Coastal flooding from sea-level rise in Nauru: Stage 1 - static inundation mapping

Prepared for the Nauru Higher Ground Project

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Executive summary

This report presents Nauru's exposure to king-tide coastal flooding events under present-day and future higher sea levels using a static "bathtub" model but excluding coastal wave effects.

This report is part of the Nauru Higher Ground study which will look at incorporating climate change adaptation considerations into the current Nauru Higher Ground rehabilitation Project, with a focus on preparing for a proactive approach to internal relocation in response to the effects of climate change and sea-level rise.

The RiskScape software tool and associated impacts and loss calculation framework were used to generate the exposure scenarios in this study. RiskScape combines hazard (i.e., coastal flooding) with asset data inputs (i.e., buildings, population) to estimate exposure (i.e., in or out of flooded area) with a rising sea level.

Methodology

The baseline coastal flooding elevation was determined from the "king-tide" elevation established from the tide gauge data from 1993-2019. King tides are a position on land where the sea will reach relatively frequently but also represents where common geomorphic markers exist as related to the frequent wetting and drying of land and vegetation. The selected event approximates a present-day king-tide sea level elevation with 1% annual exceedance probability. This is 2.7 m elevation relative to Nauru Island Datum (NID), i.e., KT1 = 2.7 m NID. This means only 1% of all high tides each year are higher than this elevation at present-day sea levels, and there are approximately 5 tides above this elevation each year.

Sea-levels rise have *already* risen over the last few decades causing an increased to the number, duration and depth of KT1 events. The analysis shows that there are now more 7.8 more hours per year when the sea level is above KT1, compared to in the early 1990s. *Future* sea-level rise (SLR) will continue to increase the number, duration and depth of tides above this KT1 elevation, with an associated increase to the area that is flooded each time.

Future sea-level rise for Nauru is incorporated into these exposure assessments using the recent projections from IPCC[1] Special Report on Oceans and Cryosphere in a Changing Climate (SROCC) measured above the 1986-2005 baseline mean sea level (MSL). The SROCC projections include scenarios for higher and lower global emissions. By 2100, sea levels will rise between 0.43 m under lower emissions scenarios and 0.84 m under higher scenarios but could be higher when accounting for uncertainty in the model predictions and local deviations. Beyond 2100 sea level will continue to rise for centuries due to continuing deep ocean heat uptake and mass loss of the global ice sheets and Antarctic ice sheets and will remain elevated for thousands of years. The IPCC projections for 2300 are less certain and range from about 1–2 m under low emissions trajectory up to 2–5.5 m for the high emissions trajectory. These projections exclude the small contribution from the slow regional subsidence in Nauru which may contribute to a *relative* rise in sea level.

Six SLR increments were selected for this high-level study; 0.2, 0.35, 0.5, 1, 1.5 and 2 m above present-day king-tide elevation. Using the SROCC higher and lower emissions trajectories, the earliest occurrence of these sea levels is 2040, 2055, 2070, 2110, 2150, 2190, respectively, but they may not occur for centuries under the most optimistic (low emissions) trajectories but could occur sooner if global emissions are unrestrained. These SLR increments are added to the KT1 elevation to

[1] Intergovernmental Panel for Climate Change

simulate the elevation of future king-tides after increments of SLR (i.e., KT1 + 0.5 m SLR = 3.2 m NID, and other increments).

Coastal flood inundation was mapped for low-lying coastal land by projecting the KT1 + SLR increments, onto the high-resolution digital elevation models (i.e., topographic models) of Nauru. Static inundation mapping (i.e., “bathtub” mapping) is then employed to show the land and assets which are *below* this elevation. Note that this static mapping excludes wave processes which wash inland and uphill from this coastline at the static elevation (waves do not occur within lagoons), further exposing assets to wave hazards. Future studies and in-country ground-truthing are required to simulate and validate the effect and hazard from wave processes with SLR.

The elements assessed were pre-existing datasets obtained from SPC. All databases remained unchanged except for the buildings and tanks databases which were updated from 2018 and 2020 aerial photographs but not ground-truthed. Elements at risk and exposed to each KT1+SLR coastal flood inundation scenario included:

- land area
- population (based on 100 m population grid and assumed to reside in residential buildings)
- buildings (5 primary use categories: Commercial, Industrial, Infrastructure, Public and Residential)

  tanks (all types, including water and septic)
- transport infrastructure (roads, airport)
- electricity infrastructure (electricity poles)
- coconut crop areas (as a proxy for potential productive land area).

Results of the exposure of each element to KT1+SLR increments are presented by way of graphs and tables, at district and national level, and supplemented with maps.

Results

At national level, elements at risk generally demonstrate a consistent increase in exposure in response to rising sea levels. Exposure increase at district levels exhibits non-linear behaviors with average exposure rates accelerating in response to SLR up to +2 m and the position/elevation of the assessed element.

Overall, the elevation of the coastal plain between the beach and the escarpment is the primary driver of exposure to future king-tide inundation with sea-level rise (excluding wave processes). This coastal plain contains much of Nauru’s assets, buildings, population and potentially productive land. Within this coastal plain, the ground elevation is highest (7-8 m NID) around the west/north west fringe (including the districts of Aiwo, Denigomodu, Nibok, Uaboe and Baiti, and the north-western end of the airport runway) and is hence the least exposed under the scenarios tested. Conversely, the low-lying land around lagoons and backshore depressions have the lowest elevation (2-4 m NID) and are the most exposed, particularly around lagoons on the southern, eastern and northern shorelines (i.e., Meneng, Anabar, Ijuw and Yaren).

Table 1-1 below summarises the national level exposure of assessed exposure datasets after increments of SLR.

Table 1-1: Summary of asset exposure to king-tide inundation with increments of sea-level rise in Nauru. [refer to text for details].

Sea-level rise above present-day king tide elevation (m)	Approx timing (decade)	Asset exposure							
		Land area (m^2)	Population (#)	Buildings (all types) (#)	Road length (m)	Tanks (#)	Electricity poles (#)	Coconut crop features (m^2)	Paved airport runway (m^2)
Nauru total	-	21,395,550	12,781	2,471	72,511	790	773	1,093,150	0
0	Present day	240,825	46	13	382	7	2	91,825	0
0.2	2040	306,675	121	31	624	11	2	117,825	0
0.35	2060	357,575	178	49	907	17	2	138,275	0
0.5	2070-2130	417,400	335	71	1,232	26	2	160,225	0
1	2110 or later	631,850	757	154	2,665	62	6	227,775	0
1.5	2150 or later	866,650	1,325	265	4,015	100	27	282,625	0
2	2190 or later	1,193,150	1,988	449	6,188	155	67	345,450	0

The airport runway is not exposed under any mapped scenario. However, the grassed areas on either side of the landing strip are inundated under higher SLR scenarios.

Maps are also presented which indicate the *frequency* of flooding with sea-level rise. These maps show approximately how many days each year that the elevation of the sea (high tide) will be above the elevation of the land. This is important when considering vulnerability of crops and assets to more and more frequent inundation.

This study represents the first step in a vulnerability assessment for Nauru's population and assets in response to rising sea levels. The information provides the Government of Nauru and other planners with locations and information to focus more detailed investigation on the potential impacts of coastal flooding in Nauru under future sea-level rise and facilitate long-term land-use management and planning for Nauru.

These results and maps should be updated as new LiDAR data and new asset data is made available, and once future studies into the increasing risk from coastal storm-driven inundation and wave overwashing (with ground truthing) can be included - proposed for the next stage of this Project. We note that these results the overall exposure is expected to increase with the inclusion of wave processes, with the additional exposure concentrated around the coastal fringe.

1 Introduction

Land rehabilitation of Nauru's mined central plateau has been underway for a number of years to enable it to be used for development, farming and relocation of assets from low-lying areas. However, it is understood that the current rate and cost of rehabilitation (~2 ha and $1 m per year) may not be sufficient to relocate assets that will be exposed to sea-level rise.

Much of Nauru's development, built assets and infrastructure are located on a low-lying coastal fringe and are exposed to damage due to shoreline change and wave-related overtopping, overwash and inundation.

As sea-level rises, particularly over the latter half of this century and beyond, the frequency of wave overwash and high tide-related inundation will significantly increase. This coastal flooding hazard will increase risk exposure to existing buildings, infrastructure and population, will reduce habitable land area and cause land to become increasingly marginal for development and productive use. We understand that relocation of assets and infrastructure to the inland higher areas will be a fundamental component of Nauru's adaptation response to climate change.

Responding to this threat is likely to require:

- speeding up the rate of land rehabilitation to accommodate future relocation inland
- relocation planning to start now, given the time that it will take to plan and implement the relocation of key infrastructure such as the airport and communities.

Incorporating climate change adaptation considerations into the current Nauru Higher Ground rehabilitation Project, with a focus on preparing for a proactive approach to internal relocation in response to the effects of climate change and sea-level rise.

This report forms part of the feasibility study for the Higher Ground project.

1.1 Background to this report

Due to global travel restrictions at the time of the study, the initially proposed in-country investigation and validation study was not possible to meet the full original intentions of this component of the Higher Ground Project.

This revised (Stage 1) study constitutes a basic inundation modelling (a "bathtub" or "static" model) approach using a tide-only sea elevation that does not account for wave/storm effects.

The bathtub model simply means treating the ocean like a bathtub, where it fills up the same way that a bathtub does when you add water. The lower parts fill up first, and the water rises at the same level everywhere. For this Project, the bathtub level was set as a known "king-tide" elevation with increments of sea-level rise added above this elevation.

Wave processes which further elevate the sea-level at the shoreline (such as wave setup, runup and overtopping) are excluded from this bathtub assessment. Wave processes are too important and complex to broadly approximate and require some specific site investigation work to enable these processes to be incorporated. Inclusion of wave processes is recommended for the next phase of the Higher Ground Project; but this current assessment provides a sound initial first step in assessing both the future timing and impact of future sea-level rise on current development on Nauru.

The scope of work for this Project includes:

- Analyse Nauru tide gauge data to establish a suitable "king-tide" elevation for hazard mapping.
- Setup basic bathtub model outputs (1x present day, 6x sea-level rise scenarios).
- Update building footprints from newer aerial photographs.
- Riskscape assessment of asset exposure.
- Reporting by way of short report to enable Calibre engineers/planners to begin assessing the trends of land/asset/population exposure to SLR.

As such, this study represents the first step in a vulnerability assessment for Nauru with rising sea levels. Future studies should be completed to better account for the increasing risk from coastal storm-driven inundation and wave overwashing.

2 Methodology

2.1 Nauru Island

The Island of Nauru is a 21 km^2 oval-shaped island in the southwestern Pacific Ocean which is divided into fourteen administrative districts (Figure 2-1). The island is a raised atoll, with land elevation up to around 70 m above current sea level. The surface of the raised atoll is characterised by limestone pinnacles with the depressions between these pinnacles filled with seabird deposited guano which has been mined for phosphate. The uplifted interior is surrounded by a 50–120 m wide fringing coral reef, which is exposed at low tide and dotted with rock pinnacles. A fertile coastal plain 150–300 m wide lies inland from the beach and at the base of the uplifted escarpment (Figure 2-1).

The coastal plain was built up by wave action breaking-down and transporting coral reef material from the fringing reef. This sand and other material deposited by waves or wind piled up between the reef and at the base of the escarpment (Jacobsen and Hill 1988). The height of the plain is a function of the wave exposure, with larger waves from the northwest creating a 7-8 m higher barrier but smaller waves from the south, east and north shorelines creating a 4-6 m high barrier (Figure 2-1). Inland from the barrier and at the base of the uplifted escarpment, the plain includes low-lying lagoons, depressions and overwash drainage paths with elevations of 2-3 m (Figure 2-1).

It is the exposure of this low-lying coastal plain which is of interest to this sea-level rise study as most of Nauru's population inhabit the coastal strip, with most assets, infrastructure and roads also on the plain.

Figure 2-1 illustrates the Island topography used in this analysis. The land elevation dataset was obtained from the Pacific Community (SPC) 1 m gridded data from airborne LiDAR topography flown in 2014. The data was converted to 5 m x 5 m gridded points for the risk assessment.

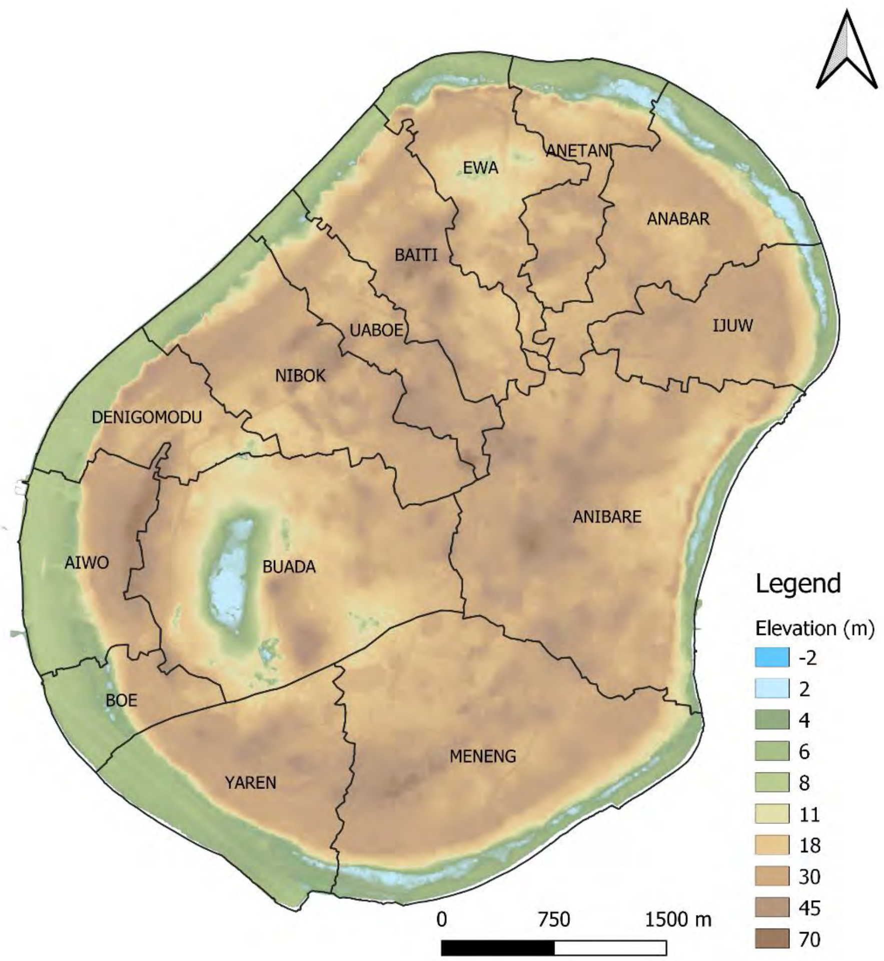

Figure 2-1: Map of the districts and elevations of Nauru referred to in this study. Colour represents elevation in metres above NID. Colours scale nonlinear to illustrate high/low topography on coastal flat below escarpment [*Data source*: SPC].

2.2 Riskscape exposure relationships

The RiskScape software tool and associated impacts and loss calculation framework described by Schmidt et al. (2011) was used to generate the exposure scenarios in this study. RiskScape combines hazard with asset data inputs, along with vulnerability relationships that describe the response of an asset to a given hazard intensity, to estimate desired exposure and/or loss results (Figure 2-2).

Specific hazards and assets datasets used in this study, as well as exposure relationships, results and limitations are described in sections below, with further technical details on datasets contained in the RiskScape Technical Annex (Appendix D).

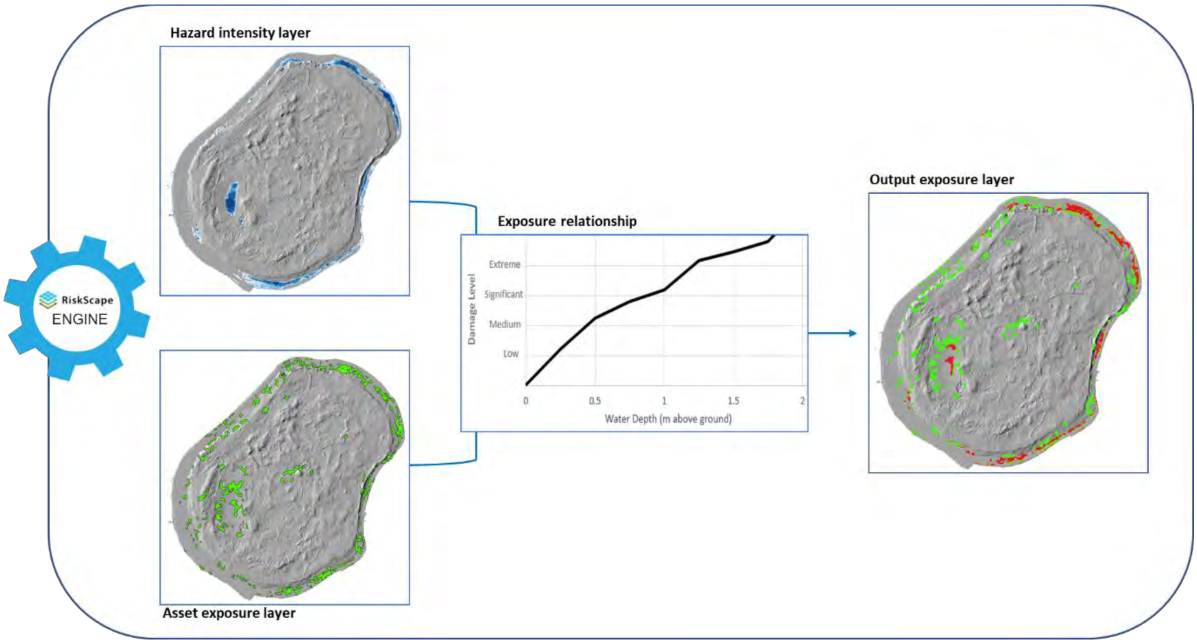

Figure 2-2: Simplified RiskScape exposure estimation workflow framework.

Exposure to inundation for each asset layer (i.e., Table 2-1) was estimated using a simple relationship whereby any asset feature that intersected with the flood inundation extent (i.e., flood depth > 0 m) for each sea level scenario was classified as 'exposed'.

The exposure is classified according to the inundation depths.

Exposure	Inundation depth (m)
None	0
Moderate	≤ 0.2 m
High	≥ 0.2 m to < 0.5 m
Extreme	≥ 0.5 m

2.3 Datasets

Key asset data sources, and modifications made prior to using them as inputs to the exposure analysis in RiskScape, are summarised in Table 2-1.

A full description of the datasets deployed to analyse the vulnerability to sea-level rise is contained in Appendix D.

Table 2-1: Asset data sources and modifications for exposure analysis in RiskScape.

Asset layer[1]	Format	Source / Year of Creation	General Description	Modifications for Analysis
Buildings	Polygons (shapefile)	SPC / 2015	Distribution of building footprints	New buildings digitized using 2018/2020 satellite basemaps. Simplified to only five primary use categories; Commercial Industrial, Infrastructure, Public and Residential. 2018 was from SPC 2020 credit Google Earth
Roads	Lines (shapefile)	SPC / 2000	Distribution of roads	Segmented into 1m interpolated points along entire road length.
Airport	Lines (shapefile)	SPC / 2015	Outline of airport landing ground	Polygonized then converted to 1 m x 1 m gridded points.
Population	Raster (100m)	SPC / 2020	Distribution of population density (100m grid)	Polygonized then converted to 5 m x 5 m gridded points. Converted to population density (persons / m^2) within residential buildings for exposure analysis
Land Area	Raster (1m)	SPC / 2014	LiDAR topography data	Polygonized then converted to 5 m x 5m gridded points.
Coconut Crops	Polygons (shapefile)	SPC / 2000	Distribution of land class types	Filtered coconut crops only then converted to 5 m x 5 m gridded points.
Cadastre	Polygons (shapefile)	SPC / 2000	Distribution of cadastre	Converted to 5 m x 5 m gridded points.
Tanks	Polygons (shapefile)	SPC / 2000	Distribution of tanks	Validated/updated using 2019/2020 satellite basemaps.
Poles	Polygons (shapefile)	SPC / 2000	Distribution of poles	No changes made.
Districts	Polygons (shapefile)	SPC / 2015	Distribution of district boundaries	No changes made.

[1] Layers which contained ‘district ID’ only were joined with the ‘Districts’ layer to represent exposure distribution by ‘district name’.

2.4 Present-day king-tide elevation

The high-water value selected as the base elevation for this study is the elevation associated with king tides. The term “king tide” is commonly used to describe an especially high spring tide. King tides occur a few times every year, when the gravitational pull of the sun and moon upon the earth is strongest. This happens when the moon is closest to the earth in its monthly orbit. When this coincides with a spring tide, it will produce an especially high tide, or king tide. In the Pacific, the highest king tides often occur during the months from November to March, when the earth is also closest to the sun in its annual orbit.

King tides can also be related to a point on land where the sea will reach relatively frequently but also represents where common geomorphic markers exist as related to the frequent wetting and drying of land and vegetation. These also indicate where buildings and vegetation will be affected by sea water ingress, e.g.:

- Only specially designed coastal wharf/port structures will survive below this elevation.
- Generally, no-one would inhabit land below this elevation.
- Only hardy or seasonal few vegetation species will survive below this elevation.
- Driftwood and seaweed will be deposited at or above this point on the outer coastal fringe on each king tide.
- Waves will wash up the beach and inland *from* this point.
- Beach rock elevation is typically at the king-tide elevation.

Essentially, areas below the king-tide elevation should be considered “in the sea” as they are already inundated 5–6 times each year, with sea-level rise affecting future king-tide events.

The king-tide elevation selected for the base elevation of this sea-level rise analysis is defined here as the 1% exceedance elevation of the Nauru tide gauge record from 1993–2020. This means that approximately one in every 100 high tides is a king tide.

Analysis of the tide gauge data (Appendix B) determined[2] that **the king tide elevation is 2.7 m NID with *approximately* 1% exceedance probability at present-day sea levels** (KT1). The true exceedance probability of a 2.7 m NID tide gauge reading is 0.72%*,* and KT1 is 1.2723 m above MSL (1993-2020).

A 0.72% exceedance probability means that, *on average at the present day (i.e., in the recent past from 1993-2020)*:

- Only 5 tides per year are higher than KT1.
- The level of the sea exceeds KT1 every 70 days or every 2.3 months .

Note that in the tropical Pacific, king tides are generally clustered in the November to March window so the 70-day interval is representative only.

However, the aforementioned limitation on modelling wave runup/overtopping processes *excludes* the potential for additional risk and vulnerability for buildings and infrastructure that are near to the coast but above 2.7 m NID, i.e., damaging waves will wash inland and uphill from this elevation but the present study cannot resolve the wave processes.

[2] The true 1% tide gauge record elevation is 2.677 m NID. However, this was simplified to 2.7 m NID for this Project.

2.5 Sea-level rise

2.5.1 Recent sea-level rise in Nauru

The latest report from the Intergovernmental Panel on Climate Change (IPCC) is the Special Report on the Ocean and Cryosphere in a Changing Climate (SROCC) which states it is virtually certain[3] that the global mean sea level is rising and the rate of rise accelerating. SROCC establishes that the global mean sea level, as measured by tide gauges and altimetry observations, has accelerated over the 20th and 21st century (Table 2-2).

Table 2-2: Annualised rate of global mean sea level increase. All values are in mm/year. Values in brackets are uncertainties ranging from 5–95% [*Sources*: IPCC SROCC (2019), Martinez-Asensio et al. (2019)].

Parameter	Period	Rate (mm/year)	Source
Global MSL	1901–1990	1.38 (0.81–1.95)	IPCC SROCC (2019)
Global MSL	1970–2015	2.06 (1.77–2.34)	
Global MSL	1993–2015	3.16 (2.79–3.53)	
Global MSL	2006–2015	3.58 (3.10–4.06)	
Nauru	1974–2014	1.4 ± 1.0	Martinez-Asensio et al. 2019
Nauru	1993–2015	5.3 ± 2.5	Martinez-Asensio et al. 2019

Sea-level rise is not globally uniform and varies regionally. Thermal expansion, ocean dynamics and land ice loss contributions will generate regional departures of about ±30% around the GMSL rise. Differences from the global mean can be greater than ±30% in areas of rapid vertical land movements (IPCC SROCC 2019). In recent decades, the measured rate of relative SLR at Nauru has been higher than the global rate (Table 2-2) and may be related to vertical land movement (refer to Section 2.5.2 below). Overall, the relative MSL in Nauru is now (at 2020) about 150 mm higher than in it was in 1974 and has been increasing at 2.4 mm/year from 1974-2019 (Figure 2-3).

[3] IPCC SROCC findings are grounded in an evaluation of underlying evidence and agreement. IPCC designate terms to indicate the assessed likelihood of an outcome or a result: virtually certain is 99–100% probability

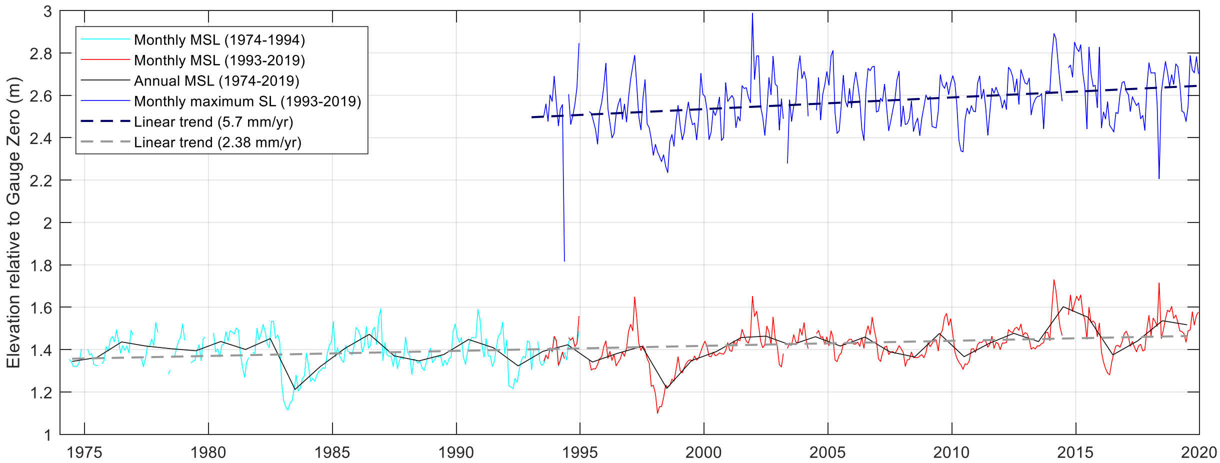

Figure 2-3: Increase in sea level at Nauru tide gauge 1974-2019. Dark blue line = monthly maximum recorded sea level (1993-2019), red/light blue = monthly mean sea level for two measurement periods, grey solid line = annual mean sea level (1974-2019). [*Data source*: PSLGM].

