Economic impacts of recent and future coastal inundation for Vanuatu

2025

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Prepared as a case study by CSIRO for the Vanuatu Climate Information Services for Resilient Development (Van-KIRAP) Project

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Contents

Abstract

This case study assesses the exposure to, and economic impacts of, extreme sea level-driven inundation for coastal buildings and roads around the Mele and Sarakata catchments in Vanuatu. These two locations have the greatest urban/peri-urban concentration of people and key infrastructure assets critical to the social and economic well-being of local communities in Vanuatu. The study was undertaken by CSIRO scope for the Vanuatu Climate Information Services for Resilient Development (Van-KIRAP) Project.

Coastal inundation data layers from the Van-KIRAP project for average return intervals of 50 and 100 years were sourced for baseline and future climate conditions, assuming low (RCP2.6) and high (RCP8.5) greenhouse gas emissions pathways. These data were combined with asset location and economic data from i) the Pacific Data Hub/PCRAFI database (buildings) and, ii) sectoral estimates (roads) as inputs to the RiskScape analytical tool to map exposure and economic impacts.

The assessments show a considerable increase in exposure and associated economic impacts from coastal inundation for the two study areas. For example, by mid-century (2041-2060), the percentage of a specified building asset class exposed to inundation from extreme sea level events for a 50-year return interval increased from 1.3 % (historical baseline: 1981-2020) to 2.0 % (an increase by 1.6 times) for low emissions or 2.2 % (an increase by 1.8 times) for high emissions. Similarly, by mid-century, the percentage of a specified road asset class exposed to inundation from extreme sea level events for a 50-year return interval increased from 0.7 % (historical baseline: 1980-2020) to 1.1 % (an increase by 1.5 times) for low emissions or 1.2 % (an increase by 1.6 times) for high emissions.

Likewise, the total replacement cost of the specified building asset class by mid-century for a 50-year return interval event is likely up to USD 87 million (8 % of GDP) for a low emissions scenario or USD 97 million (9 % of GDP) for a high emissions scenario, in comparison to the baseline cost of USD 59 million (5 % of GDP) across both catchments. These values however almost double for a high emissions scenario by late century (2081-2100), i.e. around 15% of GDP. For the road asset class, the total replacement cost by mid-century for a 50-year return interval event could be USD 1.6 million (0.15 % of GDP) for a low emissions scenario or USD 1.7 million (0.16 % of GDP) for a high emissions scenario in comparison to the baseline cost of USD 1.1 million (0.1 % of GDP). These values, however, almost double for a high emissions scenario by late century, i.e. around USD 3.3 million.

The exposure and economic impacts are not uniform across the different local government areas (LGAs) that fall within these two study areas, with most impacts evident in low-lying LGAs immediately adjacent to the major waterways. For the road asset class, Erakor and Malorua LGAs tend to have the largest exposure and replacement cost around the Port Vila/Mele catchment area, while Southeast Santo LGA tends to have the highest exposure and replacement cost around the Luganville/Sarakata catchment area.

The results of this study have significant implications for national and sub-national level risk assessments informing adaptation planning, climate-related disaster risk management, and associated decision-making for Vanuatu. In this context, important assumptions and limitations related to the methodology and (input/output) data for this analysis, including the application of the key findings in subsequent risk assessment, management planning and associated

decision-making, are also noted and discussed. For example, the economic costs of asset replacement used in this study do not include other significant costs associated with disruption to supply chains and business continuity, disaster response and recovery, health and well-being. The key climate data inputs for this study, together with guidance on undertaking sector-based climate hazard (coastal inundation) impact assessments are available as open-source, visualised and spatially-referenced outputs from the Van-KIRAP *Vanuatu Climate Futures* portal (https://vanclimatefutures.gov.vu/dashboard/home).

1. Introduction

The objective of this case study is to assess the exposure and associated economic impacts of extreme sea level (ESL) events under current and future climates for two infrastructure asset classes (coastal roads and buildings) in two locations (Mele catchment in Port Vila on the island of Efate and Sarakata catchment in Luganville on the island of Espiritu Santo) in Vanuatu (see Figure 1).

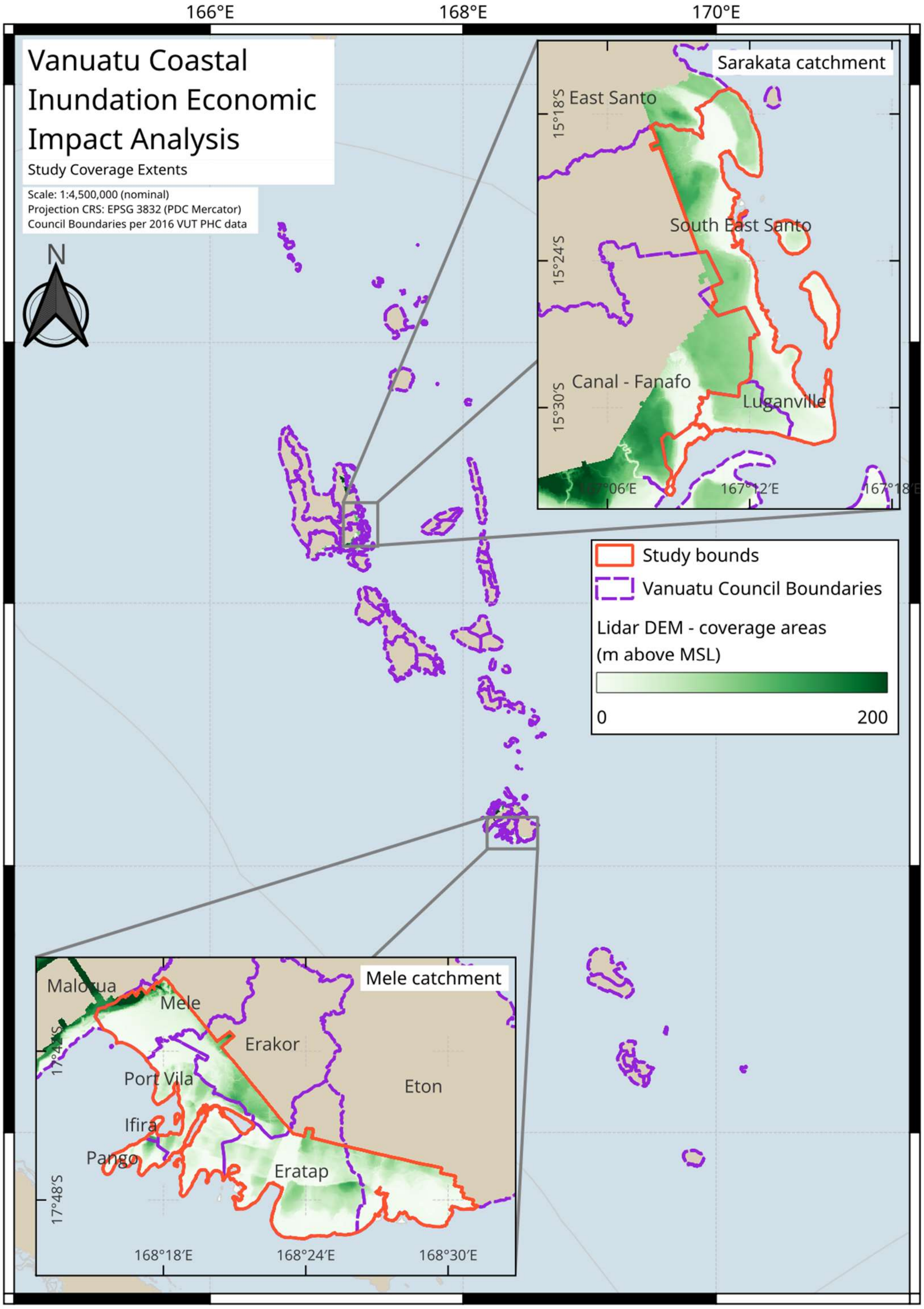

Figure 1 Spatial extent of the Sarakata and Mele catchments (study bounds) for the purposes of this study.

The Van-KIRAP project has developed a national ocean hazard modelling system to provide historical analyses and future projections of ESL events for Vanuatu (Hoeke, et. al, 2024). ESL magnitudes for average annual recurrence intervals (ARI) of 10-, 50- and 100-years, and their respective statistical uncertainties, have been calculated for the baseline (1981-2020) period as well as 20-year future sea level periods centred on 2030, 2050, 2070 and 2090, for two emissions pathways. This study utilises these locally specific ARI levels in combination with relatively simple inundation modelling and detailed infrastructure and associated asset valuation.

More specifically, the assessment for the two study areas is designed to:

a. quantify the building and road exposure to coastal inundation from ESL events with 50- and 100-year ARI levels presented as maps and bar charts for historical conditions (1981-2020) and future conditions (2021-2040, 2041-2060, 2081-2100) for low (RCP2.6) and high (RCP8.5) emissions pathways, and
b. analyse economic impacts based on specified 'value at risk' estimates from i) PCRAFI and Pacific Data Hub portal (buildings), and ii) expert local advice (Public Works Department, Vanuatu) for estimates of replacement and/or significant repairs/maintenance (roads).

2. Data and Methods

The Van-KIRAP ocean hazard modelling system utilises the SCHISM-WWMIII model (Zhang et al., 2016) in combination with historic atmospheric and ocean reanalysis data, stochastic/probabilistic tropical cyclone (TC) information and regionally specific sea level rise (SLR) projections (for RCP2.6, RCP4.5 and RCP8.5 climate emissions scenarios) to simulate the combined effects of tides, storm surge, wind waves and sea level variability (Hoeke, et. al, 2024). The SLR scenarios (Table 1) are derived from CMIP5 climate model projections (via the Pacific NextGen project (CSIRO and SPREP, 2021)), in the absence of peer-reviewed literature of equivalent regional CMIP6 projections for Vanuatu.

Table 1 Median sea-level projections (in meters) for Vanuatu with 5 – 95% uncertainty range relative to historical for RCPs 2.6, 4.5, and 8.5. (*Source*: CSIRO and SPREP, 2021).

	RCP2.6		**RCP4.5**		**RCP8.5**	
2030	0.13	[0.10–0.17]	0.13	[0.09–0.17]	0.14	[0.10–0.18]
2050	0.23	[0.17–0.30]	0.24	[0.18–0.31]	0.28	[0.22–0.37]
2070	0.32	[0.24–0.43]	0.37	[0.28–0.48]	0.48	[0.37–0.64]
2090	0.42	[0.30–0.56]	0.50	[0.38–0.68]	0.73	[0.56–0.99]

Median ESL ARI values at coastal points are used to estimate the median exposure and economic impact, while the 5^{th} and 95^{th} percentiles (i.e., the uncertainty range) are used to illustrate the uncertainty in these estimates. As an illustration, Figures 2 and 3 respectively show median ESL values for the whole of Efate.

When combined with existing asset or capital stock data such as roads, buildings, bridges, agricultural use and other public amenities (e.g. airports, hospitals, schools, evacuation centres etc.), this ESL information can highlight exposed and otherwise vulnerable sovereign infrastructure assets that are potentially impacted by coastal inundation under future climate change scenarios.

