Sustain Sci (2008) 3:171–180
DOI 10.1007/s11625-008-0052-2

ORIGINAL ARTICLE

Vulnerability assessment of sea-level rise in Viti Levu, Fiji Islands

Gabriel Gravelle · Nobuo Mimura

Received: 14 February 2008 / Accepted: 2 May 2008 / Published online: 11 June 2008

Abstract Fiji is expected to come under increasing pressure and risk from various threats resulting from climate change and sea-level rise (SLR). Fiji consists of 332 islands and thus has a predominant and large coastline. Viti Levu is the largest and most important of the islands, harboring Fiji's capital city and most of the major towns concentrated around its coast. The objectives of this study were to evaluate the extent of possible sea-level rise using GIS, and to identify high-risk locations. Potential sea level rise was shown graphically as an output to determine where inundation or flooding would take place. This analysis allowed important areas facing risk to be highlighted for future action. Flooding/inundation can be classified into two kinds: 'permanent inundation', which is the result of sea-level rise with tide; and 'temporary flooding', also including occasional storm surge events. The inundated area was displayed under different projections and quantified. The results produced output maps showing the distribution of inundation/flooding around the island of Viti Levu as well as the extent of flooding. Six scenarios for sea-level rise were used (0.09, 0.18, 0.48, 0.50, 0.59, 0.88 m). Six scenarios for storm surge were used with return intervals of 1, 2, 5, 10, 25, 50 years. High risk and priority locations are identified as Fiji's capital Suva, the major tourist center and arrival port of Nadi, and Fiji's second city Lautoka. Future action, adaptation and response strategies in these identified locations must occur to reduce risk from climate change.

G. Gravelle (✉) · N. Mimura
Department of Urban and Civil Engineering, Ibaraki University, Hitachi, Ibaraki 316-8511, Japan
e-mail: gabriel_gravelle@yahoo.com

N. Mimura
e-mail: mimura@mx.ibaraki.ac.jp

Keywords Climate change Fiji · GIS · Risk · Sea-level rise · Vulnerability

Introduction

Fiji is an island country/developing state in the South Pacific. The coastal region's of Fiji play a very large and central role geographically, with major towns and cities such as Lautoka, Nadi, Ba and Suva connected by two main highways encircling the coast of the main island, Viti Levu. The population of Fiji was 840,200 as of 31 December, 2004. Viti Levu, which is the focus of this study, harbors over 70% of Fiji's population as well the largest urban centers along its coast, thus making it the focal point of Fiji (Fig. 1). The island of Viti Levu accounts for 10,429 km^2. The urban population and city boundaries continue to increase yearly.

In Fiji, the effect of storm surges, which may experience changes in frequency and intensity as a direct result of climate change and accelerated sea-level rise (SLR), will have economic repercussions in relation to Fiji's tourism industry—on which Fiji is heavily dependent. The rise in global mean sea level will be one of the most significant effects, particularly in a country like Fiji, with its reliance on beach tourism. In addition, many villages in the lower outer islands will also be vulnerable to rising sea levels and erosion. Changes in coastline morphology and sediment processes may also occur (Maharaj 2002), and intensified coastal erosion and flooding are continuous problems due to the severity and frequency of tropical cyclones and related storm surges (Mimura and Harasawa 2000).

Increases in temperature due to climate change can also impact coral health. Viti Levu's many fringing and barrier

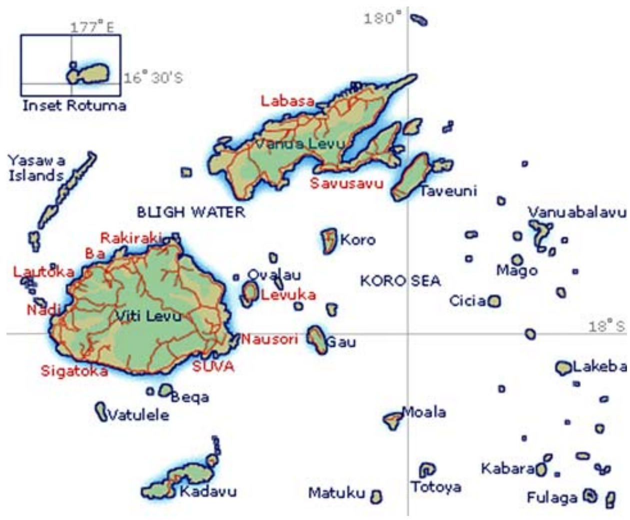

Fig. 1 Islands of Fiji including Viti Levu. Source: Fiji Government Portal, http://www.fiji.gov.fj/publish/fiji_map.shtml (cited 20 January 2008)

reefs provide coastal protection by dissipating energy from storm surges. Coral bleaching in response to increasingly high water temperatures, as well as the indiscriminate removal of mangroves along much of Viti Levu's coast, are major concerns. Indiscriminate removal has also occurred due to the increase in squatter settlements such as those near Vatuwaqa or the low income Nadawa housing complex area near the main capital of Suva. Protection measures such as the Sustainable Development Bill are rarely, if ever, enforced. This exacerbates damage from coastal erosion due to rising sea levels. Increasing urban growth as well as pressure and movement from the rural areas towards the city in the form of squatter settlements leave the poorest demographic group the most vulnerable to the effects of climate change. Also in rural communities, unsustainable actions such as coral mining, coastal resource exploitation and deforestation resulting in further erosion, have a significant impact on sustainability. Sustainable practices are often come second to short-term economic gain, even though the former are essential for Fiji's future economic stability. This is where the government needs to actively guide economic policies and businesses, and to implement sustainable policies in all of its present and future projects.

The aim of this research was to assess the extent of accelerated sea-level rise (SLR) and storm surges on the main island of Viti Levu in Fiji based on different possible scenarios and projections. This is the first time such an analysis has been carried out using GIS for the entire island of Viti Levu due to higher resolution grid data becoming available.