An increase in mean sea level also increases in the number and elevation of high-water events. In Nauru, the monthly maximum sea level (i.e., the highest tide each month) elevation has increased over 1993-2019 period at a rate of 5.7 mm/year (Figure 2-3). Relative to a fixed elevation, this increase has already led to more king-tide events, king-tide events of a longer duration and with higher water level in each event.

Figure 2-4 illustrates the *number of hours each year* where the measured mean level of the sea (the hourly average sea level) is above the KT1 elevation (2.7 m NID) and a more common tidal elevation of 2.5 m NID over the tide gauge record. This indicates that SLR has *already* caused the annual duration of sea-levels above the present-day king-tide elevation to increase from approximately 2.2 hours per year to 10 hours per year over the period 1993 to 2019, at a linear rate of an extra 0.55 hours each year. The lower reference value (2.5 m NID) has also increased from 35 to 94 hours/year over the same period, at a linear rate of an extra 3.54 hours each year.

Future sea-level rise will further increase the exceedances of the KT1 elevation leading to inundation of low-lying land more frequently, to a greater depth of water and for a longer duration each time.

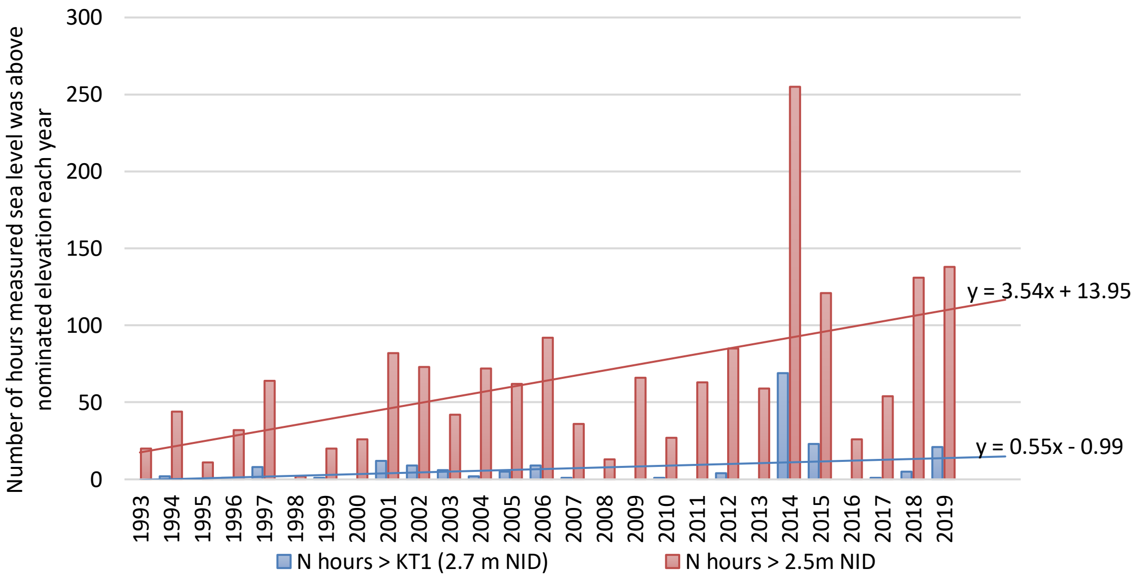

Figure 2-4: Increase in annual duration of high-water events over 1993-2020 tide gauge record. Created from hourly measured data from Nauru tide gauge [*Data source*: PSLGM].

2.5.2 Land subsidence

The sea-level rise rates here does not include the potential for the *land* to rise or fall via tectonic or deep geologic changes which would create a *relative* change in sea level. In Nauru, the rate of tectonic subsidence is below 1 mm/year as based on tide gauge analysis (-0.9 ± 0.2 mm/year) or from satellite altimetry data (-0.6 ± 0.6 mm/year) based on data from 2003-2014. (Martinez-Asensio et al. 2019).

This subsidence is small (10-17%) relative to the recent regional sea-level rise trends at Nauru (5.3 to 5.5 mm/year depending on method) observed from 1993-2015 (Martinez-Asensio et al. 2019). If this subsidence trend continued over a 100-years this would only contribute an *additional* 60-90 mm to sea-level rise over this period. However, there is considerable uncertainty in predicting geologic trends over this time and we consider that the uncertainty bounds in SLR projections will encompass this subsidence trend for the purposes of this high-level study.

2.5.3 Future sea-level rise

The future rise in global mean sea level caused by thermal expansion, melting of glaciers and ice sheets and land water storage changes, is strongly dependent on efforts to curb global emissions (IPCC SROCC 2019).

The latest projections from IPCC SROCC (2019) global mean sea level show that up to 2050, uncertainty in climate change-driven future sea level is relatively small, with sea levels relatively certain to rise between[4] 0.24 m (0.17–0.32 m, *likely* range[5]) under RCP2.6 and 0.32 m (0.23–0.40 m, *likely* range) under RCP8.5. This means that within 1-2 generations[6] sea levels will increase a

[4] Median projectile or 50th percentile
[5] IPCC define the *likely range* as encompassing the 17th to 83rd percentile.
[6] Where generations are 20-year periods

further 0.24 to 0.32 m, but could be up to 0.4 m higher. Beyond 2050, uncertainty in SLR increases substantially due to uncertainties in global efforts to curb emissions and mitigate effects.

Table 2-3: Global mean sea-level rise out to 2300 above 1986-2005 mean sea level (1.394 m NID). [*Data sources*: 2031-2100: IPCC SROCC, Chapter 4, Table 4.4; and 2200–2300: IPCC SROCC, Chapter 4, Figure 4.2].

Period	RCP2.6 (50th %ile)	Likely range (17th–83rd %ile)	RCP8.5 (50th %ile)	Likely range (17th–83rd %ile)
2031–2050	0.17	0.12–0.22	0.2	0.15–0.26
2046–2065	0.24	0.17–0.32	0.32	0.23–0.40
2081–2100	0.39	0.26–0.53	0.71	0.51–0.92
2100	0.43	0.29–0.59	0.84	0.61–1.10
2200	0.65	0.48–0.85	2.07	1.35–2.9
2300	0.82	0.82–1.06	3.7	2.25–5.35

SLR at the end of the century (2100) is projected to be faster under all scenarios, including those compatible with achieving the long-term temperature goal set out in the Paris Agreement. Global mean sea level will rise between 0.43 m (0.29–0.59 m, likely range; RCP2.6) and 0.84 m (0.61–1.10 m, likely range; RCP8.5) by 2100, relative to 1986–2005 (Table 2-3). Sea level may also rise more rapidly that this range, because there is a 17% chance that global mean sea level will exceed 0.59 m under RCP2.6 and 1.10 m under RCP8.5 in 2100 (IPCC SROCC).

Beyond 2100, sea level will continue to rise for centuries due to continuing deep ocean heat uptake and mass loss of the global ice sheets and Antarctic ice sheets and will remain elevated for thousands of years (IPCC SROCC 2019). The SROCC results show a strong divergence of global SLR between the different emissions scenarios over time, whereby the estimates in 2300 range (above 1986-2005 MSL) from about 1–2 m under RCP2.6 up to 2–5.5 m for RCP8.5 (see Table 2-3 and Figure 2-1).

Applying the global SLR projections to Nauru using the MSL offset over the same defining period (1986-2005) shows that after only 1.3 m of SLR, the mean level of the sea will be above the present-day KT1 elevation. This will occur (2.7 m NID) by 2120 at the earliest if the global emissions trajectory follows a high-emissions pathway (RCP 8.5). However, if global emissions are aggressively curbed (RCP2.6) then it may take centuries for this elevation to occur. This is shown in Figure 2-5 where the trend of MSL trend is superimposed with SLR projections and the present-day KT1 elevation.

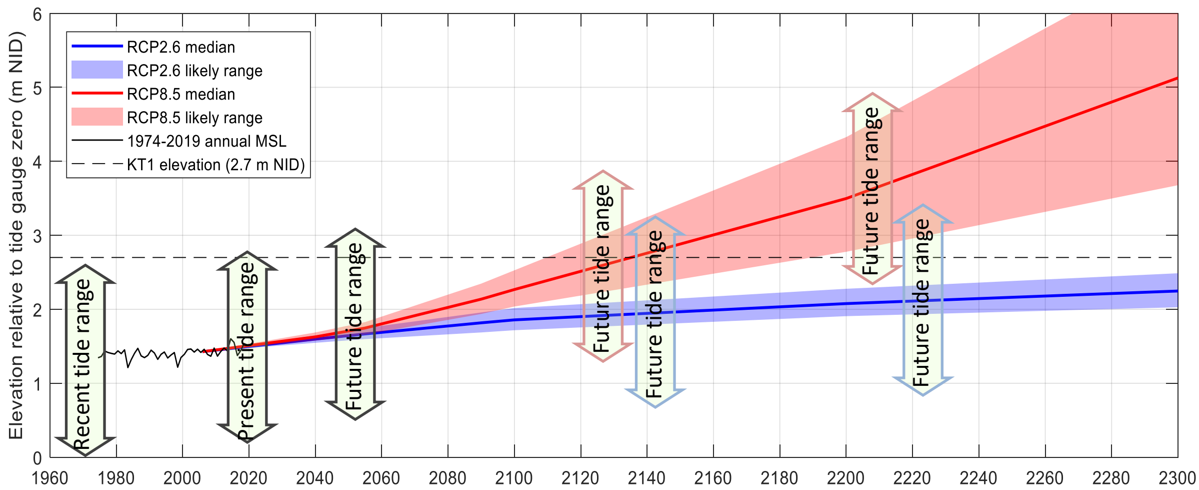

Figure 2-5: Future sea-level rise projections (and their likely range) to 2300. Elevations above 1986-2005 MSL elevation for Nauru (1.394 m NID) with measured annual MSL over the period 1974-2019 [*Data sources*: PSLGM, IPCC SROCC (2019)].

Any rise in MSL also generates a rise in the elevation of *all* tides. In relation to the king-tide elevation on Nauru (2.7 m NID), SLR will cause an increase in the number, duration and depth of tides above the king-tide elevation – which is the focus of this study.

This is exemplified in Figure 2-6 where the tidal exceedance curve for the present day (black) and four increments of SLR are shown. This demonstrates that the frequency of present-day KT1 elevation will increase from 0.72% (1 in 138 tides above this elevation) exceedance to 30% (1 in 3 tides are above this elevation) after 0.5 m SLR, and 86% after 1.0 m SLR (see also Table 2-4).

The increase in exceedances after only 0.5 m SLR means that instead of 5 tides above the present-day king-tide elevation (10 hour per year in recent years – see Figure 2-4), there will be 212 events each year, or only 3.3 days between tides above KT1 elevation (Table 2-4).

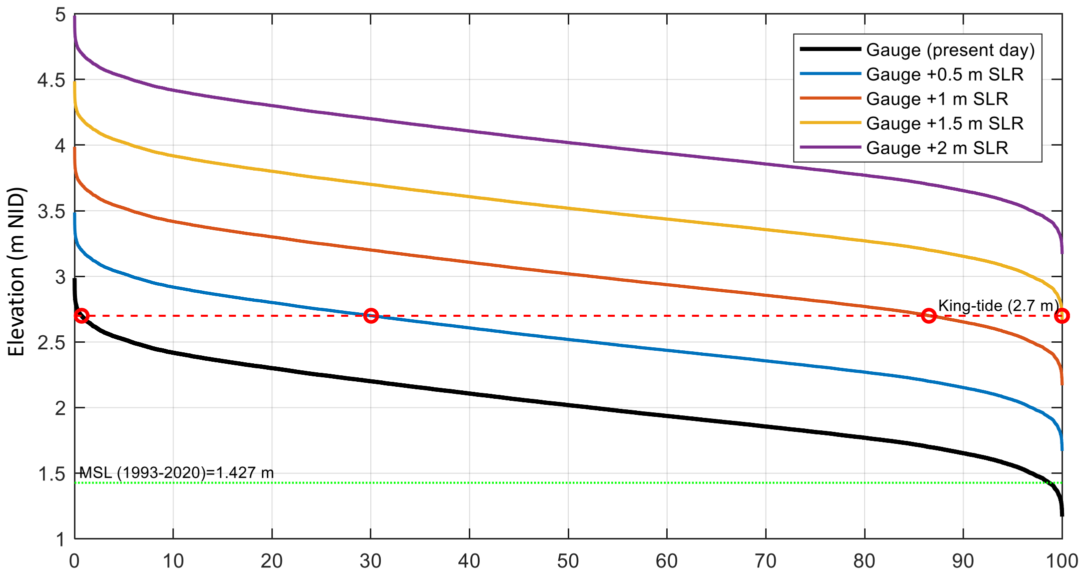

Figure 2-6: Likelihood of tidal elevations at present day and after increments of SLR. The changing frequency of present-day KT1 elevation (red dashed line and red circles) shows the increase from 0.72% exceedance to 30% after 0.5 m SLR, and only 86% after a further 0.5 m SLR. All high tides will be above the present-day king-tide after 1.5 m SLR. See Table 2-4 for details. Based on gauge data from 1993-2019. [*Gauge data source*: PSLGM].

2.5.4 Sea-level rise increments for static inundation mapping

Six SLR increments were selected for this static inundation study; 0.2, 0.35, 0.5, 1, 1.5 and 2 m above present-day sea levels. Using the IPCC's high- and low-emissions trajectories (RCP 8.5 and RCP 2.6, respectively), the earliest occurrence of these sea levels are 2040, 2060, 2070, 2110, 2150, 2190, respectively but increments of 0.5 and above may not occur for centuries under the most optimistic global emissions trajectories (Table 2-4, Figure 2-5).

The six SLR increments are added to the KT1 elevation (2.7 m NID) to simulate the elevation of future king-tides after periods of SLR. Static inundation mapping is then employed to show the land and assets which are *below* this elevation.

Table 2-4: Projected timing of modelled sea-level rise scenarios. Values linearly interpolated from IPCC SROCC values (see Figure 2-5). Values shown as median (50th centile), with likely range indicating the 17th–83rd percentile range. Shaded column indicates elevations modelled in this study. [*Projection data source*: IPCC SROCC (2019)].

SLR increment (m)	Decade of projected SLR occurrence: Low trajectory RCP2.6 (likely range)	Decade of projected SLR occurrence: High trajectory RCP8.5 (likely range)	Elevation of mean sea-level in Nauru after sea-level rise (m NID)	Proportion of high tides above present-day KT1 elevation (%)	Number of high tides per year above present-day KT1 elevation	Number of days per year with high tide above present day KT1 elevation
0	Present-day		1.4	0.72	5	2.5
0.2	2040 (1 generation from 2020)		1.6	5.7	40	21
0.35	2060 (2 generations from 2020)		1.75	15.4	108	56
0.5	2130 (2080-2220)	2070 (2060-2090)	1.9	30.0	212	109
1	beyond 2300	2110 (2090-2150)	2.4	86.5	610	315
1.5	beyond 2300	2150 (2120-2220)	2.9	99.9	705 (every high tide)	365
2	beyond 2300	2190 (2150-2270)	3.4	100	706 (every high tide)	365

Future sea-level rise will further increase proportion of tides which are above the present-day KT1 elevation and how frequently the tides will occur above this elevation (Table 2-4).

However, the aforementioned limitation on modelling wave runup/overtopping processes *excludes* the potential for *additional* risk and vulnerability for buildings and infrastructure that are near to the coast but above 2.7 m NID, i.e., damaging waves will wash inland and uphill from this elevation but the present study cannot resolve the wave processes.

Schematically, a typical cross section and the static inundation process is exemplified in Figure 2-7. Here the lagoon levels are linked to the present-day MSL (see comments on lagoons in following section), but king tides will elevate land levels across much of the island.

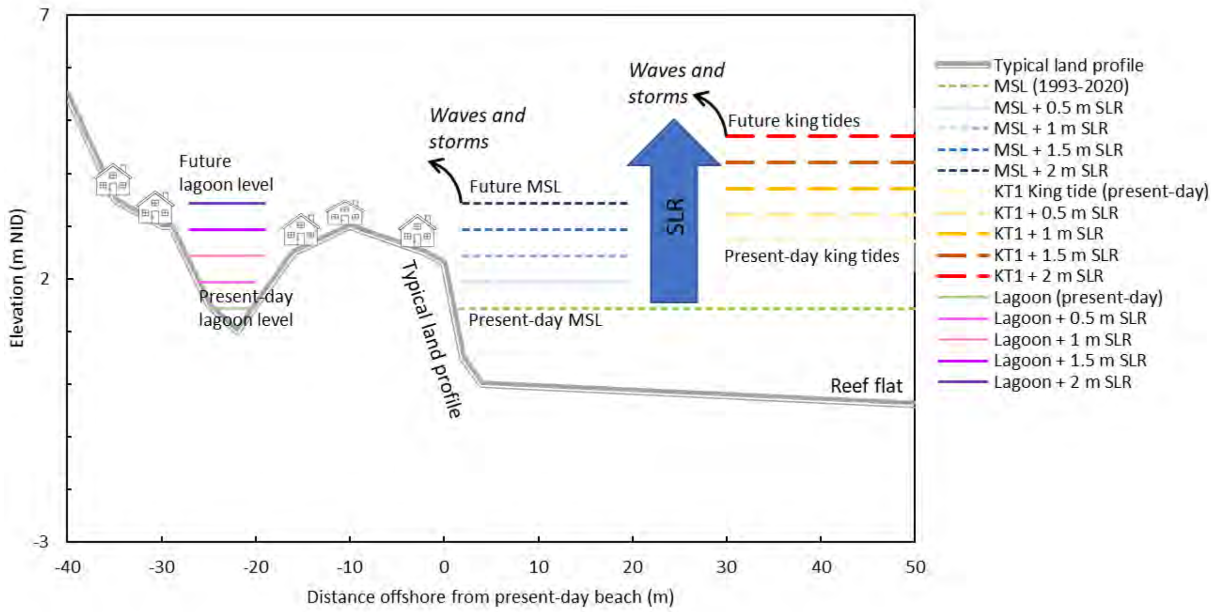

Figure 2-7: Diagram of future elevations of MSL, lagoon level and king-tide elevation after SLR increments. Lagoon level = MSL, King tide = 2.7 m NID. SLR increments of 0.5 m. Ground profile indicative only.

2.5.5 Frequency that water is above the level of land

The following plots (Figure 2-8 to Figure 2-11) provide an indication of how frequently high tide levels may result in high-tide related inundation in areas of Nauru and how this may change under 4 different amounts of future sea-level rise (0.2 m, 0.5 m, 1.0 m, 1.5 m), but excluding wave effects.

The information is presented as the *average number of days per year that high tide level would be above existing land levels*. Land levels are based on the LiDAR dataset for Nauru collected as part of the Pacific Catastrophe Risk Assessment and Financing Initiative (PCRAFI).

Here, the SLR *increments* are the same as the rest of the study, but the values of inundation *frequency* are based duplication of the tidal records with SLR increments. i.e., they show what the inundation frequency would be if the last 20 years of tide data (2000-2019) were repeated exactly but with the SLR increment added.

A full suite of large-format figures for present sea level as well as all six sea-level rise increments is contained in Appendix E.

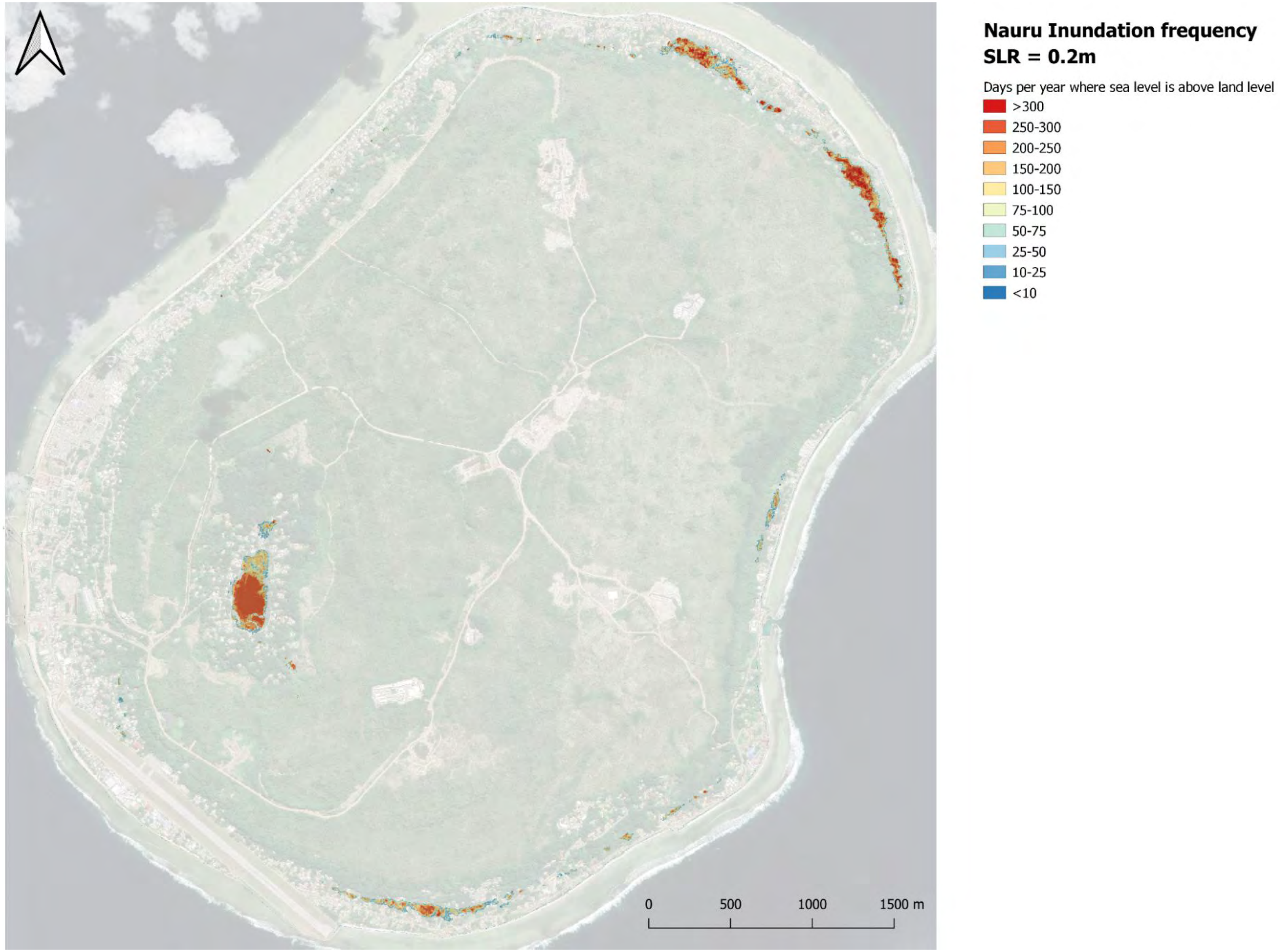

Figure 2-8: Average number of days per year that high tide level would be above existing land levels after 0.2 m SLR See text for calculation details.

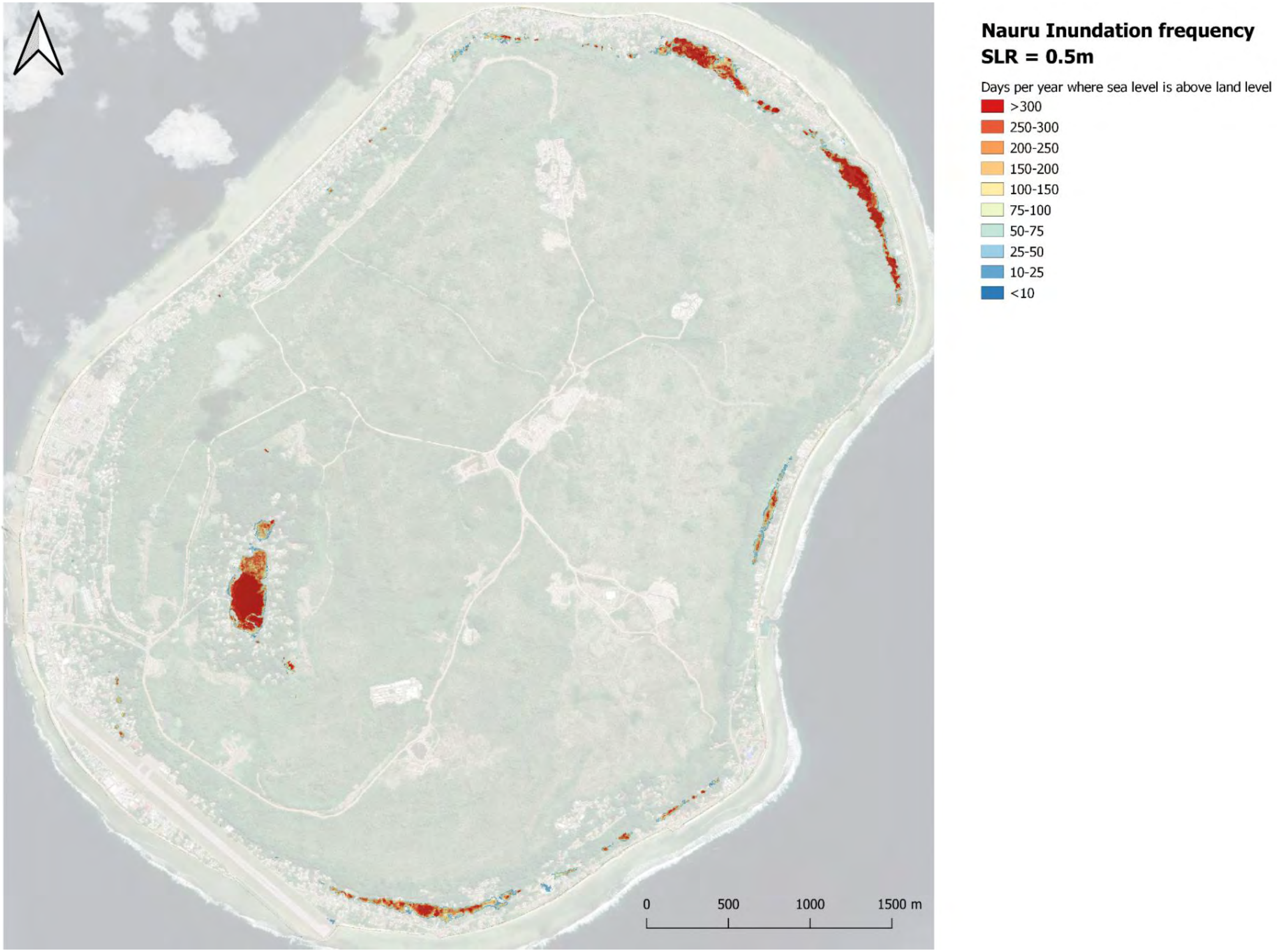

Figure 2-9: Average number of days per year that high tide level would be above existing land levels after 0.5 m SLR See text for calculation details.