Modified static (or 'bathtub') inundation mapping has been employed to create the inundation layer. This assumes all land below the mapped sea level and connected to the ocean will be inundated (at least temporarily but long enough to render infrastructure damaged beyond repair and/or otherwise inoperable for periods beyond effective existing contingency arrangements). Traditionally, 'bathtub' simulations do not account for local variability in actual inundation events related to variability in fine-scale coastal bathymetry and topography, specific asset design, condition and use, as well as potentially compounding extreme events such as extreme wind, rainfall and associated pluvial and fluvial flooding. The term 'modified bathtub' is used here since the Van-KIRAP ocean hazard modelling system does account for the spatial variability of storm surge and storm waves due to local coastal bathymetry and topography on extreme sea level (at least at the spatial resolution of the model, approximately 250 m at the coastline), although certain processes are not included (such as the runup of individual waves or compound flooding associated with pluvial and fluvial inputs). Likewise, this analysis excludes cascading and/or aggregated impacts of ESL events on infrastructure such as ports and harbours, airports, electricity generation and distribution, water storage, treatment, distribution and drainage, local trades and services etc.

The methods employed to calculate probabilistic ESL ARIs at coastal points (used in this study) are more fully described in Hoeke et. al (2024), along with caveats on interpretation associated with the analysis. The ESL information at coastal points was linearly interpolated on a 10m x 10m digital elevation model (DEM), informed by data from LiDAR surveys carried out as part of the PACCSAP project in 2012 and 2013 (https://www.pacificclimatechange.net/document/pacific-australia-climate-change-science-and-adaptation-planning-paccsap-vanuatu-lidar). DEM heights are measured relative to mean sea level as determined from tide gauge data from 2010-2012 (as part of the LiDAR survey effort), which is considered equivalent to the vertical datum of the ESL information (i.e. an average sea level of zero between 1990-1996).

Finally, RiskScape (Paulik et al., 2023) has been used to combine the coastal inundation hazard layers for specified road and building asset data to estimate exposure and associated economic impacts due to ESL over historical and future time periods. The economic impacts are based on specified damage functions and current 'value at risk' estimates from i) PCRAFI and Pacific Data Hub portal (buildings), and ii) expert local advice (Public Works Department/PWD, Vanuatu) for estimates of replacement and/or significant repairs/maintenance (roads). The most recent building and road replacement cost data (in USD), which were updated in 2024, have been utilised to estimate the associated impacts based on 'fit-for-purpose' damage functions determined as part of this case study. Hence, the economic impacts in the historical and future climate are with respect to the 2024 values.

The building cost data were obtained from the PCRAFI database/Pacific Data Hub portal (https://geonode.pacificdata.org) and refer specifically to public and privately-owned buildings. The estimated average road replacement cost (USD 85,000 per km: refer to section 4 for further information on this) was obtained from the PWD and refers specifically to public roads (both sealed and unsealed). The losses are also normalised with respect to the 2024 Gross Domestic Product (GDP) of Vanuatu, which is estimated to be USD 1.1 Billion (World Bank: https://data.worldbank.org/indicator/NY.GDP.MKTP.CD?locations=VU, Asian Development Bank: https://www.adb.org/where-we-work/vanuatu/economy). The relevant damage functions for these economic estimates are based on i) for buildings: 100% of the re-build cost, assuming the inundation impacts render the buildings no longer able to be used for intended purposes and therefore in need of complete re-build and/or major structural repairs at existing locations, and ii) for roads: 100% of the re-build cost for relevant road types (sealed, un-sealed/gravel etc), assuming the inundation impacts render the roads no longer able to be used for intended purposes and therefore in need of complete re-build and/or major structural repairs at existing locations. However, costs may be greater if there is a policy to 'build back better' to enhance climate resilience.

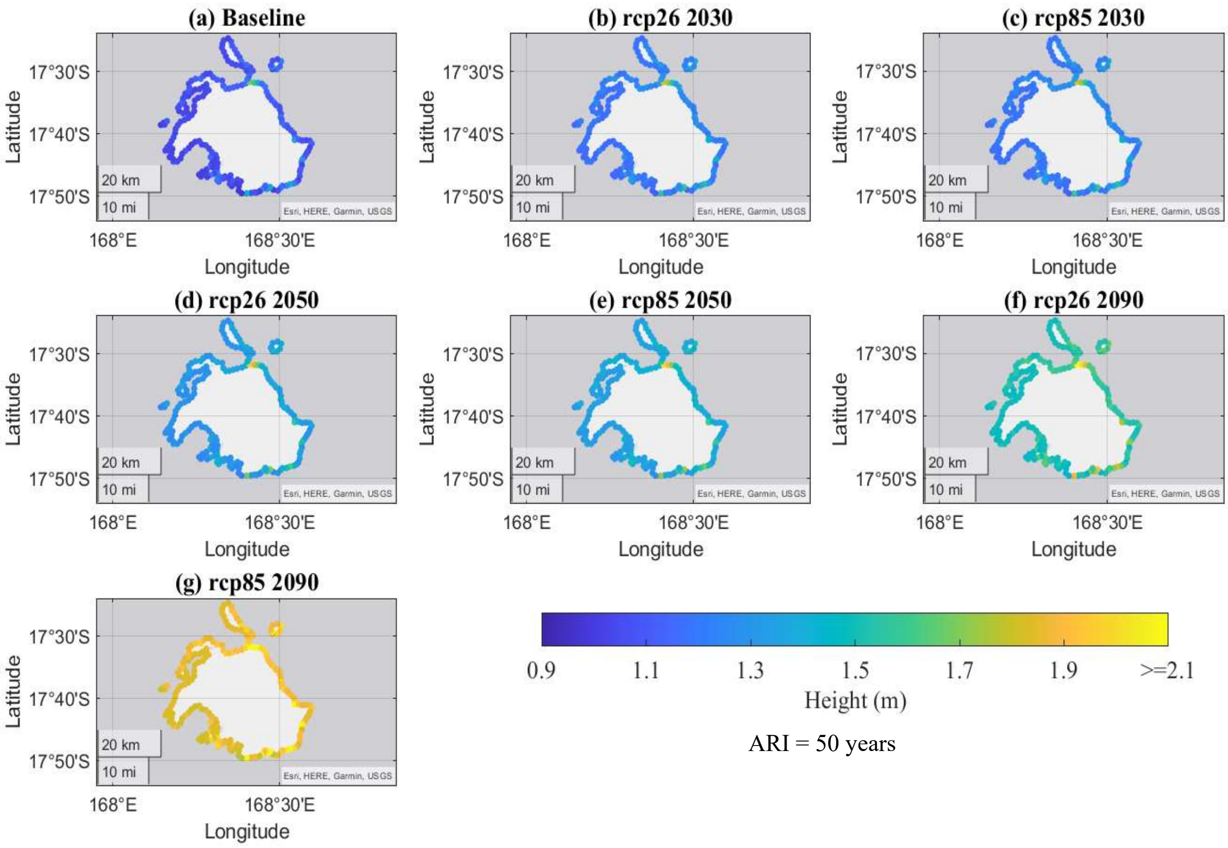

Figure 2 ESL height (metres) for ARI of 50 years over Efate for baseline (1980-2020) and future (2030, 2050, 2090) conditions for low (RCP2.6) and high (RCP8.5) emissions scenarios.

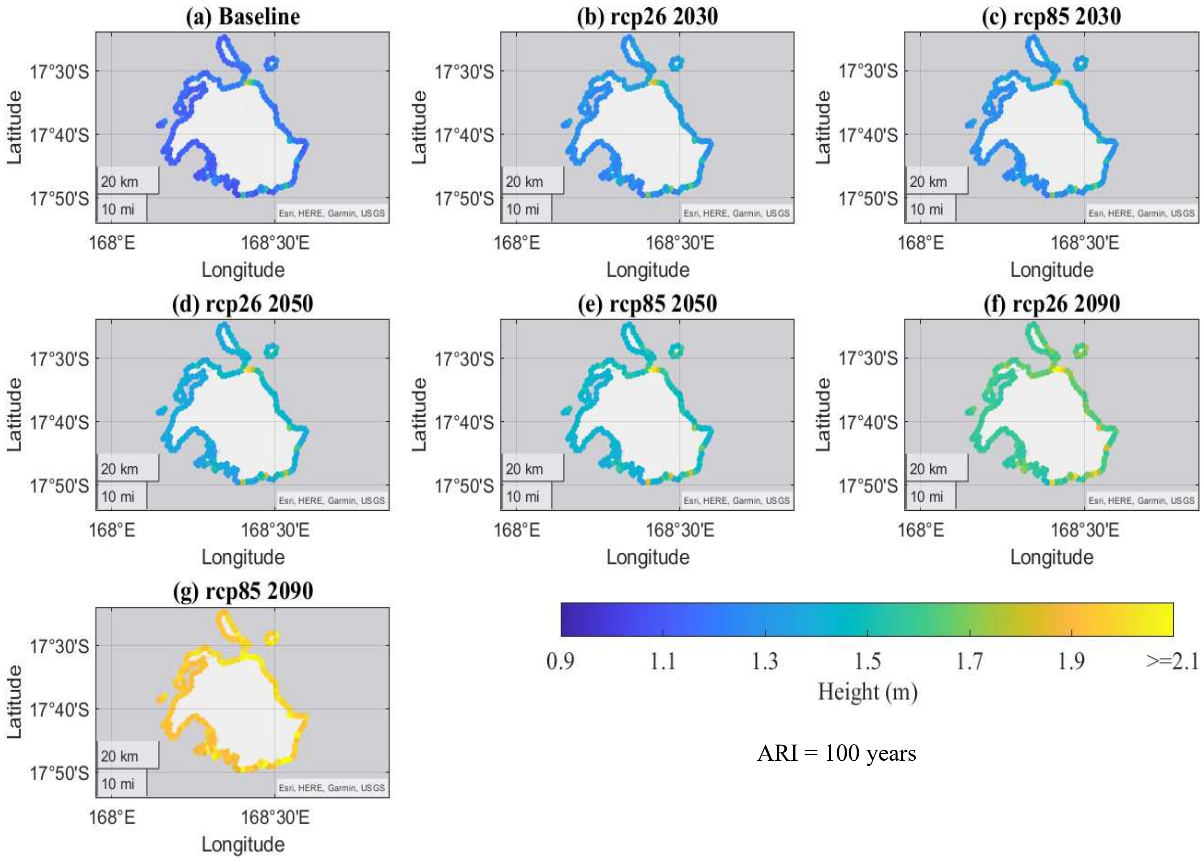

Figure 3 Same as Figure 2 except for the ARI of 100 years.

3. Results

3.1 Buildings

Figure 4a and b respectively show the total number and percentage of buildings exposed for the two ARIs and emissions scenarios over the different periods for the combined Port Vila/Mele catchment and Luganville/Sarakata catchment areas. It is evident that in comparison to the baseline (that has 313 and 364 buildings exposed for the 50- and 100-year ARIs respectively), the exposure increases over time.

For the 50-year ARI, this ranges from 414 buildings by 2030 (2 %[1]) to 665 buildings by 2090 (3%) under a low emissions scenario, and from 425 by 2030 (2%) to 946 buildings (4 %) by 2090 for the high emissions scenario (Table 2). It should also be noted here (and elsewhere in the report) that the uncertainty in the estimates increases with time. These statistics are averaged over 20-year periods - results for individual years could be much larger.