The extent of inundation and flooding were evaluated using different IPCC projections (IPCC 2001, 2007) for accelerated SLR, in addition to taking account of the tide and the increasing return intervals of possible storm surge levels. Both IPCC (2001, 2007) projections were used for comparison purposes and because of the potential for underestimation of positive feedback. Various maps of the resultant flooding were produced. These maps were then used to identify high-risk locations and detail probable impacts and important economic sectors that could be impacted.

Methods

A digital elevation model (DEM) for the entire island of Viti Levu Fiji was used for analysis in this study. Each 50 m × 50 m grid cell contains an elevation value. Errors in projection from the original text file MapInfo Fiji Map Grid were corrected to the new projection before the data could be used and displayed. This data was then correctly projected using the WGS 84 UTM projection under ArcGIS software as shown in Fig. 2. Elevation resolution was found to be very good except for two locations in the center of Viti Levu where there were no data values. These two locations correspond to the highest points on Viti Levu: Mount Tomanivi and the Nandrau Plateau. The no data elevation values for these two locations did not affect the analysis because they are at elevations above 1,000 m in cloud forest and thus are immune to the effect of lower coastal SLRs.

The concept of this analysis was a GIS overlay of the DEM or land elevation layer and a specific inundation design water level (DWL) layer comprised of created tidal, SLR projections and storm surge layers that could inundate this coastal elevation. Where the analysis showed DEM elevation to be less than or equal to the chosen DWL, flooding or inundation was identified.

DWL components

Design water level components represent a layer of possible flooding or inundation around the coastline based on the scenario of SLR or storm surge. The DWL layer consisted of, and was created from, three components:

- The maximum spring tidal range around the coastline.
- The effect of SLR (IPCC 2001, 2007 projections).
- Storm surge estimates based on residual water levels before and after a storm.

The DWL consists of SLR and a storm surge (SS) return interval added to the astronomical spring tide/mean high water springs (MHWS) difference, which is usually used as a worst case scenario. This is shown as:

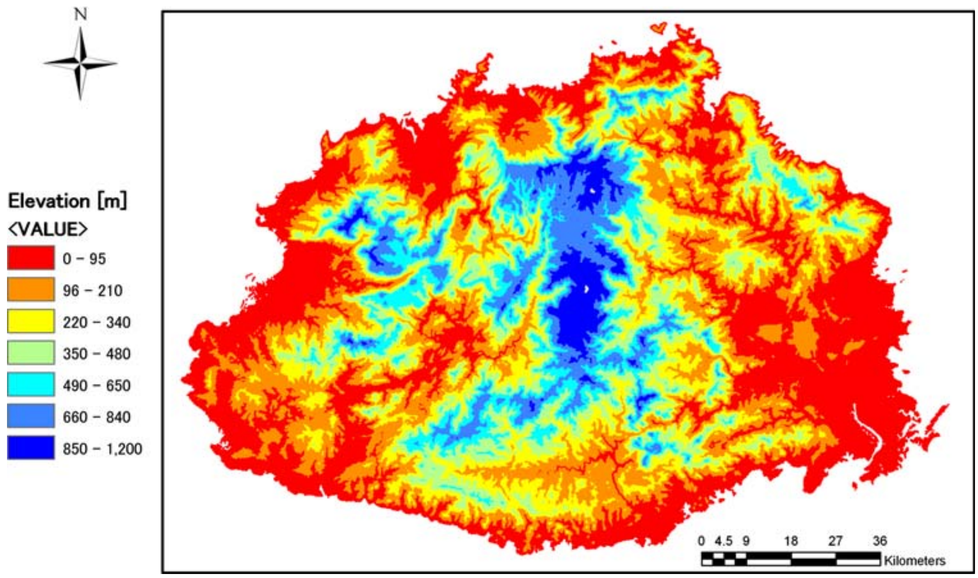

Fig. 2 Fiji digital elevation model (DEM)—elevation in meters

Table 1 Tide gauge locations and tidal difference [mean high water springs (MHWS)−mean sea level (MSL)]

Name	Tidal difference (m)
Suva Harbour	0.64
Tailevu	0.68
Lautoka	0.75
Vuda Point	0.73
Vatia Wharf	0.76
Manava cay	0.75
Ellington Wharf	0.73
Nanukuloa	0.60
Naigani	0.68
Rukua	0.56
Leleuvia Island	0.7

$$\mathrm{DWL} = \mathrm{SLR} + (\mathrm{MHWS} - \mathrm{MSL}) + \mathrm{SS}. \quad (1)$$

DWL tidal component

Fiji's tides are semi-diurnal. Often, the MHWS values are used in vulnerability analysis studies as a measure of maximum possible risk during tides. This represents: "the average of the levels of each pair of successive high waters (approximately every 14 days), when the range of the tide is greatest" (The Hydrographic Office, Fiji Islands Maritime Safety Administration 2004). Data for 11 tide gauge locations for Fiji (Table 1) were used to calculate the tidal difference between the MHWS and the mean sea level. This tidal difference (Z) was then interpolated using an inverse distance weighting to other points around the coastline for which tide gauge data do not exist.

The final tide layer component was created using an inverse distance weighted (IDW) technique in ArcGIS. This provided the coastal values for tide around the coastline of Viti Levu (Fig. 3).

