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Water, people and climate-change exposure in the Western Pacific: Anticipating the arrival of a 'perfect storm'

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Abstract

As climate change accelerates, there is a growing need to ensure that sustainable adaptive solutions are effective and equitable, especially in the Global South where many countries depend on external funding to attain water security. Perceptions of vulnerability and need among Pacific Island Countries are not always based on a region-wide evidence base. This study examines ten Western Pacific Island countries (Federated States of Micronesia [FSM], Fiji, Kiribati, Marshall Islands, Nauru, New Caledonia [French dependency], Palau, Solomon Islands, Tuvalu, Vanuatu) that include both high-island groups and low-island (atoll) groups. This study evaluates the equitability of the distribution of external funding for attaining water security. Needs are evaluated in terms of (a) population densities and growth compared with water and land availability and (b) the uneven distribution of water-focused livelihood stressors across this region, specifically those linked to climate variability, sea-level rise, tropical cyclones, and geophysical phenomena. Measures of comparative exposure of people in these countries show that those living along high-island coasts, especially in Fiji, Solomon Islands and Vanuatu, are considerably more exposed than their counterparts elsewhere, especially in atoll nations which have received greater amounts of *per capita* climate funding for water security. Results show that there is a 'perfect storm' brewing in the high-island nations of the Southwest Pacific resulting from their

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comparatively high exposure to livelihood stressors. This could be addressed by reassessing the distribution of external climate funding within the Western Pacific region. Key findings are the importance of aligning need with assistance and the foundational role of water in livelihood sustainability, both having implications for the hundreds of coastal communities forced to relocate, mostly locally on the same island, in the next few decades. The imperative of addressing such deficiencies in an era of accelerating climate change and declining levels of global support is clear.

Introduction

Climate change is affecting the Pacific Islands region more profoundly than many other parts of the inhabited world. Popularly characterized as the 'canary in the coalmine' for anthropogenic climate change, its people are often portrayed as being on the 'front line' of its widening and accelerating impacts [1,2]. While readily contestable [3], such comments align with most scientific assessments of the situation [4] and are reflected in recent statements from Pacific Island leaders that emphasize the vulnerability and needs of communities in the Pacific region. For example, the official communiqué of the 2023 Pacific Islands Forum alluded to the critical importance of managing "the ongoing challenges and impacts of the climate emergency" in the Pacific region [5: 2].

Over the past three decades, common views (by scientists and policy-makers) towards climate change in the Pacific Islands region have evolved from the specific to the general, the local to the regional, and from the adaptable to the apocalyptic. This has led to the spread of truisms about the Pacific Islands region, especially narratives of extreme vulnerability and helplessness, which has given rise to a global picture of a region that will be able to cope with future climate change only through the injection of large amounts of external funding to build resilience [6,7]. To date, the distribution of such funding within the Pacific Islands region has favoured what are perceived to be the most vulnerable countries and situations. The immediate threats of sea-level rise to vulnerable communities in low lying atoll islands in the region has been easily visualized and communicated and readily understood by governments and aid agencies worldwide [8]. The larger scale, more complex and expensive challenges of water security in high island communities with greater populations, has been largely overlooked [9,10].

To interrogate this situation, data characterizing water availability and demand (proxied by population) were gathered for island nations in the Western Pacific, together with data about the principal climate- and non-climate- driven livelihood stressors in this region. Using methods detailed in S1 and S2 Data, these data are analyzed to produce a snapshot of the spatial exposure of human livelihoods to these stressors in these nations, as well as the alignment of this exposure with external funding for addressing it.

This paper identifies disproportionately high levels of exposure of people living on higher islands in the southwestern Pacific, where most residents live in rural contexts close to the coast and subsist largely from coastal (marine and terrestrial) resources. This is also the part of the Pacific Ocean where sea level has recently been rising fastest uninfluenced by tectonics, sometimes as much as three times the global average [11,12]. We argue that this has contributed to 'a perfect storm' of circumstances that is likely to lead to major widespread societal disruption over the next 10–20 years, a scenario that appears largely unanticipated by both national authorities and international agencies; in this paper, the term 'perfect storm' refers to a critical or disastrous situation in one place created by an unforeseen concentration of factors. We further argue that people's access to sufficient water for their diverse needs is a foundational issue for this region, having the capacity to either soften or amplify the unfolding crisis.

