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How urbanization enhanced exposure to climate risks in the Pacific: A case study in the Republic of Palau

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Abstract

The increasing risk of coastal flooding and water shortage in Pacific Island Countries is usually attributed to climate change hazards. This ignores other risk components, exposure and vulnerability, of which a major contributor is urbanization.

We develop simplified analyses that can be applied to other PICs. By dividing climate risks into hazard and exposure components we determine how urbanization contributed to present-day risks and then predict how growing climate change hazards may increase future risk, using the Republic of Palau as a case study.

Results show that urbanization was responsible for 94% of the buildings exposed to coastal flooding today. Projected sea level rise, 30.2 cm by 2050, only increased exposure of today’s buildings by 0.5%. In both present and future scenarios exposure resultant from urbanization was more significant than sea level rise.

Our water scarcity index showed urbanization caused 3 of the 7 recorded water shortages from 1980–2018. From 2041–2079, analysis of projected rainfall showed mean reductions between 1.6–16.6% and increased variance between 0.3–3.4%. This led to three times as many water shortages under present population levels. In historical and future scenarios exposure from increased population was just as significant in causing water shortages as rainfall variation.

These findings suggest that urban management is an important tool to lower exposure to coastal flooding and water shortage and we recommend that decision makers prioritize urbanization within climate risk policy in Pacific Island Countries.

1. Introduction

The IPCC recognizes climate change-induced sea level rise and changing rainfall patterns as ‘key climate and ocean drivers of change’ in island nations (Nicholls et al 2007, Parry et al 2007, Nurse et al 2014, IPCC 2019). These synergistic hazards pose a particularly high threat to exposed Pacific Islands Countries (PICs) characterized by their high coastline to land mass ratio (ADB 2013; Church et al 2006, Kumar and Taylor 2015). Coastline and precipitation conditions worsen at higher rates in PICs as atmospheric warming fuels sea level rise and El Niño frequency affecting both short- and long-term hazards at unprecedented rates (Church et al 2006; Becker et al 2012, Nurse et al 2014; Chand et al 2017, Power et al 2017; Wang et al 2017, Nerem et al 2018). These hazards are very likely to continue growing in the future (IPCC 2019) and PICs remain on the front line of rapidly growing hazards.

It is important to note here that sea level rise and changing rainfall patterns are not risks themselves, but hazards affecting the risk of coastal flooding and water shortage, respectively. Since risk is defined as a function of hazard (natural weather or geological events), exposure (how likely one is to be affected by hazards) and vulnerability (one’s inability to cope with exposure to hazards) a complete risk assessment requires the analysis of socio-geographic factors like urbanization, as well (ADRC 2009).
Urbanization flourished in PICs after WWII, due to migration from rural areas to government and economic centers (ADB 2013, Connell 2015). These centers were often chosen by colonial powers for their deep ports or general access to the sea, meaning they are often located in flood prone areas (ADB 2013). Therefore, to understand risk in the Pacific it is necessary to understand how urbanization in these areas contributed to increases in coastal flooding and water shortage risk.

Nevertheless, urbanization is often overlooked in PICs’ risk studies, though it is a known contributor to risk that increases exposure and vulnerability to coastal flooding and water shortage (ADB 2013, UNIDSR 2015). Studies in other regions of the world found the combined effects of urbanization and climate change to non-linearly increase risk (Pumo et al 2017, Sofia et al 2017; Sebastian et al 2019). While Kumar and Taylor (2015) examine proximity of vital infrastructure to coastlines over several PICs, data insufficiency limits the ability of researchers to perform the same combined effects studies that quantify changes to exposure in PICs. This research investigates that gap using unique methods to overcome data availability issues. If exposure has significant impacts on risk in PICs it means that urban management can potentially act as an adaptation method to increasing climate change hazards.

2. Methodology

2.1. Case study: Republic of Palau
Urbanization research in PICs is scarce due to the sheer diversity of island lithology, varied economies (e.g. tourism, aquaculture, administrative center), and difficulty in gathering data related to urbanization such as historical maps and population changes. Palau, however, has gathered and preserved urbanization and meteorological data since the 1950s. It has more land and water resources than atoll PICs potentially enabling it to be more resilient to climate change (e.g. Forbes et al 2013). Even its corals appear to be more resistant to ocean acidification caused by climate change (Barkley et al 2017). As Palau has potential to withstand higher levels of climate change hazards, urbanization exposure becomes even more important to manage to adequately suppress climate risk.

Palau sits in the Western Pacific composed of 16 local state governments spread over more than 300 volcanic and limestone islands and sand atolls. Nine of these states are located on the largest island, Babeldaob (figure 1), but most residents (65%) live in the urban center of Koror (ROP 2015). Koror’s population has grown from 658 people in 1946 to 11 444 in 2015 (Republic of Palau (ROP) 2015). When grouped with its neighboring state, Airai, which holds the sole water source for the two states, they form Palau’s formal urban area (Republic of Palau (ROP) 2015). Palau has one of the highest urbanization rates in the Pacific, with 78% of the population residing in the urban area (ADB 2016).

Koror’s livable area is composed of three islands: Koror, Ngarkebesang and Malakal, which are connected by causeways. The peaks of these islands reach over 120 meters above sea level (MASL). Development in these steep areas is low because of the cost and difficulty of constructing buildings and roads. Main Street acts as the spine of the urban center and reaches an elevation of 50 MASL in eastern Koror. It follows a ridge through the downtown area at roughly 20 MASL. Development is generally located downhill from Main Street towards the mangroves.

The population growth coupled with limited development space has forced Koror State to lease out areas inhabited by mangroves and reefs, on which new residents clear, infill and build homes. These mangroves occur adjacent to both the coast and close to mean sea level (Woodroffe and Horton 2005), thus properties built in their place are exposed to flooding that can occur during high tides and storms/typhoons. Population growth has also increased demand on fresh water and particularly the primary shared water source, the Ngerimel Dam. When water shortages occur, the National Government and local utilities company implement water-usage hours as extreme as 1 h per day.

