 0.5 m rise in sea level in Bikenibeu during a 14-year storm event (52-knot wind – Carter, 1983) which coincides with a spring tide.

Figure 11. Projection of spring tide still waterline after a 0.95-m sea-level rise at Bairiki.

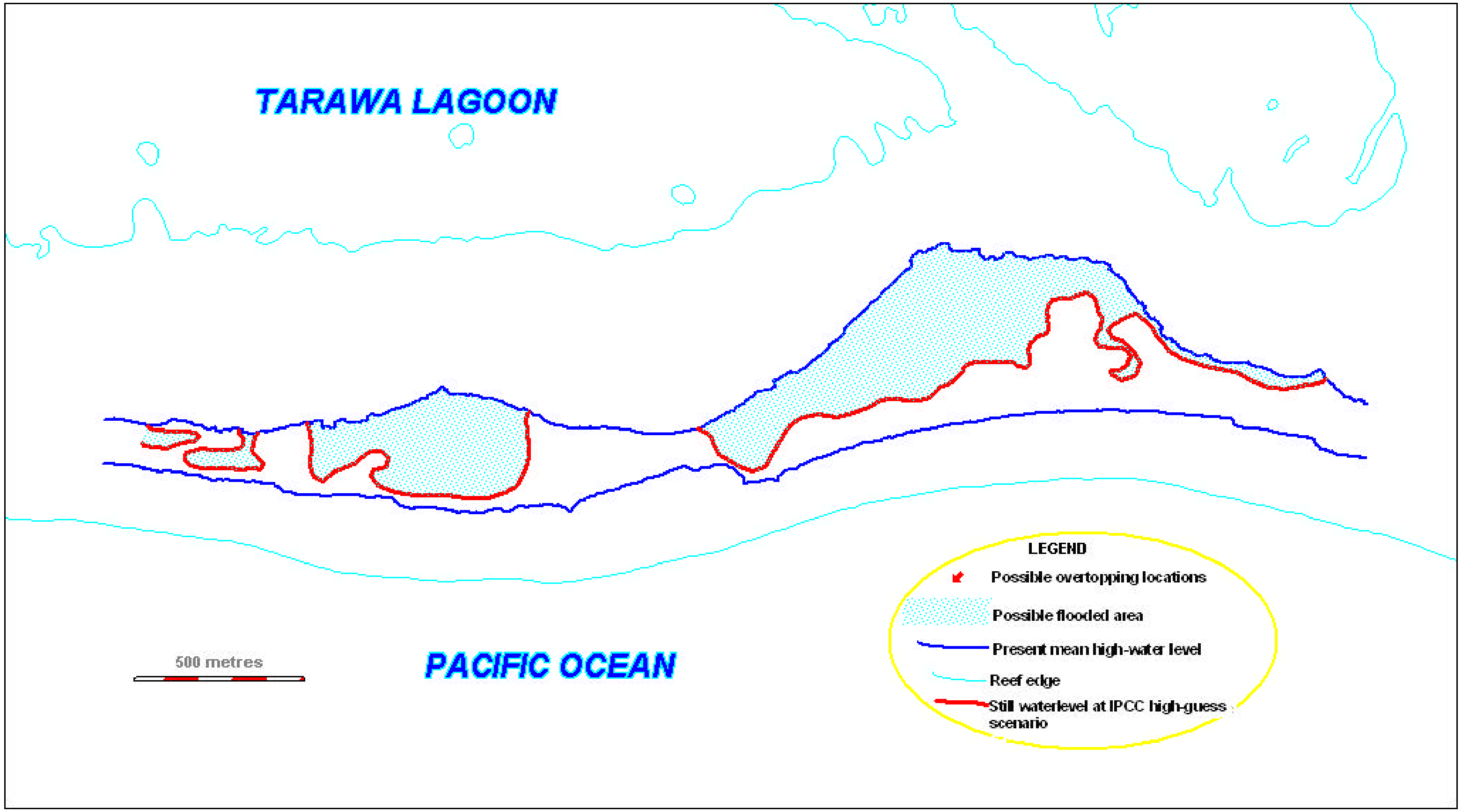

Figure 12. Projection of spring tide still waterline after a 0.95-m sea-level rise at Bikenibeu.

2. Bikenibeu assessment

Figure 12 shows the effect of a spring tide after a 0.95-m rise in sea level at Bikenibeu. Under this condition (the meteorological effects are not included), The still water line could propagate from the lagoon side and a large area of Bikenibeu will be flooded. A 14-year storm, 52-knot wind, will also cause wave setup and overwash of the whole islet.