The next two sections (Results) explain the key contributors to the 'perfect storm' in the Western Pacific, the first being population and water, specifically the numbers of (coastal) people experiencing water insecurity, and the second being climate change, principally the pace of sea-level rise and exposure to tropical cyclones. Two sections (Discussion) follow, the first describing the nature of the 'perfect storm', the next the ways of coping with it. This research has fundamental implications for ways of portraying and addressing water-associated risk in rural contexts in Western Pacific countries. It is hoped that this study will be of interest to scientists and decision-makers who are concerned with sustainable futures for people living on islands in the Western Pacific. All arguments are constructed using publicly available data, sources being given in text/captions as well as S1 and S2 Data where details of data analysis (Methods) are also given.

Population and water in the Western Pacific

To contextualize the nature of this 'perfect storm', this paper looks at ten island nations in the western Pacific Ocean, shown in bold in Fig 1A, of which six are mostly high-island nations (Fiji, Nauru, New Caledonia, Palau, Solomon Islands, Vanuatu), three are largely atoll (low-lying island) nations (Kiribati, Marshall Islands, Tuvalu), and one having people living on both island types (Federated States of Micronesia [FSM]); note that New Caledonia is a French overseas territory but treated as a country for most purposes of this analysis. The distribution of high islands can be linked to that of island-forming processes, which are especially active along convergent boundaries between lithospheric plates, while atoll islands generally dominate in intraplate locations characterized by island subsidence [13,14].

Population distribution and growth trends

Population data for these ten countries are shown graphically in Fig 1B and listed in Table 1. Of the 2.68 million people in this region today (August 2024 estimates), 2.34 million (87%) live in the four high-island countries of the southwest Pacific (Fiji, New Caledonia, Solomon Islands, Vanuatu) while 190,000 (7%) reside in the three atoll nations (Kiribati, Marshall Islands, Tuvalu). Today in the four high-island countries, a total of 626,350 people (27%) live within 1 km of the coast, more than three times the total population of the three atoll nations. In the high-island countries, almost 2 million people (85%) live within 5 km of the coast. Similar findings were obtained by Andrew et al. [15] and are implicit in the potential economic exposure shown by Kumar and Taylor [16] who found that 57% of all infrastructure (coastal built assets) in the Pacific Islands lay within 500 m of the coast, 20% being within 100 m.

Using the 2024 population distributions (% within 1 km and 5 km), Table 1 also shows that in 2050, from a projected regional population of 3.65 million, assuming no significant coastal-to-inland relocation, there are likely to be more than 2 million people (56%) in these ten countries living within 1 km of the coast and more than 3.2 million (88%) living within 5 km of the coast. For the four high-island nations in 2050, it is estimated that a total of 1.65 million people (51%) may live within 1 km of the coast while 2.8 million (86%) may live within 5 km of the coast. Elevation above mean sea level would be a better metric but there is insufficient precise elevation data at a regional scale for Pacific islands. The associated exposure is therefore proxied by number of people living within 1 km or 5 km of the coast, considered to be a valid generalization. On some high islands, people live close to the coast yet well above sea level, while others (especially in deltas) live far from the coast yet only slightly above sea level.