2.2. Urbanization data
2.2.1. Spatial data
To prepare Koror’s spatial data for coastal flooding risk analysis, we take historical maps and modern GIS data from Palau’s national GIS office (PALARIS 2018). We post-process two United States Geological Survey (USGS) maps from 1954 and 1983, both 1:25 000 scale (USGS) by geo-referencing them in ArcMap 10.1 and delineating the buildings (note the 1954 map does not show full coverage of Koror, see figure 5 for map extent). In 1954, Koror had 195 buildings (see figure 5). By 1983, Koror had 1576 buildings (see figure 5). This is equivalent to almost four new buildings every month though the population had yet to reach 10 000 people. Buildings also moved closer to the coastline and even into the mangroves.

Expansion continued and by 2018 Koror had 3219 buildings (see figure 5). As most land on flatter, more easily developable grounds were taken, new developments were forced into mangroves and low-lying areas. Faced with continued growth and land ownership issues that made inland development even more difficult, Koror continues to alleviate development pressures through coastal development, further increasing coastal flooding risk.
2.2.2. Population data
Population data was used to analyze water shortage risk. Censuses from 1980 to 2015 provided the number of households attached to the public water system. These were multiplied by the average number of people per household to get the number of public water users in the urban area. In the absence of more detailed population data we assume a linear growth or decline between all actual Census counts to estimate monthly data.

Government data also provided tourist arrivals from 1980 through 2018 and the current number of hotel rooms (PVA 2019). After June 2007, tourist arrivals are reported by month. Before that, however, annual tourist arrivals are the most detailed data available. To estimate monthly data before June 2007, the average annual share of tourists for each month after June 2007 were calculated and the resulting ratio used to make monthly tourist arrival estimates for past years. Monthly tourist arrivals were then converted to a population equivalent using tourist nights while years without tourist night data used an average of the data that was available. Finally, we assumed equal occupancy rates across all hotel rooms in Palau then multiply the proportion of rooms in the urban area (91.6%) by the tourist population equivalent. This likely makes the tourists portion of the population an underestimate as not only are most accommodations in the urban area, but an even greater proportion of tourists related facilities like restaurants, shops.

While population growth increased over the analysis period, the number of public water users grew even more as the number of households connected to the public system increased from 70% to over 95% (see figure 2). After 2000, the number of connected households stabilizes and sees only minor growth to 97% in 2015. Tourism data exhibited two high seasons, one in January to February and the other from July to August. Annual visitors fluctuated year to year, with the highest mark reaching over 163,000 in 2015, but generally showed continuing upward trends in growth.

2.3. Climate data
2.3.1. Extreme events and long term sea level
Palau has a tide gauge (Malakal-B) located in Malakal, which spans from 1969 to 2018 recording hourly water levels (University of Hawaii Sea Level Centre (UHSLC) 2019; Caldwell et al 2015) and monthly revised local reference (RLR) levels (Permanent Service for Mean Sea Level (PSMSL) 2019; Holgate et al 2013). From 1969 to 2018, mean sea level in Palau rose by around 11 cm (figure A1(a)) at 2.3 ± 0.4 mm yr⁻¹. However, closer inspection
of the tide gauge record by estimating rates of change over a range of sliding windows (where minimum two-thirds data is available) reveals an increasing rate of sea level towards the present reaching $6.6 \pm 1.0 \text{ mm yr}^{-1}$ from 1991–2018 (see figure A1(b)), which is consistent with results at the global scale (Nerem et al. 2018) though clearly amplified by local effects such as a regional ocean thermal expansion and far-field contribution from northern hemisphere glaciers (Meyssignac et al. 2017).

We evaluate whether vertical land motion (VLM) affects mean sea level in Palau by comparing satellite altimetry that measures geocentric sea level (also called absolute sea level, ASL) with the tide gauge record (measuring RSL), where $VLM = ASL - RSL$ (Kuo et al. 2004). Data showed that inferred local land motion at the tide gauge, and by extension the surrounding area including that of Koror is negligible over the last 25 years (see figure A2).

The monthly detrended tide gauge signal is anti-correlated with ENSO ($-0.62$, $p < 0.01$) over the full length of the record (see figure A1), while the magnitude increases significantly when assessing the correlation between decadal rate of sea-level change and decadal rate of ENSO ($-0.88$, $p < 0.01$). This indicates that multi-annual to decadal scale changes in RSL for Palau are strongly affected by ENSO, which is supported as a strong driver for Islands across the Western Pacific (Chowdhury et al. 2007, Zhang and Church 2012).

To analyze exposure under future sea level rise, we used probabilistic regional sea-level projections (Jackson and Jevrejeva 2016) for RCP 8.5 (Moss et al. 2010) extracted at Palau, using the mean of 27.7 cm for 2050, relative to 1986–2005. To align the sea level analysis with our GIS exposure analysis, where our baseline is the 1983 USGS topographic map, we added the mean sea-level rise from 1983 to 1995 of 2.5 cm estimated from Malakal B tide gauge to get a (Kopp et al. 2014, Moss et al. 2010) projected sea level rise of 30.2 cm in 2050 relative to 1983.

We use the hourly tide gauge water level record to estimate extreme water levels from annual maxima by first detrending all data by its relevant annual mean, then adjusting the series relative to the last 20 years (Wahl et al. 2017). Following this, we select annual maxima for each year giving 49 values. We fit an extreme value distribution to the annual maxima (see figure A3) using maximum likelihood to estimate location and scales parameters assuming the shape parameter is zero (i.e. a Gumbel distribution, see for example Hunter et al. 2017). Finally, we calculate the fitted distribution up to the 100-year flood event (see figure 3). Although criticism of the Gumbel distribution exists occurs in the literature as overestimating rare event water levels (Wahl et al. 2017), here the distribution fits annual maxima in the 1 to 100-year event range with a root mean square error of 6.83 mm,
which is supported by other extreme event analyses (Hunter et al 2017).