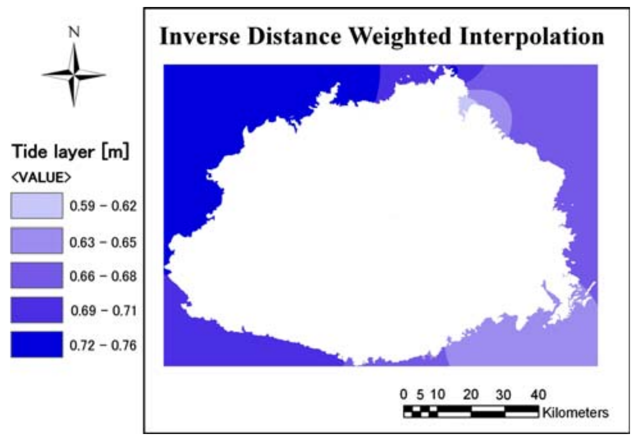

Fig. 3 The coastal tidal layer surrounding Viti Levu

DWL SLR scenario component

The second component added to the DWL layer was the SLR projection values. The three projections used for SLR came from the IPCC Third (IPCC 2001) and Fourth Assessment Reports (IPCC 2007). These are, respectively, a lower limit of 0.09 m, a median estimate of 0.50 m, and an upper limit of 0.88 m by 2100 for IPCC 2001 and 0.18, 0.48, and 0.59 m by 2100 for IPCC 2007.

DWL storm surge scenario component

The third component added was a scenario for storm surge height expected for a specific return or time period. These return periods are based on 20 years of tide data and storm

Table 2 Storm surge water level scenarios used

Storm return interval (years)	Surge height (m)
1	0.13
2	0.28
5	0.48
10	0.63
25	0.83
50	0.98

surge residuals from the period of 1975–1995 for the Suva tide gauge, which is at Fiji's reference port with the longest and most reliable record of tidal data (Solomon and Kruger 1996). Using differences between observed and predicted storm surge levels during a surge event and then using the 'Beard statistical method' to produce a regression line, the latter authors were able to calculate storm surge return intervals using a purely statistical process. These surge interval estimates (Table 2) were then used as projections for this study.

DWL layer creation

These three components were combined for the corresponding coastal grid cells of the DEM to form 36 DWL layers for each scenario as shown in Table 3.

Overlay analysis

An overlay was carried out using ArcGIS software. This showed the expected land immersion due to permanent inundation or temporary flooding. By overlaying the DEM layer on top of the different DWL layers created for all scenarios, the extent and specific cells where inundation occurs could be shown as a graphical output in red. If the land coastal elevation in the DEM was less than the DWL grid cell value for a specific scenario (DEM $\leq$ DWL), then inundation or flooding was shown to occur. This was repeated using the different DWL scenarios of storm surge levels and SLR. From this, final map outputs of inundated areas and flooded areas were produced under different combinations of the DWL component scenarios. In addition, high risk or important areas of the map such as cities or towns were examined in further detail.

The road network of GIS vector data shown in Fig. 4 (obtained from SOPAC) was also used to assist in this identification process as well as to provide feature detail when examining towns or important economic centers.

Vulnerable or high-risk areas were identified based on the following criteria: visible flooding extent, proximity to roads or known infrastructure, presence of settlements, villages, towns and cities and land use (developed, agricultural, subsistence).

Table 3 Design water level (DWL) scenarios added to tide

Sea-level rise component (m)	Added surge height component (m)	DWL layer
0.09, 0.18, 0.48, 0.50, 0.59, 0.88	0.13	1, 2, 3, 4, 5, 6
0.09, 0.18, 0.48, 0.50, 0.59, 0.88	0.28	7, 8, 9, 10, 11, 12
0.09, 0.18, 0.48, 0.50, 0.59, 0.88	0.48	13, 14, 15, 16, 17, 18
0.09, 0.18, 0.48, 0.50, 0.59, 0.88	0.63	19, 20, 21, 22, 23, 24
0.09, 0.18, 0.48, 0.50, 0.59, 0.88	0.83	25, 26, 27, 28, 29, 30
0.09, 0.18, 0.48, 0.50, 0.59, 0.88	0.98	31, 32, 33, 34, 35, 36

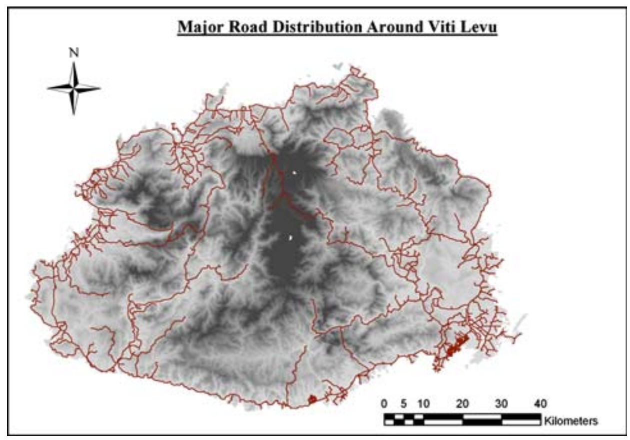

Fig. 4 Vector data road network of Viti Levu

Results

The results of analysis depicting the extent of permanent inundation due to SLR are shown in Fig. 5. Temporary flooding due to the added pressure of storm surge as well as SLR is shown in Figs. 6 and 7. From these output maps the extent of flooding in coastal locations was spatially examined. In addition, high risk or economically important locations were identified based on a set of criteria.

It should be noted that output analysis extents and area for all the different DWLs were created, although the main conclusions were drawn from Figs. 5, 6, and 7.