Tables 2 and 3 present summaries of overtopping and flooding, under sea-level rise of 0.3 m, 0.5 m and 0.95 m under a 14-year storm event (a 52-knot wind), coinciding with a spring high tide. The lagoon shorelines in both Bairiki and Bikenibeu are more vulnerable to ASLR than the ocean shoreline. In Bairiki, when the sea level rises to 0.3 m above present mean sea level, the overtopped shoreline will be 5.5%, while 17% of the shoreline at the ocean side will be under threat. When the sea level rises to 0.5 m above present mean sea level, the overtopped shoreline at the lagoon side increases to 58%, more than ten times the figure for a 0.3-m rise in sea level. Under same condition, the overtopped shoreline at ocean side doubles from 17% to 35% when sea level rises from 0.3 m to 0.5 m.

Table 2: Bairiki summary.

BAIRIKI SUMMARY		**Sea-level rise**		
		IPCC 0.3 m	***IPCC 0.5 m***	***IPCC 0.95 m***
Length of overtopped shoreline	Whole islet	640 m	2280 m	5200 m
	Ocean side	528 m	1093 m	3160 m
	Lagoon side	112 m	1187 m	2040 m
Percentage of Overtopped shoreline	Whole islet	12.31%	43.85%	100%
	Ocean side	17%	35%	100%
	Lagoon side	5.5%	58%	100%
Flooded area		80 600 m^2	161 715 m^2	464 700 m^2
Percentage of land area flooded		17%	35%	100%

Table 3: Bikenibeu summary.

BIKENIBEU SUMMARY		**Sea-level rise**		
		IPCC 0.3m	***IPCC 0.5 m***	***IPCC 0.95 m***
Length of Overtopped shoreline	Whole islet	3098 m	3448 m	8377 m
	Ocean side	86 m	350 m	3957 m
	Lagoon side	3012 m	3948 m	4380 m
Percentage of Overtopped shoreline	Whole islet	37%	51%	100%
	Ocean side	2.2%	8.8%	100%
	Lagoon side	69%	90%	100%
Flooded area		54 140 m^2	72 050 m^2	≅101 600 m^2
Percentage of land area flooded		53%	71%	≅ 100%

In Bikenibeu, the average elevation of shoreline crest and coastal-defense structures at the ocean side is about 3.25 m above present mean sea level, while the shoreline crest and coastal -defense structures at the lagoon side are only 2.38 m in average above present mean sea level. As a result, the ocean side is more stable than the lagoon side under accelerated sea-level rise.

When sea level rises to 0.3 m above the present sea-level, only 2.2% of the ocean shoreline will be subject to overtopping; but at the lagoon side, 69% of shoreline will be overtopped. When sea level rises to 0.5 m, the overtopped shoreline at the ocean side increases to 8.8%, the overtopped shoreline at the lagoon side will reach 90%. It is noteworthy that only a narrow strip of land at the ocean side of Bikenibeu is stable, because of its high elevation, and therefore, most of the land area will be vulnerable to sea-level rise and undergo inundation (Figure 8 and Figure 10). The area of Bikenibeu flooded will be 53% at 0.3-m rising sea level and 71% at 0.5-m sea-level rise (Table 3).

6. DISCUSSIONS

6.1 Response of Shoreline to ASLR

It is agreed that, in order to evaluate the effects of sea-level rise on shoreline and coast, we need to examine (1) how the shoreline and coast have responded to accelerated sea-level rise in the past and (2) how the shoreline and coast will respond in the future. The implications of historical sea-level rise on Pacific island countries are essentially unknown (Gillie, 1993); although quite a few projects have been done on shoreline change, including coastal monitoring in South Tarawa, Kiribati, in recent years. But these projects are still unable to answer the questions, because they are absolutely incomparable as a result of different dominant factors and different environment. ASLR will increase change in hydrodynamic and geomorphologic environments, aggravated by other factors caused by ASLR itself, such as increase in wave strength, variation in sand supply by coral reefs, barrier build up by high sea level, as well as humans' behavior and their response to ASLR, etc.