Extreme water levels between the 1- and 100-year event have a range of $\sim 27$ cm (95 to 122 cm) where 17 cm of this difference occurs in the first 10-year return period interval. This relatively small range implies that small changes in the position of mean sea level will dramatically alter the magnitude of extreme water levels of across all return periods (Hunter 2012). Adding the 10-year return period (111.5 cm) to 1983 and 2018 mean sea level results in water levels of 111.5 cm and 124.5 cm respectively, which were rounded to 110 and 120 cm for exposure analysis. Adding the 10-year return period to the 2050 projected sea level rise (relative to 1983) gives a water level of 144 cm, which is rounded to 140 cm. We assume that there is no climate change induced shift in storm surge statistics (Kopp et al 2014).

2.3.2. Rainfall data

Historical rainfall data for Palau was downloaded from NOAA (National Climatic Data Center) and provides daily rainfall from 1980–2018, which was compiled into monthly bins from 1980–2018 to match the population data.

The data illustrates consistent seasonal variations (see figure 4). The dry season starts in February and lasts until April, followed by the rainy season from June to July (see table A1). The maximum annual rainfall, 5400 mm, and minimum annual rainfall, 2452 mm, for the 39-year period both occurred within the last 8 years, 2011 and 2015, respectively. These extremes are consistent with regional and global studies predicting increases in annual rainfall variation due to future climate change (Karnauskas et al 2016).

To project future rainfall, nine Coupled Model Intercomparison Project Phase 5 (CMIP5, Taylor et al 2012) climate models were used to create localized climate data specific to Palau (excluding the Southwest Islands) (see table A1). To refine these models, based on RCP 8.5 scenario, we use observed rainfall data from 1961–1990 as a control and bias-corrected the annual mean and variation of the models’ outputs to more closely replicate the that rainfall data.

The three models that most accurately replicated the historical data in annual mean and variation (bc1m, hg2e and mc3) were applied to predict daily rainfall from 2041–2079. Hg2e was the most accurate in both mean rainfall and variance of rainfall when compared to observed data (see table A1). The three models projected mean annual rainfall reductions between 1.6–16.6% and increased annual variance between 0.3–3.4%. In all three models interannual variance also increased 3.9–7.4% causing unequal changes in average monthly rainfall as seen in the higher than average rainfall reductions during the dry season (see figure 4 and table A2). These models all illustrate that Palau can expect a significant rise in hazards greatly increasing future water shortage risk.

2.4. Separation of exposure and hazard

2.4.1. Coastal flooding

While 20th and early 21st century mean sea level rise has not visibly inundated the coastline of Koror, population growth resulted in the expansion of the urban footprint towards and into the mangroves and reefs that fringe the coast. We combine our tide gauge and GIS mapping analyses to determine whether sea level rise or urbanization was more significant in increasing coastal flooding risk. Due to the lack of sea level data at 1954, we only use that building data to show urban expansion.

We take the water levels derived from the mean sea level data and map them to contour layers in GIS for each year respectively. Buildings touching or lying below these elevations are considered to be exposed to the 1-in-10 year flood event at that time.

To separate coastal flooding impacts from urbanization and climate change we created an exposure matrix (see table 1). The baseline exposure (1) calculates the number of 1983 buildings exposed to a 1983 10-year flood event. Adding the rise in mean sea level at 2018 (2) and projected rise by 2050 (3) and calculating the additional exposed 1983 building shows how climate change hazards would have increased exposure if urbanization had not continued.

Current urbanization-induced exposure is determined by counting the number of buildings in 2018 that are exposed to the 1983 10-year flood event (4), as those buildings would have been exposed without climate change. Adding the rise in sea level at 2018 (5) and projected rise by 2050 (6) and counting the additional exposed buildings gives the exposure due to climate change-induced sea level rise.

2.4.2. Water shortage

Differences in data type and availability required a different approach for the water shortage analysis to separate the effects of urbanization and climate change on risk. The case study area was also expanded to include the entire urban area, Koror and Airai, because they use the same water source and together hold 78% of Palau’s population virtually all of its tourism.

There are many studies analyzing the water shortage, however, these methods are not always appropriate or possible for PICs as river water is often not the main water source. Even though Palau uses surface water, stream flow data is not sufficient for the analysis period (U.S. Geological Survey 2016). Other methods to evaluate climate change’s effects on water stress use drought indices (Edwards and
Figure 3. Water level return period for Malakal tide gauge hourly data (UHSLC).

Figure 4. Average Monthly Rainfall from 1980–2018 (National Climatic Data Center), and projected rainfall from the three most accurate CMIP5 models (bc1m, hg2e and mc3) from 2041–2079.

Table 1. Coastal flooding exposure matrix.

| Urbanization Year | Baseline Exposure | Climate Change-Induced Exposure (if urbanization stopped) | Climate Change-Induced Exposure (if urbanization stopped) |
|-------------------|-------------------|----------------------------------------------------------|----------------------------------------------------------|
| 1983              | Buildings exposed at the 1983 sea level + 10-year flood (1.1 MASL) | Additional buildings exposed at the 2018 sea level + 10-year flood (1.2 MASL) | Additional buildings exposed at the 2050 sea level + 10-year flood (1.4 MASL) |
| 2018              | 4. Current urbanization-induced exposure | 5. Current climate change-induced exposure | 6. Future climate change-induced exposure |

Mckee 1997, Zagar et al 2011, Hanasaki et al 2013, Karnauskas et al 2016, WMO 2016). However, while studies in continents focus on the supply of water, PICs limited water sources are much more subject to demand side changes. Thus, based on these drought indices and the data available in the case study area, we consider supply and demand equally and use the change in precipitation and public water users to investigate water shortages in Palau’s urban area.
Figure 5. Maps showing urbanization in Koror from 1954–2018. Exposed buildings are based on that year’s mean sea level plus the 10-year flood event.
To separate changes to rainfall and water demand we create a water scarcity index (WSI) dividing predicted demand, population growth dependent, by water supply, rainfall dependent, shown by the following equation:

$$\text{WSI} = \frac{\Delta \text{Predicted Monthly Water Demand}}{\Delta 5 \text{ Month Average Rainfall}}$$  \hspace{1cm} (1)

This index enables us to manipulate population growth to simulate how urbanization contributed to the reported water shortages and estimate if these events would have happened in the absence of this urbanization.