For the 100-year ARI, the building exposure ranges from 472 buildings by 2030 (2%) to 712 buildings by 2090 (3 %) for low emissions, and from 477 buildings by 2030 (2%) to 1003 buildings (4 %) by 2090 for high emissions scenarios.

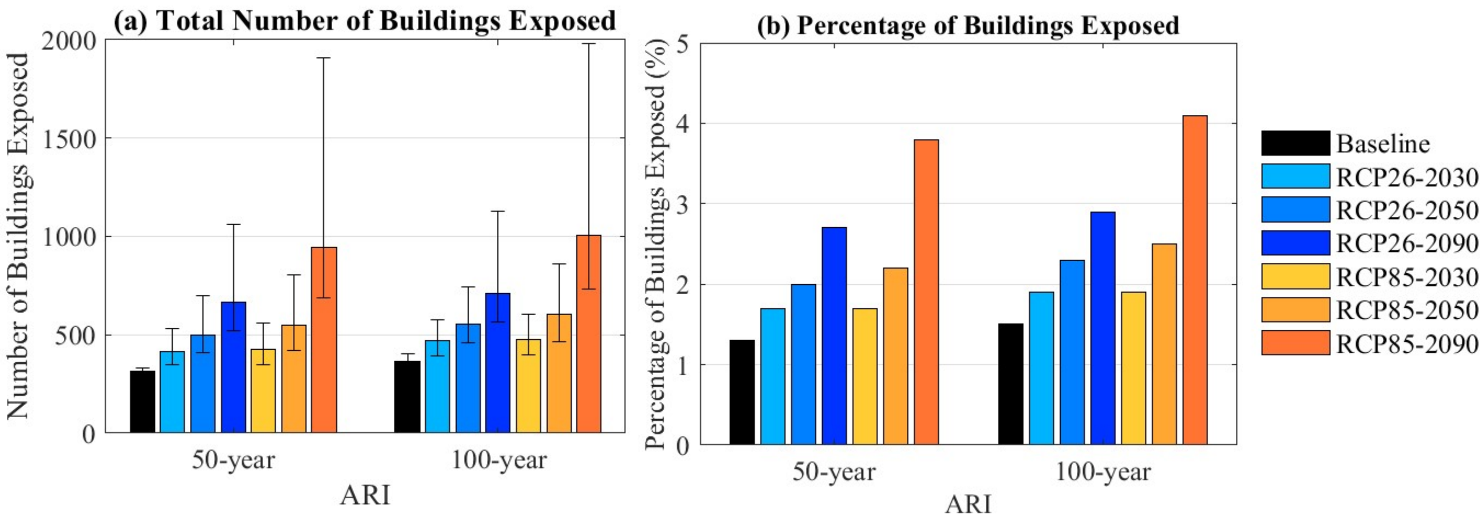

Figure 4 (a) Total number of buildings exposed and (b) percentage of buildings exposed for 50- and 100-year ARIs, for low (RCP2.6) and high (RCP8.5) emissions scenarios for 2030, 2050 and 2090 over combined Port Vila/Mele and Luganville/Sarakata catchments. The error bars, computed using the 5th and 95th percentile ESL values, represent the upper and lower bounds on the estimates. Note, the percentage is with respect to the total number of buildings in these two areas of study (see Table 2 for further details).

[1] The percentage of exposure (or cost) computed here and elsewhere in the document is with respect to the total for the asset class for the area/s under study.

The total exposure over the two case study areas has further been subdivided into their respective local government areas (LGAs). These comprise Erakor, Eratap, Eton, Ifira, Mele, North Efate, Pango and Port Vila for the Port Vila/Mele catchment. The relevant LGAs for the Luganville/Sarakata catchment area are Luganville and Southeast Santo. Table 2 shows the number of buildings exposed for the 10 regions in Figure 5.

The response is similar to that reported above: the exposure increases with time for the two emissions scenarios (see Figure 5a and b). However, it is evident that within the Mele catchment, Port Vila LGA has the highest number of exposed buildings in the current and future climate, followed by Erakor, with the least increase in exposure for Eton for both ARIs (Figure 5a and b). The percentage of exposure is highest for Ifira followed by Erakor, and the least is for Eratap and Mele (Figure 6a and b). As an illustration, exposure maps for ARI of 50 years and each emissions scenario over Port Vila/Mele catchment and Sarakata catchment are presented in Figures 7 – 10.

Table 2 Number of buildings exposed, grouped according to the different LGAs within the Mele catchment (unshaded) and Sarakata catchment (shaded). A total of 24,647 buildings are located within the jurisdiction of these two regions. Estimates are given for the baseline period B (1980-2020) and 20-year periods centred on 2030, 2050 and 2090, for low (RCP2.6) and high (RCP8.5) emissions scenarios, for inundation events for 50-year and 100-year ARIs.

Total number of Buildings		**Number of Buildings Exposed**													
Region	**Number**	**ARI = 50 Years**							**ARI = 100 Years**						
			RCP 2.6			**RCP 8.5**				**RCP 2.6**			**RCP 8.5**		
		B	**2030**	**2050**	**2090**	**2030**	**2050**	**2090**	**B**	**2030**	**2050**	**2090**	**2030**	**2050**	**2090**
Erakor	1387	30	42	53	82	44	62	117	34	48	62	90	49	71	120
Eratap	1076	9	11	17	19	12	18	24	10	13	18	19	14	18	25
Eton	159	3	5	7	7	5	7	7	5	7	7	7	7	7	7
Ifira	343	11	23	25	30	23	26	38	20	25	26	31	25	28	45
Mele	1395	13	15	17	29	16	19	34	15	17	20	30	17	22	36
N Efate	156	4	8	8	8	8	8	11	7	8	8	8	8	8	11
Pango	549	2	4	6	11	5	8	39	2	6	9	17	6	10	52
Port Vila	12884	186	221	255	323	226	279	441	197	244	282	340	246	300	457
Luganville	5174	43	59	71	101	60	81	152	52	70	82	110	70	94	166
SE Santo	1524	12	26	37	55	26	41	83	22	34	41	60	35	47	84
Total	**24647**	**313**	**414**	**496**	**665**	**425**	**549**	**946**	**364**	**472**	**555**	**712**	**477**	**605**	**1003**

Over the Luganville/Sarakata catchment, Luganville LGA has the highest number of exposed buildings in future followed by SE Santo for both ARIs (Figure 5a and b). However, the percentage of exposure is higher for SE Santo (Figure 6a and b).

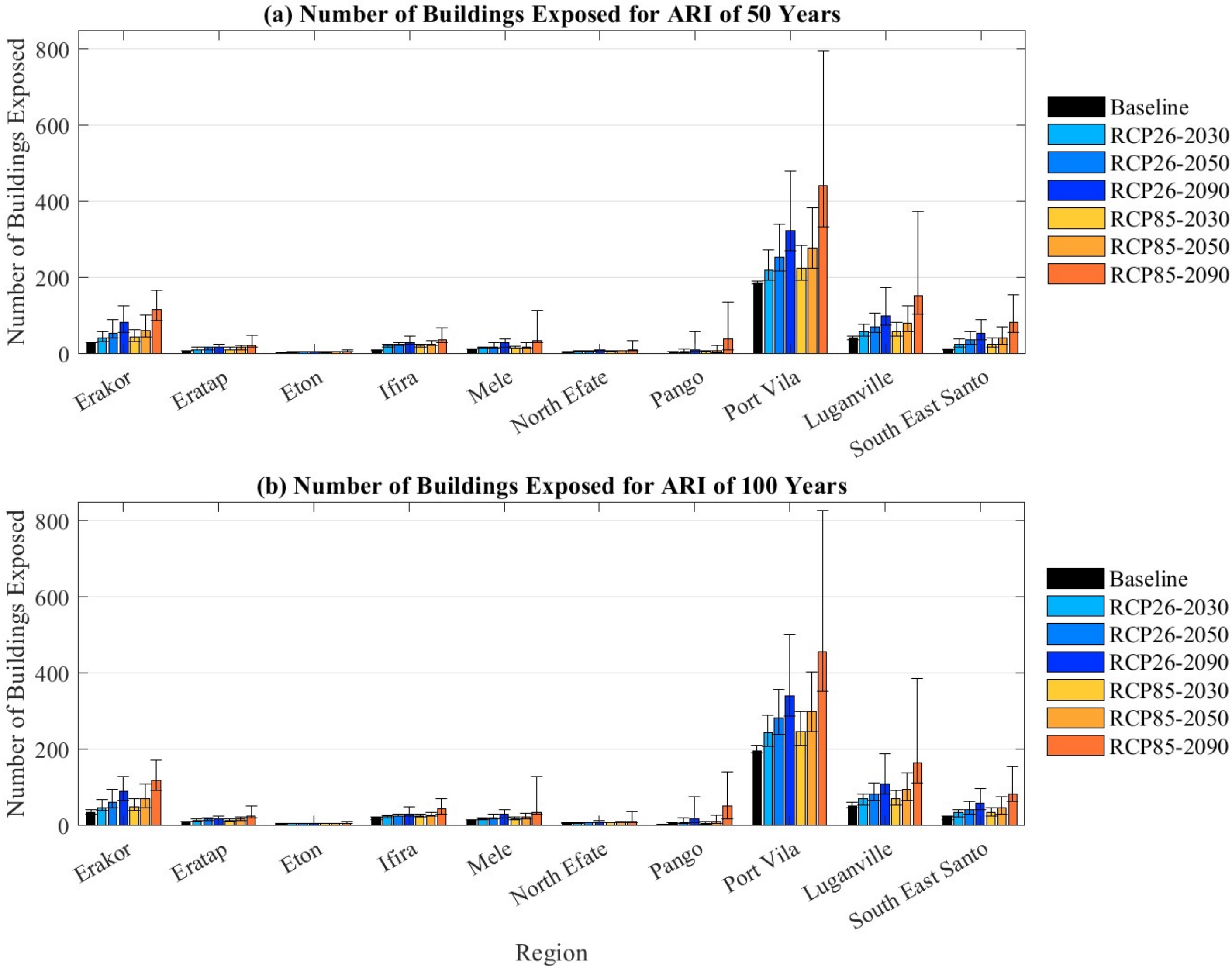

Figure 5 Number of buildings exposed for (a) 50-year and (b) 100-year ARIs stratified by LGA region, for the baseline period (1980-2020) and low (RCP2.6) and high (RCP8.5) emissions scenarios for 2030, 2050 and 2090 over Port Vila/Mele and Luganville/Sarakata catchments. The error bars show the 5th and 95th percentile building exposure.