The Bruun Rule is the approach recommended by IPCC to address how the shoreline and coast will respond to ASLR in the future. But it is clear that the Bruun Rule of erosional response related to adjustment of an equilibrium shoreface profile (recommended for use in this guideline) has very limited validity. It is not generally applicable to supply-limited carbonate coasts, where landward losses may be expected (Thom and Roy, 1988), new sediment can be produced on the reef (Hopley and Kinsey, 1988) and where there is a non-erodible underlying reef pavement which limits profile adjustment (Forbes and Solomon, 1997).

Although there are many uncertain factors in assessing coastal and shoreline responses to ASLR, it still can be imaging that more severe erosion will occur as a result of increasing water depth and wave energies caused by rising sea level.

At the present sea level, the direction of sediment movement on North and South Tarawa is to a large extent dependent on the orientation of these two arms of the atoll rim with respect to the Easterly Trade Winds and the ENSO-related Westerly wind pattern (Shorten et al. 1990). During a long ENSO period, the shoreline of South Tarawa, built up by the dynamic system dominated by easterly trade winds between ENSO periods, can be reshaped inversely. Analysis of beach profiles and coastal dynamics shows that there is significant sand movement and transport around the islands, causing erosion in some places and accretion in others under different meteorological conditions. Beach measurement during this study has shown that a large volume of sand has built up at the ocean side of the Tungaru Central Hospital, where a study in 1995 showed a high rate of erosion during the unusual and persistent El Nino condition from 1991 to 1995. Beach recession occurring along the lagoon shore just east of the Bairiki jetty also shows the same evidence. At this location, three houses belonging to the Kiribati Housing Corporation have been demolished and another has been abandoned because of severe backcutting on the beach. This site has been threatened since the early 1980s (Howorth, 1983), when severe erosion during the 1982-1983 El Nino was followed (after panic construction of a gabion seawall) by rebuilding of the beach, a pattern repeated by the 1987 El Nno event (Harper, 1989b). Another section of the beach, 500 m to the east showed a reverse pattern of change, implying temporary longshore exchange of sediment (Shorten, Forbes and Etuati 1996). El Nino has complicated the studies attempting to predict the response of shoreline and coast to ASLR in Tarawa.

Many aspects of coastal vulnerability can be found around South Tarawa. Figure 13 shows the scouring on the top of the breakwater of Bairiki jetty by overtop seawater. A benchmark established here indicated the height of this breakwater to be 3.749m in Cox datum, 2.646 m above the present mean sea level. This figure is approximately equal to 2.64 m, the average height of beach crest and coastal defense in Bairiki, and much higher than 2.38 m, the average height of beach crest and coastal defense at the lagoon side of Bikenibeu. This implies that the study areas of this project are vulnerable even at present sea level. Balinga Seneviratne reported that, in the second week of February in 2001, a high tide drowned many causeways linking villages in Tarawa, forcing cars, buses and trucks to drive through seawater (Source from Climate newswire: www.sidnet.org, 16 February 2001)

Figure 13. Scouring at the top of breakwater of Bairiki jetty by overtopping seawater. View to the Northwest.

An attempt was made to analyze coastal erosion in Bairiki by using the present 11 bi-annual beach-monitoring profiles around Bairiki (Figure 7 shows the locations of these profiles). However because of uncertain datum for these beach profiles, and loss of some control points (e.g. houses linked with control point were washed away by high sea), this was impossible. Data plotted on a GIS map show that different datum systems have been used during the project period since 1982. It becomes impossible to make a quantitative assessment of sand loss and accretion around Bairiki. In Bikenibeu, ten beach profiles, which were established by SOPAC in 1995, were resurveyed during this study. It indicates that all beach profiles at the lagoon side of Bikenibeu are slightly accretional, while the beach profiles at the east ocean side show erosion and those at the west ocean side show accretion.

6.2 Coral Heath and Reef Response

Coral reefs are one of the most important natural resources on atoll islands. It is a natural defense to the coast by reducing wave energy, and supplies sediment the beach. Obviously, a healthy coral reef is vital to the stability of shoreline and coastal infrastructure.

It is still unclear how coral reefs respond to sea-level rise. According to IPCC Special Report on The Regional Impacts of Climate Change, An Assessment of Vulnerability, projected rates of sea-level rise per se are not expected to have widespread adverse effects on coral reefs. Indeed, some researchers argue that a rising sea level actually may be beneficial because the new conditions would be favorable for inducing vertical growth; in contrast, reef growth has been largely horizontal in the recent past, as a consequence of lower sea levels (Wilkinson and Buddemeier, 1994, cited by Robert 2000). Edwards (1995) further suggested that even slowly accreting reef flats should be able to cope with projected sea-level rise, in the absence of other negative forces.