We use per person water consumption estimated in 2007 (ADB). These rates will be multiplied by the number of tourists and residents and days in the respective month to calculate the predicted monthly water demand (PMWD), shown by the following equation:

$$\text{PMWD} = d(xP_t + yP_r)$$  \hspace{1cm} (2)

where \(d\) is the number of days in the given month, \(P_t\) is the population of tourists, \(P_r\) is the population of residents. The value of \(x\) and \(y\) represent the water use in liters person\(^{-1}\) d\(^{-1}\), 1366 and 443 respectively (ADB 2007).

The water supply portion of the WSI uses millimeters and not liters because of obstacles in converting rainfall over the watershed to volume. The catchment area for the Ngerimel Dam is known and the yield can be roughly estimated (by simply multiplying the watershed area by rainfall), but it is supplemented by another river source via a pump and pipe, the yield of which cannot be estimated. Due to these complications, we simply used rainfall and treated the WSI as a unitless index.

The WSI estimates water scarcity, but to determine the level of water scarcity that triggers a water shortage we set a water shortage threshold (WST). To establish the WST, we reviewed historical records (government reports and newspapers, from 1992 when regular newspapers entered publication) in Palau and cataloged three major water shortage events (1983, 1998 and 2016) affecting water supply and agriculture across Palau and four minor ones (2002, 2005, 2010 and 2018) only affecting Koror between 1980–2018. We then set the WST so that the WSI most accurately replicated these events. To further calibrate the WSI, a 5-month moving average of monthly rainfall was chosen after testing averages ranging from!1–24 months because it most closely simulated actual water shortages.

The WSI successfully replicated 6 out of 7 of these water shortages and recorded 18 months above the WST, though it counts 2 water shortages for the major 2016 water shortage, which was only one event (see figure 6). The index failed to reproduce a minor water shortage that occurred in 2002, likely because it was between Census counts and the population may have grown more quickly than the assumed linear growth.

To determine how individual exposure and hazard components (past/present population and observed/projected rainfall) contributed to risk, we made a water shortage exposure matrix (see table 2). However, because this analysis involves time periods and not single, discrete years, instead of comparing all scenarios to a base year (like in the coastal flooding exposure matrix) this matrix shows the number of water shortage events and months above the WST for each scenario. Scenarios 1 establishes an estimated baseline exposure by simulating water shortage risk if the urban area population stopped growing after 1980, with actual tourist growth from 1980–2018, over the observed rainfall period (1980–2018). Scenario 2 projects future climate change-induced exposure by combining the 1980 population and 2015 tourist numbers (tourist arrivals will vary based on the month to mimic the tourist season) with the three future rainfall models. Scenario 3 demonstrates how urbanization increased exposure today by combining actual population/tourist growth and rainfall over the observed rainfall time period. Scenario 4 projects how future climate change-induced exposure will affect risk at present urbanization levels, using 2015 population and tourist arrivals (tourist arrivals will vary based on the month to mimic the tourist season). This will illustrate how urbanization and climate change independently and jointly affect water shortage risk.

3. Results

3.1. Coastal flooding

Koror’s substantial post-WWII building growth (see figure 5) had large impacts on coastal flooding exposure. In 1983 a 10-year flood event exposed 79 buildings. By 2018, the same sea level and flood event exposed 207 buildings, more than doubling the exposure in 35 years. Three additional buildings from 1983 and 14 from 2018 were exposed by the same flood event at the 2018 sea level, meaning that sea level rise from 1983 to 2018 did not significantly increase hazards to coastal flooding. Adding the 2050 projected sea level rise to the flood event resulted in another three additional buildings from 1983 and eight from 2018 to be exposed, again showing that sea level rise is not as big a contributor to coastal flooding (see table 3).

Urban expansion in Koror caused 93.7% of coastal flooding exposure found in 2018. Future sea level rise still only exposes eight more buildings even though Palau is predicted experience above average global increases. This is due to Palau’s relatively lower average global increases. This is due to Palau’s relatively
3.2. Water shortage
The baseline exposure resulted in three water shortage events, the same years as major recorded events, and 6 months above the WST (see table 4). Adding urbanization-induced exposure doubled the number of water shortage events, the same years as three of the minor recorded events, and tripled number of months above the WST (see figure 6). These findings suggest that not only did urbanization cause the three minor events after 2000, but also increased the severity of what may have been minor events, illustrating how population growth within a small water supply system can have significant consequences.

Using the three projected rainfall models, changes to climate change-induced exposure ranged from decreases in both water shortage events, 2, and months above the WST, 2, to large increases, 13 and 38, respectively, using 1980 urbanization levels (see table 4). This illustrates uncertainty in estimating future rainfall. However, when combining projected rainfall with 2018 urbanization levels all three rainfall models predicted significant increases in water shortage risk. The most optimistic model, hg2e, still estimated 18 water shortage events and 39 months above the WST, more than doubling the number of observed events (see table 4 and figure A5). This does not even account for potential urban growth that economists and statisticians project (EconMAP 2019) and is likely to occur as new hotels in Koror are being constructed today.