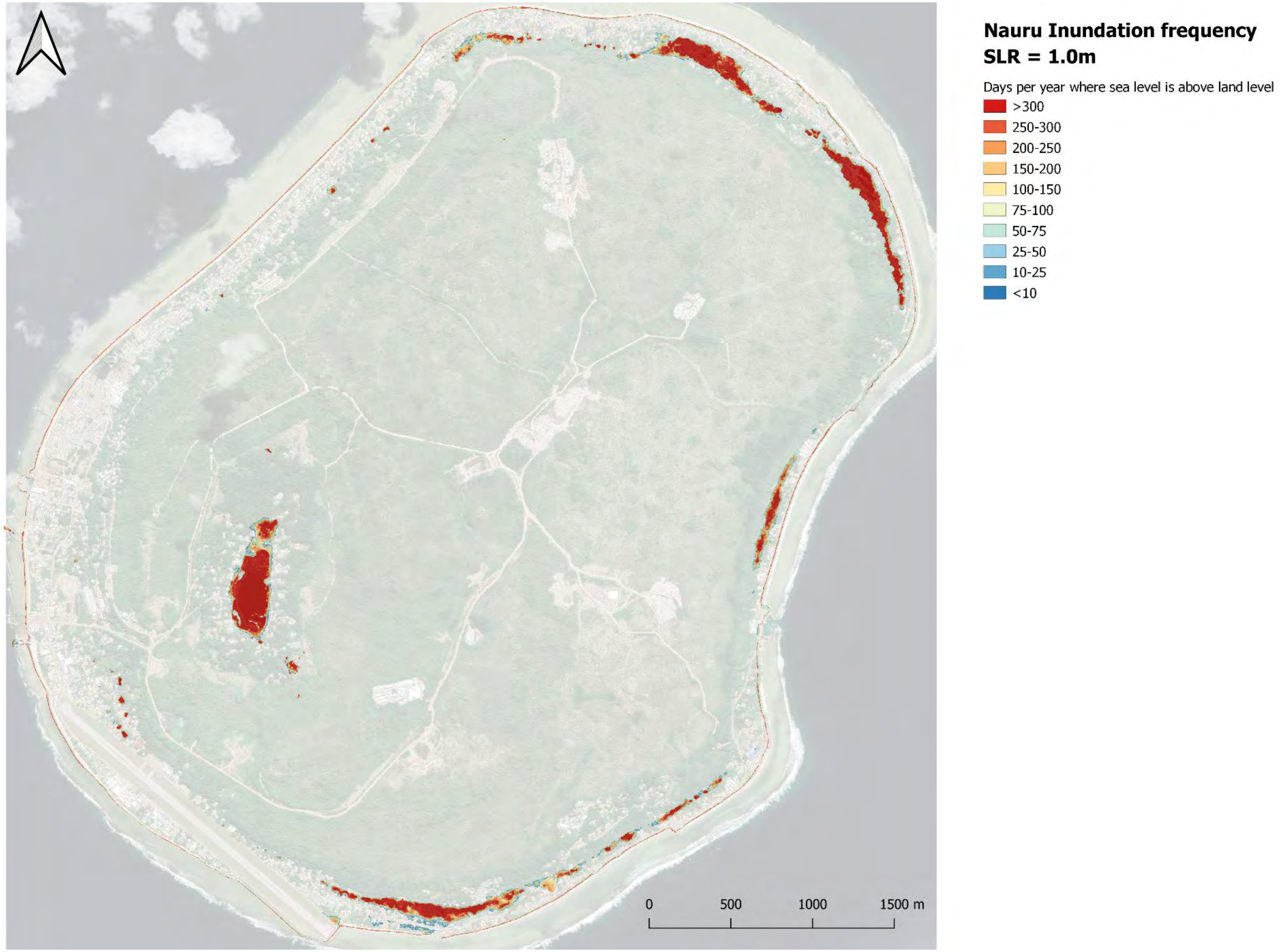

Figure 2-10: Average number of days per year that high tide level would be above existing land levels after 1.0 m SLR See text for calculation details.

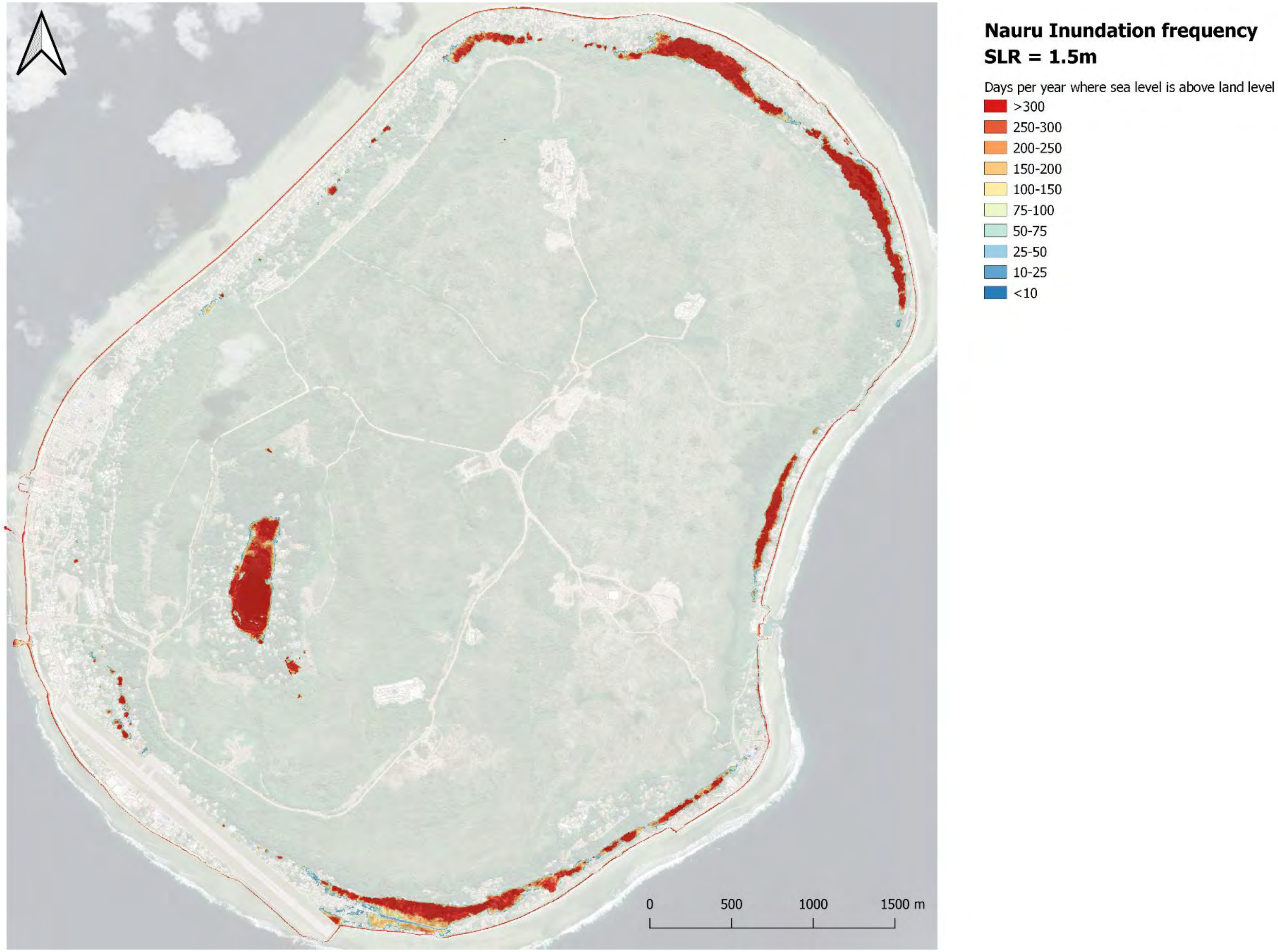

Figure 2-11: Average number of days per year that high tide level would be above existing land levels after 1.5 m SLR See text for calculation details.

2.6 Lagoons

The lagoons around Nauru (except Buada Lagoon - see below) are known to be tidally responsive. Meaning that changes in water level in the ocean (such as tides) are transmitted (more or less efficiently) to the lagoons via underground connection between the lagoon and the ocean. The damping of the tide in these connections is described in the tidal efficiency and depends on distance to sea and subterranean sediment properties (Jacobson & Hill 1988, Alberti et al. 2017). The slow onset of sea-level rise (relative to the tide) is much less sensitive to the tidal efficiency and expected to be transmitted in full on tidally responsive lagoon.

For the purposes of this high-level study all lagoons (except Buada Lagoon) are assumed to be fully connected to the sea elevation and respond linearly to SLR. This is likely to *overestimate* the flood hazard by neglecting any damping of the tidal signal (Alberti et al. 2017 estimate tidal efficiency of about 0.5, i.e., 50% of the king tide elevation above MSL), but still exemplify risk and exposure to future coastal flooding hazards or account for potential wave-driven overwashing (which is not modelled in this assessment).

These lagoons are expected to respond linearly with sea-level rise (i.e., 1 m SLR = 1 m lagoon level rise).

2.6.1 Buada Lagoon

There is disagreement in the literature about the level and fluctuation of Buada Lagoon in response to coastal tide elevations. Jacobson and Hill (1988) report Buada Lagoon is part of a perched groundwater table and does not respond to tidal fluctuations at the sea. In their study the mean lagoon elevation in October 1987 was 2.234 m NID[7] which was 1.05 m above the 1988 mean sea level with this level considered to be predominantly affected by rainfall and evaporation (Jacobson and Hill, 1988). However, Alberti et al. (2017) monitored a more extensive network of groundwater boreholes around Nauru and suggest that, contrary to previous studies, Buada Lagoon shows levels that respond to tidal variations with a tidal lag of 1.5 hrs and tidal efficiency of 0.54 at a borehole close to Buada Lagoon (Alberti et al., 2017).

For the purposes of this high-level study we have assumed that Buada Lagoon is also fully connected (tidal efficiency = 1.0) with sea and will flood to an elevation equal to the modelled king-tide elevation (2.7 m NID) and that its elevation will respond linearly with sea-level rise. This is expected to *overestimate* the flood level near Buada Lagoon by approximately[8] 0.6 m, including future inundation events.

This results in a conservative assessment but the modelled results still exemplify risk and exposure to future flooding hazards (coastal or rainfall) as land around it is still relatively low-lying and supports important resources (cropping activities such as bananas, pineapples, vegetables, pandanus trees and indigenous hardwoods), houses and assets.

[7] For the present study, the groundwater RLs have been corrected to NID. Jacobson and Hill (1988) adopted a Reduced Level (RL) as reference point for all their groundwater and lagoon measurements. Even today, all the hydrogeological data collected in Nauru refer to this RL. However, the tide and LiDAR data refer to NID which was located 0.166 m (in 1988) above the RL (Jacobson and Hill 1988). MSL in 1988 was 1.186 m, but has risen to 1.3 m i.e., 2.4 m RL = 2.234 m NID.

[8] Using a tidal efficiency of 0.54 from Alberti et al. (2017); (2.7-1.427)*(1-0.54) = 0.586 m overestimate

A hydrogeological study will be required to assess how Buada Lagoon and other groundwater/lagoon levels around the coastal plain, is linked to the level of the sea and to further understand how it will respond to sea-level rise. However, this is beyond the scope of this study.

2.7 Coastal flood mapping

Coastal flood inundation maps were created for KT1 and SLR increments of SLR up to +2 m above KT1. Modelled KT1 levels were then intersected with the Nauru DEMs, to create inundation area polygons. This static level or “bathtub” inundation mapping approach assumes all land below the mapped sea level and connected to the ocean will be inundated. RiskScape then combines the inundation hazard maps with asset databases to estimate desired exposure and/or loss results.

The major assumption in the GIS mapping procedure was the “bathtub” method use to map and assign the land area below sea-levels as inundated. King-tide peaks however, last for 1–3 hours close to high tide. This duration may not be sufficient to temporally inundate large land areas, particularly if flow rates are restricted by a narrow connection to the sea e.g., drainage channels, culverts.

The coastal flood inundation area maps therefore do not fully capture the dynamic and time-variant processes that occur during a coastal-storm event, but rather are indicative of areas coastal inundation from static sea-levels, or residual risk behind coastal defences such as stop banks.

This static mapping also excludes wave processes which wash inland and uphill from this coastline at the static elevation (substantial waves do not occur within lagoons), further exposing assets to wave hazards. Future studies and in-country ground-truthing are required to simulate and validate the effect and hazard from wave processes.

3 Results

All results are plotted, mapped and tabulated on a district and national level.

3.1 Land area

The calculated land areas exposed in Nauru are presented in Figure 3-1 (absolute area) and Figure 3-2 (percentage of district total), enumerated in Table 3-1 and mapped in Figure 3-3.

At the present day, most districts have little to no exposure except for districts with lagoons and other low-lying land *already* inundated in king-tide events (below 2.7 m NID). These low-lying/lagoon areas are illustrated in Figure 3-3 and are seen to be concentrated in Buada, Ijuw, Anabar and Meneng districts. The reported values include the area of the lagoons that are semi-permanent water body (i.e., not *dry* land) hence the district exposures are overrepresented by the area of the lagoon (if present).

All districts show an increase in exposure from future king-tides with SLR, particularly the marginal areas which surround the low-lying lagoons and depressions. On average each district has approximately 1% exposed at present day (including lagoons) which rises to an average of 5.3% across all districts after 2 m of SLR.

The most exposed areas are concentrated around the low-lying former backshore depressions and lagoon areas which encircle the island behind the elevated beach barrier (refer schematic Figure 2-7) and are lowest in the north, east and south. The most exposed districts by percentage land area are, in order, Anabar (4.11% at KT1 rising to 11.68% after 2 m SLR), Anetan (3.08% rising to 9.3% after 2 m SLR), Buada (3.11% rising to 7.09% after 2 m SLR) and Meneng (1.21% rising to 9.4% after 2 m SLR).

The west to north western shoreline generally has a higher elevation (due to higher wave exposure creating a higher barrier beach than other areas of the island) and hence lower exposure to rising sea levels and future king-tides. The least exposed district by percentage land area are Nibok, Denigomodu, Uaboe, Baiti and Aiwo, with typically 0.05% at present day, rising to 1.65% after 2 m of SLR.

Overall, of the total land area of Nauru (21.4 km^2) the total exposure increases from 0.24 km^2 (1.13%) for present day KT1 (includes lagoon areas) to 1.19 km^2 (5.56%) as sea-level rises to 2 m above present day MSL.

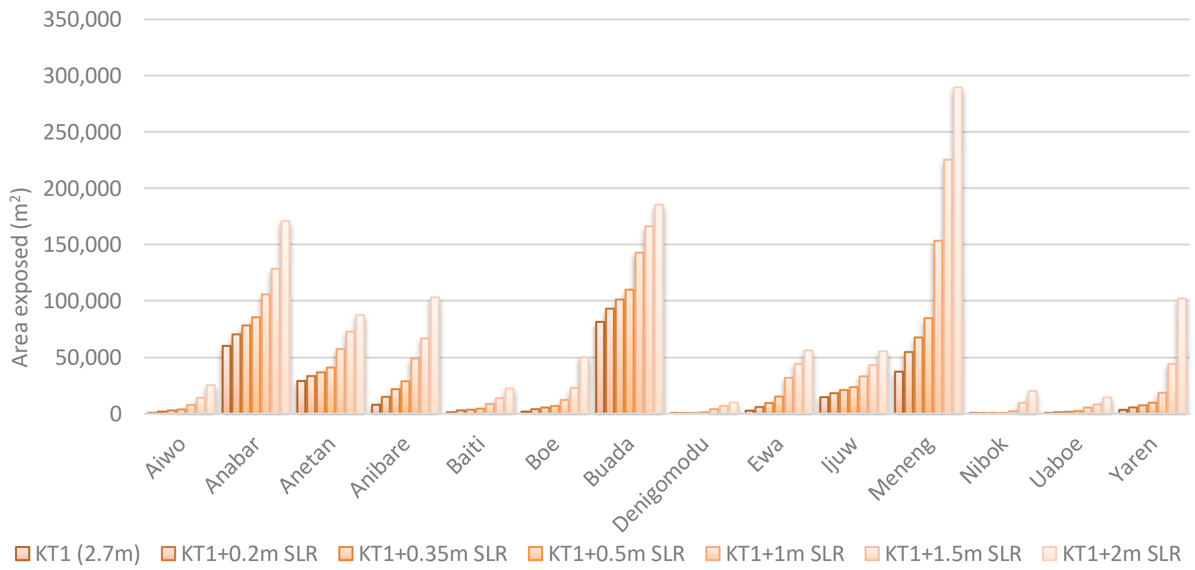

Figure 3-1: Land area of each district exposed (m^2) to KT1 and KT1+SLR increments. Refer to Table 3-1 for values.

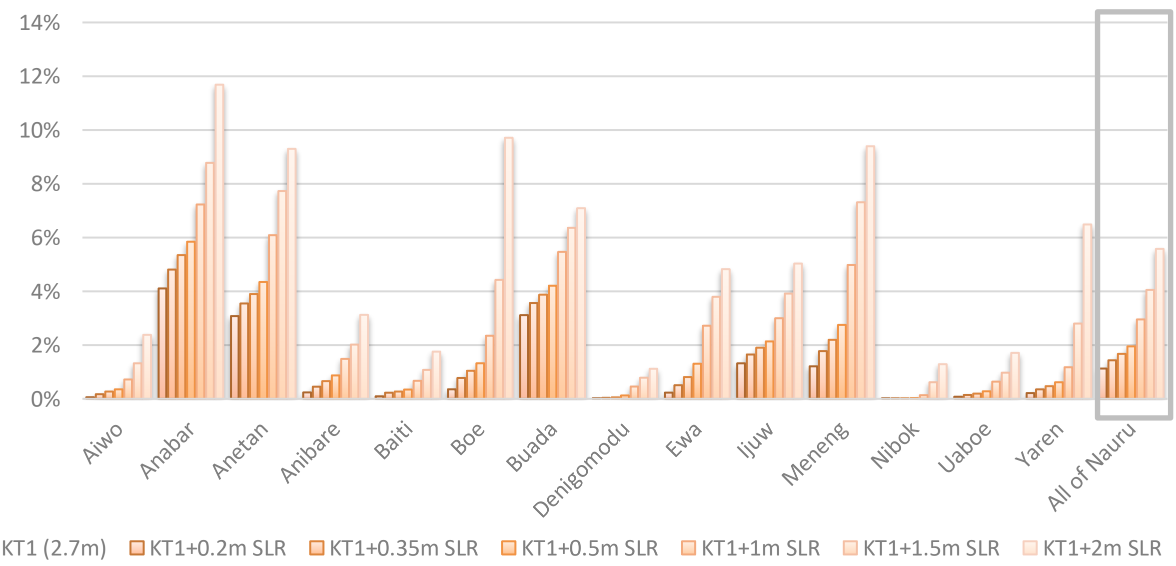

Figure 3-2: Percentage of land area in each district and all of Nauru exposed to KT1 and KT1+SLR increments. Refer to Table 3-1 for values.

Table 3-1: Land area of each district exposed (m²) and percentage of total district area exposed for KT1 and KT1+SLR increments. All of Nauru total highlighted in bold.

District name	Total district area (m²)	Area exposed (m²)							Proportion of district total area exposed							Average rank of percentage exposed
		KT1 (2.7m NID)	KT1 +0.2m SLR	KT1 +0.35m SLR	KT1 +0.5m SLR	KT1 +1m SLR	KT1 +1.5m SLR	KT1 +2m SLR	KT1 (2.7m NID)	KT1 +0.2m SLR	KT1 +0.35m SLR	KT1 +0.5m SLR	KT1 +1m SLR	KT1 +1.5m SLR	KT1 +2m SLR	
Aiwo	1,063,800	625	1,825	2,875	3,750	7,650	14,050	25,300	0.06%	0.17%	0.27%	0.35%	0.72%	1.32%	2.38%	10
Anabar	1,464,950	60,150	70,425	78,325	85,600	105,900	128,575	171,175	4.11%	4.81%	5.35%	5.84%	7.23%	8.78%	11.68%	1
Anetan	941,650	28,975	33,400	36,700	40,925	57,325	72,775	87,550	3.08%	3.55%	3.90%	4.35%	6.09%	7.73%	9.30%	2
Anibare	3,306,750	7,875	14,900	21,750	28,775	49,075	66,675	103,250	0.24%	0.45%	0.66%	0.87%	1.48%	2.02%	3.12%	8
Baiti	1,278,200	1,200	2,900	3,450	4,400	8,550	13,750	22,425	0.09%	0.23%	0.27%	0.34%	0.67%	1.08%	1.75%	11
Boe	515,975	1,825	4,000	5,375	6,825	12,100	22,825	50,100	0.35%	0.78%	1.04%	1.32%	2.35%	4.42%	9.71%	6
Buada	2,615,800	81,450	93,200	101,325	110,000	142,975	166,350	185,500	3.11%	3.56%	3.87%	4.21%	5.47%	6.36%	7.09%	3
Denigomodu	882,950	75	325	475	1,100	4,025	6,925	9,850	0.01%	0.04%	0.05%	0.12%	0.46%	0.78%	1.12%	13
Ewa	1,165,150	2,675	5,900	9,425	15,200	31,675	44,200	56,200	0.23%	0.51%	0.81%	1.30%	2.72%	3.79%	4.82%	7
Ijuw	1,103,150	14,575	18,175	20,975	23,550	33,075	43,175	55,500	1.32%	1.65%	1.90%	2.13%	3.00%	3.91%	5.03%	5
Meneng	3,084,025	37,275	54,725	67,650	84,775	153,525	225,500	289,750	1.21%	1.77%	2.19%	2.75%	4.98%	7.31%	9.40%	4
Nibok	1,556,600	125	150	225	450	2,100	9,600	20,050	0.01%	0.01%	0.01%	0.03%	0.13%	0.62%	1.29%	14
Uaboe	841,850	650	1,200	1,625	2,350	5,375	8,175	14,375	0.08%	0.14%	0.19%	0.28%	0.64%	0.97%	1.71%	12
Yaren	1,574,700	3,350	5,550	7,400	9,700	18,500	44,075	102,125	0.21%	0.35%	0.47%	0.62%	1.17%	2.80%	6.49%	9
All of Nauru	**21,395,550**	240,825	306,675	357,575	417,400	631,850	866,650	1,193,150	1.13%	1.43%	1.67%	1.95%	2.95%	4.05%	5.58%	-

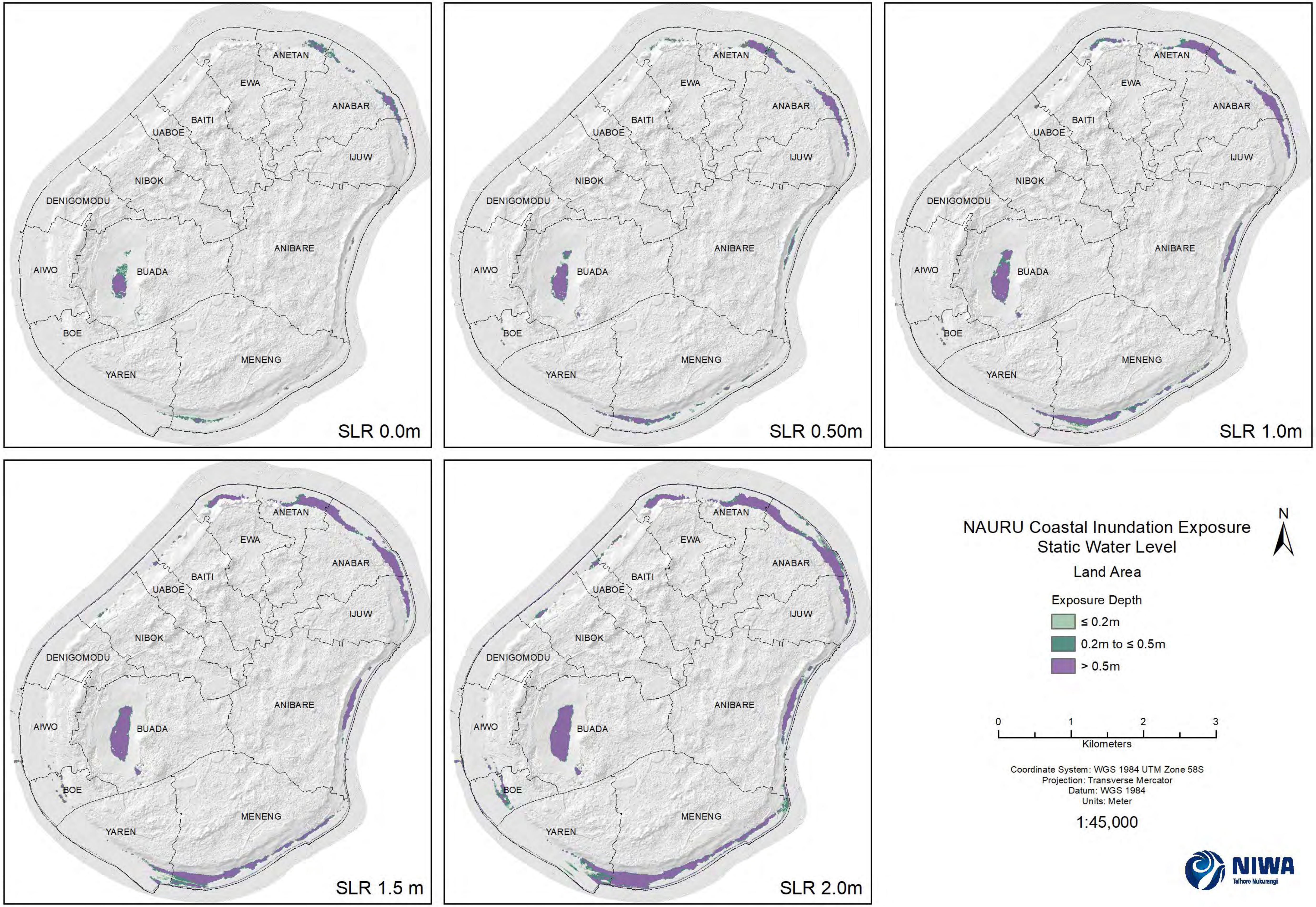

Figure 3-3: Map of land-area exposed to present day king-tide inundation and after increments of sea-level rise. Coloured areas represent depth of inundation above ground (see legend). Refer to Table 3-1 for totals of district level exposure.

3.2 Population/Occupancy

The population/occupancy exposure is presented in Figure 3-4 (absolute values) and Figure 3-5 (percentage of district total), enumerated in Table 3-2 and mapped in Figure 3-6.

The population dataset from 2019/2020 identified a total Nauruan population of 12,871, with four districts of over 1000 inhabitants (Aiwo, Boe, Denigomodu and Meneng) and two districts with less than 400 inhabitants (Ijue, Anibare).

The population exposure in Nauru is calculated from combining the population dataset and the residential building datasets. The calculation establishes an average occupancy as a function of total residential floor area in each 100 m grid-cell (i.e., persons/m^2 of residential building in each 100 m grid cell). The population exposure is then calculated from the total exposed residential building floor area.