Although sea-level rise itself may not exert direct adverse effect on coral reefs, several processes caused and aggravated by sea-level rise will be harmful to health of coral reefs.
1. Coastal erosion facilitated and accelerated by sea-level rise will cause sediment suspension, increasing the turbidity of the water and decreasing the strength of light in water, which are most important factors given the association of coral with algae;
2. Inappropriate human response to sea-level rise;
3. Adverse effect to coral reef caused by special events, such as ENSO phenomenon and cyclones, and aggravated by sea-level rise,

6.3 Humans and Human Activities

The last population census for Kiribati was in 1995, the population of the country as counted at last census was 77 658. According to the statistics provided by United Nations Economic and Social Commission for Asia and the Pacific (ESCAP) and United Nations Population Informative Network, UN Population Fund (UNPF), the population of Republic of Kiribati was 83000 in Year 2000. Table 1 is population projection for Kiribati 1985 to 2000. The figures show that the growth rate of Kiribati population was very unstable. In the late 1980s, the annual growth rate was 2.45% and then dropped to 1.45% in first half of 1990s; and had a negative increase from 1997 to 1999 after reaching a high of 4.24% in 1995-1996 and was recovered to a 1.22 % in 1999 to 2000.

Table 4. Population projection for Kiribati

Year	1985	1990	1995	1996	1997	1998	1999	2000
Population (51000)	64.1*	72.3*	77.7*	81.0*	83.4*	---	82.0**	83.0**
Growth rate	12.8%	6.9%	4.24%	2.96%	-1.62%		1.22%	
Annual growth rate	2.45%	1.45%	4.24%	2.90%	-0.85	-0.85	1.22	

* Data source: Statistics Division, United Nations Economic and Social Commission for Asia and the Pacific (ESCAP)
** Date source: Statistics Division, UN Population Informative Network, UN Population Fund

The South Tarawa is the most highly populated area in Kiribati, with a population of 32356 in 1995, which accounted for approximately 35% of the total Kiribati population. As a result of unavailability of new population data on Tarawa, the real picture of present Tarawa population growth is unclear. According to the Oceania Population 2000 produced by the Demography/Population Program of Secretariat of the Pacific Community (SPC), Kiribati's population will growth at a rate of 2.5% and it will only take 28 years to double. Based on the SPC result, in the years 2030, 2050 and 2100, the population of Kiribati will reach 195 005, 31 7450 and 108 8400 respectively and the population densities projected for these three years are 240 people/km^2, 392 people/km^2 and 1344 people/km^2. For Tarawa, residents will amount to 68 251 in Year 2030, 111 107 in Year 2050 and 380 940 in Year 2100. At present, the average household size (AHZ) in Tarawa is 7 people, if the same AHZ can be kept, the demand for new houses will be 5500 units till Year 2030, 11 555 till Year 2150 and 50 842 units till Year 2100. And under same house density, one house would need to hold on average 15 people by Year 2030, 25 people by Year 2050 and 84 people by Year 2100.

The above statistics indicate that Tarawa will be under very serious population pressure, exacerbated by the very limited land resources, amounting to only 1571 ha (Howorth 1982a). Because of the narrow island widths and overall land scarcity, even small changes in shoreline position can be significant (Forbes, 1995). Therefore, overtopping and flooding caused by sea-level rise will produce a disastrous consequence by eroding and flooding valuable and scarce land and contaminating ground water with seawater. To reduce further harm to the system, people living on the coast need to have a proper manner to use it and an appropriate method to respond to these natural changes.

Coastal defenses and shoreline structures was inspected during this study. Around Bairiki and Bikenibeu, there are several kinds of coastal structure: causeway (Figure 14); breakwater (Figure 13), groyne (Figure 15), sea wall (Figure 16), and gabion (Figure 17). Most of these structure are inappropriate and failed (Figure 14, Figure 16 and Figure 17), and cause erosion and increase adverse effects on the coastal ecosystem. For example, the Nippon Causeway has changed the sediment movement patterns and has caused erosion on the seaward side of Betio. Forbes reported that tidal exchange of water between the ocean and lagoon has been reduced by 95% to 97% or more. Lagoon flushing relies on a small channel which is silted up frequently by the longshore drift on both the oceanic and lagoon sides, and needs to be dredged periodically by Public Works Department (Figure 18).