4. Discussion
4.1. Urbanization exposure: coastal flooding
Historical maps demonstrated urban expansion towards the coastline and eventually past it in certain areas reflecting a commonality with other PICs. As people moved to Palau’s sole economic center and former capital, Koror State Government leased state land for people to build their homes. As growth continued and land became scarce the State began leasing out areas of mangrove providing reimbursement to leasers for filling the land, essentially subsidizing coastal development. This development pattern exposed 6.4% of all buildings to coastal flooding. By 2018, the rise in mean sea level only increased exposure half a percent and 2050 sea level projections added a further quarter of a percent, though in both cases (due to mapping resolution) water levels were rounded down by 1 and 4 cm potentially leading to a small underestimation (see section 2.3.1). Given the deep uncertainty associated with mean sea level projections, particularly in the second half of this century but discernible by 2050, future sea level rise will continue to increase exposure in the long term. For example, if mean sea level rise in Palau were to instead double by 2050 (53 cm relative to 1983, 95th percentile RCP 8.5, Jackson and Jevrejeva 2016), present-day exposure would increase significantly more to 30%. Overall though, these results confirm urbanization’s disproportionate effect on coastal flooding risk.

However, buildings we determined to be exposed may vary in the frequency and severity to which they are actually affected by coastal flooding today. As long term mean sea level rises the number of affected buildings will continue to increase as well. Shorter term ENSO-dependent sea level variations will also have great effects on whether and how frequently exposed buildings are affected by
coastal flooding (e.g. Chowdhury and Chu 2015, Han et al. 2017).

Furthermore, while Koror’s volcanic and limestone lithology is prevalent across other PICs, there are many atoll islands (including other states in Palau) that are much more exposed to changes in sea level. For example, like the Marshall Islands are a much lower mean altitude and flatter, meaning that even more minor increases in sea level over the 20th century will have increased exposure more relative to urbanization than we found in Koror.

4.2. Urbanization exposure: water shortage

While the population of Palau grew, its number of public water users grew with increasing tourism, and policies aimed at increasing access to running water as a means to increase quality of life were implemented (ADB 2013). Reliance on the newly expanded water supply infrastructure came at the expense of formerly common rainwater catchment systems and their use dropped dramatically from 48% in 2000 to only 5% by 2015 (Republic of Palau (ROP) 2015). Our analysis showed this urbanization likely caused three water

Table 4. Water shortage risk matrix results.

| 1980–2018 observed rainfall | 2041–2079 projected rainfall |
|-----------------------------|-----------------------------|
| Water shortage events       | 3                           | 2 | 4 | 13 |
| Months above the WST         | 6                           | 2 | 8 | 38 |
| Water shortage events       | 6                           | 19| 18| 23 |
| Months above the WST         | 18                          | 64| 39| 88 |

Figure 6. Water shortage index shows urbanization’s impact on water scarcity (Actual WSI) and predicted WSI had growth not occurred (1980 Public Water Users WSI), 1980–2018
shortages and an additional extra 12 months above the WST, increasing the severity of the water shortages that may have occurred regardless. Our future rainfall projections exhibited the possibility of reducing water shortage events to two at 1980 urbanization levels. However, with the current population major increases to water shortage events and their severity that resulted in anywhere from 18 to 23 water shortage events at two to four times the severity at present population levels. Based on these findings it is evident that urbanization in Palau played a major role in water shortage risk over the past several decades and both urbanization and climate change have the potential to equally impact future water shortage risk.

Though Koror and Airai’s water reservoir satisfies the populations’ demand most of the time, the increased water use makes it more susceptible to ENSO-induced rainfall variations already occurring (Power et al. 2017, Wang et al. 2017). Understanding these variations are just as important for planning how to manage water resources as estimating long-term rainfall changes.

PICs that raise demand on freshwater resources immediately adjacent to swelling urban populations may also exhibit increased exposure to rainfall variations. As Palau has one of the highest urbanization rates in the increasingly urban Pacific (Asian Development Bank (ADB) 2016), other PICs that are not currently experiencing the same water shortage issues as Palau may see their future in Palau’s current situation. Even if urbanization does not increase as predicted, future short and long term rainfall variations may push their water supply limits to the point where they too cannot reliably produce water when faced with more frequent and severe droughts.

4.3. Pathways to lower risk in PICs
Growing climate risk research in PICs has reframed the conversation to not only understand long-term changes in climate, but also short term climate variations and how human activity produces local impacts (e.g. Chowdhury and Chu 2015, Han et al 2017, Power et al 2017, Wang et al 2017). Fortunately, this bolsters the toolbox from which PICs can address climate risk. They can track and respond to seasonal sea level and rainfall variations and, as this research found, manage urban development, all while continuing to demand carbon emission reductions in international forums.

Our correlation analysis concurred with other studies that PICs are particularly susceptible to shorter time scale elevated sea levels during La Niña years (Chowdhury and Chu 2015, Han et al 2017). The results of this research also demonstrated PICs exposure to rainfall variations created by the same phenomenon. In fact, until January 2020, the Pacific ENSO Applications Climate Services (PEAC) provided seasonal sea level and rainfall forecasts to US Associate Pacific Islands allowing them (in theory at least) to make temporary coastal management and water usage plans at this timescale (www.weather.gov/peac/sealevel). For sea level, the empirical correlation-based model provided high skill scores when combining zonal wind fluctuations to sea-surface temperature to drive seasonal forecasts (Chowdhury et al 2015), however these did not incorporate long term projections of mean sea level, nor evaluate exposure as we have performed here.

Utilizing these relationships to inform near-term sea level and rainfall projections would allow PICs to implement temporary protection measures in a timely fashion that can lead to long term solutions. After first identifying coastal exposure to short term (2–3 years) elevated sea level, governments could decide those areas to protect, whilst incentivizing land-owners/tenants in those areas or other areas with high long term exposure to move with buy-outs of land combined with infrastructure support (residential, electricity, water and transportation) of inland development areas. Those development areas could utilize different water sources to reduce pressure on urban water supplies while urban homes utilize tools such as rainwater harvesting and use of salt-water for toilets. This should be tempered by the point that further seaward development will erode the natural flood protection provided by the mangroves, and place further stress upon currently limited water resources.

However, PICs are a diverse group of island lithologies and in a atoll nation such as the Marshall Islands moving residents from the lowest lying sand atolls to higher islands may help against coastal flooding only to increase water shortage risk in those areas. There are other complexities that must be taken into account, such as the use of groundwater and land subsidence (Erban et al 2014), and the fact that PICs may need international support to implement these adaptation strategies. While an uncertain climate future still promises major changes (Church 2006, Becker 2012, Power et al 2017, Wang et al 2017), there is a growing range of options for PICs to reduce future climate risk through tracking short term climate variations, urban management, all while they continue lobbying for carbon emission reductions.