Limitations of this approach include multi-use buildings where residential is not the primary use (i.e., commercial shopfront with secondary residential dwelling above). This method also determines population exposure based on *average* occupancy rates for each square metre of residential building in each 100 m grid cell, not a building by building occupancy basis (as would require detailed census information).

For all of Nauru, the population exposure rises from 46 people at present-day KT1 elevation to 1,988 at KT1+2m SLR. Most districts show an increase in population exposure from future king-tides with SLR. On average each district has approximately 0.5% exposed at present day which rises to 15.6% across all districts after 2 m of SLR.

There is significant variability between districts at all SLR increments, from no exposure (Denigmodu) to 45% exposed after 2 m SLR (Yaren). After the 2 m SLR the exposure can be grouped as:

- 0-10 people exposed : Aiwo, Baiti, Denigmodu, Nibok
- 10-100 people exposed : Uaboe, Anabar, Anetan, Anibare, Ijuw
- 100-1000 people exposed : Boe, Buada, Ewa, Meneng, Yaren.

The districts with the greatest increase in exposure are Meneng (1.6% at KT1 rising to 39.9% after 2 m SLR) and Yaren (0.2% to 45.6%), but a cluster of other districts see population exposure rise from about 1% to 20% or more after 2 m of SLR (Anabar, Anibare, Boe, Buada, Ewa, Ijuw).

The least exposed districts are the north-western districts with slightly higher land elevation (Aiwo, Baiti, Denigomodu, Uaboe and Nibok) which each see a rise in exposure from zero at KT1 but remain below 7% exposure (53 people total across all these 5 districts) after 2 m of SLR.

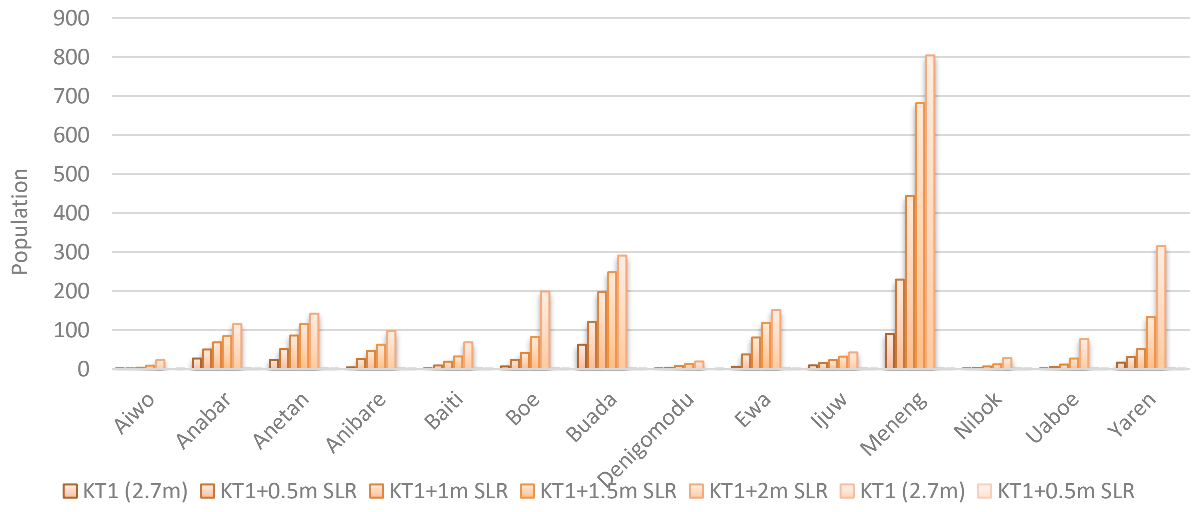

Figure 3-4: Population of each district exposed to KT1 and KT1+SLR increments. Refer to Table 3-2 for values.

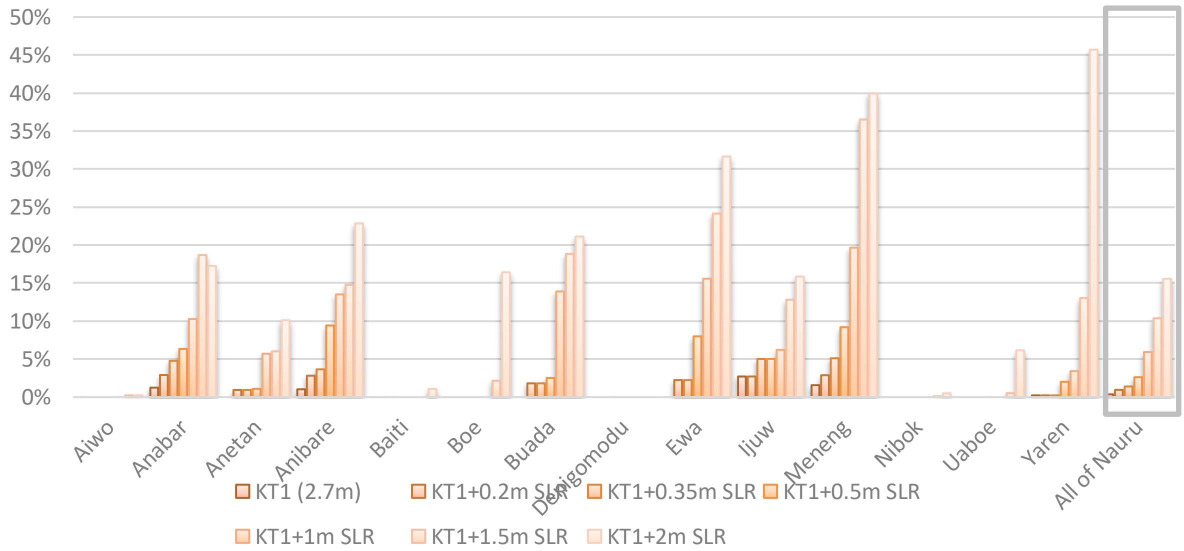

Figure 3-5: Percentage of each district population exposed to KT1 and KT1+SLR increments. Refer to Table 3-2 for values.

Table 3-2: Population of each district exposed and percentage of total district population exposed for KT1 and KT1+SLR increments. All of Nauru total highlighted in bold. Average ranking of percentage of district population exposed across all SLR scenarios (1 = most exposed, 14 being least exposed).

District name	Total district area (m^2)	Population exposed							Proportion of district population exposed							Average rank of percentage exposed
		KT1 (2.7m NID)	KT1 +0.2m SLR	KT1 +0.35m SLR	KT1 +0.5m SLR	KT1 +1m SLR	KT1 +1.5m SLR	KT1 +2m SLR	KT1 (2.7m NID)	KT1 +0.2m SLR	KT1 +0.35m SLR	KT1 +0.5m SLR	KT1 +1m SLR	KT1 +1.5m SLR	KT1 +2m SLR	
Aiwo	1,676	-	-	-	-	-	4	4	-	-	-	-	-	0.2%	0.2%	12
Anabar	450	6	13	21	28	46	84	78	1.2%	2.9%	4.8%	6.3%	10.3%	18.7%	17.3%	3=
Anetan	822	-	8	8	9	47	49	83	-	0.9%	0.9%	1.1%	5.7%	6.0%	10.1%	8
Anibare	399	4	11	15	38	54	59	91	1.0%	2.8%	3.7%	9.4%	13.5%	14.8%	22.8%	2
Baiti	762	-	-	-	-	-	-	8	-	-	-	-	-	-	1.1%	12
Boe	1,006	-	-	-	-	-	22	165	-	-	-	-	-	2.1%	16.4%	9
Buada	955	-	17	17	24	133	180	202	0.0%	1.8%	1.8%	2.5%	13.9%	18.8%	21.1%	6
Denigomodu	1,976	-	-	-	-	-	-	-	-	-	-	-	-	-	-	14
Ewa	530	-	12	12	42	82	128	168	-	2.2%	2.2%	8.0%	15.6%	24.1%	31.6%	3=
Ijuw	236	6	6	12	12	15	30	37	2.7%	2.7%	5.0%	5.0%	6.2%	12.8%	15.8%	5
Meneng	1,785	28	51	91	164	351	652	713	1.6%	2.9%	5.1%	9.2%	19.7%	36.5%	39.9%	1
Nibok	703	-	-	-	-	-	1	3	-	-	-	-	-	0.1%	0.5%	12
Uaboe	609	-	-	-	-	-	3	37	-	-	-	-	-	0.5%	6.2%	10
Yaren	872	2	2	2	18	30	114	398	0.2%	0.2%	0.2%	2.0%	3.4%	13.0%	45.7%	7
All of Nauru	**12,781**	**46**	**121**	**178**	**335**	**757**	**1,325**	**1,988**	**0.4%**	**0.9%**	**1.4%**	**2.6%**	**5.9%**	**10.4%**	**15.6%**	-

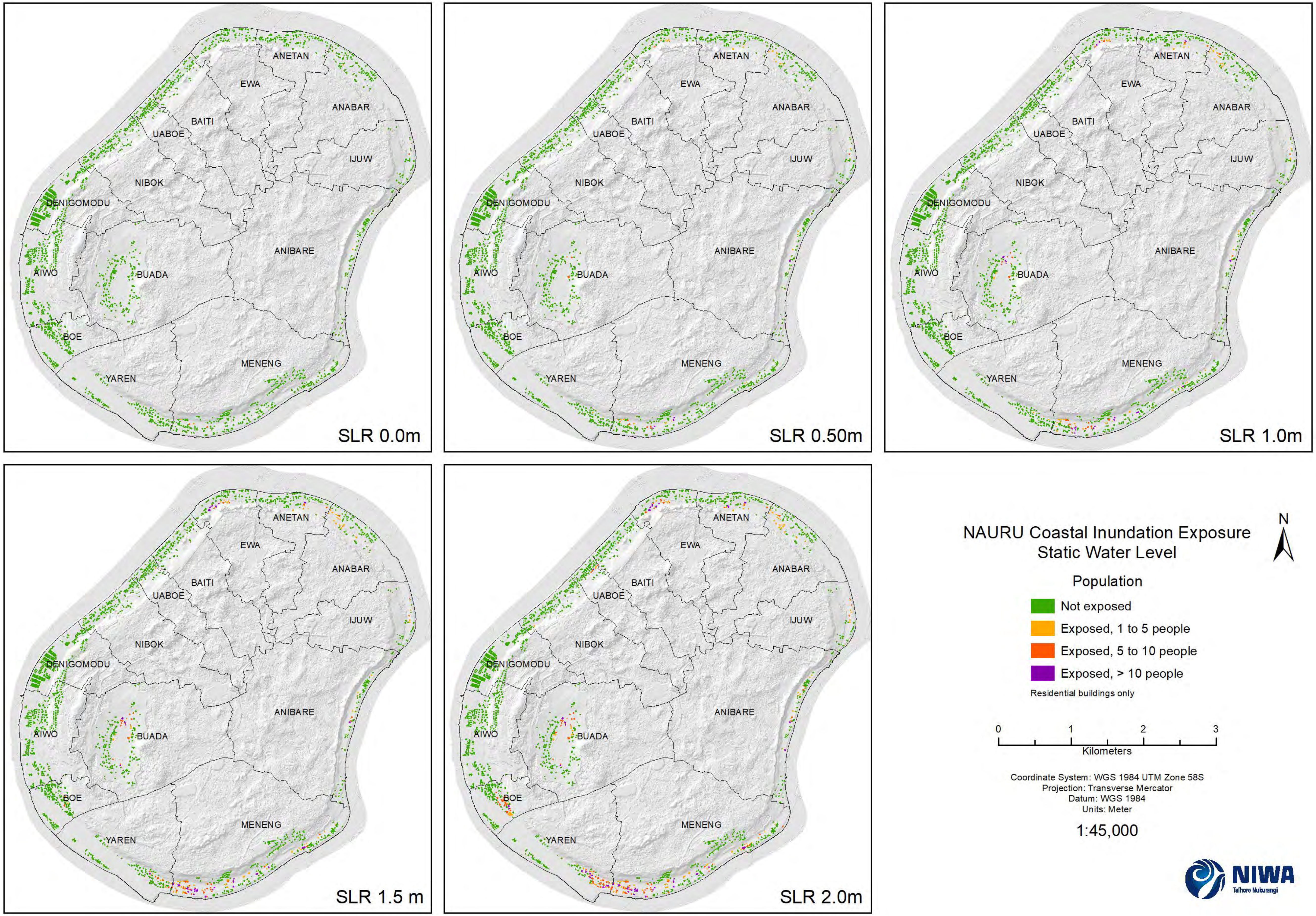

Figure 3-6: Map of population exposed at present day king-tide elevations and after increments of sea-level rise. Population exposed based on residential building area and population statistics 100 m grid. Colours represent of number of people in each residential building exposed to inundation (see legend). Refer to Table 3-2 for totals of district level population exposure.

3.3 Buildings

The calculated building exposure in Nauru are presented in Table 3-3 (building count by type) with the district level breakdown in Figure 3-7 and Figure 3-8. Values are enumerated in Table 3-4 and mapped in Figure 3-9.

Exposure of a building does not necessarily mean inundation inside the building, rather it means the ground level around the building is below the static water level. This is because there is no information available on building floor levels such as a structure on piles or stilts. The total number of buildings on Nauru in the updated dataset is 2471[9], across 5 primary building types; Commercial, Industrial, Infrastructure, Public and Residential (Table 3-3). During the present-day king-tide events only 13 buildings are exposed (0.5% of building stock, only Residential buildings) but this rises to 449 buildings or 18% of building stock after 2 m of SLR. No industrial and infrastructure buildings are exposed in this mapping (Table 3-3) and these categories are removed from the subsequent tables.

The majority of buildings on Nauru are Residential (2085 buildings or 84% of all buildings). Similarly, the majority of buildings exposed to future KT1 events are Residential, comprising at least 88% of the total number of buildings exposed in all future scenarios. Although, the Commercial sector has a greater proportional exposure at KT1+2m SLR with 24% of commercial buildings exposed, compared to 19% of Residential buildings (Table 3-3).

Table 3-3: Total building type exposure for all of Nauru for KT1 and KT1+SLR increments.

Building type	Total number	KT1 (2.7m)	KT1 +0.2m SLR	KT1 +0.35m SLR	KT1 +0.5m SLR	KT1 +1m SLR	KT1 +1.5m SLR	KT1 +2m SLR
Commercial	208	0	0	2	2	4	10	50
Industrial	59	0	0	0	0	0	0	0
Infrastructure	17	0	0	0	0	0	0	0
Public	102	0	0	0	0	2	2	3
Residential	2085	13	31	47	69	148	253	396
Total	2471	13	31	49	71	154	265	449

Table 3-4 provides the district level breakdown of building exposure. Meneng has the highest total exposure with 139 of its 300 buildings exposed (33%) under the highest KT1+2m SLR increment, these are predominantly residential (122 of 139) with 22 commercial and 2 public buildings. Anabar and Yaren are the next most exposed with 17% and 16% of their buildings exposed at the highest KT1+2m SLR increment.

Denigomodu, Aiwo, Nibok, Baiti and Uaboe have less than 10 buildings (all types) exposed even at KT1+2m SLR, this exposure reflects the generally higher ground elevations on the west/north-western sides of Nauru (Refer discussion in Land Area, Section 3.1).

[9] The total number reported may vary in each region as dataset also contained 45 'null points'.

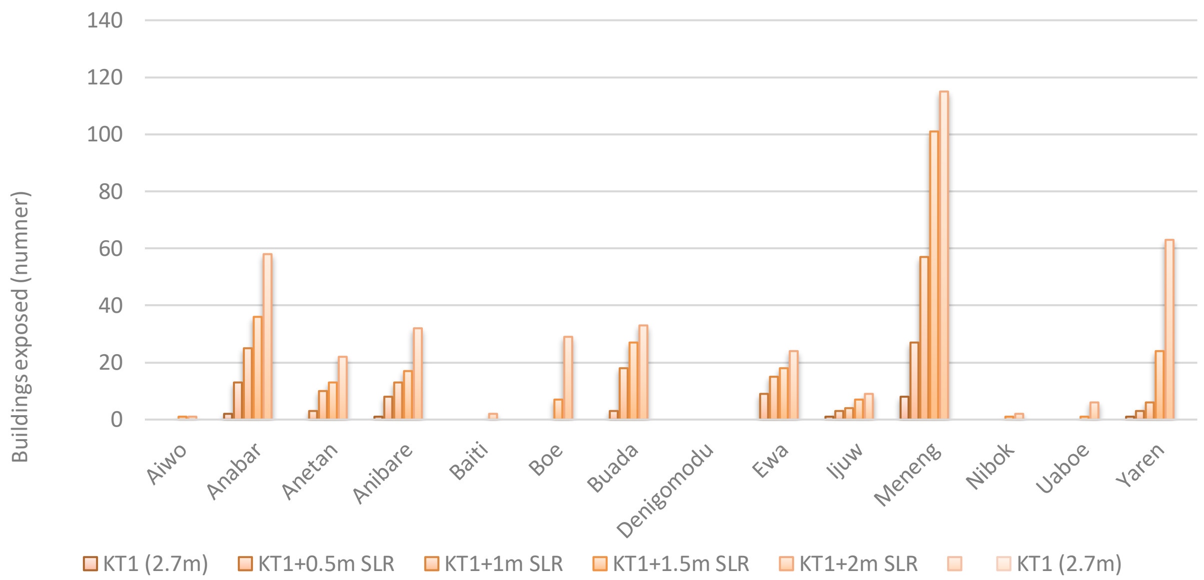

Figure 3-7: Residential building count exposed within each district for KT1 and KT1+SLR increments. Refer to Table 3-4 for values.

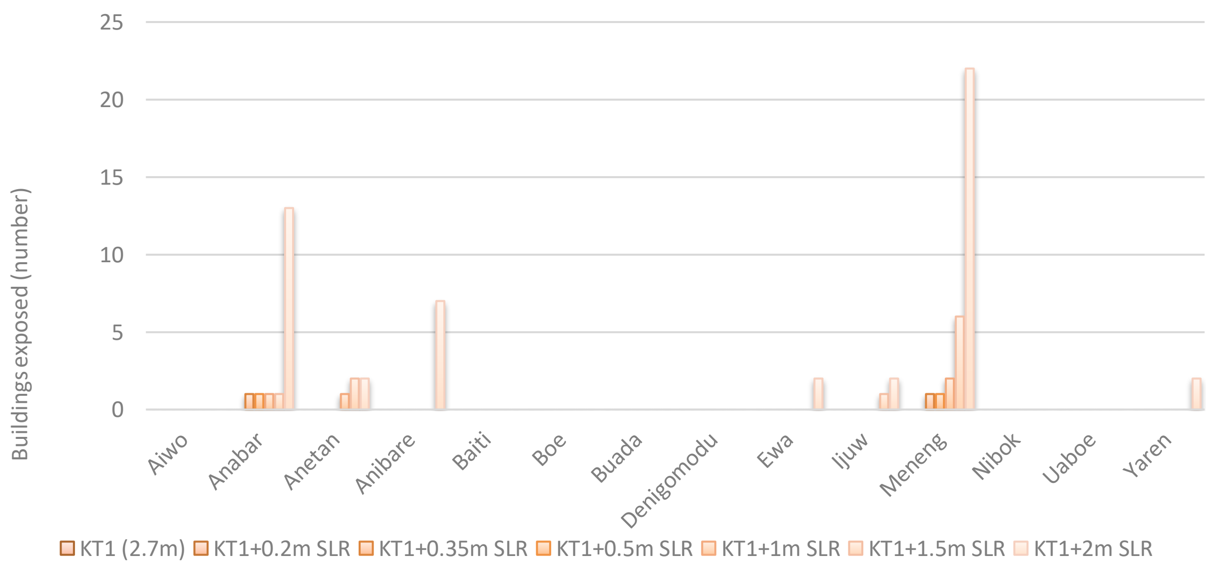

Figure 3-8: Commercial building count exposed within each district for KT1 and KT1+SLR increments. Refer to Table 3-4 for values.

Table 3-4: Building count and building type exposed within each district for KT1 and KT1+SLR increments. All of Nauru total highlighted in bold. Infrastructure and Industrial categories have no exposure and are removed from exposure table for simplicity (refer Table 3-3). Average rank of total exposure indicates percentage of the total number of building (all types) exposed across all SLR scenarios (1 = most exposed, 14 = least exposed).

District name	Building stock count by building type					Building exposure by type for each district																												Average rank of total exposure
						KT1 (2.7m)				KT1+0.2m SLR				KT1+0.35m SLR				KT1+0.5m SLR				KT1+1m SLR				KT1+1.5m SLR				KT1+2m SLR				
	Commercial	Industrial	Infrastructure	Public	Residential	Commercial	Public	Residential	Total	Commercial	Public	Residential	Total	Commercial	Public	Residential	Total	Commercial	Public	Residential	Total	Commercial	Public	Residential	Total	Commercial	Public	Residential	Total	Commercial	Public	Residential	Total	
Aiwo	50	40	4	12	308	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	1	1	12
Anabar	19	0	0	0	130	0	0	2	2	0	0	5	5	1	0	9	10	1	0	13	14	1	0	25	26	1	0	36	37	13	0	58	71	2
Anetan	9	0	0	4	117	0	0	0	0	0	0	2	2	0	0	2	2	0	0	3	3	1	0	10	11	2	0	13	15	2	0	22	24	8
Anibare	17	2	0	2	83	0	0	1	1	0	0	4	4	0	0	5	5	0	0	8	8	0	0	13	13	0	0	17	17	7	0	32	39	3
Baiti	6	0	0	1	104	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	2	13
Boe	4	0	1	2	144	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	7	7	0	0	29	29	9
Buada	1	0	0	1	183	0	0	0	0	0	0	2	2	0	0	2	2	0	0	3	3	0	1	18	19	0	1	27	28	0	1	33	34	5
Denigomodu	21	1	6	15	186	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	14
Ewa	10	0	0	15	98	0	0	0	0	0	0	0	0	0	0	2	2	0	0	9	9	0	0	15	15	0	0	18	18	2	0	24	26	6
Ijuw	4	0	0	0	48	0	0	1	1	0	0	2	2	0	0	3	3	0	0	3	3	0	0	4	4	1	0	7	8	2	0	9	11	7
Meneng	43	0	0	17	300	0	0	8	8	0	0	15	15	1	0	23	24	1	0	27	28	2	1	57	60	6	1	101	108	22	2	115	139	1
Nibok	4	13	1	3	143	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	2	2	11
Uaboe	2	2	0	0	64	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	6	6	10
Yaren	12	0	4	26	144	0	0	1	1	0	0	1	1	0	0	1	1	0	0	3	3	0	0	6	6	0	0	24	24	2	0	63	65	4
All of Nauru	**202**	**58**	**16**	**98**	**2052**	**0**	**0**	**13**	**13**	**0**	**0**	**31**	**31**	**2**	**0**	**47**	**49**	**2**	**0**	**69**	**71**	**4**	**2**	**148**	**154**	**10**	**2**	**253**	**265**	**50**	**3**	**396**	**449**	-

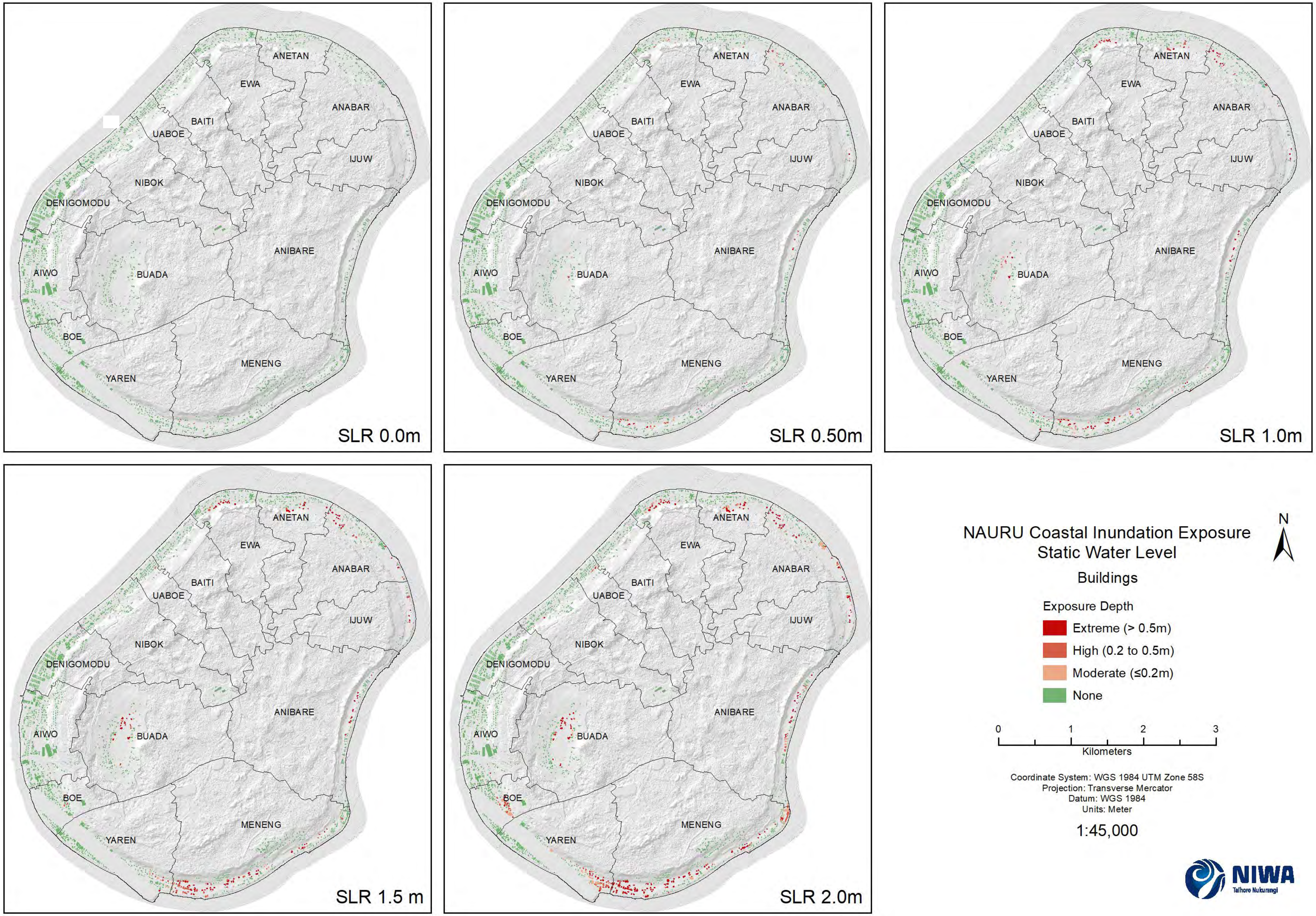

Figure 3-9: Map of building exposure to present day king-tide inundation and after increments of sea-level rise. Colours represent depth of inundation above ground at building (see legend). Refer to Table 3-2 for totals of district level exposure.

3.4 Roads

The calculated road length exposure in Nauru are presented in Figure 3-4 (roads by district), enumerated in Table 3-2 and mapped in Figure 3-6. Roads were segmented into 1 m lengths for this analysis.