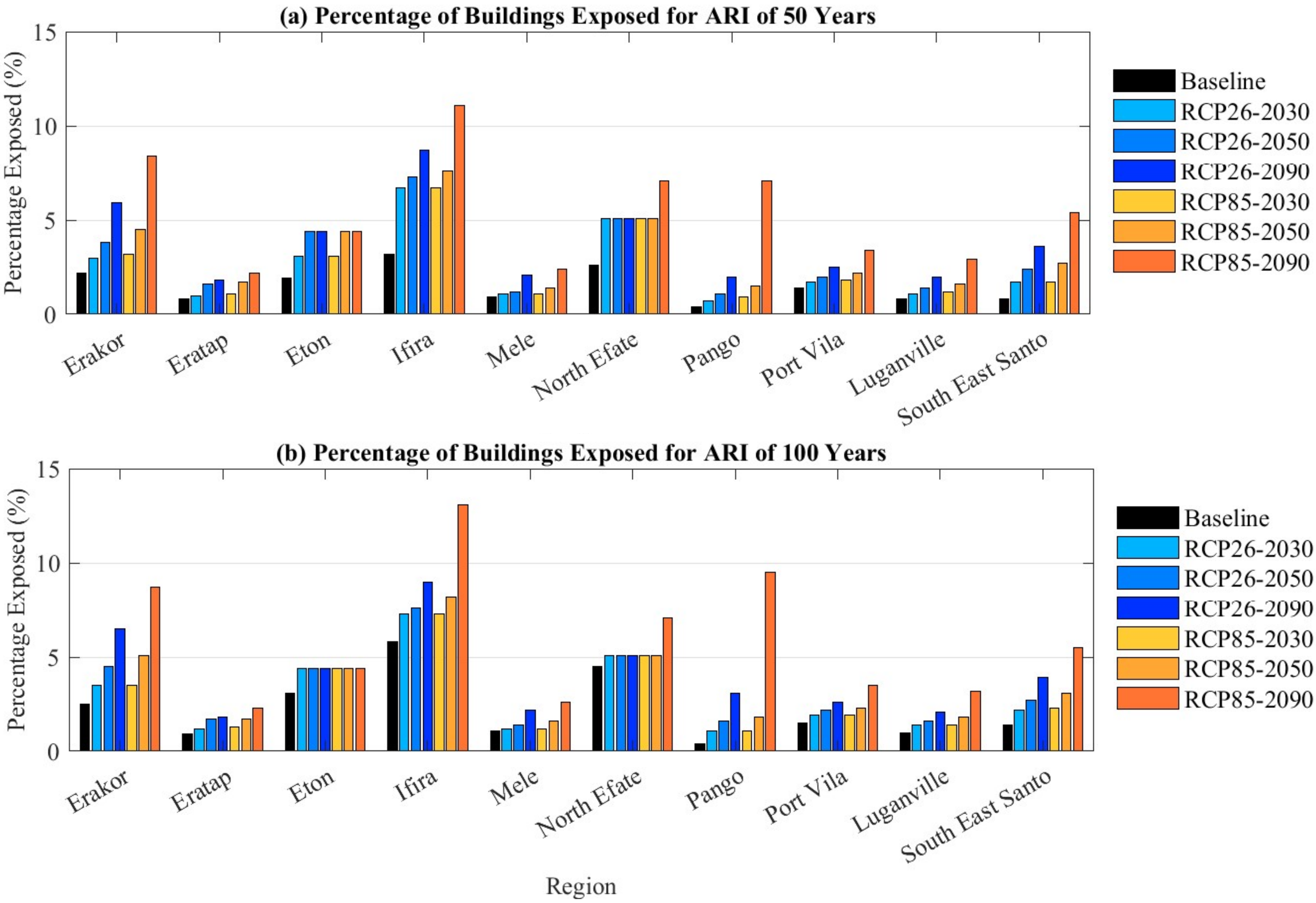

Figure 6 Percentage of buildings exposed for (a) 50- and (b) 100-year ARI for the baseline period (1980-2020) and low (RCP2.6) and high (RCP8.5) emissions scenarios for 2030, 2050 and 2090 over LGAs within the Port Vila/Mele and Luganville/Sarakata catchments.

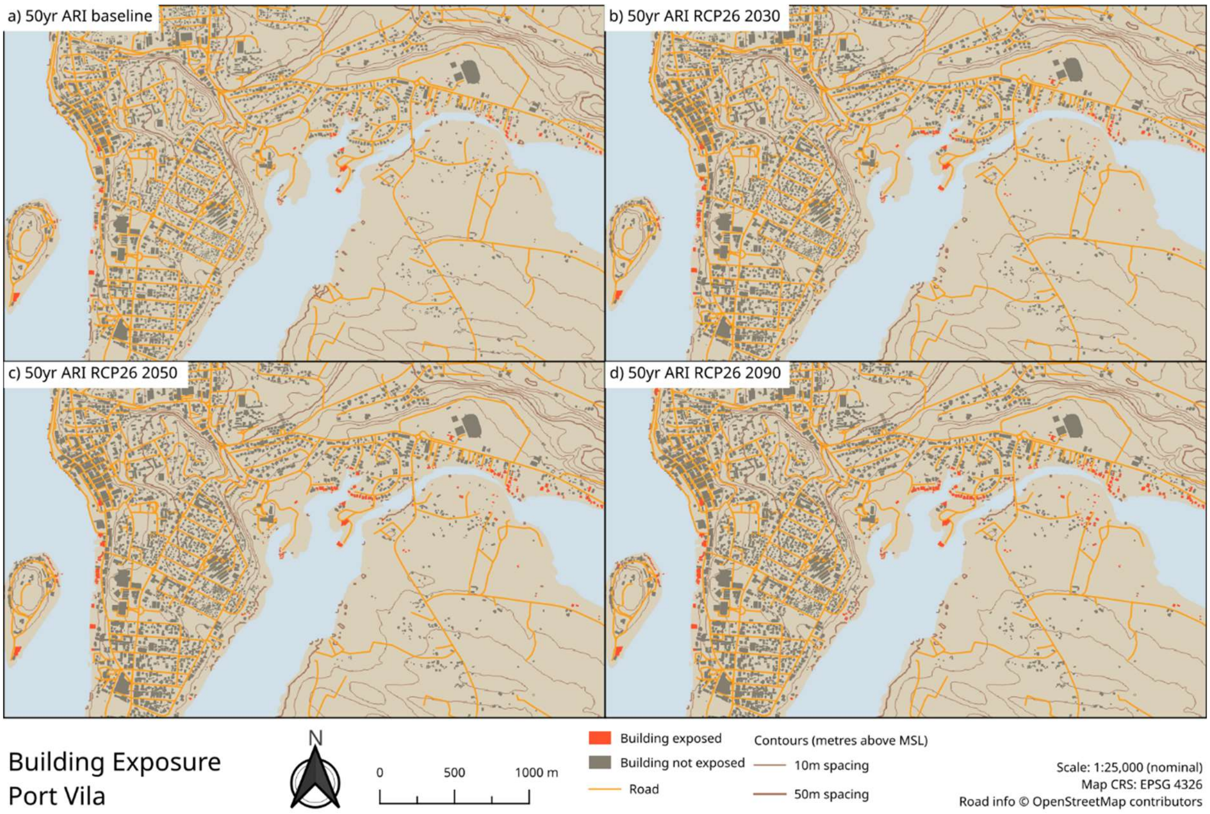

Figure 7 Map of building exposure for ARI of 50 years around Port Vila for the baseline period (1980-2020) and future periods (2030, 2050, 2090) for a low (RCP2.6) emissions scenario. The blue space represents the ocean/water, beige represents the land area, yellow lines are the roads, red markings are the exposed buildings and grey markings over land are buildings not exposed.

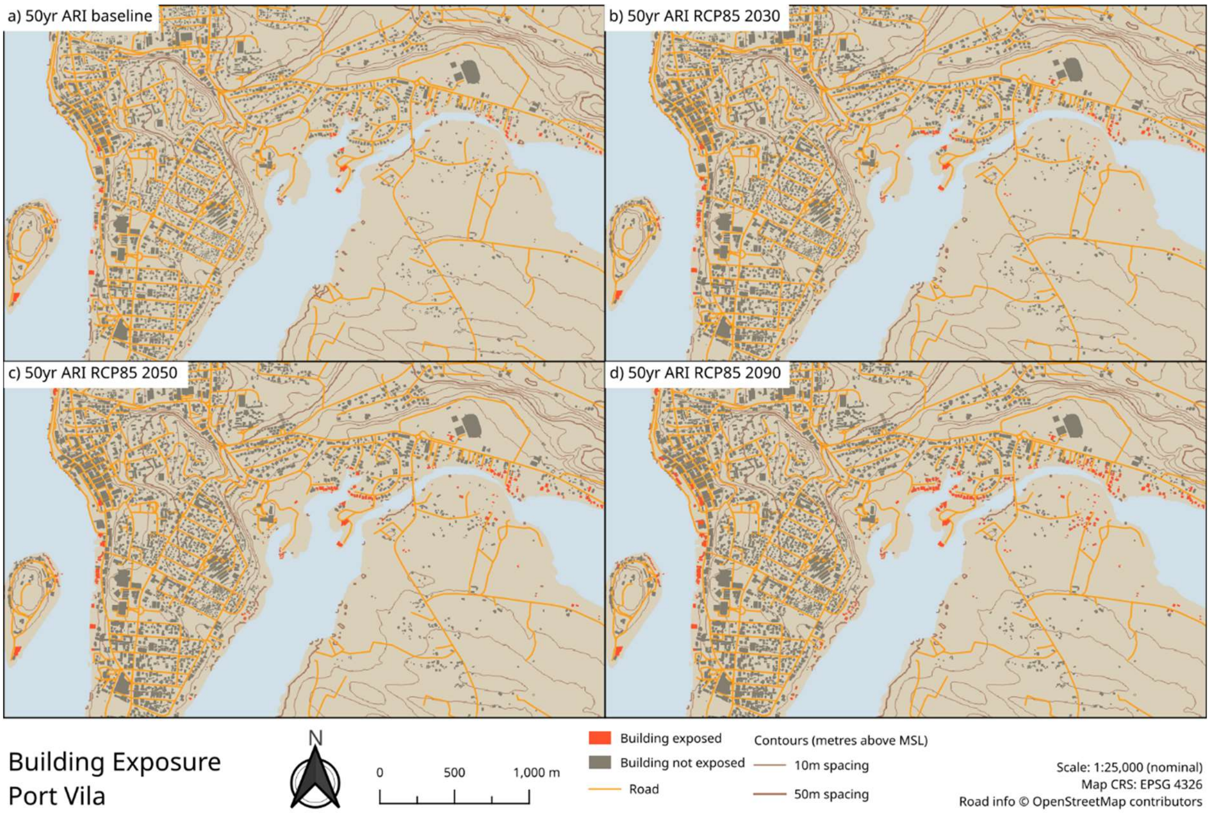

Figure 8 Same as Figure 7 except for a high (RCP8.5) emissions scenario.