Identified high-risk areas

The result locations identified as vulnerable based on the extent of flooding are: Suva, Nadi, Lautoka, Navua, Likuri Harbour, Nailaga (near the town of Ba) and Tavua. These

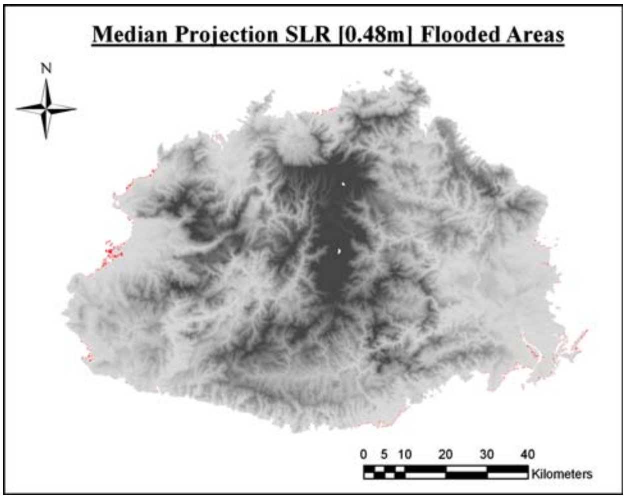

Fig. 5 Viti Levu, 0.48 m sea-level rise (SLR) as the median projection

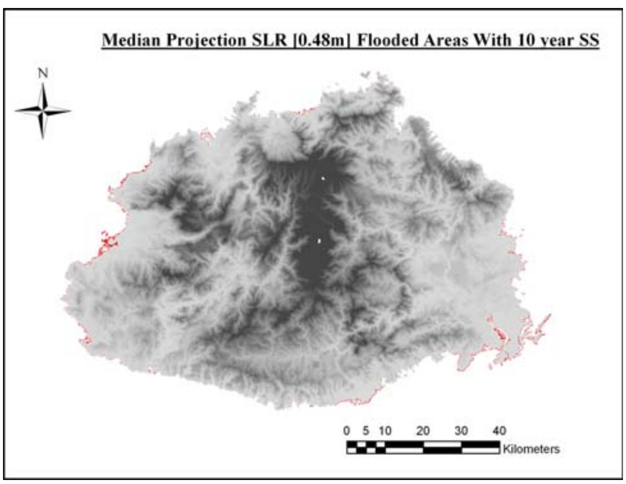

Fig. 6 Viti Levu, 0.48 m SLR with a 10-year storm surge level

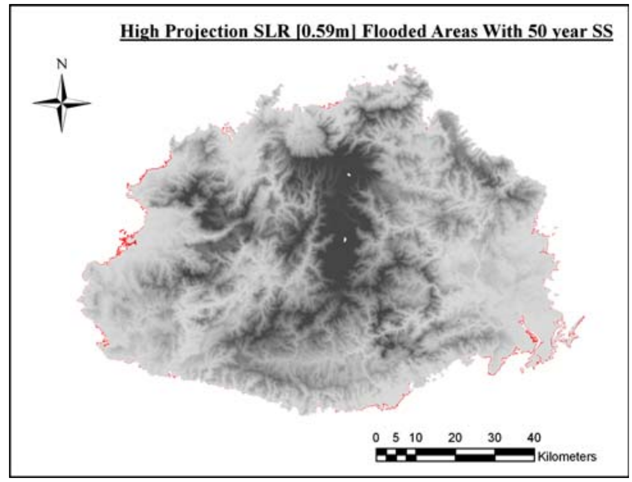

Fig. 7 Viti Levu, SLR (0.59 m) with a 50-year storm surge level

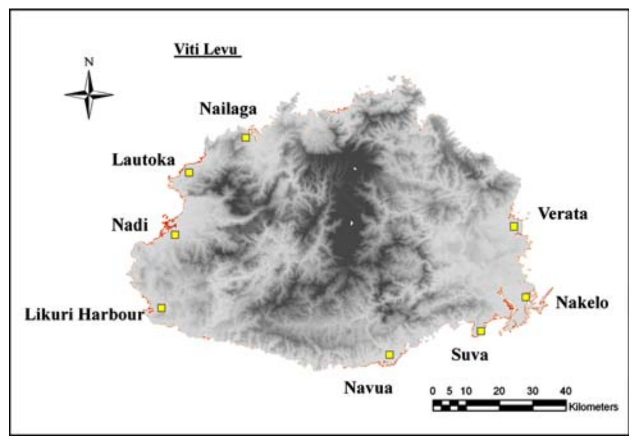

Fig. 8 Identified high-risk locations

identified areas of importance facing a high level of risk are shown in Fig. 8. Additional flooding was observed in the Verata and Nakelo areas.

Figure 9 shows the quantified results of area (km^2) expected to be inundated based on DWL scenarios for both the IPCC (2001, 2007) projections. The trend increases linearly as storm surge events increase in intensity, and, even without SLR, the single effect of storm surges is quite severe. If we include SLR projections for a 0.48 m SLR and 25-year storm surge then the area flooded is over 50 km^2.

Discussion

The Suva peninsula is the site of Fiji's capital and has a high population density of 77,300 in the urban area and