There are approximately 72.5 km of roads on Nauru. At the present day only 382 m of are exposed (0.5% of all roads) but this rises to 6,188 m or 8.5% of all roads (Table 3-5).

Table 3-5 provides a district level summary of road exposure with SLR. The exposure is concentrated to Anabar, Anetan, Buada and Meneng until SLR exceeds 1 m. As SLR increases beyond 1m the exposure broadens to include small lengths in Nibok and Uaboe districts (total <100 m), and at 2 m SLR also includes small lengths in Anibare, Baiti and Yaren. At KT+2m SLR only five districts have no road exposure (Aiwo, Boe, Denigomodu, Ewa and Ijuw).

However, this exposure excludes wave overtopping of coastal defences for roads which are along the coastline. The wave overtopping occurs above the simulated static water level and would flow across the road, leading to temporary inundation and a hazard to road users. We understand this occurs periodically in Anabar during large storm waves. Resolving this level of detail should be part of any future studies.

Roads in Buada are shown to be exposed, however note the assumption made in Section 2.6 about groundwater connection between Buada Lagoon and the sea, and this is likely to result in conservative (i.e., higher) exposure.

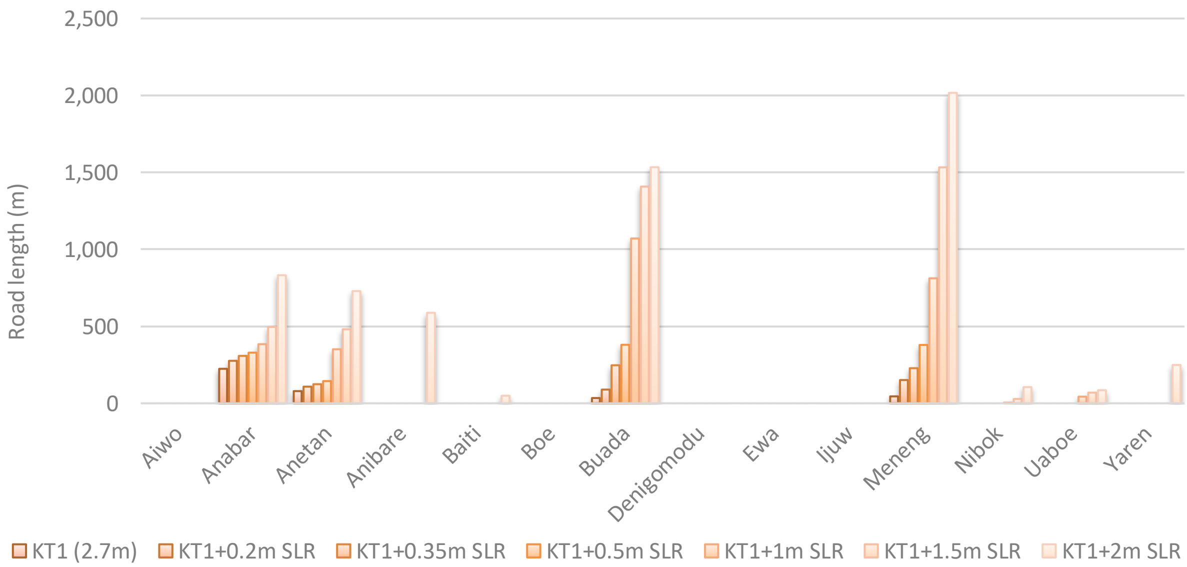

Figure 3-10: Road length for each district exposed (m) to KT1 and KT1+SLR increments. Refer to Table 3-5 for values.

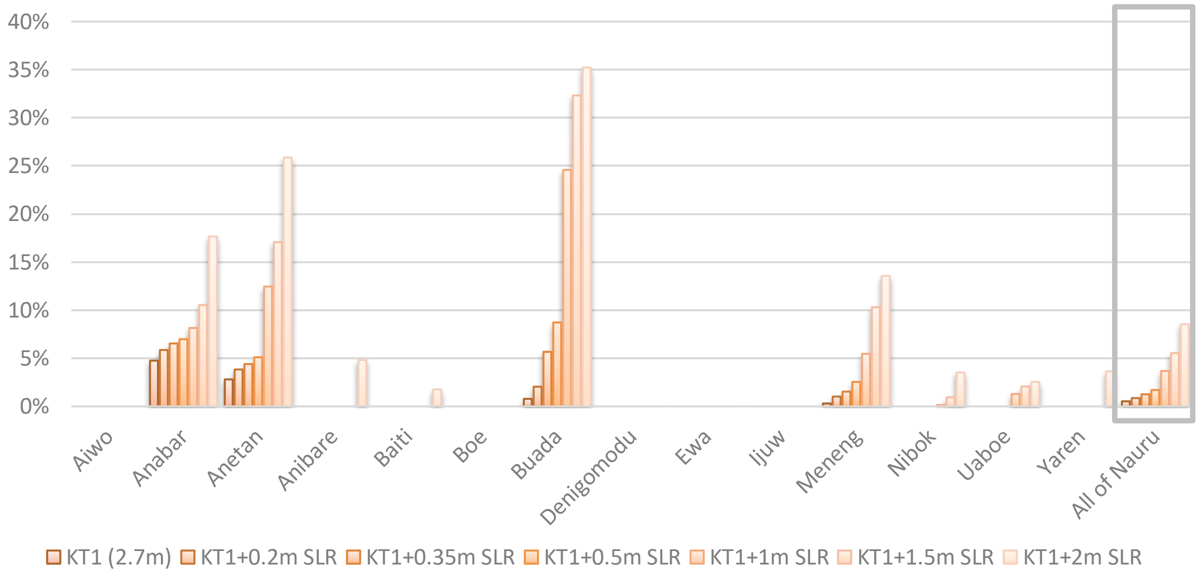

Figure 3-11: Percentage of road length for each district exposed to KT1 and KT1+SLR increments. Refer to Table 3-5 for values.

Table 3-5: Road length within each district and percentage of district road length exposed for KT1 and KT1+SLR increments. All of Nauru total highlighted in bold.

District name	Total district road length (m)	Road length exposed (m)							Proportion of district total road length exposed (%)						
		KT1 (2.7m NID)	KT1 +0.2m SLR	KT1 +0.35m SLR	KT1 +0.5m SLR	KT1 +1m SLR	KT1 +1.5m SLR	KT1 +2m SLR	KT1 (2.7m NID)	KT1 +0.2m SLR	KT1 +0.35m SLR	KT1 +0.5m SLR	KT1 +1m SLR	KT1 +1.5m SLR	KT1 +2m SLR
Aiwo	5,060	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Anabar	4,710	224	276	308	329	384	496	832	4.8%	5.9%	6.5%	7.0%	8.2%	10.5%	17.7%
Anetan	2,818	79	108	124	144	351	481	729	2.8%	3.8%	4.4%	5.1%	12.5%	17.1%	25.9%
Anibare	12,218	-	-	-	-	-	-	588	-	-	-	-	-	-	4.8%
Baiti	2,787	-	-	-	-	-	-	49	-	-	-	-	-	-	1.8%
Boe	2,067	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Buada	4,356	34	89	247	380	1,071	1,408	1,534	0.8%	2.0%	5.7%	8.7%	24.6%	32.3%	35.2%
Denigomodu	3,448	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Ewa	3,853	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Ijuw	3,136	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Meneng	14,874	45	151	228	379	812	1,533	2,017	0.3%	1.0%	1.5%	2.5%	5.5%	10.3%	13.6%
Nibok	2,980	-	-	-	-	4	28	105	-	-	-	-	0.1%	0.9%	3.5%
Uaboe	3,351	-	-	-	-	43	69	85	-	-	-	-	1.3%	2.1%	2.5%
Yaren	6,853	-	-	-	-	-	-	249	-	-	-	-	-	-	3.6%
All of Nauru	**72,511**	**382**	**624**	**907**	**1,232**	**2,665**	**4,015**	**6,188**	**0.5%**	**0.9%**	**1.3%**	**1.7%**	**3.7%**	**5.5%**	**8.5%**

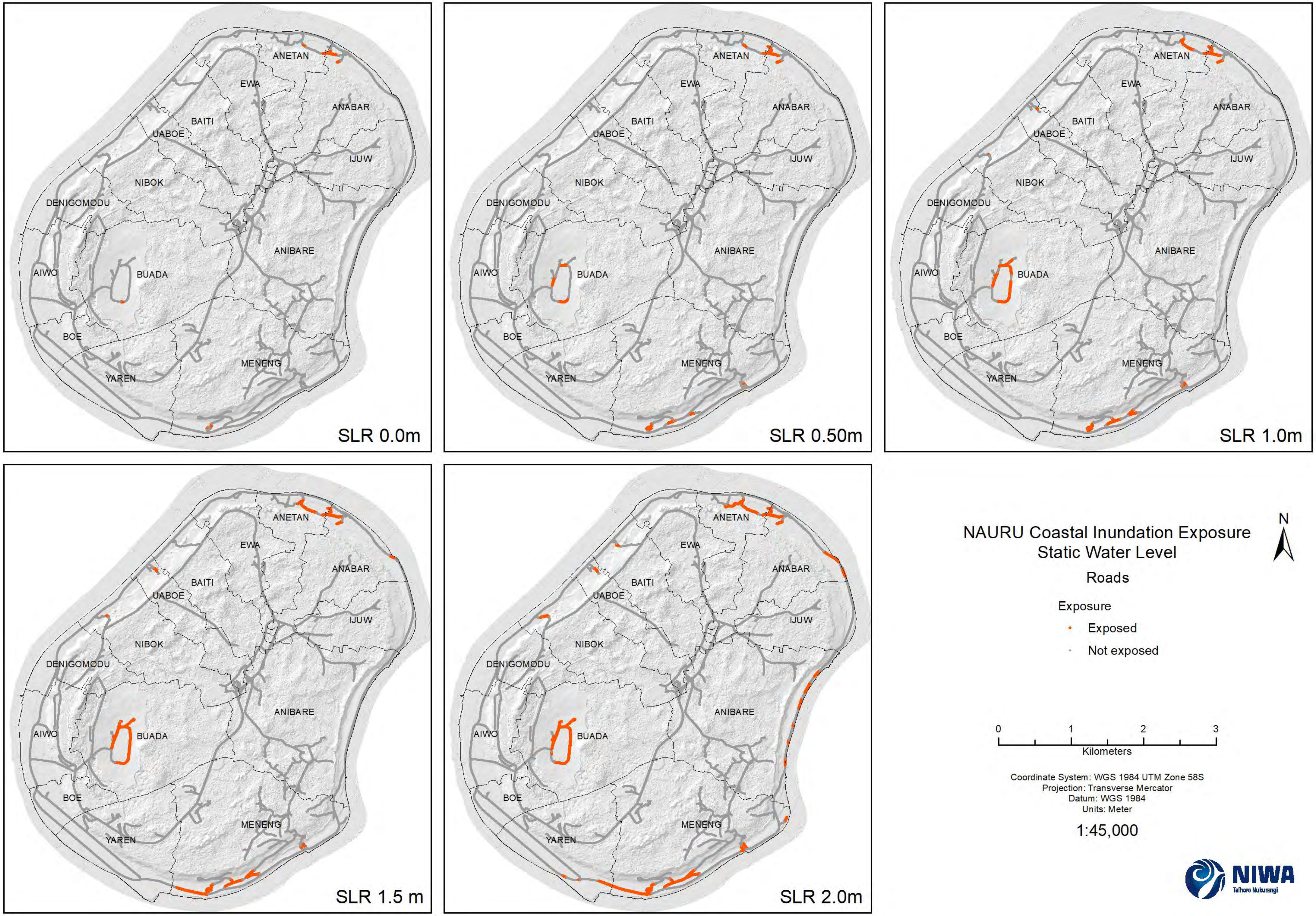

Figure 3-12: Map of roads exposed to present day king-tide inundation and after increments of sea-level rise. Colours show whether road is below static water level elevation (see legend). Refer to Table 3-5 for totals of district level exposure.

3.5 Tanks

The calculated exposure of tanks in Nauru are presented in Figure 3-13 (tanks by district), enumerated in Table 3-6 and mapped in Figure 3-15.

The database for tanks included few details on the type of tank noted, only designations for "tank/small dam" and "unknown tank". Consequently, it is unclear whether the tanks refer to water supply tanks, septic tanks or other tanks (i.e., fuel supply, oil or other), or whether the tanks are in use or derelict.

Exposure of a tank does not necessarily mean exposure of its contents to the sea, rather it means the ground level around the tank is below the static water level. This may be important in relation to salt-water ingress/corrosion to water supply pipes, or flooding of septic tanks and preventing waste from draining away. Further, the databases contain no information as to whether the tanks are located on elevated platforms as is common to provide some water pressure in pipes.

There are approximately 790 tanks in the database for Nauru. At the present day only 7 individual tanks of are exposed (all in Meneng) but this rises to 155 (19.6%) of all tanks after 2 m SLR (Table 3-6).

All districts show an increase in exposure of tanks as sea levels rise. After 0.5 m SLR, an average of 6.3% of tanks are potentially exposed, increasing to 25% at 2 m SLR.

The potential exposure of tanks to rising sea levels is greatest in Meneng (57 of 121 tanks) but Anibare has the greatest percentage exposed (52%, or 13 of its 25 tanks). Meneng also has the highest population (see Figure 3-4) and thus would be expected to have the most tanks. Across the other districts, only 5-15 tanks are exposed in each district, representing 10-30% of each district total.

Only Aiwo, Denigomodu and Nibok have no exposure of tanks under the SLR increments.

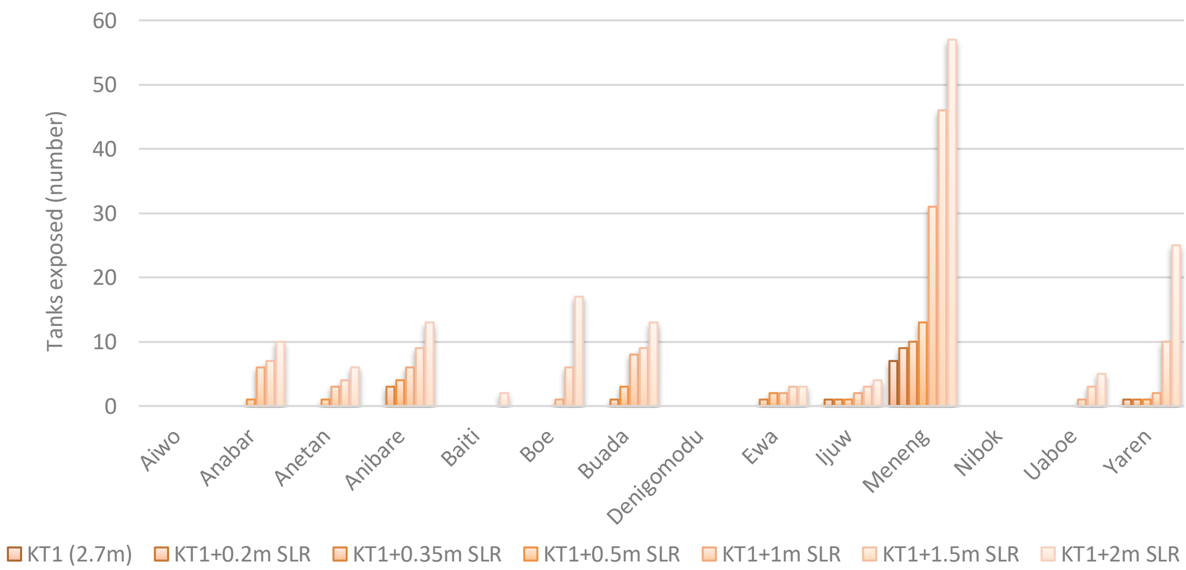

Figure 3-13: Number of tanks within each district exposed to KT1 and KT1+SLR increments. Refer to Table 3-6 for values.

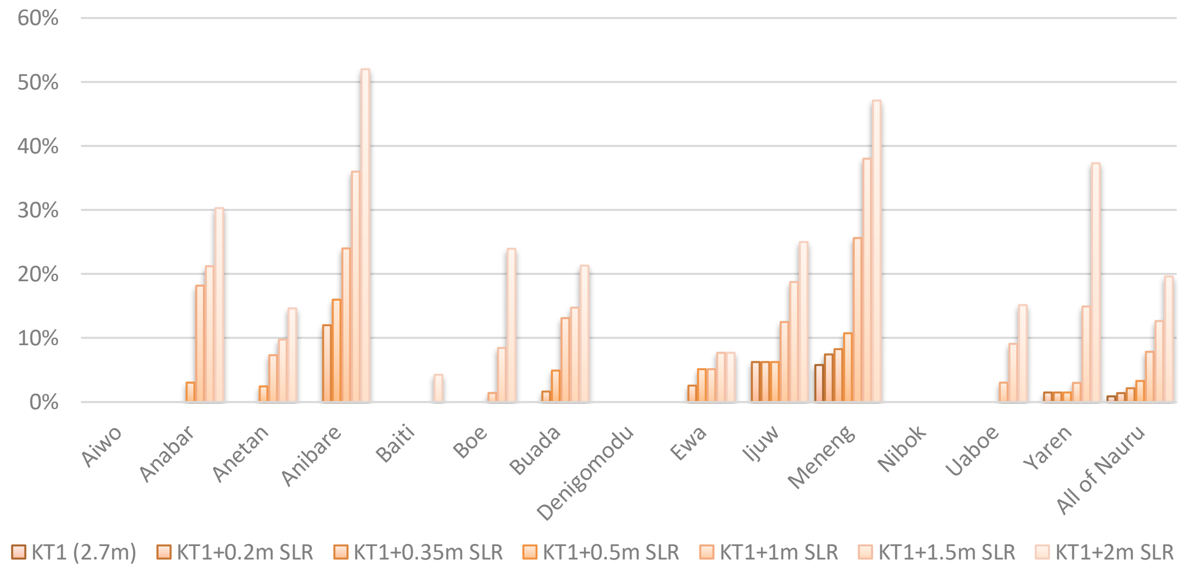

Figure 3-14: Percentage of tank exposure within each district for KT1 and KT1+SLR increments. Refer to Table 3-6 for values.

Table 3-6: Number of tanks within each district and percentage of tanks exposed within each district for KT1 and KT1+SLR increments. All of Nauru total highlighted in bold.

District name	Total district road length (m)	Number of tanks exposed							Percentage of district total exposed (%)						
		KT1 (2.7m NID)	KT1 +0.2m SLR	KT1 +0.35m SLR	KT1 +0.5m SLR	KT1 +1m SLR	KT1 +1.5m SLR	KT1 +2m SLR	KT1 (2.7m NID)	KT1 +0.2m SLR	KT1 +0.35m SLR	KT1 +0.5m SLR	KT1 +1m SLR	KT1 +1.5m SLR	KT1 +2m SLR
Aiwo	151	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Anabar	33	-	-	-	1	6	7	10	-	-	-	3.0%	18.2%	21.2%	30.3%
Anetan	41	-	-	-	1	3	4	6	-	-	-	2.4%	7.3%	9.8%	14.6%
Anibare	25	-	-	3	4	6	9	13	-	-	12.0%	16.0%	24.0%	36.0%	52.0%
Baiti	47	-	-	-	-	-	-	2	-	-	-	-	-	-	4.3%
Boe	71	-	-	-	-	1	6	17	-	-	-	-	1.4%	8.5%	23.9%
Buada	61	-	-	1	3	8	9	13	-	-	1.6%	4.9%	13.1%	14.8%	21.3%
Denigomodu	35	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Ewa	39	-	-	1	2	2	3	3	-	-	2.6%	5.1%	5.1%	7.7%	7.7%
Ijuw	16	-	1	1	1	2	3	4	-	6.3%	6.3%	6.3%	12.5%	18.8%	25.0%
Meneng	121	7	9	10	13	31	46	57	5.8%	7.4%	8.3%	10.7%	25.6%	38.0%	47.1%
Nibok	50	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Uaboe	33	-	-	-	-	1	3	5	-	-	-	-	3.0%	9.1%	15.2%
Yaren	67	-	1	1	1	2	10	25	-	1.5%	1.5%	1.5%	3.0%	14.9%	37.3%
All of Nauru	**790**	**7**	**11**	**17**	**26**	**62**	**100**	**155**	**0.9%**	**1.4%**	**2.2%**	**3.3%**	**7.8%**	**12.7%**	**19.6%**

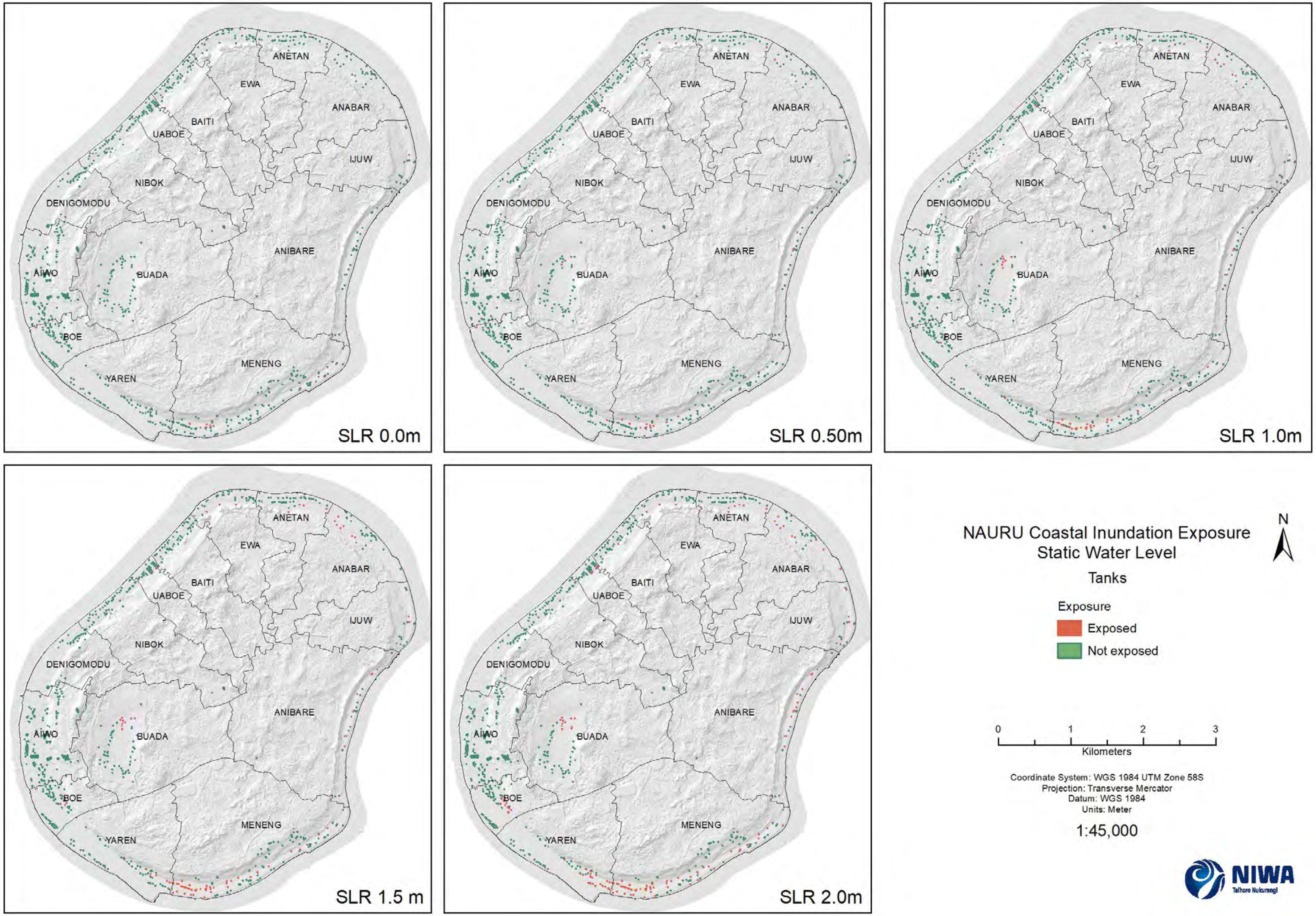

Figure 3-15: Map of tank exposure to present day king-tide inundation and after increments of sea-level rise. Colours show whether road is below static water level elevation (see legend). Refer to Table 3-2 for totals of district level exposure.

3.6 Electricity poles

The calculated exposure of electricity poles in Nauru are presented in Figure 3-16 (by district) and Figure 3-17 (percentage of district total), enumerated in Table 3-7 and mapped in Figure 3-18.

Note that exposure of a pole does not necessarily mean exposure of the electrical supply to the sea water, rather it means the ground level around the pole is below the static water elevation. This may be important for buried electricity conduits and connections at the base of poles.

There are 788[10] known electricity poles in the database for Nauru, this includes some on the reef flat at the boat harbours and port cantilevers. At the present day only 2 individual poles of are exposed in Buada (note previous comments about lagoon levels) and this rises to 67 (8.7%) of all poles after 2 m SLR (Table 3-7).

Only the electricity poles which are around the low-lying coastal fringe are exposed with the large number on the Island Topside and up the escarpment not exposed. The southern districts of Meneng and Yaren have 63% (42 of 67) of all poles exposed at KT1+2m SLR with exposed poles primarily concentrated along a 700 m stretch east of the southern runway extent (Figure 3-18).

All other districts have 11 or less poles exposed even for KT1+2m SLR.

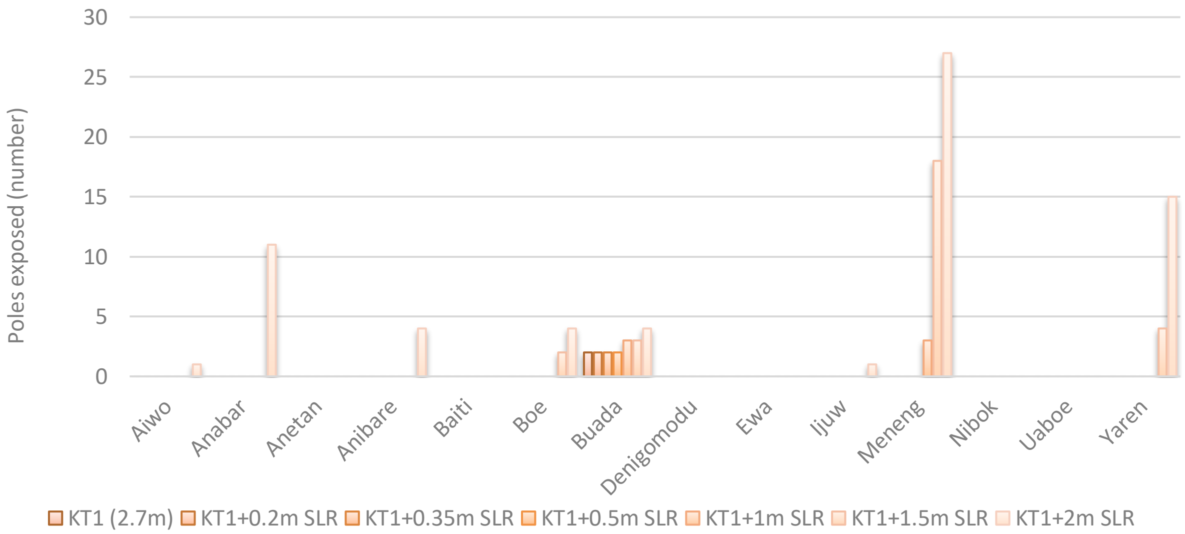

Figure 3-16: Number of electricity poles of each district exposed to KT1 and KT1+SLR increments. Refer to Table 3-7 for values.