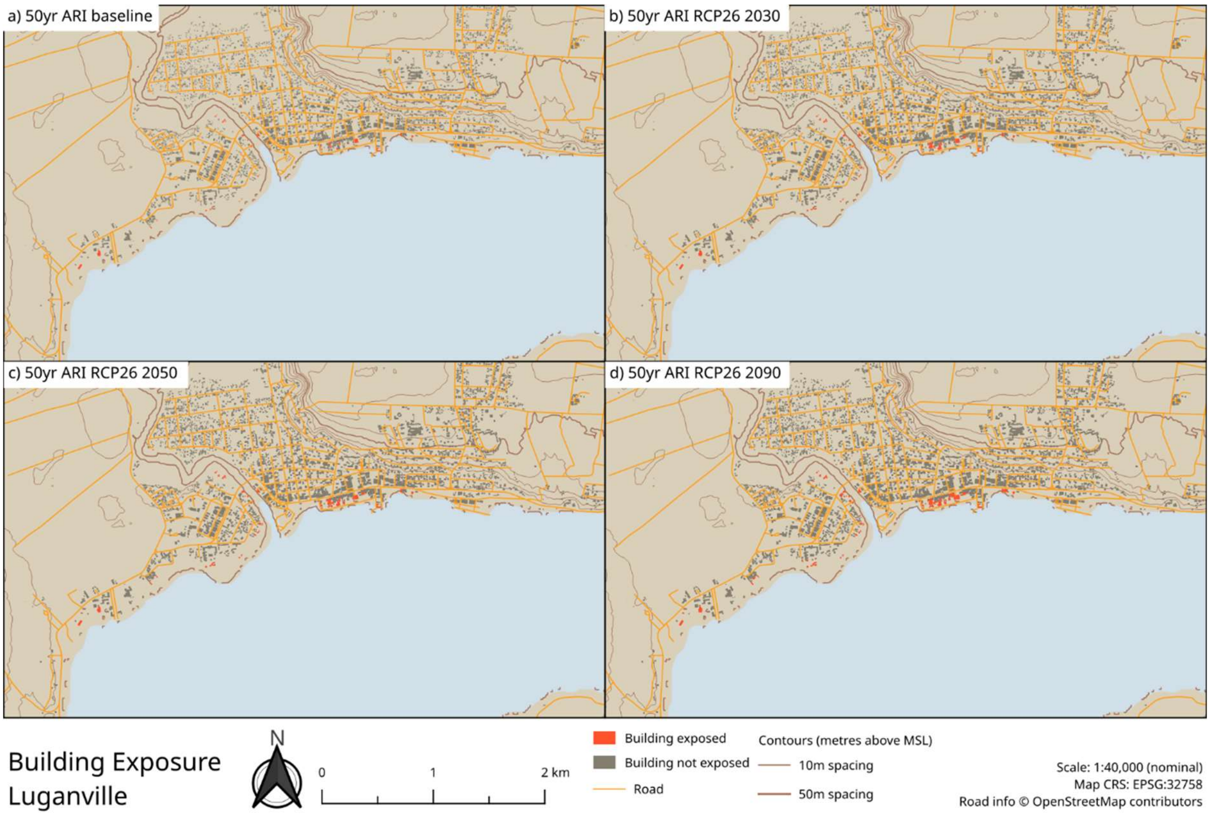

Figure 9 Same as Figure 7 except for the Sarakata catchment.

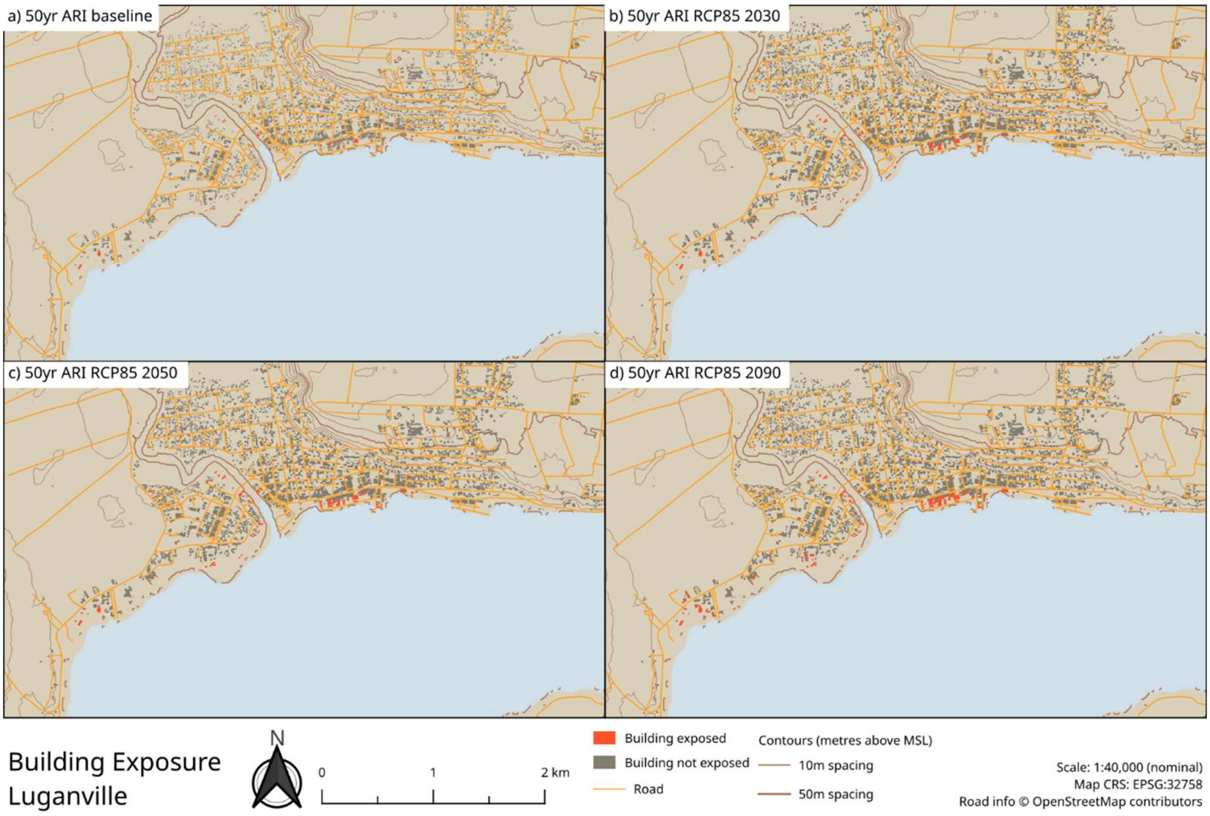

Figure 10 Same as Figure 8 except for the Sarakata catchment.

3.1.1 Building Replacement Cost

The replacement costs (in USD) associated with the coastal inundation over the two regions (i.e., combined) for the four periods, two scenarios and two ARIs are shown in Table 3 and Figure 11. As expected, the replacement cost is higher for a 100-year ARI event in comparison to a 50-year ARI event. For a 50-year event, the total cost in the future climate, in comparison to the baseline period replacement cost of USD 59 million, could range from USD 74 million by 2030 for low emissions (7% of GDP) to USD 163 million (15% of GDP) by 2090 for high emissions, whereas for a 100-year event (that has a baseline replacement cost of USD 67 million) the cost could be USD 83 million by 2030 for low emissions (8% of GDP) to USD 174 million by 2090 for high emissions (16 % of GDP).

Table 3 Replacement cost of buildings exposed, grouped according to the different LGAs about the Mele Catchment (unshaded) and Sarakata Catchment (shaded). Estimates are given for the baseline period B (1980-2020) and 20-year periods centred on 2030, 2050 and 2090, for low (RCP2.6) and high (RCP8.5) emissions scenarios, for inundation events for 50-year and 100-year ARIs.

Total Value of Buildings		**Replacement cost of Buildings Exposed (USD million)**														
Region	**Value (USD million)**	**ARI = 50 Years**							**ARI = 100 Years**						
			RCP 2.6			**RCP 8.5**				**RCP 2.6**			**RCP 8.5**		
		B	**2030**	**2050**	**2090**	**2030**	**2050**	**2090**	**B**	**2030**	**2050**	**2090**	**2030**	**2050**	**2090**
Erakor	106	2.0	2.4	3.7	6.5	2.5	4.6	8.9	2.0	3.0	4.6	6.8	3.0	5.5	9.5
Eratap	82	4.2	4.8	6.3	6.5	4.9	6.3	7.5	4.5	5.4	6.3	6.5	5.8	6.3	7.9
Eton	10	0.6	0.8	0.9	0.9	0.8	0.9	0.9	0.8	0.9	0.9	0.9	0.9	0.9	0.9
Ifira	35	2.2	4.5	5.4	6.3	4.5	5.9	7.1	4.4	5.4	5.9	6.3	5.4	5.9	7.7
Mele	125	2.1	2.2	2.5	5.2	2.4	2.7	6.1	2.2	2.5	2.8	5.2	2.5	3.0	6.6
N Efate	13	0.2	0.3	0.3	0.3	0.3	0.3	0.4	0.3	0.3	0.3	0.3	0.3	0.3	0.4
Pango	48	0.2	0.5	0.6	1.3	0.6	1.0	3.2	0.2	0.6	1.1	2.1	0.6	1.3	4.7
Port Vila	2089	37.2	44.6	51.6	63.7	45.8	56.2	88.4	38.9	49.2	56.4	68.0	50.2	60.1	91.8
Luganville	556	9.4	12.2	13.6	19.4	12.4	15.9	34.1	11.8	13.4	15.9	22.1	13.4	17.5	37.8
SE Santo	91	0.9	2.0	2.6	4.2	2.0	3.3	6.4	1.8	2.3	3.3	4.4	2.4	3.6	6.4
Total	**3155**	**59**	**74**	**88**	**114**	**76**	**97**	**163**	**67**	**83**	**98**	**123**	**85**	**104**	**174**

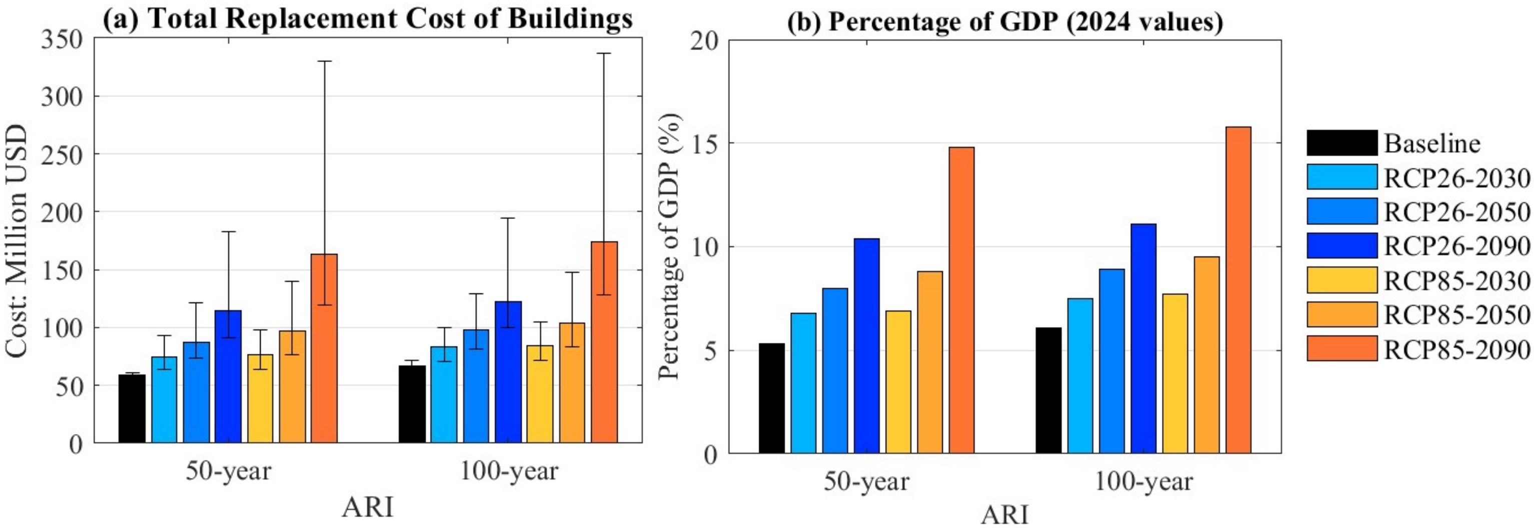

Figure 11 (a) Total replacement cost of exposed buildings and (b) replacement cost as a percentage of GDP (2024 values) for 50- and 100-year ARIs, for baseline (1980-2020), low (RCP2.6) and high (RCP8.5) emissions scenarios for 2030, 2050 and 2090. The error bars show the 5th and 95th percentile building replacement cost.