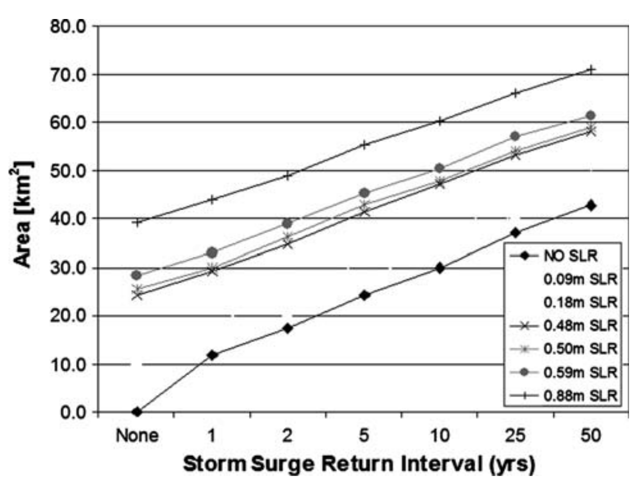

Fig. 9 Area inundated under different scenarios

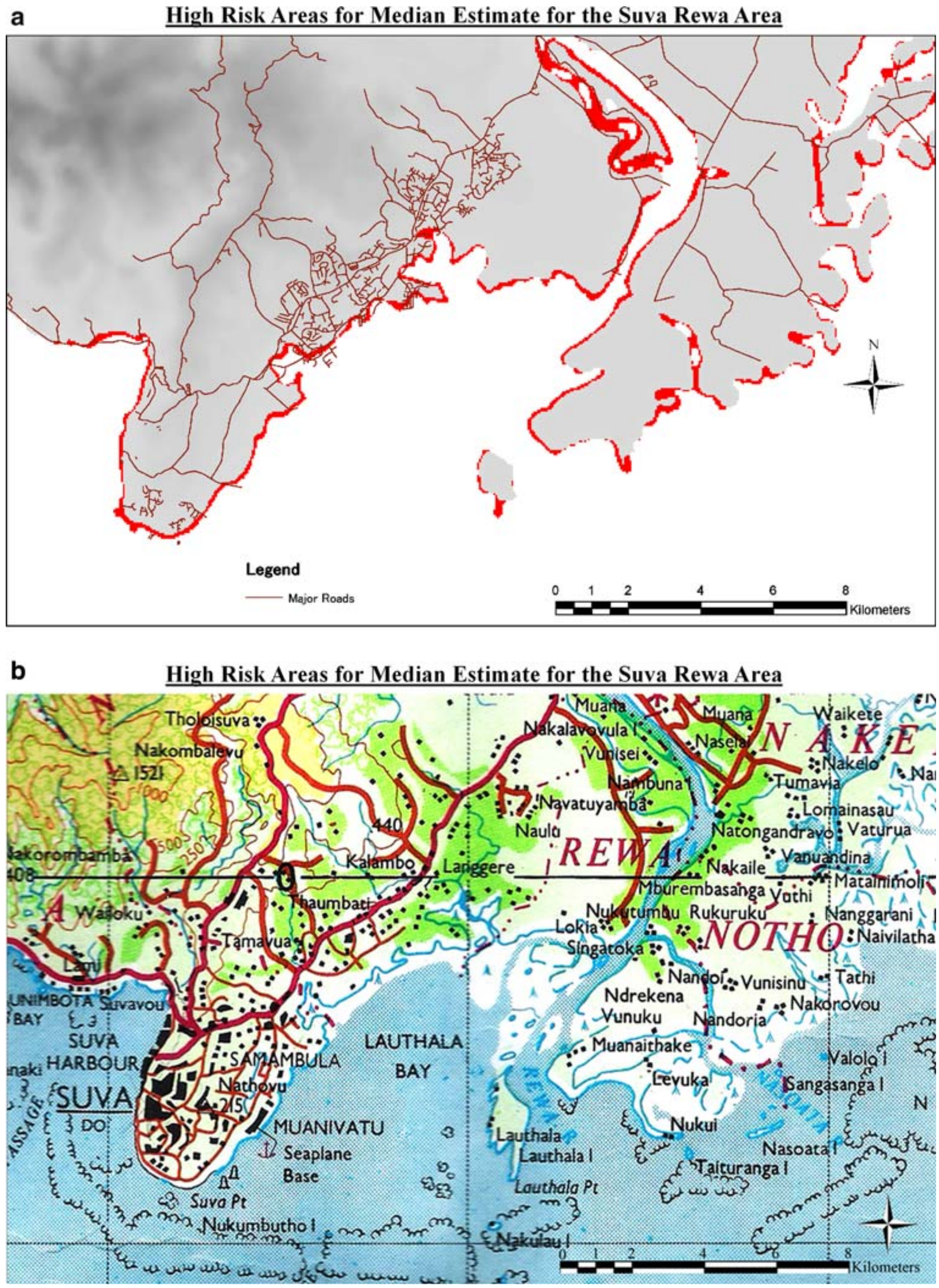

Fig. 10 **a** Flooding detail for Suva, 0.48 m SLR with 10-year storm surge (SS). **b** Detail for Suva, Fiji

about 90,000 in the peri-urban area (Fiji Islands Bureau of Statistics 2005). Suva is the administrative center with a high degree of infrastructure. It has Fiji's largest central business district spread along the peninsula as well as the main port and the Suva campus of the University of the South Pacific. The Parliament and Government Buildings are also located on the peninsula area. Although it is a vulnerable location with possible flooding (Fig. 10a, b) it benefits from being one of the most well-protected in terms of adaptation measures such as sea-walls. In addition, part of the central business district and the industrial area of the city, Walu Bay, is located on reclaimed land close to the sea (Solomon and Kruger 1996). Options for retreat are limited so protection strategies remain the only viable future solution. However, in comparison to other parts of Viti Levu, the likelihood of adaptation action being taken is higher due to its high importance as Fiji's capital. Thus, although the vulnerability of Suva is high, the resilience level and willingness to allocate resources (adaptive capacity) is very good.

The Rewa River, which lies to the east of Suva between Nakelo and Suva, often causes extreme flooding and flood

Fig. 11 Nadi flooding 2007 (courtesy of A. Nacola)

damage to homes in the surrounding low-lying Rewa delta. It is important to note here that the effect of storm surges in combination with these high river discharges during a tropical cyclone event mean that damage can be extremely high in areas of close geographical proximity to a major river. This is also the case in Nadi town and Navua, which are also identified as high-risk locations in this study. This poses an increased level of risk.