[10] The total number reported may vary in each region as dataset also contained 15 'null points'.

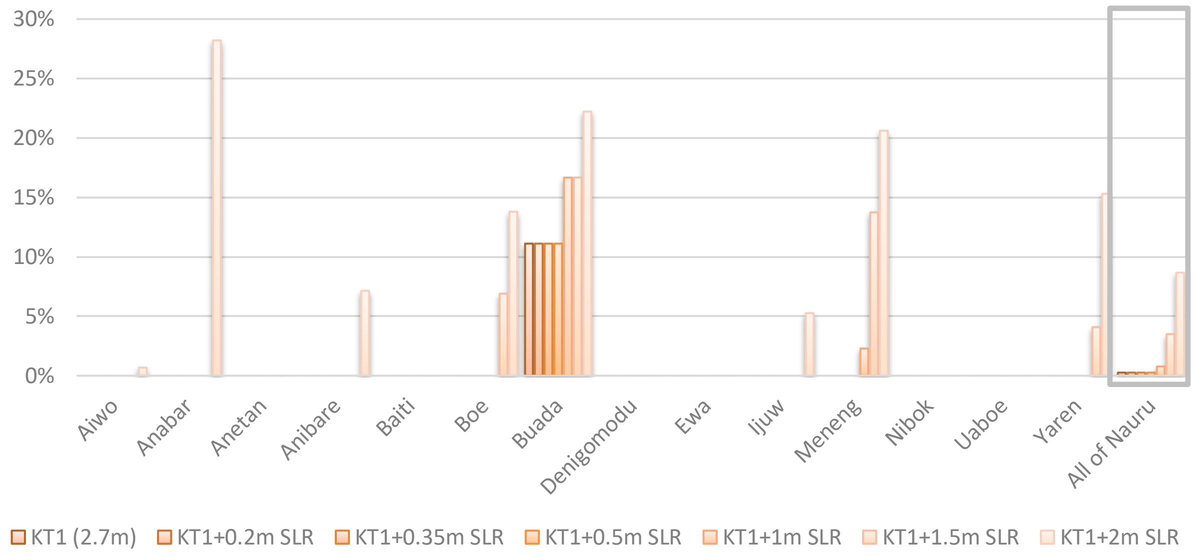

Figure 3-17: Percentage of electricity poles in each district exposed to KT1 and KT1+SLR increments. Refer to Table 3-7 for values.

Table 3-7: Electricity poles of each district exposed and percentage of electricity poles per total district exposed for KT1 and KT1+SLR increments. All of Nauru total highlighted in bold.

District name	District total	Number of electricity poles exposed							Percentage of district total exposed (%)						
		KT1 (2.7m NID)	KT1 +0.2m SLR	KT1 +0.35m SLR	KT1 +0.5m SLR	KT1 +1m SLR	KT1 +1.5m SLR	KT1 +2m SLR	KT1 (2.7m NID)	KT1 +0.2m SLR	KT1 +0.35m SLR	KT1 +0.5m SLR	KT1 +1m SLR	KT1 +1.5m SLR	KT1 +2m SLR
Aiwo	147	-	-	-	-	-	-	1	-	-	-	-	-	-	0.7%
Anabar	39	-	-	-	-	-	-	11	-	-	-	-	-	-	28.2%
Anetan	22	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Anibare	56	-	-	-	-	-	-	4	-	-	-	-	-	-	7.1%
Baiti	19	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Boe	29	-	-	-	-	-	2	4	-	-	-	-	-	6.9%	13.8%
Buada	18	2	2	2	2	3	3	4	11.1%	11.1%	11.1%	11.1%	16.7%	16.7%	22.2%
Denigomodu	86	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Ewa	33	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Ijuw	19	-	-	-	-	-	-	1	-	-	-	-	-	-	5.3%
Meneng	131	-	-	-	-	3	18	27	-	-	-	-	2.3%	13.7%	20.6%
Nibok	61	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Uaboe	15	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Yaren	98	-	-	-	-	-	4	15	-	-	-	-	-	4.1%	15.3%
All of Nauru	**773**	**2**	**2**	**2**	**2**	**6**	**27**	**67**	**0.3%**	**0.3%**	**0.3%**	**0.3%**	**0.8%**	**3.5%**	**8.7%**

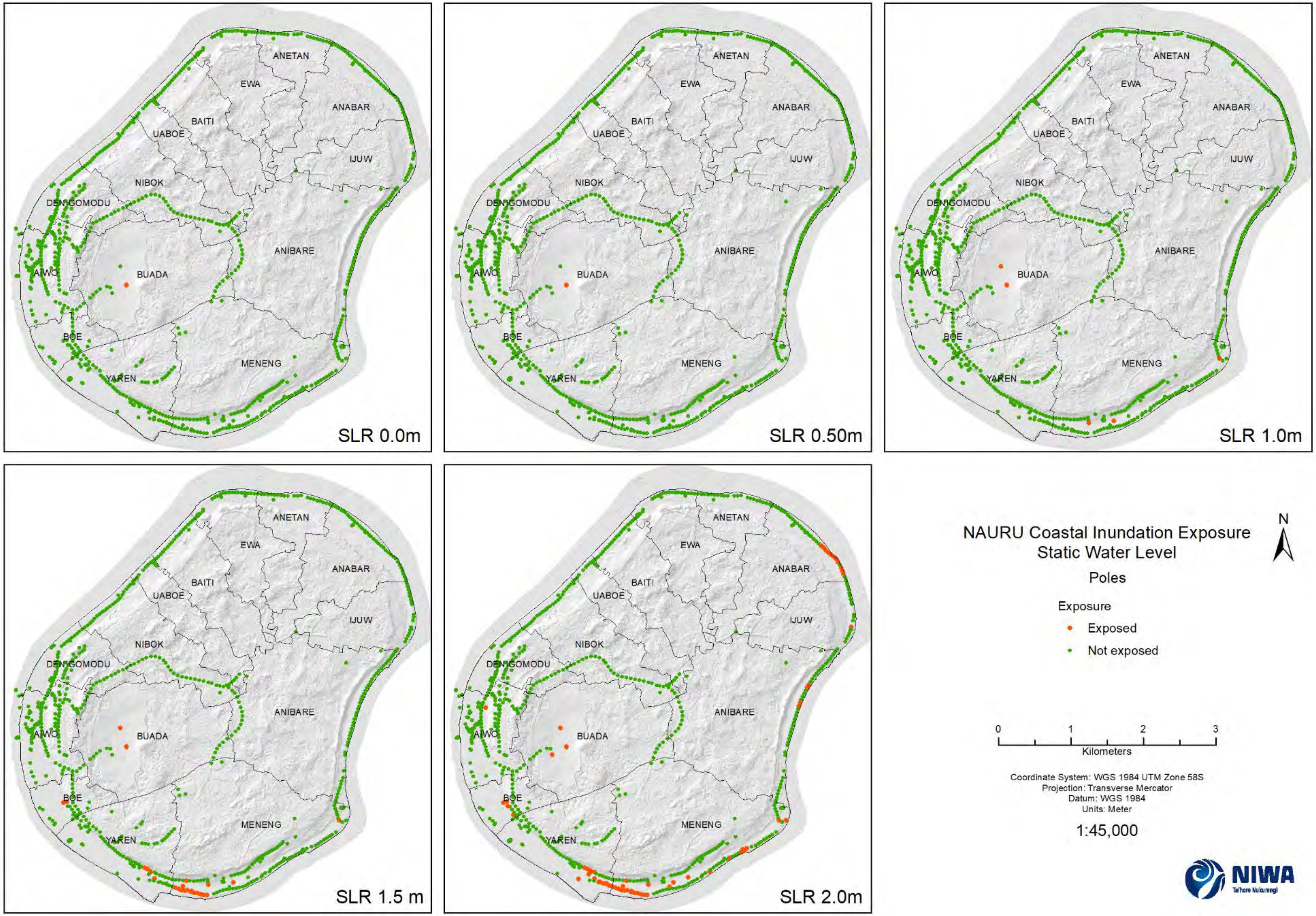

Figure 3-18: Map of electricity exposed to present day king-tide inundation and after increments of sea-level rise. Colours show whether the and at the base of the pole is inundated (see legend). Refer to Table 3-7 for totals of district level exposure.

3.7 Coconuts

The exposure of coconut crops to rising sea levels was requested as a proxy for potentially productive land area as related to food security concerns for the Island.

The exposure of coconut crops is reported below, however note that the accuracy of the data is unknown, as the database is from the year 2000 and has not been updated. Within the data it is unclear if the original "coconut crop polygons" dataset refers to single coconut palm, an aggregate of palms within a set area, or open ground which could suit coconut palms. For this study, we converted the polygons to represent an area of potential coconut crop features as evaluated over the 5 m DEM grid. In this study the output represents the area (m^2) of potential coconut cropping.

However, this exposure does not account for the survival rate of coconuts palms to increased inundation depth and frequency by future king tides is unknown, nor is the relationship between coconut crops and food security.

The calculated exposure of potential coconut crops area in Nauru are presented in Figure 3-19 (by district) and Figure 3-20 (percentage of district total), enumerated in Table 3-8 and mapped in Figure 3-21.

Across Nauru, the potential coconut crops area is 1.09 km^2 which is approximately 5% of the total Island area (21.4 km^2). At the present day there are 0.09 km^2 (8.4% of total) below the KT1 elevation with most districts showing some exposure, this rises to 0.35 km^2 (31.6% of total) in the KT1+2m SLR scenario.

The northern districts of Anetan and Anibar have the highest absolute and proportional exposure at the present day, with from 20,000 m^2 (25%) below KT1 elevation. This rises to 60,000 m^2 (65%) at KT1+2m SLR, but is overtaken by Meneng with 80,000 m^2 exposed (53%). Most other districts show a linear increase from 5% to 25% over the scenarios tested.

However, similar to the land area exposure (see Section 3.1), the western/north-western districts of Aiwo, Denigomodu, Nibok and Uaboe have the lowest exposure, with less than 2000 m^2 exposed for KT1+2m SLR, which is less than 5% of each district's total coconut crop "feature" count.

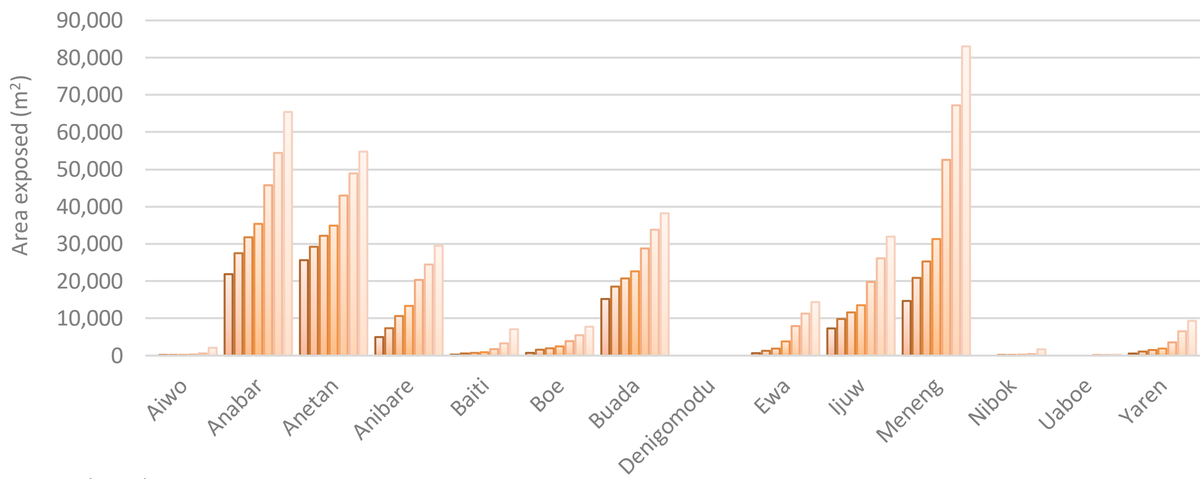

Figure 3-19: Potential coconut crops area within each district exposed to KT1 and KT1+SLR increments. Refer to Table 3-8 for values.

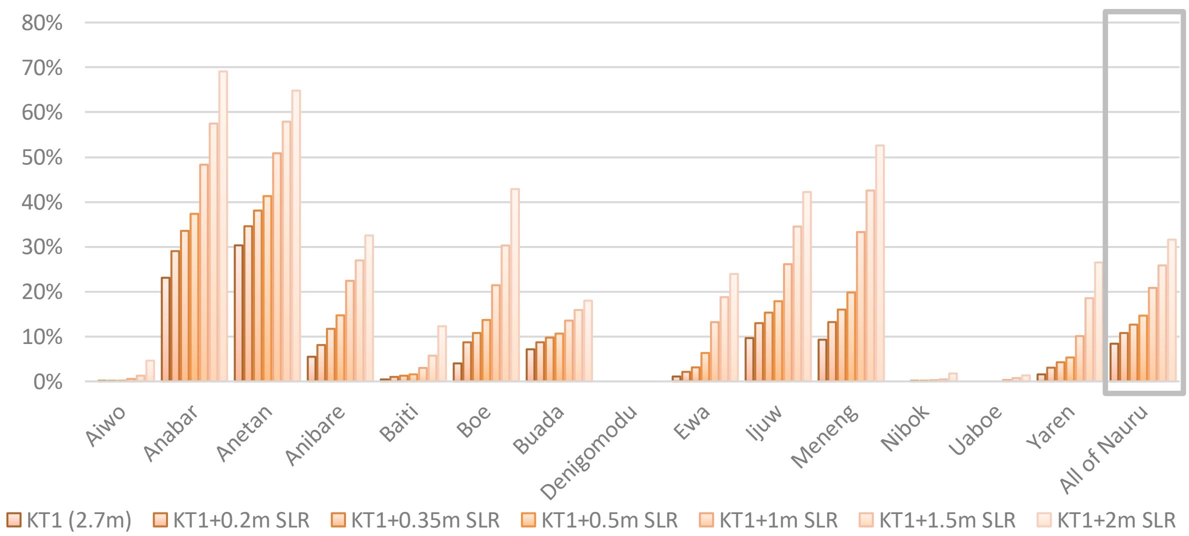

Figure 3-20: Percentage of electricity poles in each district exposed to KT1 and KT1+SLR increments. Refer to Table 3-8 for values

Table 3-8: Coconut crops features exposed within each district and percentage of district road length exposed for KT1 and KT1+SLR increments. All of Nauru total highlighted in bold.

District name	District total (m^2)	Potential coconut crop area exposed (m^2)							Percentage of district total exposed (%)						
		KT1 (2.7m NID)	KT1 +0.2m SLR	KT1 +0.35m SLR	KT1 +0.5m SLR	KT1 +1m SLR	KT1 +1.5m SLR	KT1 +2m SLR	KT1 (2.7m NID)	KT1 +0.2m SLR	KT1 +0.35m SLR	KT1 +0.5m SLR	KT1 +1m SLR	KT1 +1.5m SLR	KT1 +2m SLR
Aiwo	45,525	-	25	25	50	250	575	2,100	-	0.1%	0.1%	0.1%	0.5%	1.3%	4.6%
Anabar	94,700	21,875	27,500	31,775	35,375	45,750	54,425	65,425	23.1%	29.0%	33.6%	37.4%	48.3%	57.5%	69.1%
Anetan	84,500	25,625	29,225	32,175	34,900	42,975	48,925	54,775	30.3%	34.6%	38.1%	41.3%	50.9%	57.9%	64.8%
Anibare	90,650	4,975	7,350	10,625	13,350	20,325	24,450	29,500	5.5%	8.1%	11.7%	14.7%	22.4%	27.0%	32.5%
Baiti	57,550	250	575	725	900	1,725	3,300	7,075	0.4%	1.0%	1.3%	1.6%	3.0%	5.7%	12.3%
Boe	18,075	725	1,575	1,950	2,475	3,875	5,475	7,750	4.0%	8.7%	10.8%	13.7%	21.4%	30.3%	42.9%
Buada	212,450	15,200	18,525	20,725	22,625	28,775	33,800	38,225	7.2%	8.7%	9.8%	10.6%	13.5%	15.9%	18.0%
Denigomodu	48,325	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Ewa	60,025	650	1,275	1,875	3,800	7,925	11,275	14,375	1.1%	2.1%	3.1%	6.3%	13.2%	18.8%	23.9%
Ijuw	75,675	7,300	9,825	11,600	13,525	19,775	26,125	31,950	9.6%	13.0%	15.3%	17.9%	26.1%	34.5%	42.2%
Meneng	157,925	14,675	20,875	25,275	31,300	52,575	67,200	83,050	9.3%	13.2%	16.0%	19.8%	33.3%	42.6%	52.6%
Nibok	95,700	-	-	25	50	225	425	1,675	-	-	0.0%	0.1%	0.2%	0.4%	1.8%
Uaboe	16,875	-	-	-	-	50	125	225	-	-	-	-	0.3%	0.7%	1.3%
Yaren	35,175	550	1,075	1,500	1,875	3,550	6,525	9,325	1.6%	3.1%	4.3%	5.3%	10.1%	18.6%	26.5%
All of Nauru	**1,093,150**	**91,825**	**117,825**	**138,275**	**160,225**	**227,775**	**282,625**	**345,450**	**8.4%**	**10.8%**	**12.6%**	**14.7%**	**20.8%**	**25.9%**	**31.6%**

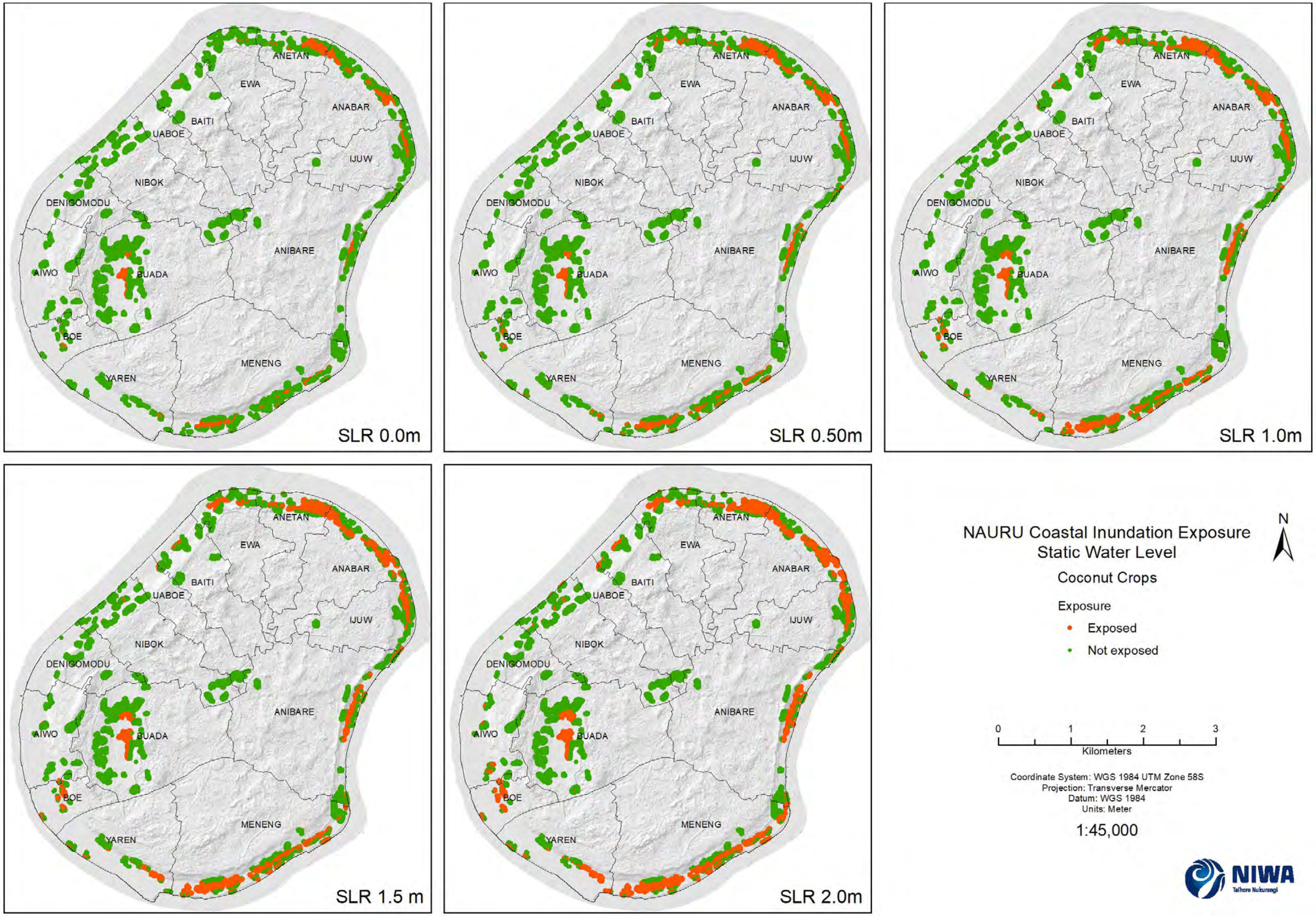

Figure 3-21: Map of coconut crops features exposed to king-tide inundation and after increments of sea-level rise. Colours show whether land elevation beneath coconut crop feature is below static water level elevation (see legend). Refer to Table 3-8 for district level summary of values.

3.8 Airport

The elevation of the paved runway grades from 7.5 m in the northwest, to a low point of 5 m at approx. 1.6 km, before rising again to 6.7 m at the south-eastern extent. The lowest point of the paved runway is 0.3 m above the king tide elevation for the highest sea-level rise level tested (4.7 m) and as such is not shown to be inundated by tides alone in the study (see Figure 3-22).

The grassed areas on either side of the runway have a low point of about 4.5 m, grading to this low point from 7.5 m elevation in the north and 6.5 m in the south. These low-lying areas are shown to be inundated by the highest king-tide inundation with 1.5 and 2 m SLR. The maps (Figure 3-22) show that the inundation patterns are consistent with graded drainage channels on either side of the runway.

However, this excludes the effect of waves which may overwash the revetment on the southern boundary of the airport and will lead to water flowing across the grass/paving at times. Wave overtopping here would occur above the calculated static water level and would flow across the grassed areas to drain into the aforementioned stormwater channels. During particularly severe wave overtopping there may be water spreading over the southern sections of the paved runway. The effect of this on the paved runway will depend on the magnitude of overwashing (size of waves), coastal defence design, sea level at the time (tide + SLR) and the capacity of the airport drainage system, infiltration rates, antecedent rainfall and groundwater levels.

Resolving this level of detail should be part of any future studies.

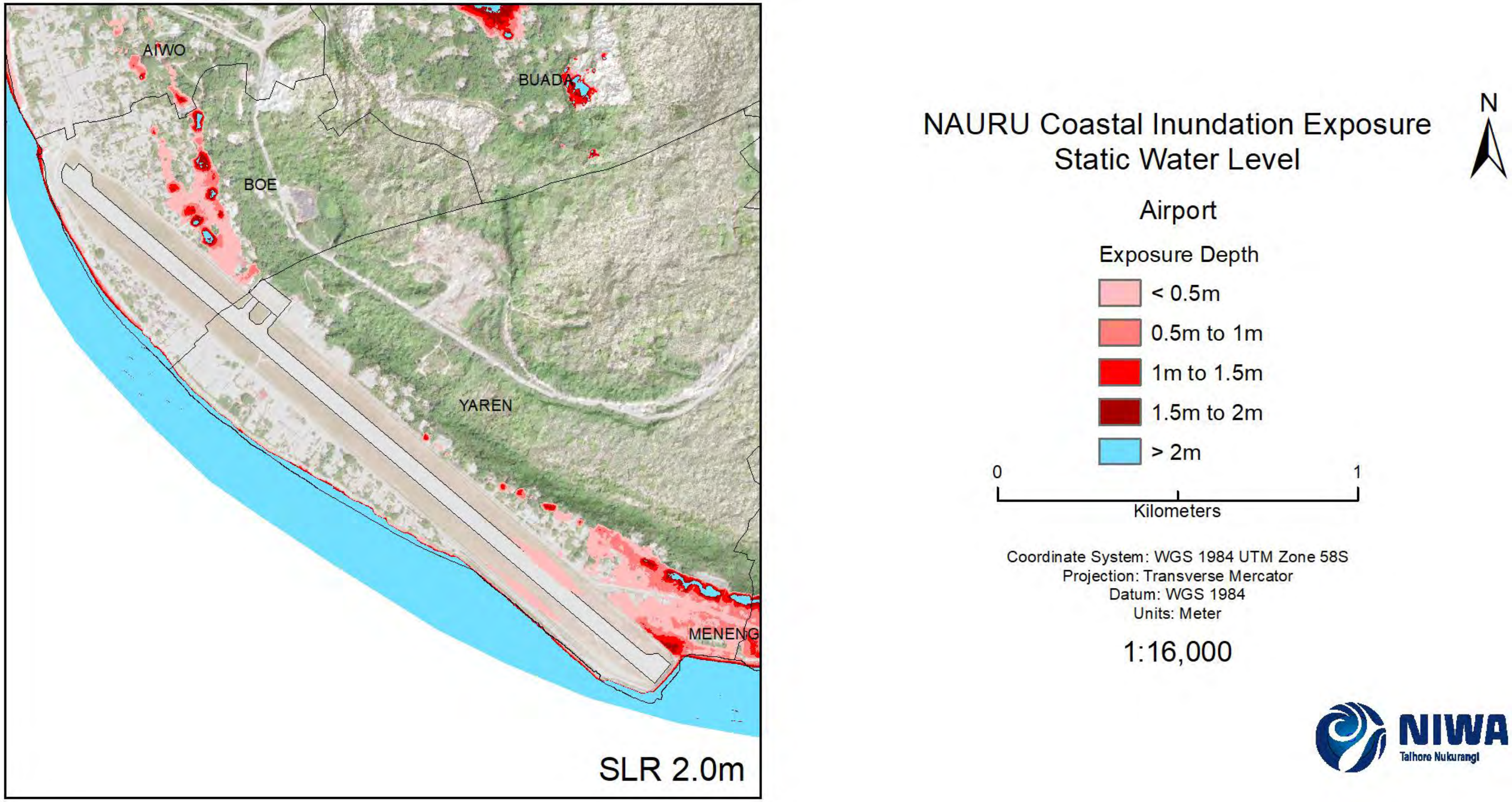

Figure 3-22: Exposure of airport to static inundation from KT1+2m SLR event. .