Aggregate mining is still one of the major causes contributing to coastal erosion in South Tarawa as a result of increasing demand for construction material. In 1992–1993, in the South Tarawa lagoon, including the islands of Betio, Bairiki, Bikemaan, Bikenibeu, and Buota, 40 000-50 000 m^3 of sand was extracted from back-reef areas (Maharaj, 2000). Reduction and control of sand and aggregate mining is critical to avoid further shoreline erosion and recession. Smith and Biribo in 1995 carried out a project to delineate a mining area in Tarawa for further needs of construction material; the suggestion and conclusion from this project shall be considered. Figure 19 shows aggregate mining on Bikenibeu beach.

Increasing anthropological stress such as solid-waste disposal (including sewage) (Figure 20) is a major contributor to reef and lagoon degradation, causing death of corals and a reduction of natural coastline protection provided by reef systems. Eagar provided evidence that the number of Ostracode increases away from the area of dense population, and he pointed out that increased pollution (increase in levels of faecal coliform bacteria) by human activity, especially inshore (Biosystems, 1995); can be accounted for by an increase in population and a decrease in water replenishment from the open ocean (Eagar, 1997). Figure 19 shows waste disposal on Bairiki beach. This increases the vulnerability of coastal communities and infrastructure in the future. Control of waste disposal and pollution is needed for Tarawa.

Figure 14. Nippon Causeway linking Bairiki and Betio. View to the West.

Figure 15. A failed groyne at Bairiki beach. View to the West.

Figure 16. The scoured seawall at Bairiki Looking Northwest.

Figure 17. A failed gabion system on Bairiki beach. View to the East.

Figure 18. Periodic dredging by Public Works Department in the lagoon-side channel of Nippon Causeway. View to the North.

Figure 19. Aggregate mining on Bikenibeu beach. Looking West.

Figure 20. Solid-waste disposal on Bairiki beach. View to the South.

6.4 Tectonics

Subsidence by tectonic movement is another contributor to relative sea-level rise. Long-term rates of subsidence for the Gilbert Group can be estimated from other mid-ocean atolls. Subsidence rates range between 0.03 and 0.06 m/ka for Bikini, Eniwetak and Midway (Paulay and McEdward, 1990). In the central Pacific during the Cainozoic the average rate of sinking had been about 0.02 m/ka, with a possible increase to about twice this value in the last five million years (Schofield, 1977). Therefore, the rate of subsidence in the Gilbert Group is probably in the order of 0.05 m/ka or 0.05 mm/a. By comparison, the rate of global sea-level rise is estimated to be 1–2 mm/a (Wyrtki 1990), 20 times at least the rate of subsidence. On this basis the islands of the Gilbert Group can be consider as relatively stable. Therefore, the data analysis of this report ignores the contribution to the relative sea-level rise from subsidence caused by tectonic movement.

6.5 Groundwater

Groundwater resources are the most vulnerable to the projected sea-level rise. Rising sea level can lead to a reduction of island width with a consequent reduction in extent and thickness of the freshwater lends. Flooding and inundation by seawater may lead to salination. Furthermore, reduction of island land area will also cause a decrease in catchment area for rainfall, and affect the hydrological cycle by decreasing groundwaer recharge.

7. CONCLUSIONS AND RECOMMENDATIONS

7.1 Conclusions

Based on the study and analyses, the following conclusions can be made:

1. Elevations of the beach crest and coastal defense structures show that the average heights above 1974 - 1976 Mean Sea Level are as follows:

Bairiki	2.64 m
Bikenibeu	3.25 m at ocean side
	2.38 m at lagoon side

2. Computing results of overtopping coastline and flooding area under sea-level rises of three IPCC guess scenarios of 0.3 m, 0.5 m and 0.95 m above present sea level during a 14-year storm event (52-knot wind - Carter, 1983) which coincides with a spring tide for Bairiki and Bikenibeu are as following.

2a. In Bairiki, When sea level rises 0.3 m above present mean sea level during a 14-year storm event which coincides with a spring tide, 17% of the ocean-side shoreline will be overtopped, while 5.5% of the lagoon-side shoreline is undergoing overtopping. The total overtopped shoreline in Bairiki will be 640 m, accounting for 12.31% of total shoreline of the islet; the flooded land area in Bairiki is 80600 sq. m, 17% of total Bairiki land area. When the sea level continues to rise, vulnerability at the lagoon side can increase. The overtopped shoreline at the lagoon side will quickly increase to 1187 m at IPCC 0.5-m guess scenario, from 5.5% at 0.3 m rising to 58%, more faster than what is happening at the ocean side. Under the IPCC high-guess scenario, the whole islet will be over washed.