4.4. Limitations and future research
Research in PICs is difficult due to data availability and though we were able to find usable data in Palau there are still some factors on which to improve. More accurate and precise DEM data could better estimate coastal flooding exposure in Koror. The USGS data
used was created in 1983 and is both not precise and does not account landscape changes that occurred. However, with the limited data available the significant coastal flooding results leads us to think that more accurate DEM data will show similar results. Similarly, the WSI could be improved with a more accurate estimate of water supply instead of simply using rainfall. However, without historical data on dam levels, rainfall data was sufficient to accurately replicate water shortage events. It is more likely that the five years between population counts contributed to inaccuracy more on the demand side than rainfall on the supply side. Even with these shortcomings, we believe the results still clearly show urbanization had a substantial effect on climate risks, which is often overlooked in Pacific research.

Both coastal flooding and water shortage risk analyses would be made more complete with a study of vulnerability to complete the risk equation. Vulnerability is traditionally low in PICs due to strong social and community ties, which foster strong resilience in the face of naturally occurring and anthropogenic environmental changes (e.g. Firth 1959, Rappaport 1963, Lessa 1964, Marshall 1979, Campbell 1990). Throughout the course of research for this paper, surveys and interviews with residents in Koror found they remained resilient to increased risk as people relied on both soft solutions through social and community bonds and hard solutions like filling their own land or using water storage tanks. This resiliency is common to the Pacific and is a vital to maintain and enhance as climate change alters hazards (Barnett 2001).

Future research would do well to combine seasonal variations like those in PEAC, long term trends and exposure analysis to look at other urban areas in the Pacific with different lithologies, population and per capita GDP. Palau serves as a good example for Post-WWII urbanization, however, research into other islands may come to different conclusions based on these factors. Even if the results are the same, differing circumstances such as availability of alternative water sources may require different solutions. The development of a strategic adaptation framework embedding analyses of the type presented here with a consistent, repeatable methodology would allow PICs to tailor solutions to their people and islands.

5. Conclusion

We attempted to disentangle the effects of climate change and urbanization on coastal flooding and water shortage risk in Palau and the Pacific, adding to the growing body of literature examining all components of risk in PICs (e.g. White and Falkland 2010, Forbes et al 2013, Kumar and Taylor 2015, Kench et al 2018, Kelman 2019). At present, coastward urbanization (into mangrove and reef) and population growth have dominated the increase in coastal exposure and reduced water resilience respectively. Therefore, the future coastal stability of Koror requires coastal management encompassing sensitive urban development and preservation of its vital coastal ecosystem (Forbes et al 2013). Furthermore, improvements to the internal management of water resources in Palau’s urban area will strongly improve water resilience in response to public demand and the likely increases in rainfall variability (White and Falkland 2010, Kelman 2019).

We have shown in this study the importance of continued observations drawn from in-situ measurements, geospatial mapping, and climate modelling to understand the factors governing urban exposure to environmental change. This objective approach informs a range of stakeholders from governments, private developers and individual homeowners. While continuing to advocate for strong emission reduction targets on the international level, PICs would do well develop procedures to track short-term sea level and rainfall variations (like PEAC) and implement policies which facilitate short term risk minimizing actions that can evolve into long term solutions that ensure proper coastline and water supply management to lower exposure to coastal flooding and water shortage risks.

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Competing Interests

The authors declare no competing financial interests.

Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.
Appendix

Figure A1. (a) Malakal B tide gauge record monthly observations (PSMSL). (b) Rate of RSL for different sliding window lengths. (c) ENSO 3.4 Index. (d) Rate of change of sea-surface temperature (SST) for range of sliding window lengths.

Table A1. Climate model accuracy in replicating historical rainfall data, 1961–1990 (* models chosen for future analysis). Coefficient of variation shows the difference in historical annual variation and model annual variation. Mean sums the absolute difference between historical average monthly rainfall and model average monthly rainfall for each month in a calendar year to account for seasonal variations in rainfall while comparing average annual mean rainfall.

| Climate Model | Abbreviation | Coefficient of Variation | Mean (mm) |
|---------------|--------------|--------------------------|-----------|
| BCC-CSM1.1(m) | bc1m*        | 0.039                    | 529.1     |
| CNRM-CM5      | cc5          | 0.040                    | 529.6     |
| CanESM2       | ce2          | 0.023                    | 531.6     |
| CSIRO-Mk3.6.0 | cs36         | 0.214                    | 530.6     |
| GFDL-ESM2M    | ge2m         | 0.086                    | 529.4     |
| HadGEM2-ES    | hg2e*        | 0.005                    | 516.4     |
| IPSL-CM5A-LR  | ic5l         | 0.146                    | 529.4     |
| MIROC5        | m50          | 0.055                    | 529.6     |
| MRI-CGCM3     | mc3*         | 0.013                    | 529.7     |

Table A2. Past rainfall and future rainfall projections summary.

|                                | Historical (1980–2018) | bc1m (2041–2079) | hg2e (2041–2079) | mc3 (2041–2079) |
|--------------------------------|------------------------|------------------|------------------|-----------------|
| Mean Annual Rainfall           | 3728                   | 3426             | 3667             | 3111            |
| Maximum Annual Rainfall        | 5483                   | 5215             | 5792             | 3995            |
| Minimum Annual Rainfall        | 2452                   | 2169             | 2706             | 2131            |
| Annual Rainfall Variance       | 16.7%                  | 18.3%            | 20.1%            | 17.1%           |
| Dry Season Mean Monthly Rainfall| 224                    | 184              | 194              | 149             |
| Rainy Season Mean Monthly Rainfall| 446                    | 425              | 400              | 346             |
Figure A2. (a) Altimetry (AVISO) and Tide gauge (Malakal B, PSMSL) records for Palau. (b) Altimetry minus Tide gauge records over same period to infer vertical land motion.