When stratified by the different LGAs, the bulk of the replacement cost (Figure 12) under future climate scenarios for the Port Vila/Mele catchment is over Port Vila LGA (USD 44.6 million by 2030 for low emissions to USD 88.4 million by 2090 for high emissions for the 50-year ARI, and USD 49.2 million by 2030 for low emissions to USD 92 million by 2090 for high emissions for the 100-year ARI), while the rest of the LGAs have costs below USD 10 million combined under all scenarios and periods.

Over the Luganville/Sarakata catchment, Luganville LGA has the highest estimated building replacement cost (USD 12.2 million by 2030 for low emissions to USD 34.1 million by 2090 for high emissions for a 50-year ARI, and 13.4 million by 2030 for low emissions to USD 37.8 million by 2090 for high emissions for a 100-year ARI) compared to SE Santo LGA (USD 2.0 - 6.4 million and 2.3 - 6.6 million respectively for 50- and 100-year ARIs).

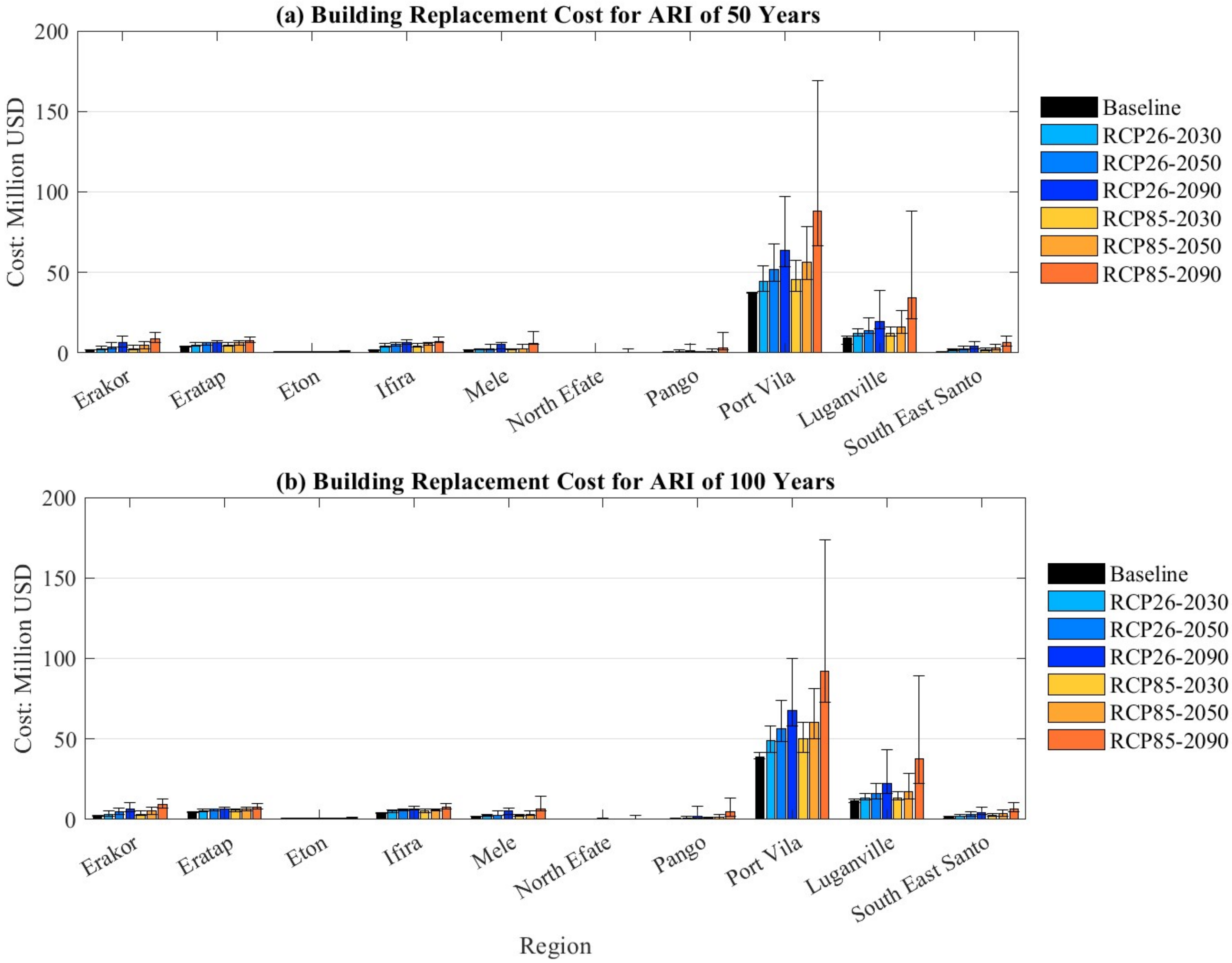

Figure 12 Building replacement cost for 50- and 100-year ARIs grouped by LGAs, for low (RCP2.6) and high (RCP8.5) emissions scenarios for 2030, 2050 and 2090. The error bars show the 5th and 95th percentile building replacement cost.

3.2 Roads

For the baseline period, 12.7 and 14.5 km of roads are exposed for the 50- and 100-year ARIs, respectively (Figure 13a and b).

In future, for the 50-year ARI, exposure ranges from 16.3 km by 2030 to 25.1 km by 2090 (equivalent to 1% of the total length of roads) in a low emissions scenario, and from 16.6 km by 2030 (1%) to 39 km by 2090 (2%) for a high emissions scenario (Figure 13).

For the 100-year ARI, the exposure ranges from 18.7 km by 2030 to 28.1 km (1%) by 2090 for low emissions, and from 19.1 km by 2030 (1%) to 42.9 km by 2090 (2%) for high emissions (Figure 13).

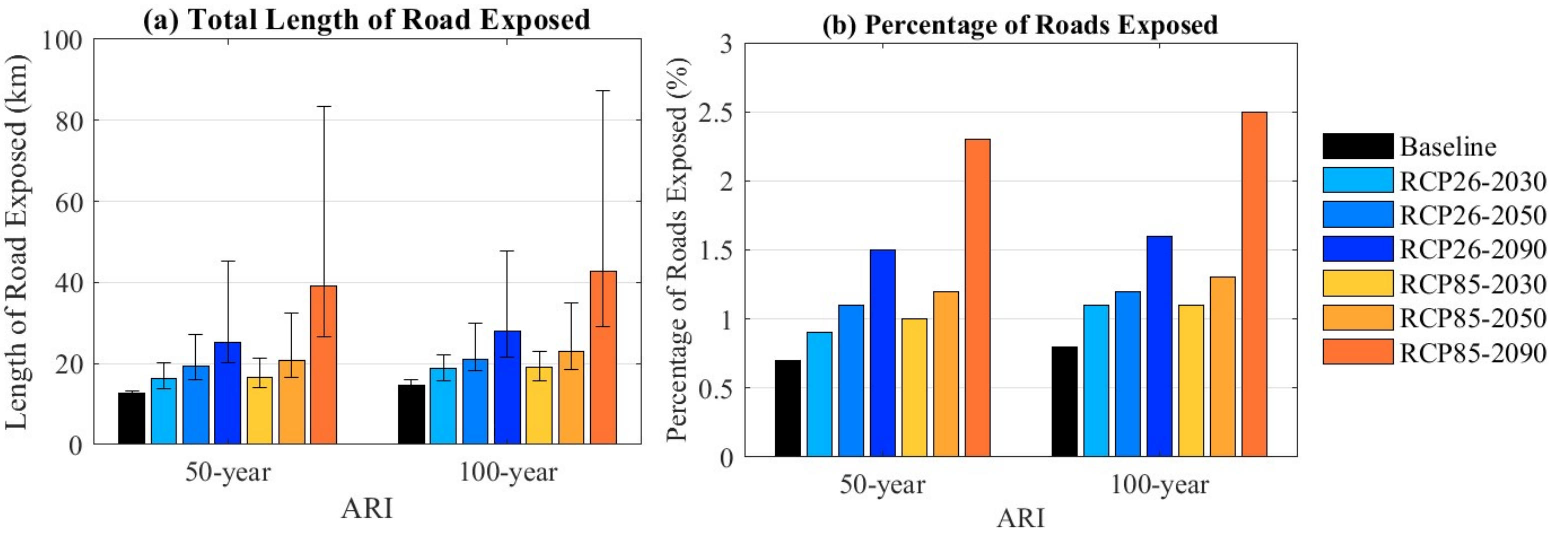

Figure 13 (a) Total length and (b) percentage of roads exposed for 50- and 100-year ARIs, for low (RCP2.6) and high (RCP8.5) emissions scenarios for 2030, 2050 and 2090. The error bars show the 5th and 95th percentile road exposure.

The road exposure for the two study areas has further been subdivided into 13 LGAs. Table 4 shows the lengths of roads exposed for each LGA which are also graphically depicted in Figure 14. Over the Port Vila/Mele catchment, Erakor and Malorua tend to have the highest length of road exposed, while Ifira and Pango have the least exposure. For example, for a 50-year ESL event, by 2050 in Erakor, the exposure is 2.7 km for a low emissions scenario and 2.9 km for a high emissions scenario, relative to a baseline of 2.0 km. Exposure is larger by 2090, especially for a 100-year ESL event.

Table 4 Length of road exposed, grouped according to the different regions within the Mele catchment (unshaded) and Sarakata catchment (shaded). A total of 1721.1 km of roads fall within these regions. B is the baseline period (1980-2020).