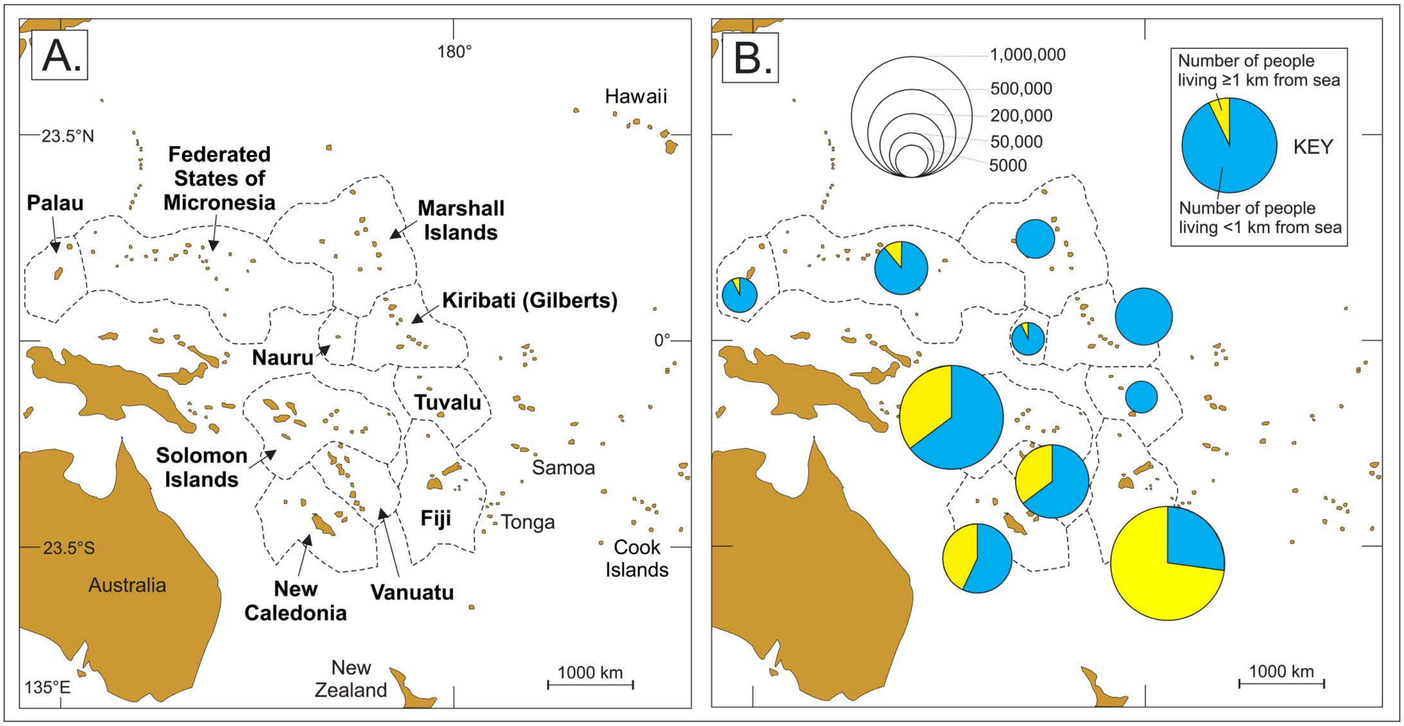

Fig 1. A: Map of the ten Western Pacific island countries, names bolded, considered for this study, showing the extents of their Exclusive Economic Zones (EEZs); note that only the western part of the Kiribati EEZ is shown. B: Population size shown by proportional circles (see top right key), divided by those living within 1 km of the coast and those living further inland (see top left key).

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This analysis shows that, by virtue of living close to the coast, six times as many people in these high-island nations (1.14 million) are currently exposed to sea-level rise than are exposed in atoll contexts (190,000). This is not of course to deny either the importance or the profundity of the challenge for atoll peoples, which has been much discussed [17,18], but to emphasize that the number of exposed people is far greater in the high-island countries, a situation that has received far less attention in most science-informed and policy-focused reports about this region.

Implicit in the 2050 projections are the population growth rates shown in Table 1. There are three countries in the region (FSM, Marshall Islands, Palau) expected to have a lower population than today in 2050, largely attributable to out-migration to the USA [19]. In contrast, the two island nations with the fastest population growth rates are Solomon Islands (average 2.15) and Vanuatu (average 1.9); a 2% growth rate means the doubling of the population in 35 years. Projected growth rates will disproportionately increase the exposure of people in these countries to climate change compared to others in the Western Pacific.