4 Data limitations and recommendation for future improvement

As with all data analysis, the outputs presented are subject to inherent uncertainties associated with the input datasets used and where required, assumptions made:

- Sea level bathtub models are assumed to be representative of present-day king-tide sea level and incremental sea-level rise.
- The buildings layer was updated remotely using satellite imagery and has not been ground-truthed by way of in-country surveys.
- The road layer used represents the centre of the road and does not represent road-edges that may potentially be exposed. Future exposure studies should use a polygonized road-edges layer to better represent areas on the road which are exposed.
- The population analysis assumes a uniform distribution within each 100 m grid cell, and subsequent 5 m grid cells within each parent cell (i.e., 100m).
- The coconut crops layer was extracted from a dataset created in 2000 with no further modification/ground-truthing. Future studies should consider updating the crops layer to provide more representative results.
- The cadastre layer was created in 2000 and contained areas in the northeast and southwest which did not appear to have cadastral ownership.
- The poles data used was created in 2000 with no further validation/ground-truthing. Future studies should consider validating/updating the poles dataset.
- Lagoon level elevation is equal to the coastal sea-level elevation, including Buada Lagoon.

Nevertheless, the results provide benchmark scenario representations based on current available datasets that 'paint a picture' of the estimated exposure of assets assessed to present/future sea level.

These baselines should be iteratively refined and updated as new hazard, assets and vulnerability information become available, particularly wave processes which are anticipated for the next phase of this work.

5 Summary

This report presents Nauru's exposure to king-tide coastal flooding events under present-day and future higher sea levels using a static "bathtub" model.

Future sea-level rise is incorporated into the inundation assessments with increments of 0.2 m, 0.35 m, 0.5 m, 1m, 1.5 m and 2 m above the present-day king-tide elevation of 2.7 m NID.

At national level, elements at risk generally demonstrate a consistent increase in exposure in response to rising sea levels as directly related to land elevation. Exposure increase at district levels exhibits non-linear behaviors with average exposure rates accelerating and decelerating exposure in response to SLR up to +2 m and the asset being examined.

Overall, for this study, the elevation of the coastal plain between the beach and the escarpment is the primary driver of exposure to future king-tide inundation (which excludes wave processes). This coastal plain contains most assets, buildings, population and potentially productive land. Within this coastal plain, the ground elevation is highest around the west/north west fringe (Aiwo, Denigomodu, Nibok, Uaboe and Baiti), are hence the least exposed under the scenarios tested. Conversely, the low-lying land around lagoons and the backshore depressions are the most exposed, particularly around the south, east and northern shorelines (Meneng, Anabar, Ijuw and Yaren). In this assessment, land elevation correlates directly to the asset exposure, with the lower elevation districts showing more exposure across all asset types compared to the higher elevation districts.

This information provides locations to focus more detailed investigation on the potential impacts, management implications of coastal flooding in Nauru under future sea-level rise.

These results and maps should be updated as new LiDAR data and new asset data is made available and once ground truthing of wave runup/overtopping models can be included (proposed for stage 2 of this Project).

6 Acknowledgements

The authors would like to acknowledge:

- The provision of datasets, reports and references files from SPC.
- The cooperation of the Government of Nauru in providing data and facilitating travel visa's before the site visit field survey was cancelled (COVID-19 related).
- Input and discussions from Peter Ollivier (Calibre Group Limited).
- The Pacific Sea Level and Geodetic Monitoring Project (PSLGM) operated by the Bureau of Meteorology and Geoscience Australia for the tide gauge data and ground surveying information.

7 Glossary of abbreviations and terms

Bathtub model	A bathtub model simply means treating the ocean like a bathtub, that fills up the same way that a tub does when you add water. The lower parts fill up first, and the water rises at the same level everywhere.
Built asset	Physical structures as part of the built environment e.g., buildings, infrastructure (e.g., roads, railways, electricity transmission lines etc.,.).
DEM	Digital elevation model.
ENSO	El Nino Southern Oscillation.
GIS	Geographic information system.
Inundation	Coastal inundation is the flooding of normally dry, low-lying coastal land. This is primarily caused by severe weather events along the coasts, estuaries, and adjoining rivers but will caused by rising sea levels in the future.
IPCC	Intergovernmental Panel for Climate Change.
KT1	The selected king-tide elevation calculated from the tide gauge record which has exceedance probability of approximately 1% (KT1 elevation = 2.7 m NID in this study).
LiDAR	Airborne Light Detection and Ranging (LIDAR), is a remote sensing method that uses light in the form of a pulsed laser to measure ranges (variable distances) to the Earth. A LiDAR survey produces a DEM which can be used to evaluate coastal inundation.
MSL	is the mean sea level a relative to a vertical datum over a defined epoch, usually of several years.
NID	Nauru Island vertical datum, defined as 7.2929 m below the NAU1 deep-driven survey benchmark. NID = 0 m is also equal to the tide gauge zero (TGZ) elevation.
PSLGM	Pacific Sea Level and Geodetic Monitoring Project. The project which setup and operates the Nauru tide gauge.
SLR	Sea-level rise.
SROCC	Special Report on the Ocean and Cryosphere in a Changing Climate.
TGZ	Tide gauge zero elevation. Equal to 0 m NID.

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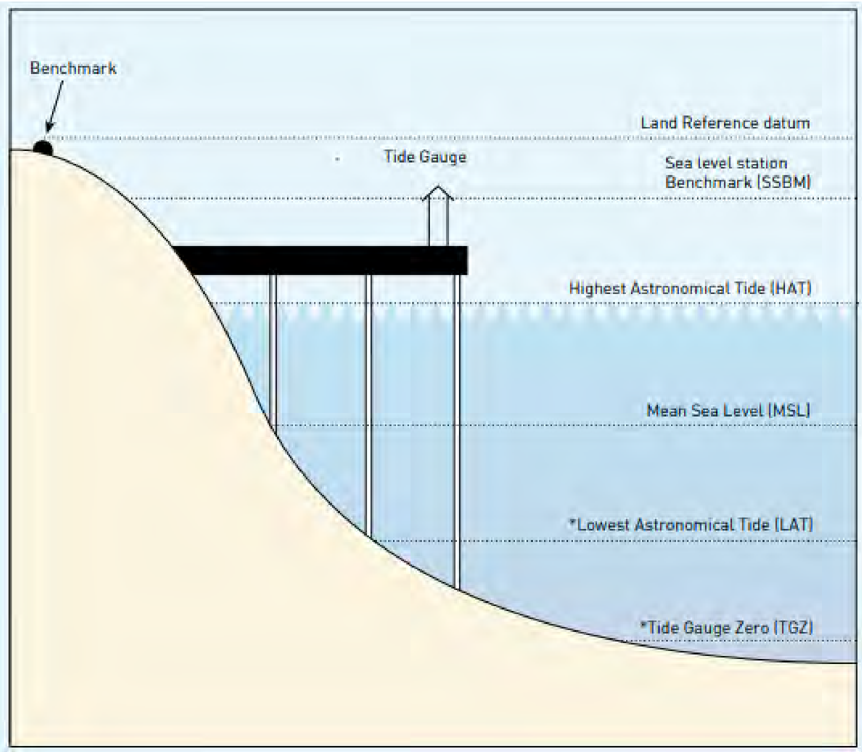
Appendix A Island Datum

All elevations are relative to Nauru Island Datum (NID) which is 7.2929 m below the NAU1 fixed survey point (e.g., Figure A-2) which is a deep driven survey benchmark within wharf compound. The elevation of this datum is periodically surveyed by Geoscience Australia and SPC with precise levelling and continuous GPS measurements used to tie this datum into the tide gauge (e.g., AusAid 2009, Yates & Lal 2013).

The zero elevation of the tide gauge is set equal to 0 m NID (i.e., TGZ=0 m NID).

Figure A-1: Diagram of tide gauge datum and references. [Source: AusAID (2009)].



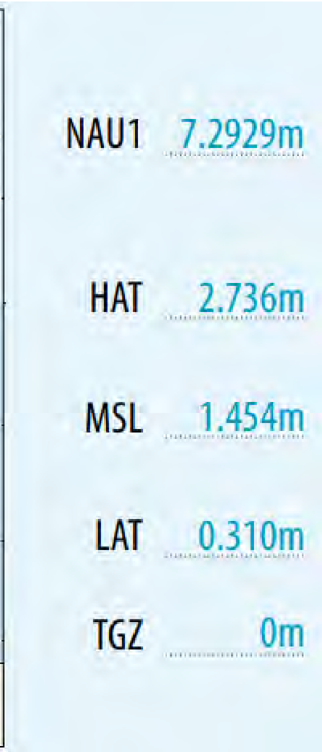


Figure A-2: Key tide component elevations for Nauru. [Source: 2020 Tide Predictions Calendar[11]].

[11] http://oceanportal.spc.int/portal/library/assets/Nauru.2020.Tide.Calendar.Work.Plan.pdf

Appendix B Tide gauge analysis

Tide gauge data

Tide gauge data was obtained from the Pacific Sea Level and Geodetic Monitoring Project (PSLGM) operated by the Bureau of Meteorology (Station ID: 200858). The gauge record contains sea level data from 1993-April 2020 at hourly intervals. The hourly data was not modified (i.e., de trended or de-spiked) from the downloaded PSLGM record.

The tide gauge records the level of the sea as averaged over 1 hour and as such it includes non-tidal changes in water level that arise from various oceanic phenomena as averaged over each hour's measurement. This includes phenomena that take place over decades (e.g., ENSO[12] caused a fall in sea level in 1997-1998, AusAID 2009), inter-seasonal variability (summer-winter winds), storm-by storm swell waves and wave runup, and transient features like tsunami waves or vertical land motion (seismic uplift or subsidence) and long term sea-level rise associated with climate change.

Gaps in the data were excluded from the analysis. The total gap length is 7.3% of the 27-year data record. Figure B-1 illustrates the measured sea level elevation with identified gaps in the record. The annual mean sea levels and overall mean sea level (MSL) in the gauge record is also illustrated. Mean (1993-2020) = 1.427 m NID.

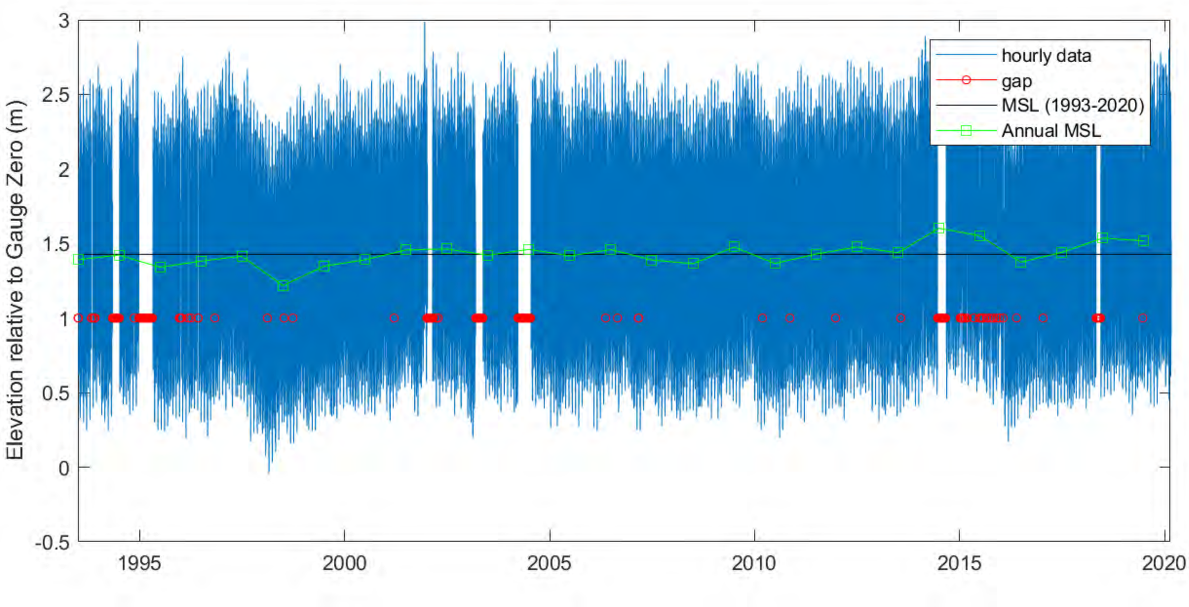


Figure B-1: Hourly sea level data from Nauru PSLGM gauge. MSL is determined over the entire record length excluding gaps (indicated by red circles).

[12] ENSO: El Nino Southern Oscillation.

High water level analysis

All high tides measured in the gauge record were identified, sorted by height and normalised by the number of tides in the gauge record to create a cumulative probability distribution (see Figure B-1). This plot demonstrates the percentage exceedance value of all measured high tide elevations (i.e., how frequently the sea level has exceeded this elevation) throughout the gauge record 1993–2020. Increments of SLR are included on

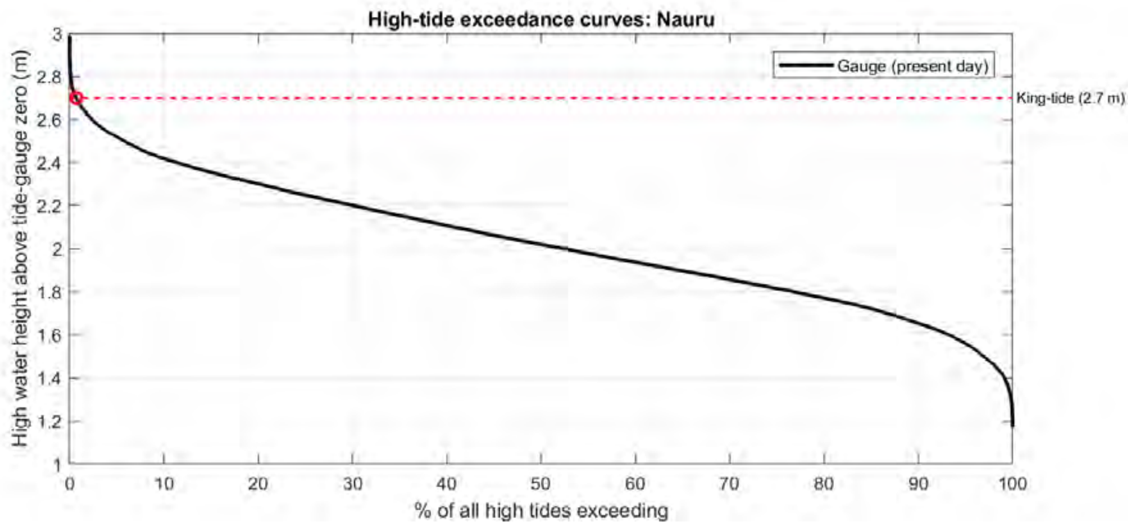


Figure B-1: High-tide exceedance curves based on gauge record. Elevations are above MSL of 1.4273 m NID.

A probability of 1% is typically associated with king-tide elevations. This means that approximately one in every 100 high tides is a king tide. Analysis of the Nauru gauge data determines the 1% value as 2.677 m NID.

However, for the purposes of this Project and to simplify analysis and reporting, **the selected king tide elevation is 2.7 m NID with *approximately* 1% exceedance probability** (KT1). The true exceedance probability of a 2.7 m NID tide gauge reading is 0.72%.

KT1 is 1.2723 m above MSL (1993-2020).

Land subsidence

A sea-level rise rate does not include the potential for the *land* to rise or fall via tectonic or deep geologic changes which would create a *relative* change in sea level. In Nauru, the rate of tectonic subsidence is below 1 mm/year as based on tide gauge analysis (-0.9 ± 0.2 mm/year) or from satellite altimetry data (-0.6 ± 0.6 mm/year) based on data from 2003-2014. (Martinez-Asensio et al. 2019).

This subsidence is small (10-17%) relative to the recent regional sea-level rise trends at Nauru (5.3 to 5.5 mm/year depending on method) observed from 1993-2015 (Martinez-Asensio et al. 2019). If this subsidence trend continued over a 100-years this would only contribute an *additional* 60-90 mm to sea-level rise over this period. However, there is considerable uncertainty in predicting geologic trends over this time and we consider that the uncertainty bounds in SLR projections will encompass this subsidence trend for the purposes of this high-level study.

Appendix C Update of building footprints

Building polygons

Original buildings polygon file that were supplied by SPC were used as source file for this dataset. The coordinate system used is WGS72 (Zone 58S).

The original dataset was from 2011 and appeared relatively comprehensive across the island, but a number of buildings were offset, missing or had changed between this dataset and newer aerial photographs (e.g., Figure C-1) and some large structures have been replaced (e.g., police station, Figure C-2). The original data included building outlines and building usage classes.

Figure C-1: Example of original building outlines (left) and updated building outlines (right). [Source: SPC].

The building outlines were updated using available aerial photographs, with sources including:

- Imagery from 2014, 0.15 m resolution.
- Imagery from 2018, 0.3 m resolution.
- Satellite imagery from Google Earth, dated 29-07-2019.

Building polygons were edited or updated where the building footprint has changed over the time between aerial photographs (e.g., Figure C-2) and where new buildings and water tanks were identified. Some buildings were partially covered by trees, in these cases images from previous year was referenced and outline of the building was estimated.

Resolution of aerial photos meant that the condition of a structure could not be assessed, thus, if a roof or tank was visible it was included in the dataset regardless of whether the buildings were in use. We recommend ground confirmation of building usage and condition if the dataset is to be used for more detailed studies.

Buildings on the topsides were not digitized as they are not relevant to this coastal inundation assessment.

Figure C-2: Example comparison of original (pink) and updated (black) building outlines at the police station. [Data source: SPC].

Building usage

Alongside building outlines, the original dataset provided building points data with building class usage.

Within GIS, the building *polygons* were dissolved and joined to the provided building *points* dataset to assign building class data. A search radius of 4 m was used to find a nearest point with building class data. The values from "MainOcc" field was used and propagated to the updated building outlines. The resulting 5 building classes are Residential, Public, Commercial, Industrial and Infrastructure.

Previous building "sub-type" categories (i.e., public – religion) remained in their original locations, but are excluded from any new buildings without ground-validation of the building usage.

A number of buildings that did not receive updates were either new building polygons or the point was further than 4 m distant. New points were created for the unassigned polygons, with the buildings manually assigned the above-mentioned classes based on interpretation of building size, google maps data, adjacent buildings and neighborhood type.

In addition, several key buildings were simplified within the above classes:

- schools, hospitals, government buildings were assigned public
- hotels and business were assigned as commercial, and
- solar farm, power supply etc., were assigned as infrastructure.

The updated building dataset is illustrated in Figure C-1. The updated dataset will be returned to SPC and the Nauru Government as part of this Project.

Figure C-1: Overview of updated building polygon dataset developed for this project. Colours indicate building use type (yellow= residential, red=industrial, purple = commercial, pink = public. [Data sources: Aerial photographs].

Appendix D RiskScape technical annex

Buildings

Building footprint polygons sourced from the Pacific Catastrophe Risk Assessment and Financing Initiative (PCRAFI) database for Nauru were modified/updated using 2019/2020 Satellite Imagery to include new buildings. This provided the 'building' asset input data for the analysis with the output results showing exposure distributions according to building use type, geographic location and district. Key building attributes used to represent exposure distribution are shown in Table D-1.

Table D-1: Asset building data used in this study.

Asset	Attribute Types	Comments
Buildings	Geographic Location	Used to estimate exposure distribution by geographic location.
	District Name	Used to estimate exposure distribution by district name.
	Use Type	Used to estimate exposure distribution by building use type.

Roads

Road lines data sourced from the Pacific Catastrophe Risk Assessment and Financing Initiative (PCRAFI) database for Nauru were segmented into 1m interpolated points along the entire road length. This provided the 'road' asset input data for the analysis with the output results showing exposure to of total road lengths in each district for each sea level scenario. Key road attributes assessed are shown in Table D-1.

Table D-1: Asset road data used in this study.

Asset	Attribute Types	Comments
Roads	Geographic Location	Used to estimate exposure distribution by geographic location.
	Road length (m)	Used to estimate length of exposed roads.

Airport

Airport landing ground lines data sourced from the Pacific Catastrophe Risk Assessment and Financing Initiative (PCRAFI) database for Nauru was polygonised and converted to 1m x 1m gridded centroids/points. This provided the 'airport landing ground' asset input data for the analysis with the output results showing the area within the landing ground that are inundated under each sea level scenario. Key landing ground attributes assessed are shown in Table D-1.

Table D-1: Asset airport data used in this study.

Asset	Attribute Types	Comments
Landing ground	Geographic Location	Used to estimate exposure distribution by geographic location.
	Land Area (m^2)	Used to estimate total area exposed on landing ground.

Population/Occupancy

Population Raster (100 m grid) sourced from SPC Data Hub for Nauru was polygonised and converted to 5m x 5m gridded centroids/points. Data in the originally sourced Raster was created using Nauru household locations from the 2019 PHC conducted using Survey Solutions Computer Assisted Personal Interview. A 'Year Population Growth Rate' of 0.8 % was applied to update the estimated population up to 2020. The household locations vector layer was transformed into a 100 m resolution raster (SPC 2020) creating the 'population' asset input data for the analysis.

The 'population' input data which was combined with the residential buildings dataset (see Table D-1) to produce a population density as a function of total floor area in each grid-cell (i.e., persons/m^2 in each 100 m grid cell).

This means the population exposure is estimated as a function of residential building exposure (i.e., residential floor area). This provides a realistic and consistent exposure estimate which relates population to an occupancy rate averaged over 100 m grid cells. Note this not a building by building occupancy basis as would come from a census survey.

The total exposed points represent the estimated total population in each district, aggregated from the occupancy rate and inundated under each sea level scenario. Key population attributes assessed are shown in Table D-1.

Table D-1: Population data used in this study.

Asset	Attribute Types	Comments
Population grid (100 m)	Geographic Location	Location and distribution of exposed population grid cells.
	Density (persons / 0.01 km^2)	Exposure density of population in each grid cell.

Land Area

LiDAR data sourced from the Pacific Catastrophe Risk Assessment and Financing Initiative (PCRAFI) database for Nauru were converted to 5m x 5m gridded centroids/points. This provided the 'land area' asset input data for the analysis with the output results showing the total land area that are inundated under each sea level hazard scenario. Key coconut crops attributes assessed are shown in Table D-1.

Table D-1: Asset road data used in this study.

Asset	Attribute Types	Comments
Land Area	Geographic Location	Location and distribution of exposed land area.
	Land Area (m^2)	Exposure area.

Coconut Crops

Coconut crops polygon data sourced from the Pacific Catastrophe Risk Assessment and Financing Initiative (PCRAFI) database for Nauru was extracted from the original 'land class' dataset and converted to 5m x 5m gridded centroids/points. This provided the 'coconut crops' asset input data for the analysis with the output results showing the area within the coconut crop areas that are inundated under each sea level scenario. Key coconut crops attributes assessed are shown in Table D-1.

Table D-1: Coconut crop data used in this study.

Asset	Attribute Types	Comments
Coconut crops	Geographic Location	Location and distribution of exposed coconut crops.
	Land Area (m^2)	Exposure area in coconut crop boundary.

Cadastre

Cadastre polygon data sourced from the Pacific Catastrophe Risk Assessment and Financing Initiative (PCRAFI) database for Nauru were converted to 5m x 5m gridded centroids/points. This provided the 'cadastre' asset input data for the analysis with the output results showing the area within each cadastral/property boundary that are inundated under each sea level hazard scenario. Key coconut crops attributes assessed are shown in Table D-1.

Table D-1: Cadastre data used in this study.

Asset	Attribute Types	Comments
Cadastral	Geographic Location	Location and distribution of exposed cadastre.
	Land Area (m^2)	Exposure area in cadastral boundaries.

Tanks and Poles

Tanks polygon data sourced from the Pacific Catastrophe Risk Assessment and Financing Initiative (PCRAFI) database for Nauru were validated/updated using 2019/2020 satellite base maps. This provided the 'tanks' asset input data for the analysis with the output results showing the total tanks that are exposed to inundation under each sea level hazard scenario. Key tanks attributes assessed are shown in Table D-1.

Table D-1: Asset tanks and poles data used in this study.

Asset	Attribute Types	Comments
Tanks	Geographic Location	Location and distribution of exposed tanks.
Poles	Geographic Location	Location and distribution of exposed tanks.

Appendix E Flood inundation frequency

The following plots provide an indication of how frequently high tide levels may result in potential high-tide related inundation in areas of Nauru and how this may change under different amounts of future sea-level rise, but excluding wave effects.

The information is presented as the *average number of days per year that high tide level would be above existing land levels*. Land levels are based on the LiDAR dataset for Nauru collected as part of the Pacific Catastrophe Risk Assessment and Financing Initiative (PCRAFI).

These plots were developed as part of Stage I of the Higher Ground Project supported by the NZ Ministry of Foreign Affairs (MFAT) an addition to the static inundation mapping and RiskScape assessment.

Methodology

20 years (January 2000 to December 2019) of high tide levels measured at the Pacific Sea Level and Geodetic Monitoring Project (PSLGM) tide gauge at Nauru were used to define a ‘Present day’ high tide record.

The same 20-year high tide record was then duplicated several times with each duplicate adjusted by adding on different increments of future sea-level rise.

For each of these 20 year records, the average number of days per year that high tide levels would be above land levels were calculated and plotted for Nauru.