Figure A3. Extreme value distribution of annual sea level maxima.
Figure A4. Map of coastal flooding exposure in Koror, Palau.
Figure A5. Future WSI, 2041-2079. Subfigures a, b and c show the WSI for scenario 3 using 1980 urbanization levels and future rainfall a) bc1m b) hg2e c) mc3. Subfigures d, e and f show the WSI for scenario 4 using 2015 urbanization levels and future rainfall d) bc1m e) hg2e f) mc3.
References

Asian Development Bank (ADB) 2007 Water Resources Report, ADB TA 4977 Preparing the Babeldaob Water Supply Project
Asian Development Bank (ADB) 2013 Moving from risk to resilience: sustainable urban development in the Pacific (Mandaluyong City: Asian Development Bank)
Asian Development Bank (ADB) 2016 The emergence of pacific urban villages: Urbanization trends in the Pacific islands (Mandaluyong City: Asian Development Bank)
Asian Disaster Risk Center (ADRC) 2009 Total disaster risk management: good practices 2009
Barclay H, Cohen A, McCorrkle D and Golbuu Y 2017 Mechanisms and thresholds for pH tolerance in Palau corals J. Exp. Mar. Biol. Ecol. 489 7–14
Barnett J 2001 Adapting to climate change in Pacific Island countries: the problem of uncertainty World Dev. 29 977–93
Becker M, Meysignac B, Letetret C, Llovel W, Cazenave A and Delcroix T 2012 Sea level variations at tropical Pacific islands since 1950 Glob. Planet. Change 80–81 85–98
Calderwood P, Juckes M and Thompson P R 2015 Sea level data measured by tide gauges from global oceans — the Joint Archive for Sea Level Holdings (NCEI Accession 0019568), Version 5.5, NOAA National Centers for Environmental Information, Dataset, 2015
Campbell J 1990 Disasters and development in historical contest: tropical cyclone response in the Banks Islands, northern Vanuatu Int. J. Mass Emergencies Disasters 8 401–24
Chand S S, Terry K, J Y H and Walsh K J 2017 Projected increase in El Niño-driven tropical cyclone frequency in the Pacific Nat. Clim. Change 7 123–7
Chowdhury M R and Chu P S 2015 Sea level forecasts and early-warning applications: expanding cooperation in the South Pacific Bull. Am. Meteorol. Soc. 96 381–6
Chowdhury M R, Chu P S and Schroeder T 2007 ENSO and seasonal sea-level variability—a diagnostic discussion for the US-Affiliated Pacific Islands Theor. Appl. Climatol. 88 213–24
Church J, White N and Hunter H 2006 Sea-level rise at tropical Pacific and Indian Ocean Islands Glob. Planet. Change 53 135–68
Connell J 2015 Vulnerable islands: climate change, tectonic change, and changing livelihoods in the Western Pacific Contemp. Pac. 27 1–36 EconMAP 2019 Economic Review Palau FY 2018 December 2019 https://pittiviti.org/initiatives/economics/palau.php
Edwards D C and McKeen T B 1997 Characteristics of 20th century drought in the United States at multiple time scales Climatolography Report 97-2 (Fort Collins, CO: Department of Atmospheric Science, Colorado State University)
Erban LE, Gorelick SM and Zebker HA 2014 Groundwater extraction, land subsidence, and sea-level rise in the Mekong Delta, Vietnam Environ. Res. Lett. 9 084010
Firth R 1959 Social Change in Tokopia (London: Macmillan)
Forbes D L, James T S, Sutherland M and Nichols S E 2013 Physical basis of coastal adaptation on tropical small islands Sustainability Sci. 8 327–44
Han W, Mehl G A, Stammer D, Hu A, Hamlington B, Kenigson J, Palanisamy H and Thompson P 2017 Spatial patterns of sea level variability associated with natural internal climate modes Integrative Study of the Mean Sea Level and Its Components (Berlin: Springer) pp 221–54
Hanasaki N et al 2013 A global water scarcity assessment under shared socio-economic pathways – part 1: water use Hydrolog. Earth Syst. Sci. 17 2375–91
Holgate S J, Matthews A, Woodworth P L, Rickards I J, Tamisera M E, Bradshaw E, Foden P R, Gordon K M, Jevrejeva S and Pugh J 2013 New data products and projects at the permanent service for mean sea level J. Coast. Res. 29 493–504
Hunter J R, Woodworth P L, Wahl T and Nicholls R J 2017 Using global tide gauge data to validate and improve the representation of extreme sea levels in flood impact studies Glob. Planet. Change 156 34–45
Hunter J 2012 A simple technique for estimating an allowance for uncertain sea-level rise Clim. Change 113 239–52
IPCC, 2019 IPCC Special Report on the Ocean and Cryosphere in a Changing Climate eds H-O Pörtner, D C Roberts, V Masson-Delmotte, P Zhai, S Peolet, D Poloczanska, K Mintenbeck, A Alegría, M Nicolai, A Okem, J Petzold, B Rama and N M Weyer In press
IPCC 2013 Climate change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate change eds (Cambridge: Cambridge University Press) pp 1535
Jackson L and Jevrejeva S 2016 A probabilistic approach to 21st century regional sea-level projections using RCP and high-end scenarios Glob. Planet. Change 146 179–89
Karnauskas K, Donnelly J and Anchukaitis K 2016 Future freshwater stress for island populations Nat. Clim. Change 6 720–5
Kelman I 2019 Pacific island regional preparedness for El Niño Envir. Dev. Sustainability 21 405–28
Kench P S, Ford M R and Owen S D 2018 Patterns of island change and persistence offer alternate adaptation pathways for atoll nations Nat. Commun. 9 605
Kopp R E, Horton RM, Little CM, Mitrovica JX, Oppenheimer M, Rasmussen DH, Strauss BH and Tebaldi C 2014 Probabilistic 21st and 22nd century sea-level projections at a global network of tide-gauge sites Earth’s Future 2 383–406
Kumar L and Taylor S 2015 Exposure of coastal built assets in the South Pacific to climate risks Nat. Clim. Change 5 992–6
Kuo C Y, Shum C K, Braun A and Mitrovica JX 2004 Vertical crustal motion determined by satellite altimetry and tide gauge data in Fennoscandia Geophys. Res. Lett. 31 L01608
Lessa W 1964 The social effects of typhoon Ophelia (1960) on Ulithi Micronesia 1 1–47
Marshall M 1979 Natural and unnatural disaster in the Mortlock Islands of Micronesia Hum. Organ. 38 263–72
Meysignac B et al 2017 Evaluating model simulations of twentieth-century sea-level rise. Part II: regional sea-level changes J. Clim. 30 8565–93
Moss RH et al 2010 The next generation of scenarios for climate change research and assessment Nature 463 747–56
National Climatic Data Center NEDIS, NOAA (US Department of Commerce)
Nerem R, Beckley B, Basullo J, Hamlington B, Masters D and Mitchum G 2018 Climate-change–driven accelerated sea-level rise Proc. Natl Acad. Sci. 115 2022–3
Nicholls R J, Wong P F, Burkett V R, Codigioia J O, Clay J E, Mclean R F, Ragondanus S and Woodroffe C D 2007 Coastal systems and low-lying areas Climate change 2007: impacts, adaptation and vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate change eds M L Parry, O F Canziani, J P Palutikof, P J van der Linden and C E Hanson (Cambridge: Cambridge University Press) pp 315–26
Nurse L A, Mclean R F, Agard J, Briguglio L P, Duvat-Magnan V, Lessa W, Mclean R F, Ragoonaden S and Woodroffe C D 2007 Coastal systems and low-lying areas Climate change 2007: impacts, adaptation and vulnerability. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate change eds M L Parry, O F Canziani, J P Palutikof, P J van der Linden and C E Hanson (Cambridge: Cambridge University Press) pp 1535–26
Palau Automated Land and Resource Information System (PALARIS) 2018 Data obtained February 2018
Palau Visitor’s Authority (PV A) 2019 Accessed: 26 December 2019
Parry M L, Canziani O F, Palutikof J P, van der Linden P J and Vignarelli M L M, Matthews L K, Cerovec J A and Palutikof J P 2007 Adaptation and vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate change (Cambridge: Cambridge University Press)
Permanent Service for Mean Sea Level (PSMSL) 2019 Tide Gauge Data Accessed 5 December 2019 www.psmsl.org/data/obtaining/