Total Length of Roads (km)		**Length of Roads Exposed (km)**													
Region	**Length**	**ARI = 50 Years**							**ARI = 100 Years**						
			RCP 2.6			**RCP 8.5**				**RCP 2.6**			**RCP 8.5**		
		B	**2030**	**2050**	**2090**	**2030**	**2050**	**2090**	**B**	**2030**	**2050**	**2090**	**2030**	**2050**	**2090**
Erakor	114.8	2.0	2.4	2.7	4.0	2.4	2.9	5.8	2.3	2.7	3.0	4.2	2.7	3.4	6.3
Eratap	175.5	0.8	0.9	1.0	1.5	0.9	1.2	3.0	0.9	0.9	1.2	1.7	0.9	1.3	3.6
Eton	283.1	0.8	1.3	1.5	1.8	1.3	1.6	2.2	1.2	1.5	1.6	2.0	1.5	1.7	2.3
Ifira	1.4	0.2	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
Malorua	177.4	2.0	2.6	2.8	3.2	2.7	2.9	4.9	2.2	2.8	2.9	3.8	2.8	3.1	5.2
Mele	54.5	0.5	0.9	1.1	1.6	0.9	1.2	2.3	0.7	1.0	1.2	1.7	1.1	1.4	2.5
N Efate	45.9	0.9	1.0	1.2	1.5	1.0	1.3	2.7	1.0	1.2	1.4	1.8	1.2	1.4	3.0
Pango	22.1	0.3	0.3	0.3	0.3	0.3	0.3	1.3	0.3	0.3	0.3	0.6	0.3	0.3	1.6
Port Vila	187.2	0.8	1.4	1.9	2.6	1.4	2.1	3.9	1.0	1.8	2.1	2.7	1.8	2.3	4.2
C-Fanafo	244.4	0.7	0.8	1.2	1.7	0.9	1.3	3.0	0.7	1.1	1.3	2.1	1.1	1.5	3.4
Luganville	119.4	0.4	0.5	0.8	1.0	0.5	0.8	1.1	0.4	0.8	0.8	1.0	0.8	0.9	1.2
SE Santo	219.0	2.8	3.5	4.2	5.2	3.5	4.5	7.9	3.1	4.0	4.6	5.8	4.1	4.9	8.6
S Santo	76.5	0.4	0.4	0.5	0.5	0.4	0.5	0.6	0.4	0.5	0.5	0.5	0.5	0.5	0.7
Total (km)	**1721.1**	**12.7**	**16.3**	**19.4**	**25.1**	**16.6**	**20.7**	**39.0**	**14.5**	**18.7**	**21.1**	**28.1**	**19.1**	**22.9**	**42.9**

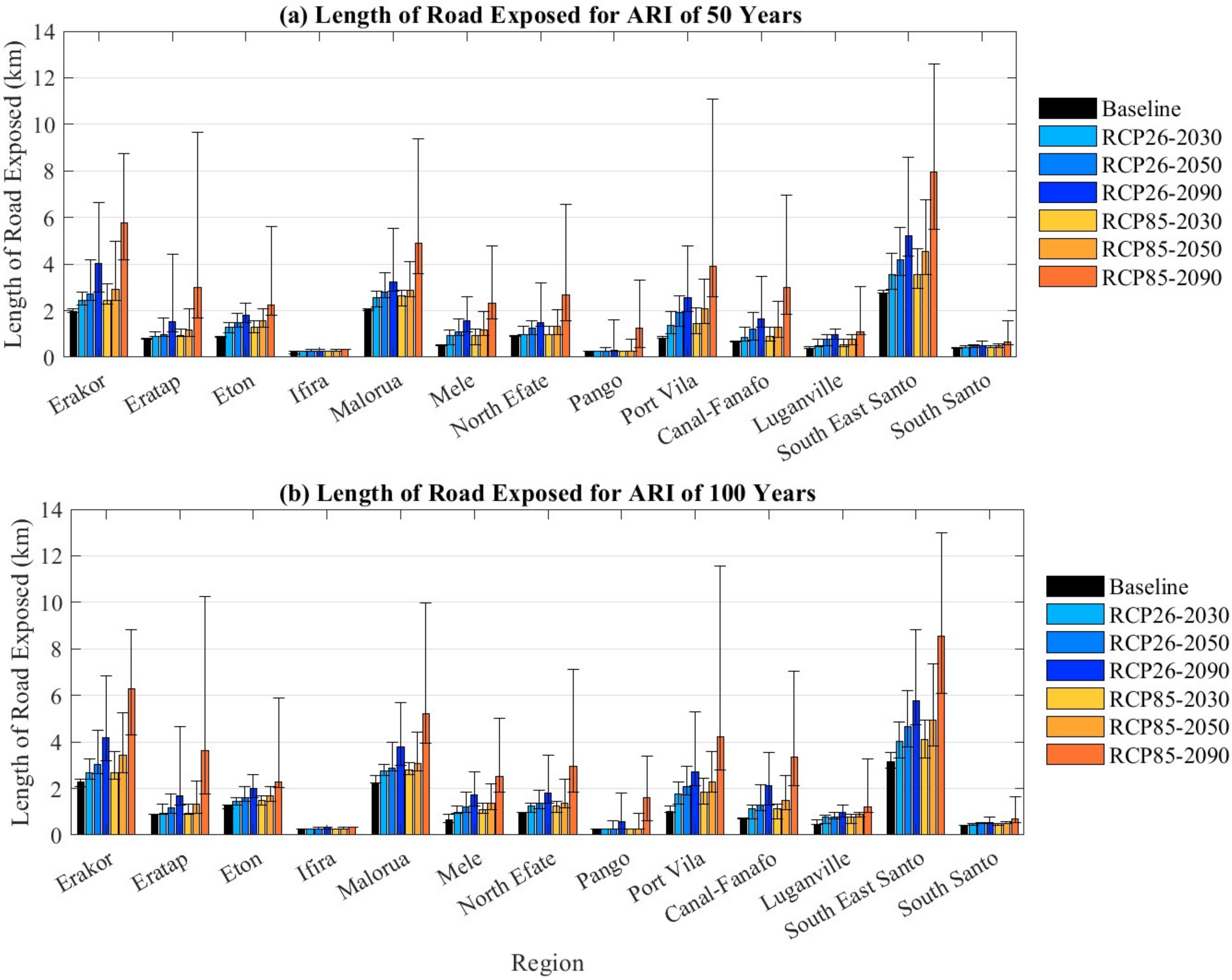

Figure 14 Length of roads exposed for 50- and 100-year ARIs stratified by LGAs, for low (RCP2.6) and high (RCP8.5) emissions scenarios for 2030, 2050 and 2090. The error bars show the 5th and 95th percentile road exposure.

3.2.1 Road Replacement Cost

The replacement cost of inundated roads over the two study areas combined is shown in Figure 15. The cost is higher for a 100-year ARI event in comparison to a 50-year event. For a 50-year event, the baseline replacement cost is USD 1.1 million while the future cost (Figure 15a) is from USD 1.4 million by 2030 for low emissions to USD 3.3 million by 2090 for high emissions (i.e. 0.1 - 0.3 % of GDP: Figure 15b). For a 100-year event, the baseline replacement cost is USD 1.2 million, while the future cost is USD 1.6 million by 2030 for low emissions to 3.6 million by 2090 for high emissions (or 0.1 - 0.3 % of GDP).

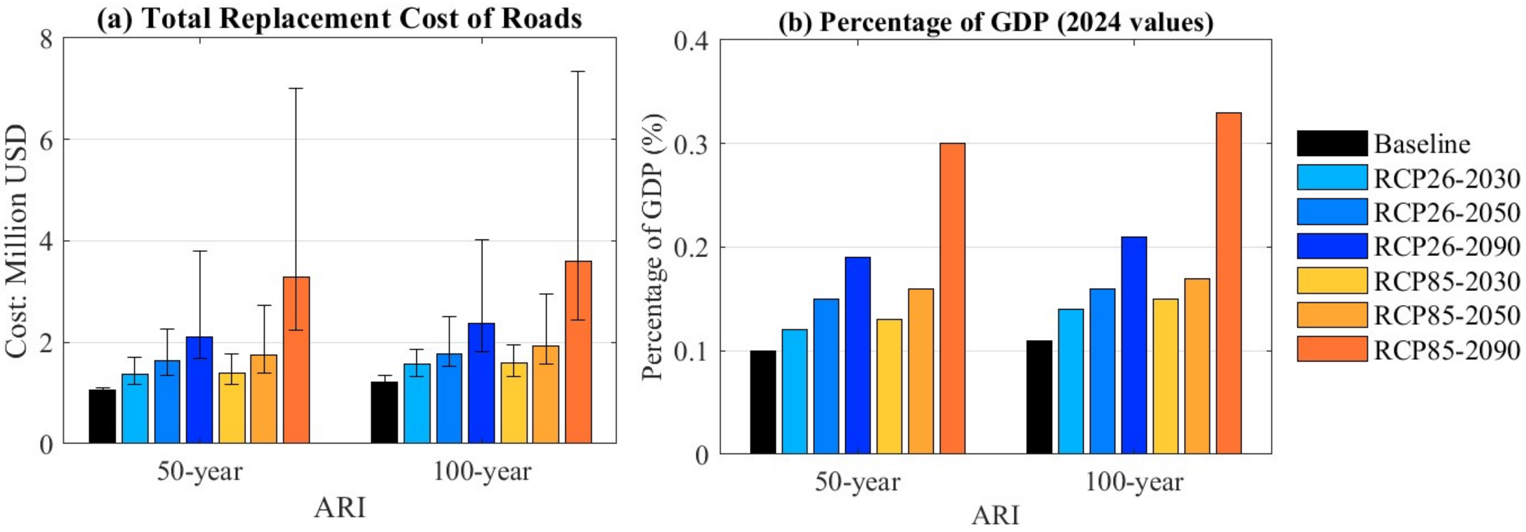

Figure 15 (a) Total replacement cost of exposed roads and (b) replacement cost as a percentage of GDP (2024 values) for 50- and 100-year ARIs for baseline (1980-2020), low (RCP2.6) and high (RCP8.5) emissions scenarios for 2030, 2050 and 2090. The error bars show the 5th and 95th percentile road replacement cost.

When stratified by the different LGAs (Figure 16), Erakor and Malorua have the highest replacement costs for the Mele catchment, while Ifira has the lowest costs (Figure 16a and b). Southeast Santo has the highest replacement costs for the Sarakata catchment, followed by Canal Fanafo, Luganville and South Santo.