An additional concern that affects the climate-change exposure of island countries in the Western Pacific is urbanization. While accurate data are difficult to source, especially post-COVID when de-urbanization occurred throughout the region [20], long-term (post-1970) urbanization rates are comparatively fast globally. From a 2010 baseline of 2.3 million urban dwellers in the Pacific Islands, there is expected to be another 4.3 million (total 6.6 million) by 2050, more than twice the projected global average [21]. While urbanization rates differ little among the ten Western Pacific Island nations under consideration, the effects are likely to be most noticeable in those countries with currently the smallest urban populations, namely Solomon Islands (26%) and Vanuatu (27%). Sustainable urban development in Pacific Island countries is closely linked to economic growth, which is likely to be slowed by future climate change, making current and projected

Table 1. Land area, population data and water security index for the ten Western Pacific Island countries. Data from SPC Pacific Data Hub, Asian Development Bank and UNICEF/WHO (details in S1 Data). Atoll nations are shaded.

Country	Land area (km^2)	Current population (August 2024)	Population living within 1 km of coast		Population living within 5 km of coast		Average annual population growth		Projected population in 2050	Population living within 1 km of coast		Population living within 5 km of coast		National Water Security Index reverse-scaled (NWSI)	Number of people in 2022 without access to at least basic drinking water	
			Number	%	Number	%	2020-2030	2030-2050		Number	%	Number	%		Number	%
Federated States of Micronesia	700	116,395	103,592	89	116,395	100	0.1	-0.4	98,000	87,220	89	98,000	100	14	11,640	10
Fiji	18,270	943,665	254,790	27	717,185	76	0.3	0.1	1,100,000	297,000	27	836,000	76	76	47,183	5
Kiribati (Gilbert)	284	123,043	123,043	100	123,043	100	1.6	1.3	170,683	170,683	100	170,683	100	14	30,307	25
Marshall Islands	180	42,451	42,451	100	42,451	100	-0.1	-0.1	52,000	52,000	100	52,000	100	4	6368	15
Nauru	20	12,893	11,990	93	12,893	100	0.7	0.7	14,700	13,671	93	14,700	100	1	387	3
New Caledonia	18,280	296,224	168,848	57	266,602	90	0.5	0.6	353,200	201,324	57	317,880	90	27	5984	2
Palau	460	18,050	16,787	93	18,050	100	0.0	-0.4	16,000	14,880	93	16,000	100	1	181	1
Solomon Islands	27,990	758,101	492,766	65	689,872	91	2.3	2.0	1,200,000	780,000	65	1,092,000	91	77	212,268	28
Tuvalu	30	11,485	11,485	100	11,485	100	0.6	0.3	13,200	13,200	100	13,200	100	1	115	1
Vanuatu	12,190	343,012	219,528	64	322,431	94	2.1	1.7	578,600	370,304	64	543,884	94	34	30,871	9
TOTALS	**78,404**	**2,665,319**	**1,445,278**		**2,320,407**				**3,596,383**	**2,000,282**		**3,154,347**			**345,303**	

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rates of urbanization a cause for concern [22]. Most island governments recognize this in their strategic plans and invest in ways (like rural electrification and infrastructure upgrades) of enhancing the attractiveness of rural living and thereby slowing urbanization [23].

Water security

Water is a perennial challenge in most Pacific Island countries, specifically access to an adequate supply of water of an appropriate quality for the needs of everyone [24]. One way of measuring a nation's water security is through the calculation of its National Water Security Index (NWSI), shown in Table 1, determined by the measurement of key parameters to be somewhere along a continuum between 'nascent' and 'water secure' [25]. This is reverse-scored (100-n) and population-weighted in Table 1, allowing calculation of a National Water Security Index for each country in which higher values indicate lower water security and low values indicate greater water security (full details in S1 Data).

A second measure of water security is also shown in Table 1 and consists of the number of persons in each of the ten Western Pacific island countries who do not have access to 'at least basic' supplies of drinking water; the meaning of 'basic supply' in this study refers to the UNICEF/WHO's definition, adopted by the World Bank, of 'basic drinking water services' from an improved source that can be accessed by a person in a round trip of less than 30 minutes. These data show that far more people in the higher-island countries of the southwest Pacific, a total of almost 319,000 in Fiji, New Caledonia, Solomon Islands and Vanuatu (86% of the total), lack such access compared to 39,113 persons in the atoll nations of Kiribati, Marshall Islands and Tuvalu (10.6% of the total). At a global scale, these percentages are exceptionally high; as noted elsewhere, Pacific Island countries have collectively "the lowest rates of access to safely managed or basic drinking water and sanitation globally" [24: 467].