Power S et al 2017 Humans have already increased the risk of major disruptions to Pacific rainfall Nat. Commun. 8 14368

Pumo D, Arnone E, Franciapeake A, Caracciolo D and Noto L V 2017 Potential implications of climate change and urbanization on watershed hydrology J. Hydrol. 554 80–99

Rappaport R 1963 Aspects of man’s influence upon island ecosystems: alteration and control Man’s Place in the Island Ecosystem ed F Fosberg (Honolulu, HI: Bishop Museum Press) pp 155–70

Republic of Palau (ROP) 2015 Office of Planning and Statistics. Census

Sales R F M Jr 2009 Vulnerability and adaptation of coastal communities to climate variability and sea-level rise: their implications for integrated coastal management in Cavite City, Philippines Ocean Coast Manag. 52 395–404

Sebastian A, Gori A, Blessing RB, van der Wiel K and Bass B 2019 Disentangling the impacts of human and environmental change on catchment response during Hurricane Harvey Environ. Res. Lett. 14 124023

Singh V P, Wang S X and Zhang I. 2005 Frequency analysis of nonidentically distributed hydrologic flood data J. Hydrol. 307 175–95

Sofia G, Roder G, Dalla Fontana G and Tarolli P 2017 Flood dynamics in urbanised landscapes: 100 years of climate and humans’ interaction Sci. Rep. 7 40527

Taylor K E, Stouffer R J and Meehl G A 2012 An overview of CMIP5 and the experiment design Bull. Am. Meteorol. Soc. 93 485–98

U.S. Geological Survey 2016 National water information system data available on the World Wide Web (USGS water data for the nation) Accessed December 2019 http://waterdata.usgs.gov/nwis/

UNISDR 2015 Making Development Sustainable: The Future of Disaster Risk Management. Global Assessment Report on Disaster Risk Reduction (Geneva: United Nations Office for Disaster Risk Reduction (formerly UNISDR))

University of Hawaii Sea Level Centre (UHSLC) 2019 Tide Gauge Data Accessed 6 December 2019 https://uhslc.soest.hawaii.edu/stations/

Wahl T, Haigh I D, Nicholls R J, Arns A, Dangendorf S, Hinkel J and Slagen A B 2017 Understanding extreme sea levels for broad-scale coastal impact and adaptation analysis Nat. Commun. 8 1–12

Wang G, Cai W, Gan B, Wu L, Santoso A, Lin X, Chen Z and Mcphaden M J 2017 Continued increase of extreme El Niño frequency long after 1.5°C warming stabilization Nat. Clim. Change 7 568–72

White I and Falkland T 2010 Management of freshwater lenses on small Pacific islands Hydrogeol J. 18 227–46

Woodroffe S A and Horton B P 2005 Holocene sea-level changes in the Indo-Pacific https://repository.upenn.edu/ees_papers/21

World Meteorological Organization (WMO) and Global Water Partnership (GWP) 2016 Handbook of drought indicators and indices Integrated Drought Management Programme (IDMP), Integrated Drought Management Tools and Guidelines Series 2 eds M Svoboda and B A Fuchs (Geneva: WMO)

Zargar A, Sadiq R, Naser B and Khan F I 2011 A review of drought indices Environ. Res. 19 333–49

Zhang X and Church J A 2012 Sea level trends, interannual and decadal variability in the Pacific Ocean Geophys. Res. Lett. 39 L21701