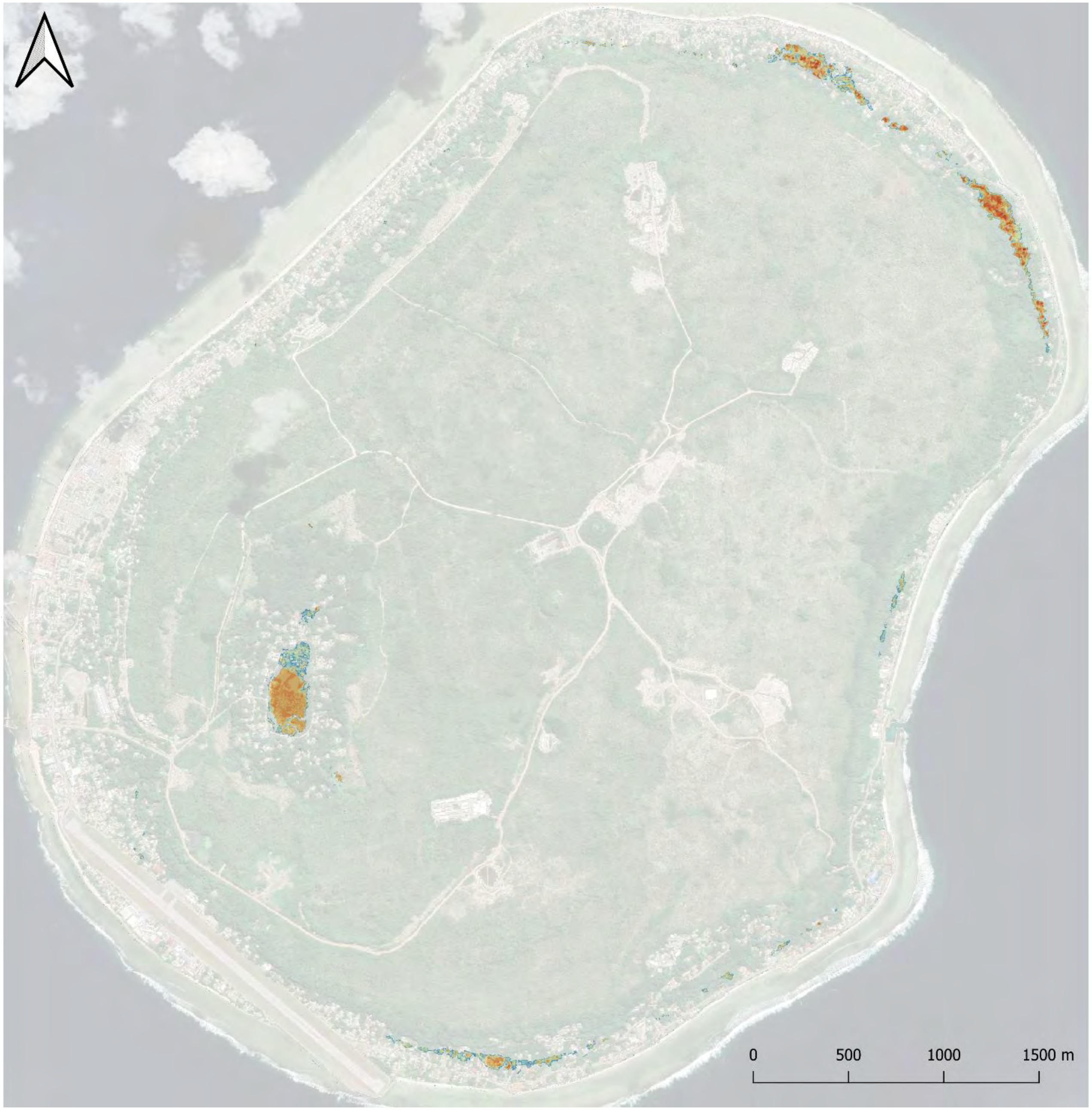
Note that this data differs from that in

Limitations

The plots should be treated only as indicative of areas of inundation. Low-lying inland areas that may not be directly connected to high tide levels on the ocean or lagoon shoreline are also shown. However, these areas may well be affected by high groundwater levels, particularly as sea levels rise, or ponding during heavy rainfall events.

The plots only take account of static high tide levels. The effects on waves on shoreline water levels, run-up and overwash is not accounted for. As a result inundation of areas, such as the higher-elevation ocean-side berms, are not represented.

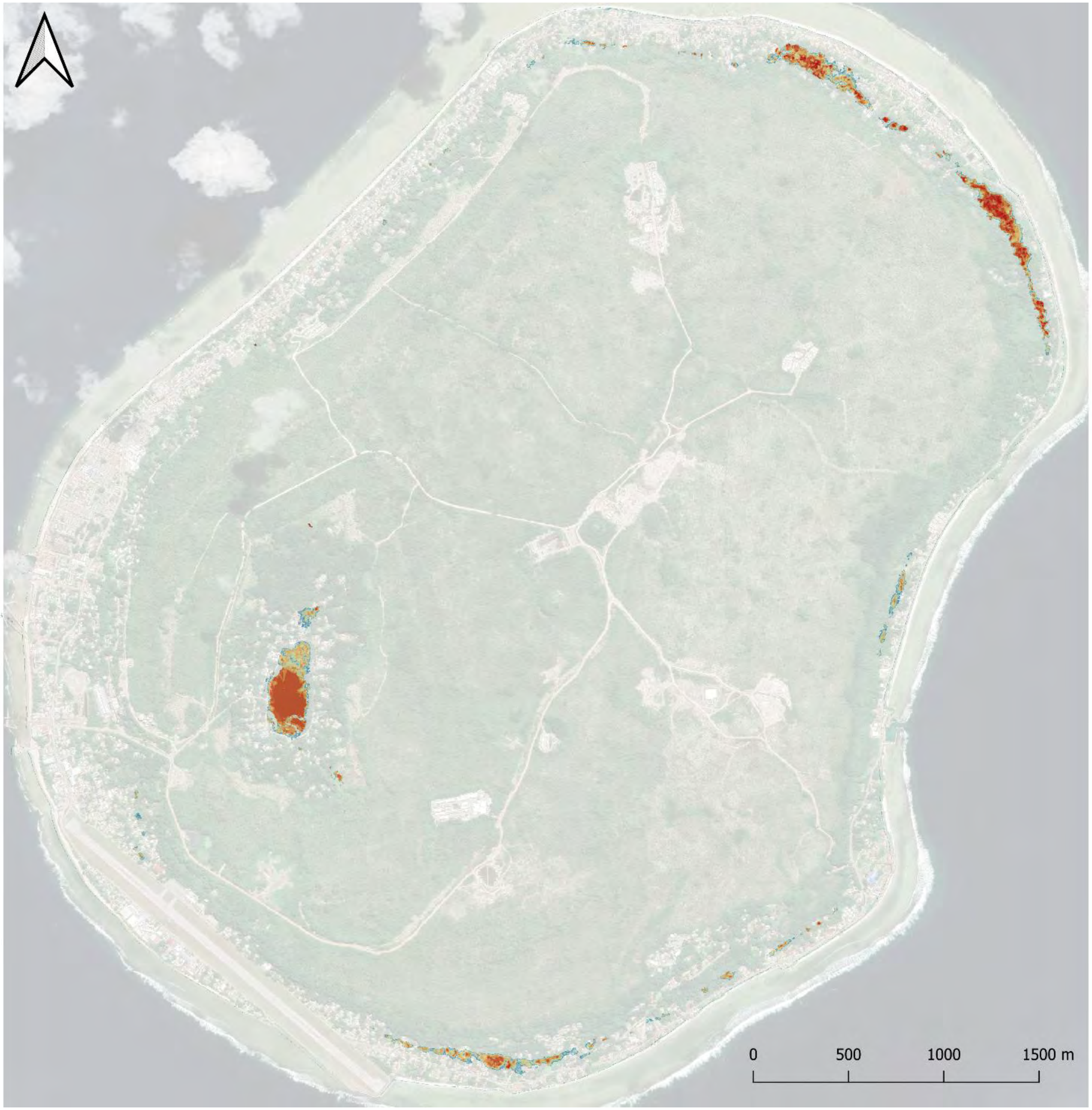
The effects of episodic extreme cyclone or swell wave events that can cause severe inundation are also not considered.



Nauru Inundation frequency
SLR = present day

Days per year where sea level is above land level

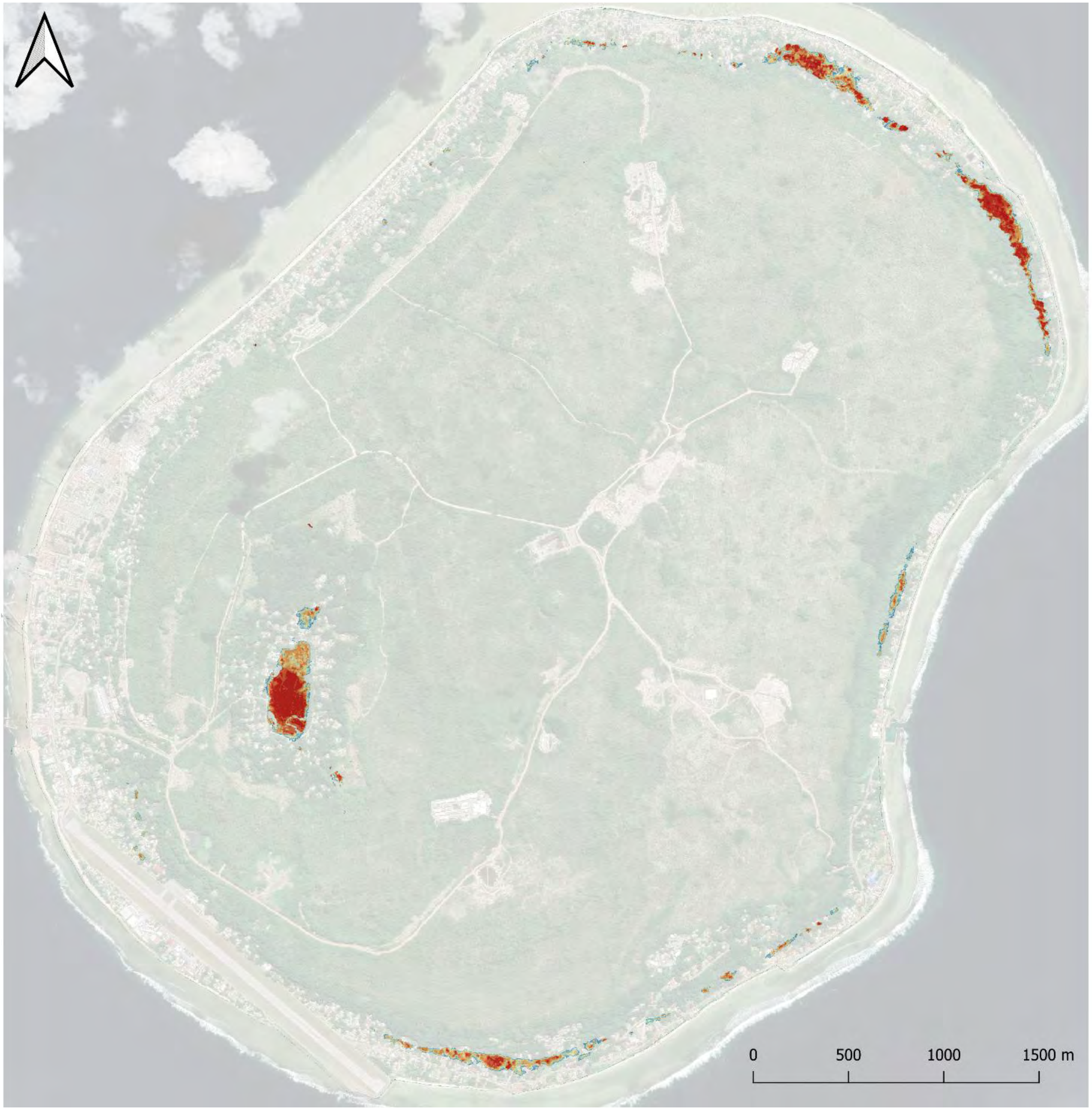
- >300
- 250-300
- 200-250
- 150-200
- 100-150
- 75-100
- 50-75
- 25-50
- 10-25
- <10



Nauru Inundation frequency SLR = 0.2m

Days per year where sea level is above land level

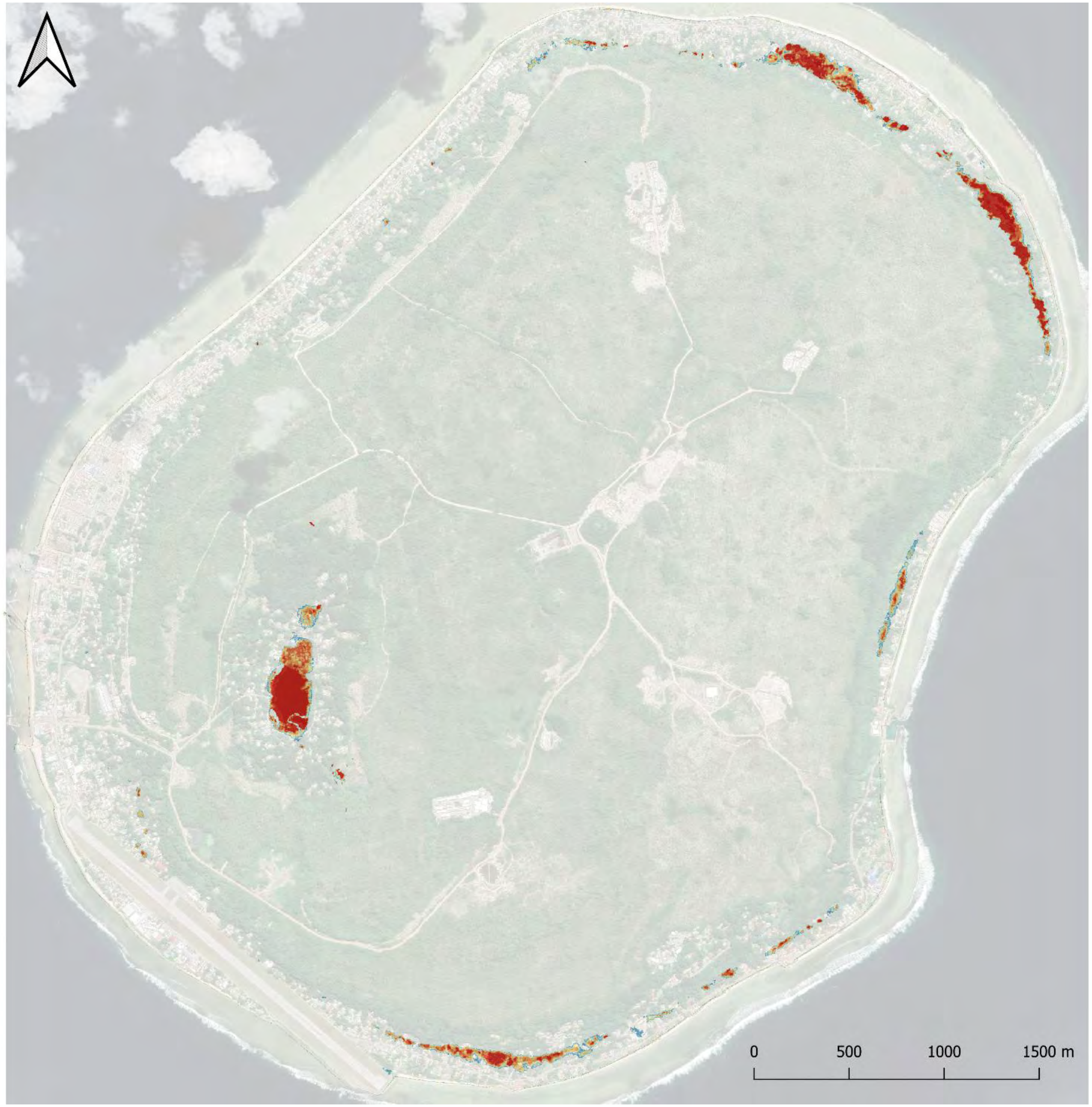
- >300
- 250-300
- 200-250
- 150-200
- 100-150
- 75-100
- 50-75
- 25-50
- 10-25
- <10



Nauru Inundation frequency
SLR = 0.35m

Days per year where sea level is above land level

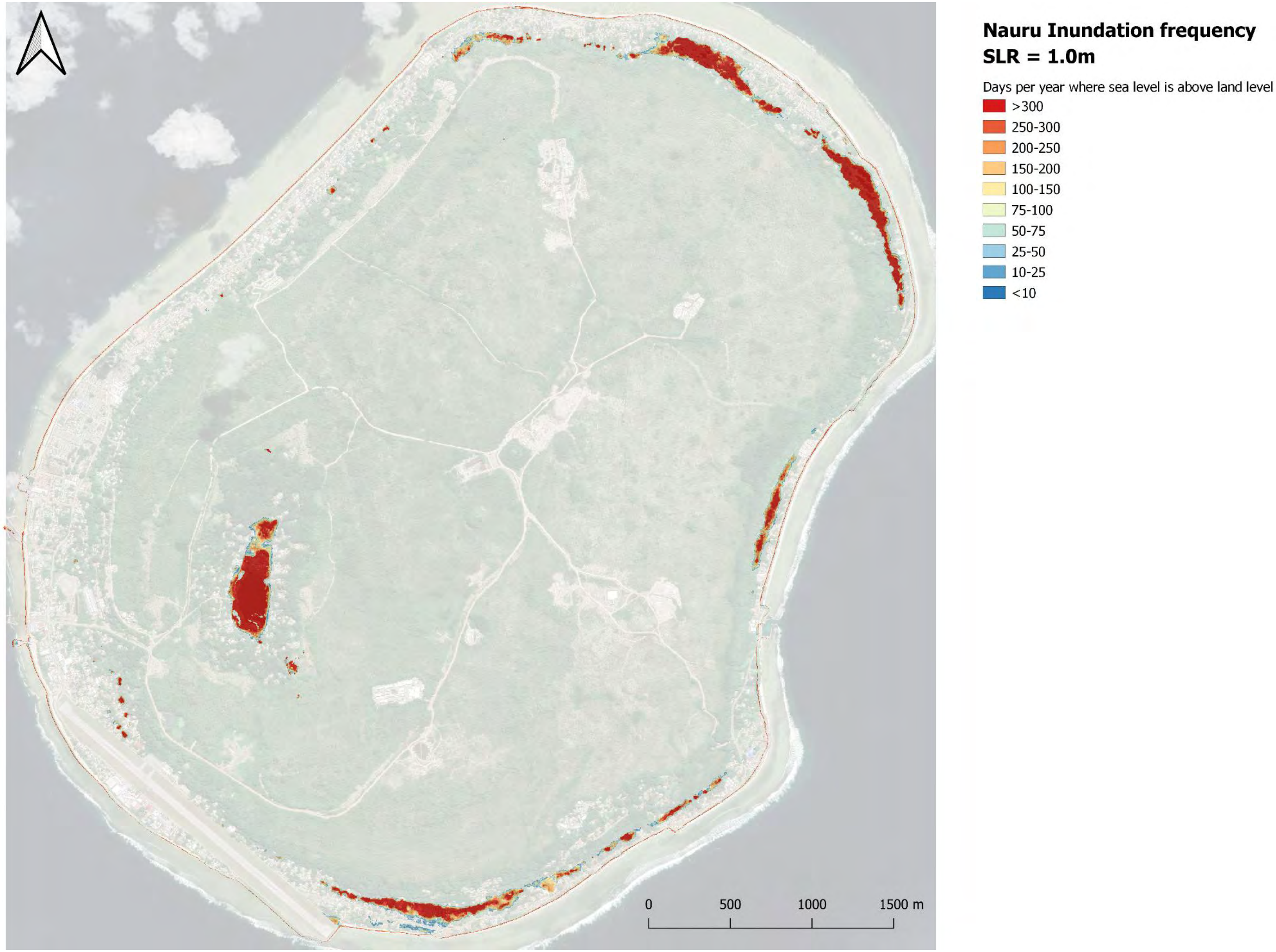
- >300
- 250-300
- 200-250
- 150-200
- 100-150
- 75-100
- 50-75
- 25-50
- 10-25
- <10



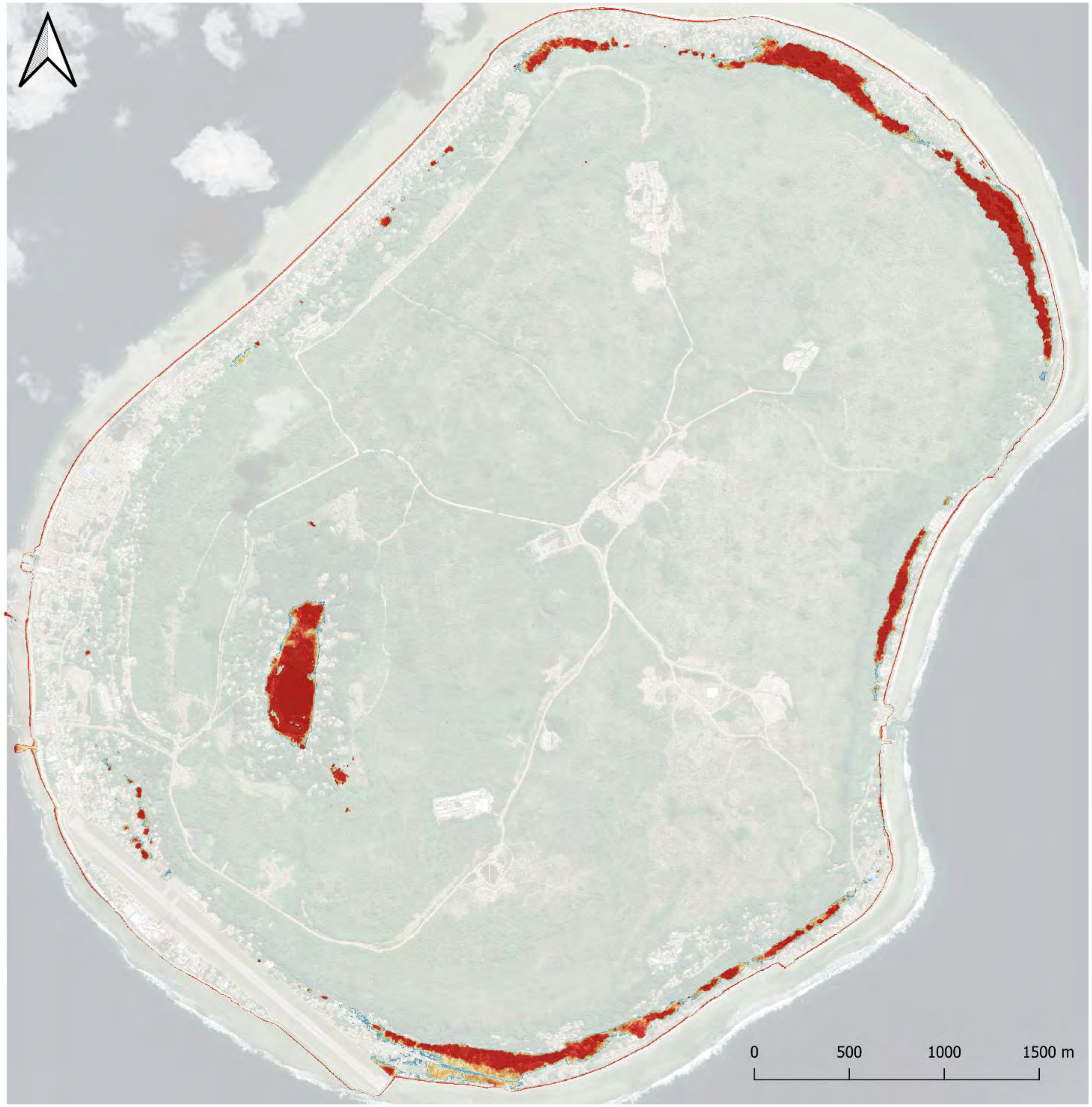
Nauru Inundation frequency
SLR = 0.5m

Days per year where sea level is above land level

- >300
- 250-300
- 200-250
- 150-200
- 100-150
- 75-100
- 50-75
- 25-50
- 10-25
- <10



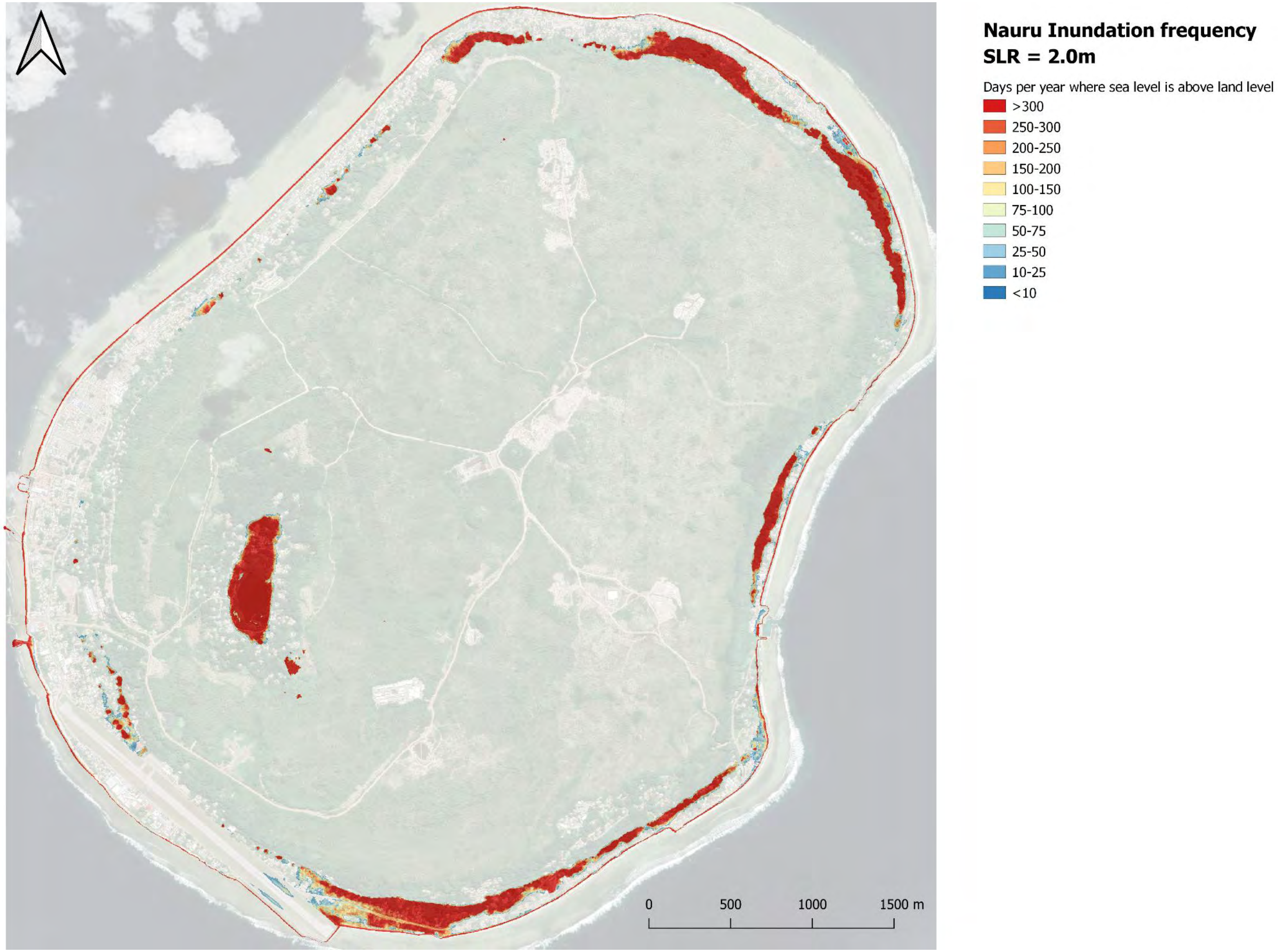
Nauru Inundation frequency
SLR = 1.0m
Days per year where sea level is above land level
>300
250-300
200-250
150-200
100-150
75-100
50-75
25-50
10-25
<10
0
500
1000
1500 m



Nauru Inundation frequency
SLR = 1.5m

Days per year where sea level is above land level

- >300
- 250-300
- 200-250
- 150-200
- 100-150
- 75-100
- 50-75
- 25-50
- 10-25
- <10



Nauru Inundation frequency
SLR = 2.0m
Days per year where sea level is above land level
>300
250-300
200-250
150-200
100-150
75-100
50-75
25-50
10-25
<10
0
500
1000
1500 m