Nadi is Fiji's third largest town with a population of about 30,800 (Fiji Islands Bureau of Statistics 2005). Nadi is identified as a highly vulnerable area and deserving of immediate attention. In February 2007, Nadi town was submerged under 2 m of water due to flash flooding (Fig. 11) and 700 people were evacuated with damage calculated at US $30 million (National Emergency Operation Center 2007). This is due not only to the fact that it suffers from heavy inundation in and around the city proximity (Fig. 12a, b) but also because of its economic importance. The inundation includes many of the coastlines of small offshore islands such as Yakuilau Island, and Denarau, Yavulo, Vunamoli and Cuvu Islands. Increased river discharge at the Nadi river mouth in cyclone events has increased the vulnerability of Nadi town to a level where infrastructural damage reached US $1 million dollars for one event in 2007 (Fiji Government Press release 2007). *Nadi* is the center of the tourist industry and is the site of Fiji's international airport and several major tourist hotel chains, which form the backbone of the Fiji economy and foreign revenue. Tourism earnings in 2003 were F$638.6 million/US $428 million (Fiji Islands Bureau of Statistics 2005). Thus inundation risk, site importance and damage is high, while resilience is low due to the need to be situated very close to the coastline where tourism activities occur.

Lautoka is also vulnerable and has a large population of 36,000 (Fiji Islands Bureau of Statistics 2005) in the city with an additional 7,200 people located in peri-urban areas. Most of the population is centered close to or near the city. It is important as an industrial center, with the largest sugar mill, a major wharf and shipping location as well as being the site of Fiji's sugar processing industry. In 2003, the export value of Fiji's sugar was F$230 million/US $154 million (Fiji Islands Bureau of Statistics 2005). Inundation analysis shows that the entire coastline of Lautoka city will suffer some inundation (Fig. 13a, b). This will result in disruptions to the sugar industry, the surrounding mill and wharf as well as damage to homes and businesses in Lautoka city. Thus vulnerability is quite high since damage to Fiji's sugar industry would be severe if mills were to be affected. Since growing seasons rely on certain key harvesting periods, this leaves the industry especially susceptible to disruptions affecting farmer's livelihoods. Crop damage has also been known to occur. The presence of a seawall in Lautoka city means it has a higher resilience to coastal flooding, although damage to sugarcane crops has been severe at times (National Emergency Operation Center Press release 2007).

Additional vulnerable areas identified by the analysis include Tavua (population 2,400). The Northern Kings Highway, which is close to the area inundated, is one of only two access roads linking Suva and Nadi, leaving Suva isolated from the international airport if flooding occurs. The other Queens Highway, links Suva and Nadi around the southern coast of Viti Levu, and this is also prone to flooding near the Navua area (Chand 2004). Navua (population 4,200) lies on the south coast of Viti Levu and is largely agricultural. The close proximity of the Navua River means that it is often flood-stricken, with damage to livestock and crops. It is extremely vulnerable although adaptive capacity is limited.

The Verata and Nakelo districts are mostly rural in nature with many villages and a heavy reliance on subsistence lifestyles including fishing. Fringing reefs offer some protection to storm surges. In Nakelo, the coast is heavily covered by mangrove vegetation. Infrastructure is limited. Vulnerability can be high for some settlements but the option of retreat is possible due to the communal and subsistence village lifestyle.

Likuri Harbour, which is just south of Nadi, is comprised mostly of small villages and communal settlements. However, it has been the focus of a push towards a major hotel development in the nearby Natadola beach. Thus, damage in the future and risk to investments could be large if the area is developed. Ba town near Nailaga is also a major sugar center with its own mill and sugar production, and inundation in these areas could result in sugar production disruptions and loss of earnings.