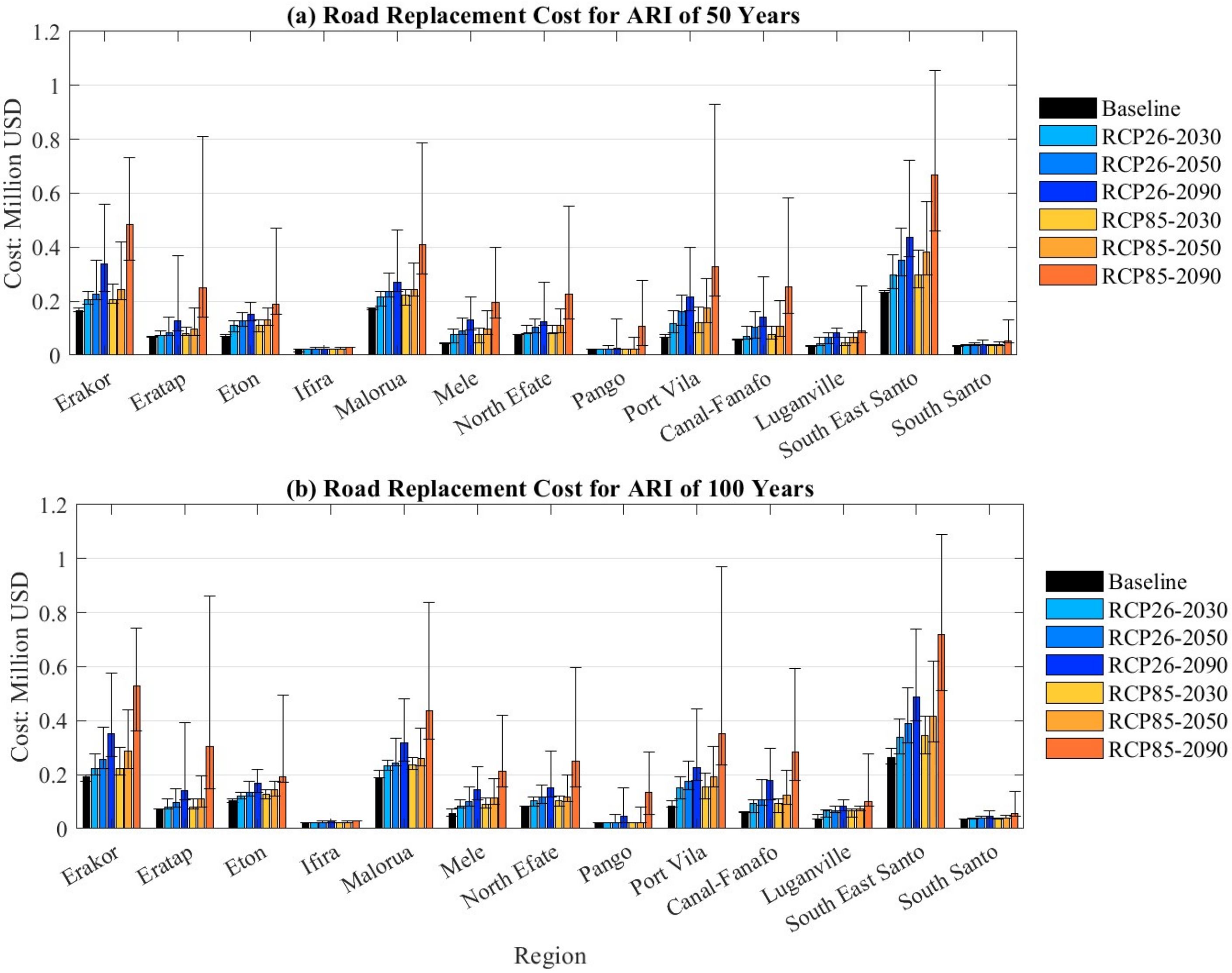

Figure 16 Road replacement costs for 50- and 100-year ARIs grouped by the LGAs, for baseline (1980-2020), low (RCP2.6) and high (RCP8.5) emissions scenarios for 2030, 2050 and 2090. The error bars show the 5th and 95th percentile road replacement cost.

4. Discussion

Estimates of the economic impacts of recent and future coastal inundation for roads and buildings in two Vanuatu study areas have been undertaken for two greenhouse gas emissions scenarios, as part of the Van-KIRAP project. These analyses are designed primarily to elucidate the expected value (costs and benefits) of the development and application of science-based 'climate information services' (CIS: data and information products designed to inform risk assessment, disaster risk management and adaptation planning) to the economy of Vanuatu. These analyses are based on a robust methodology that combines recent and future ESL and coastal inundation data from the Van-KIRAP project with detailed information about road and building exposure and replacement value.

This study provides exposure and economic impact estimates for buildings and roads for 13 LGAs in two relatively densely populated locations (Port Vila and Luganville). For buildings, by 2050, for an inundation event with a 50-year return interval, costs could be up to USD 87 million (8 % of GDP) for a low emissions scenario or USD 97 million (9 % of GDP) for a high emissions scenario, in comparison to the baseline (1980-2020) cost of USD 59 million (5 % of GDP) across both catchments. For roads, by 2050, for an equivalent event, costs could be USD 1.6 million (0.15 % of GDP) for a low emissions scenario or USD 1.7 million (0.16 % of GDP) for a high emissions scenario, in comparison to the baseline cost of USD 1.1 million (0.1 % of GDP). This information represents an important new line of evidence informing risk assessment at a scale relevant to the national economy; thereby demonstrating the functionality and utility of this approach for broader applications going forward (e.g. for other hazards and sectors as part of new national disaster risk assessment, adaptation planning and associated policy development.

The RiskScape analytical tool together with relevant asset data has been employed in other regions and countries to map exposure and/or economic impacts associated with coastal inundation and climate change (e.g., Allis et al. 2020, Paulik et al. 2021 and Wandres et al. 2023). For example, Allis et al. (2020) quantified Nauru's exposure (excluding economic cost) to king-tide coastal flooding events under recent (1993-2019) and future conditions for various asset classes. Their results showed that the level of exposure for the various asset classes increases over time in response to rising sea levels. In another study, Paulik et al (2021) evaluated changes to building exposure and economic loss from tsunami-driven inundation in southeast Upolu Island, Samoa. These studies, together with the methodology presented in our paper, have broader relevance to the Pacific region, especially given the high exposure and vulnerability of people and assets in the coastal zone (Kumar and Taylor, 2015; Andrew et al., 2019).

A major difference, however, exists between the damage function used here and that used by Paulik et al. (2021). Paulik et al. (2021) estimate physical building damage from empirical fragility curves representing Samoan buildings damaged in the 2009 South Pacific tsunami inundation. The fragility curves apply a cumulative lognormal function for 'timber', 'masonry' and 'reinforced concrete' building construction frame typologies to determine the conditional probability (0 – 1) of "light", "minor", "moderate", "severe", and "collapse" damage states (DS) being reached or exceeded for a maximum tsunami inundation depth. The present study over Vanuatu, however, considers a simple damage function based on 100 % of the re-build cost, assuming the inundation impacts render the buildings no longer able to be used for intended purposes and therefore in need of complete re-build and/or major structural repairs.

Likewise, for roads, the damage function is based on 100 % of the re-build cost for relevant road types (sealed, un-sealed/gravel etc), assuming the inundation impacts render the roads no longer able to be used for intended purposes and therefore in need of complete re-build and/or major structural repairs. Thus, these assumptions could lead to overestimation of asset replacement/repair cost which, therefore, should be taken into consideration.

However, there could be some underestimation of the economic impacts due to the following factors:

(i) Buildings data from the Open Street Map (OSM) layer have not been included in the database due to the unavailability of ground truthing information needed for modelling (Thompson Auri (SPC), Personal Communication).

(ii) Assumption of replacing rather than improving buildings and roads. Enhancing climate resilience after disasters requires 'building back better', which may involve higher initial costs for greater long-term benefits. This requirement may be included in updated building standards in future.

(iii) The ESL return period levels used here are likely to be conservative (biased low). The Van-KIRAP ocean hazard modelling system simulates the probabilistic combined effects of tides, storm surge, storm waves, annual sea level variability and sea level rise but does not include individual wave runup (which may be locally import, e.g. via overtopping of sea walls) or compound flooding associated with combined marine (storm surge plus tide) and pluvial/fluvial (river and rainfall) processes.

(iv) Lower average estimates of road replacement cost (USD per km). Roads in Vanuatu are mostly either Double Bituminous Surface Treatment (DBST) or gravel and only small sections are comprised of asphalt (Department of Water Resource, Government of Vanuatu). The replacement cost (inclusive of labour cost) of DBST ≈ USD 100, 000 per km, Asphalt ≈ USD 400,000 per km and Gravel ≈ USD 70,000 per km (asphalt is almost 4-6 times the cost of DBST and gravel). For this study, the average replacement cost (per km) is used since detailed information about the inundated road types is currently not available in the database. However, given the large difference in the cost between asphalt and the other two types, the average replacement cost is computed only using DBST and gravel (to avoid bias towards asphalt). A more accurate estimate of the replacement cost would require the aggregation of the cost associated with each type of road inundated, and this could be considered in future studies when such information becomes available for Vanuatu.

(v) Full cost of economic impacts. The analysis is limited to direct replacement values. It does not cover associated indirect and intangible costs such as business and supply-chain disruption, emergency response, evacuation, temporary housing, clean-up, fatalities, injuries, mental health issues, and chronic diseases (Deloitte, 2017, 2021). These costs can cascade and compound across multiple inter-dependant sectors and systems (e.g. transport including ports/harbours and airports, health, education, energy, tourism, water, fisheries and agriculture etc). Moreover, costs may be greater if there is a policy to 'build back better' to enhance climate resilience. It follows that the full cost of coastal road inundation to the economy of Vanuatu is likely to be significantly greater than what is cited in this report.

While the intensity and frequency of inundation have been assessed in the study, the duration of inundation has not been assessed. Short-duration events (e.g., 1 hour) may cause nuisance flooding with minor impacts while long-duration events (e.g., 1-3 days) may cause significant flooding with major impacts. In this context, the difference between minor and major impacts will potentially result in significantly different estimates for the related costs of maintenance and/or replacement of inundated roads and buildings. ESL events include the combined effects of tides (peaking twice per day), storm surges (lasting hours to days), wind waves (lasting hours to days), sea level variability due to ENSO (lasting 6-12 months) and sea level rise (over decades). Further research is needed to produce intensity-frequency-duration (IFD) graphs, typically used by hydrologists and engineers, to assess projected changes in flood characteristics causing minor versus moderate versus major damage to assets. This would improve the damage function.

In terms of the next steps, the Vanuatu Climate Futures web portal includes a coastal risk mapping tool that could be augmented by the results presented in this paper. Some of the features from the Australian CoastAdapt tool could be incorporated into the Vanuatu Climate Futures web portal, such as the Coastal Climate Adaptation Decision Support (C-CADS) process and adaptation guidance. The *Coastal hazards and climate change guidance* for New Zealand councils (ME, 2024) also has relevance to the Pacific region, using Dynamic Adaptation Planning Pathways in a ten-step process. The learnings from this analysis, including the methodological approach developed through the Van-KIRAP project, have the potential for broader application both in Vanuatu and elsewhere in the Pacific. This is particularly the case as risk managers, policy analysts and adaptation planners seek to better understand the full costs, impacts and associated interdependencies of future climate change as part of the emerging 'loss and damage' dialogue in the Pacific.

5. Conclusions

This report estimates building and road exposure to coastal inundation from extreme sea level events focussed on the Mele catchment (Efate) and Sarakata catchment (Espiritu Santo), in Vanuatu. Extreme sea level heights were derived from the Van-KIRAP project for events with 50 and 100-year average return intervals for baseline conditions (1981-2020) and future conditions centred around 2030, 2050, and 2090 for low and high emissions scenarios (Hoeke et al, 2024). The associated economic impacts were based on replacement cost estimates from the Pacific Hub Data portal and PCRAFI database, using the RiskScape analysis tool.

For a 50-year event, across both catchments, the total replacement cost of exposed buildings by 2050 could be USD 87 million (8 % of GDP) for a low emissions scenario or USD 97 million (9% of GDP) for a high emissions scenario compared to the baseline cost of USD 59 million (5 % of GDP). These values almost double for a high emissions scenario by 2090 (15-16% of the GDP for 50 and 100-year return intervals).

For a 50-year event, across both catchments, the total replacement cost of exposed roads by 2050 could be USD 1.6 million (0.1 % of GDP) for a low emissions scenario or USD 1.7 million (0.2 % of GDP) for a high emissions scenario compared to the baseline cost of USD 1.1 million (0.1 % of GDP). These values almost double for a high emissions scenario by 2090 (USD 3.3 to 3.6 million for 50 and 100-year return intervals).

However, the extent of exposure and associated costs vary considerably between different council levels. For buildings, Port Vila has the highest exposure and replacement cost in the Mele catchment, while Luganville has the highest exposure and replacement costs in the Sarakata catchment. For roads, Erakor and Malorua have the largest exposure and replacement costs in the Mele catchment, while Southeast Santo has the highest exposure and replacement costs in the Sarakata catchment.

Given the increasing level of coastal inundation in a warming climate with ongoing sea-level rise, the results from this study have significant implications for disaster risk management and future council planning over Vanuatu.

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