2b. As a result of high elevations at the ocean side in Bikenibeu, the overtopping mainly occurs at the lagoon side of the islet. At the 0.3-m IPCC low-guess scenario during a 14-year storm event which coincides with a spring tide, 69% of the lagoon side-shoreline will undergo overtopping, while almost all of the ocean-side shoreline (97%) still keeps stable; the total overtopped shoreline is 3098 m, 37% of total Bikenibeu shoreline, and the flooded land area will be 54140 sq.m, accounting for 53% of total land area. With sea-level rise 0.5 m under the same meteorological condition, the overtopping shoreline increases to 51% at the lagoon side and 8.8% at the ocean side; and the flooded area reach 73050 sq.m, 71% of total land area. At the IPCC high guess scenario, almost the whole islet will be over washed.

3. It is still not known how the low-lying atoll coastal system will react to ASLR. At present sea level, the direction of sediment movement on North and South Tarawa is, to a large extent, dependent on the orientation of these two arms of the atoll rim with respect to the easterly trade winds and the ENSO-related westerly wind pattern. During a long ENSO period, the shoreline of South Tarawa, built up by the dynamic system dominated by easterly trade winds between ENSO periods, can be reshaped inversely. Analysis of beach profiles and dynamics shows that there is significant sand movement and transport around the island, causing erosion in some places and accretion in others under different meteorological conditions. Sand accretion at the beach near Tungaru Central Hospital was linked to unusual and persistent El Nĩno conditions, in 1991-1995. This complicates the studies attempting to predict the change of the coastal system to ASLR in the future. Undoubtedly, ASLR will increase water depth, increase wave strength and accelerate coastal erosion.

4. The response of coral reefs to ASLR is another unclear factor. According to IPCC Special Report on "The Regional Impacts of Climate Change, An Assessment of Vulnerability", current projected rates of sea-level rise per se are not expected to have widespread adverse effects on coral reefs. But indirectly, other adverse effects aggravated by ASLR will damage the health of coral reefs, such as coastal erosion and inappropriate human response to ASLR, as well as special events, like the ENSO phenomenon and cyclones.

5. Increasing anthropic stress caused by waste disposal (including sewage) is one of the major contributors to reef and lagoon degradation, causing death of coral species and a reduction of natural coastline protection provided by reef systems. This increases the vulnerability of coastal communities and infrastructure in the future.

7.2 Recommendation

In summary, there is no retreat to Tarawa when sea level rises, a small low-lying atoll with the elevation rarely higher than 4 m above mean sea level. In struggling for existence and pursuing a better life, it is wise to avoid overexploiting the natural resources. The equilibrium between economic development and environmental protection should be kept in a sustainable manner. Vulnerability can be minimized if consideration is given to:

, *Public awareness of preservation of reef environments;*
, *Waste disposal and pollution control;*
, *Establishment of building setback strategy;*
, *Reduction and control of sand and aggregate mining;*
, *Code of practice for coastal-structure design and engineering.*

As Tarawa geographically and ecologically is an ideal place for present and future monitoring of environmental change under global climate change, it has became one of the indicative coral atolls in case study in the South Pacific since global climate change came to attention. A continuous study of vulnerability assessment could be beneficial to both Kiribati people and scientific communities. At present, more and more scientific data on land use, population, vegetation coverage, coral reef, soil, water, land elevation, coastal mapping, natural dynamic of shoreline, as well as new economic data, are available for Kiribati. Availability of this information and new technological methodologies and tools in vulnerability assessment could fully facilitate and equip a new vulnerability study for the whole of Tarawa and the whole nation. This study and the previous study for Betio shall be combined into the vulnerability assessment for the whole of Tarawa. On the project-debriefing meeting at the Ministry of Environment and Social

Development, the Kiribati Government put a request to extend the coverage of this study to the rest of South Tarawa. However, a recommendation from this study is that it is necessary and proper to consider Tarawa as a whole system to assess its vulnerability to climate change, not only to ASLR.

For long-term monitoring of shoreline stability, the present bi-annual beach-profile monitoring system should be extended to cover larger area around Tarawa, especially at the more dynamic areas. All the measurement data should be calibrated to the same datum system.

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