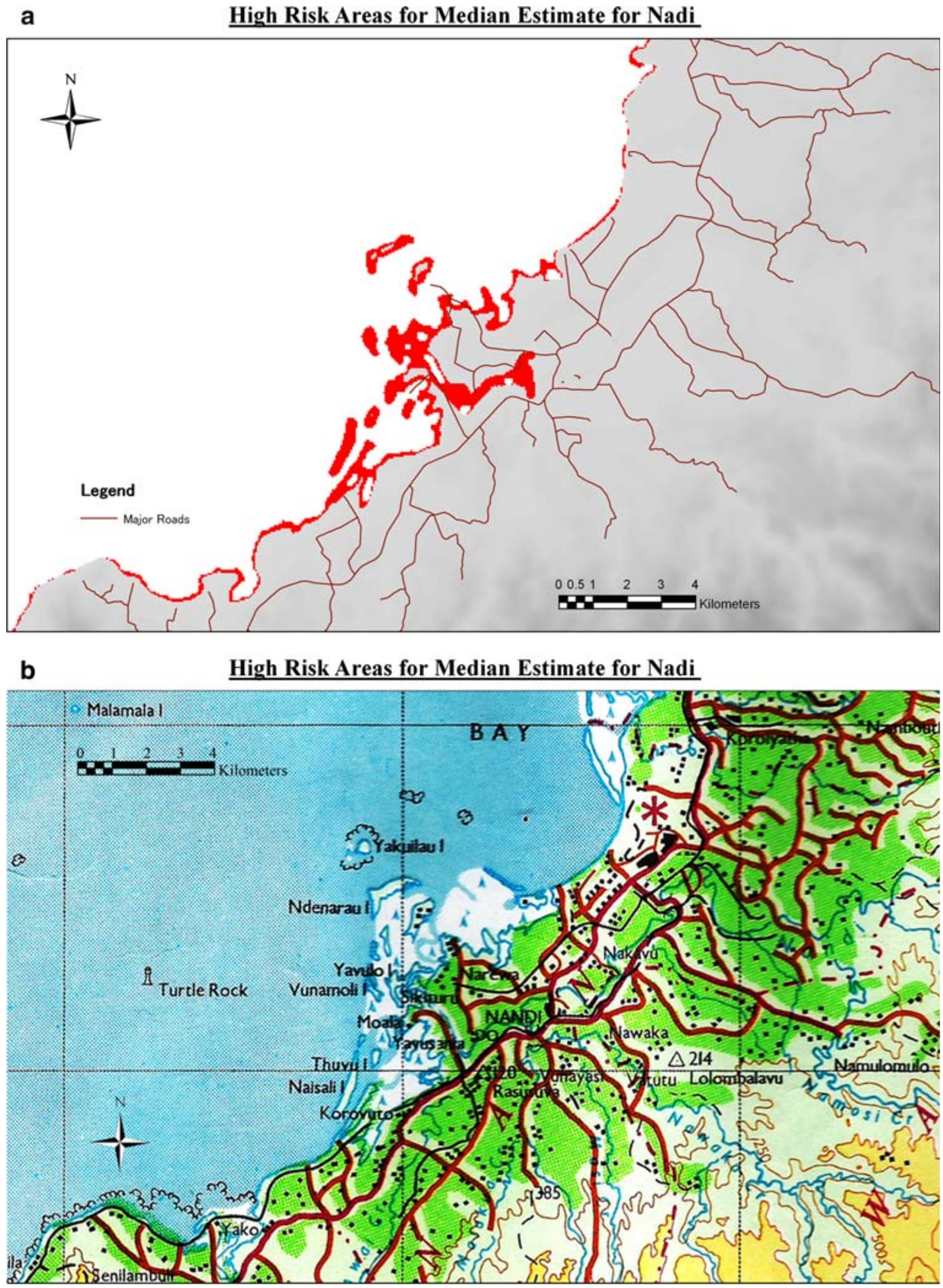

Fig. 12 **a** Flooding detail for Nadi, 0.48 m SLR with 10-year SS. **b** Detail for Nadi, Fiji

Conclusions

This study used GIS analysis to determine the mapped inundation risk involving sea-level rise on the island of Viti Levu under different possible combinations of storm surge scenarios and SLR scenarios. In order to better prepare for the effects and problems of climate change and extreme weather events, high-risk locations on Viti Levu were identified. Most of the major towns and cities in Fiji are located along the coastline of Viti Levu. This means that, since the coastline is vulnerable to climate change effects, most of Fiji's cities and towns are placed at high risk by default. This was confirmed when most of these towns or cities showed high degrees of inundation inside the city boundaries. In addition, most of the quantified area inundated in the analysis lies on prime coastal land. It is not just a matter of total area but also the value of this land, especially in urban areas.

However, it is often the smaller, rural locations such as Tavua or Nailaga, which find it harder to take adaptive measures simply because the financial cost outweighs the benefit of protecting these areas. In these cases, the strategy

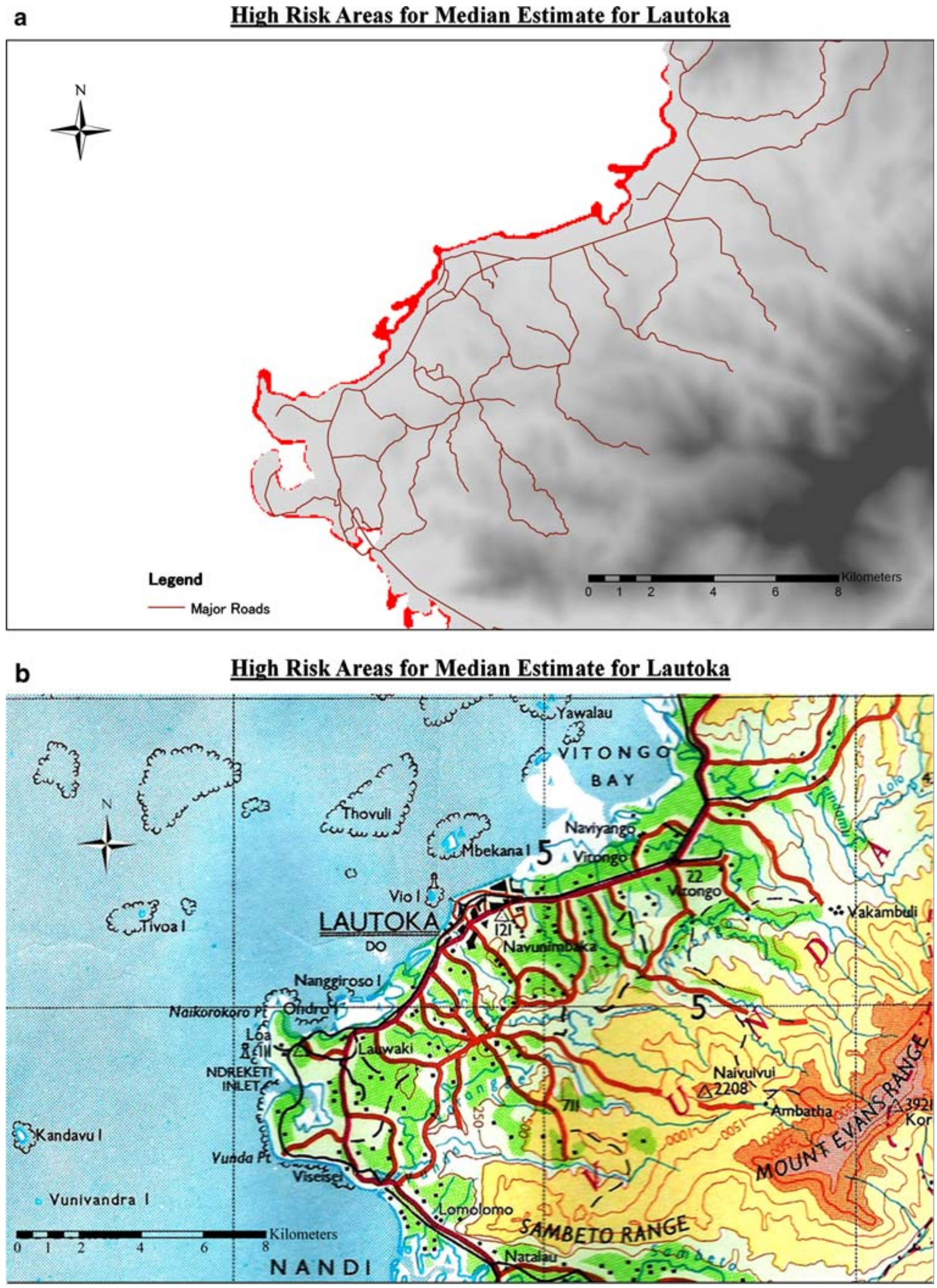

Fig. 13 **a** Flooding detail for Lautoka city, 0.48 m SLR with 10-year SS. **b** Detail for Lautoka city

of retreat may be the only option. In rural areas or villages under a communal land tenure system, this may be a possible, if not the only, solution. In urban areas where land titles are owned by individuals this may be unacceptable, or existing infrastructure may make protection structures or methods the only possibility.

Nadi in particular needs immediate action to protect its tourism infrastructure. The proximity of the Nadi River running through the town increases its vulnerability, and dredging of this river to deepen the channel and reduce flooding can be viewed as only a temporary measure. The threat of SLR means that some retreat away from the town may be financially cheaper in the long run than the damage that could occur without such action.

Tools such as GIS in simulating areas of potential inundation are very useful, as well as representing a time- and cost-effective method for a small country such as Fiji. Limitations on the availability of GIS population or infrastructure databases still exist but hopefully these will be addressed in the future by the respective departments. The identification of major locations such as Suva, Lautoka and Nadi should be used to formulate response strategies now for the future, and for future monitoring and comparison.

Sustainability is achieved by recognizing risks and taking steps to reduce these risks. Effective action towards reducing vulnerability has been shown to be more effective when carried out in the initial stages of projects or investments (Bettencourt et al. 2006). Thus the identified high-risk locations would also benefit from so-called 'no regret' adaptation measures being implemented now. Bettencourt et al. (2006) suggest several ways to achieve this, e.g., strengthening the enabling environment, supporting decision-making education and public awareness, mainstreaming development plans policies and regulations, and then implementing measures such as early warning systems or erosion control measures. Through constant review of these actions, 'risk management of natural hazards' (RMNH) such as those from sea-level rise can then be solved (Bettencourt et al. 2006).

A suitable response strategy includes legislation, allocation of funds, education or public awareness, and responsible action by the Fiji government to implement treaties such as the UN Framework Convention on Climate Change into economic policies (Nunn et al. 1994, 1996). Thus, local case-study vulnerability assessments and GIS studies can be an important tool in achieving sustainability by directing these resources and response strategies to the places where they are most needed.

Acknowledgments The authors are grateful to the staff at the South Pacific Applied Geoscience Commission, in particular Mr. A. Lal and Ms. L. Biukoto for their kind assistance in providing data. We are also indebted to Dr. Y. Kuwahara for his time and help.

References

Bettencourt S, Croad R, Freeman P, Hay J, Jones R, King P, Lal P, Mearns A, Miler G, Psawarayi-Riddihough I, Simpson A, Teuatabo N, Trotz U, Van Alst M (2006) Not if, but when: adapting to natural hazards in the Pacific Islands region. A Policy Note 2006. Pacific Islands Country management Unit, East Asia and Pacific Region, The World Bank

Chand V (2004) Floods—a drain on the economy. Fiji Government Online, Ministry of Information, Fiji. http://www.fiji.gov.fj/publish/printer_2504.shtml. Cited 20 January 2008

Fiji Government Press release (2007) Flood damages estimated at a million in Nadi Feb 23, 2007. http://www.fiji.gov.fj/publish/page_8426.shtml. Cited 20 January 2008

Fiji Islands Bureau of Statistics (2005) Key statistics, June 2005. Suva, Fiji Islands

IPCC (2001) Climate change 2001: the scientific basis. Cambridge University Press, Cambridge

IPCC (2007) Climate change 2007: the physical science basis. In: Solomon S, Qin D, Manning M, Chen Z, Marquis M, Averyt KB, Tignor M, Miller HL (eds) Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge

Maharaj RJ (2002) Pacific islands at risk: foreshore development and their vulnerability and implications for adaptation strategies to climate change. In: Mimura N, Yokoki H (eds) Proceedings of the APN/SURVAS/LOICZ joint conference on coastal impacts of climate change and adaptation in the Asia–Pacific region, Kobe, Japan, 14–16 November, 2000. Kobe, Japan, Asia-Pacific Network on Climate Change (AP-Net)

Mimura N, Harasawa H (eds) (2000) Data book of sea-level rise 2000. Center for Global Environmental Research, Japan

National Emergency Operation Center Press Release (2007) Situation Report/National Emergency Operation Centre-15 Feb 2007, National Disaster Management Office, Government of Fiji

Nunn PD, Ravuvu AD, Aalbersberg W, Mimura N, Yamada K (1994) Assessment of coastal vulnerability and resilience to sea-level rise and climate change, case study: Yasawa Islands, Fiji, Phase 2: Development of Methodology. South Pacific Regional Environment Program, p 118

Nunn PD, Ravuvu AD, Aalbersberg W, Mimura N, Yamada K(1996) Integrated coastal zone management programme for Fiji and Tuvalu, coastal vulnerability and resilience in Fiji: assessment of climate change impacts and adaptation, Phase IV. South Pacific Regional Environment Program, p 105

Solomon S, Kruger J (1996) Vulnerability and adaptation assessment: coastal impact of sea-level change, Suva and vicinity, Viti Levu, Fiji Islands. SOPAC, Suva, Technical Report 242, p 82

The Hydrographic Office, Fiji Islands Maritime Safety Administration (2004) Fiji Nautical Almanac 2005. Suva, Fiji Islands