Assuming that water security should be calculated based on the number of people experiencing water stress rather than population density (which assumes that people are spread evenly across available land area), what these data show is that larger higher-island nations in the southwest Pacific (Fiji, Solomon Islands, Vanuatu) are considerably less water-secure than most others. The issue with these countries is not generally the availability of freshwater - localized pollution of coastal aquifers is an issue on many Pacific islands [26] - but its lack of suitability for the purposes required, especially for rural households, for economic activities, for urban dwellers, for environmental management, and for disaster-affected people [25,27].

In sharp contrast, continuing to assume that the measure of a nation's water insecurity is based on the number of people experiencing water stress, it is clear that smaller and lower-island countries in the Western Pacific (like Marshall Islands, Nauru, Palau and Tuvalu) are comparatively less water-insecure, largely because of relatively lower exposure to many disasters (like extreme waves and winds) and smaller populations that equate to water demand that is better aligned to supply. Such comparative measures should not be taken as trivializing the challenges that exist on many lower islands especially, for instance, around the spreading pollution of aquifers and inshore marine environments [28,29] as well as the uneven benefits of small-scale desalination plants [30].

Drought is not included in the NWSI because its definition, incidence and effects are commonly variable [31]. So although coefficients of variability of annual rainfall are included in many such indices, for the purposes of this analysis, it is assumed that drought is a livelihood stressor that impacts all ten island countries in the Western Pacific equally.

Climate change and sea-level rise in the Western Pacific

Another other major contributor to the 'perfect storm' developing in the Western Pacific is climate change, specifically sea-level rise which is a defining challenge in island worlds. For while it is well known that Pacific Island countries face enduring and transformational challenges arising from recent and future climate change [4,32,33], there have been comparatively few attempts to subdivide the region based on the nature of climate-associated livelihood stressors. This section looks at several of these livelihood stressors, including two that affect parts of the Western Pacific region more than other parts of the Pacific Basin. These are rates of sea-level rise and changing intensities of tropical cyclones, complemented in this section with a discussion of other climate-linked stressors.

Rates of sea-level rise in the Western Pacific

Three common effects of sea-level rise along island coasts in the Western Pacific Islands region are shoreline erosion, groundwater salinization, and an increased frequency and magnitude/extent of coastal flooding. Each of these phenomena is attributable to long-term (multi-decadal) sea-level rise that allows ocean water to penetrate further inland than it customarily did at the time coastal settlements and infrastructure (including systems for food production) were first built [16,33].

Over the past 50–75 years, as a result of interdecadal water transfer from the low latitudes of the East Pacific to the West Pacific Ocean, the rate of sea-level rise in the latter region has exceeded that in other parts of the Pacific Basin, a result of the combination of this water transfer and anthropogenic sea-level rise [34,35]. There are several datasets that illustrate this, the most precise being those of Becker et al. [12] which shows the longest-term effects. Fig 2A shows their map of sea-level trends derived from satellite altimetry data, redrawn on the map of the Western Pacific region.

The highest rates of sea-level rise for 1993–2009, greatly in excess of the global mean rate of 3.35 ± 0.4 mm/year [for 1993-2017 - [37], are found in two parts of the Western Pacific, approximately equidistant from the Equator. These are centred on the EEZ of FSM in the north and on the EEZ of Solomon Islands in the south where rates of sea-level rise in places exceed 12 mm/year for 1993–2009. In both places, field evidence for uncommonly rapid shoreline erosion, attributable to relatively rapid sea-level rise over the past few decades, has been published. This includes evidence for the disappearance of entire (low-lying) islands off the coasts of Santa Isabel (Solomon Islands) and Pohnpei (FSM) [38,39].

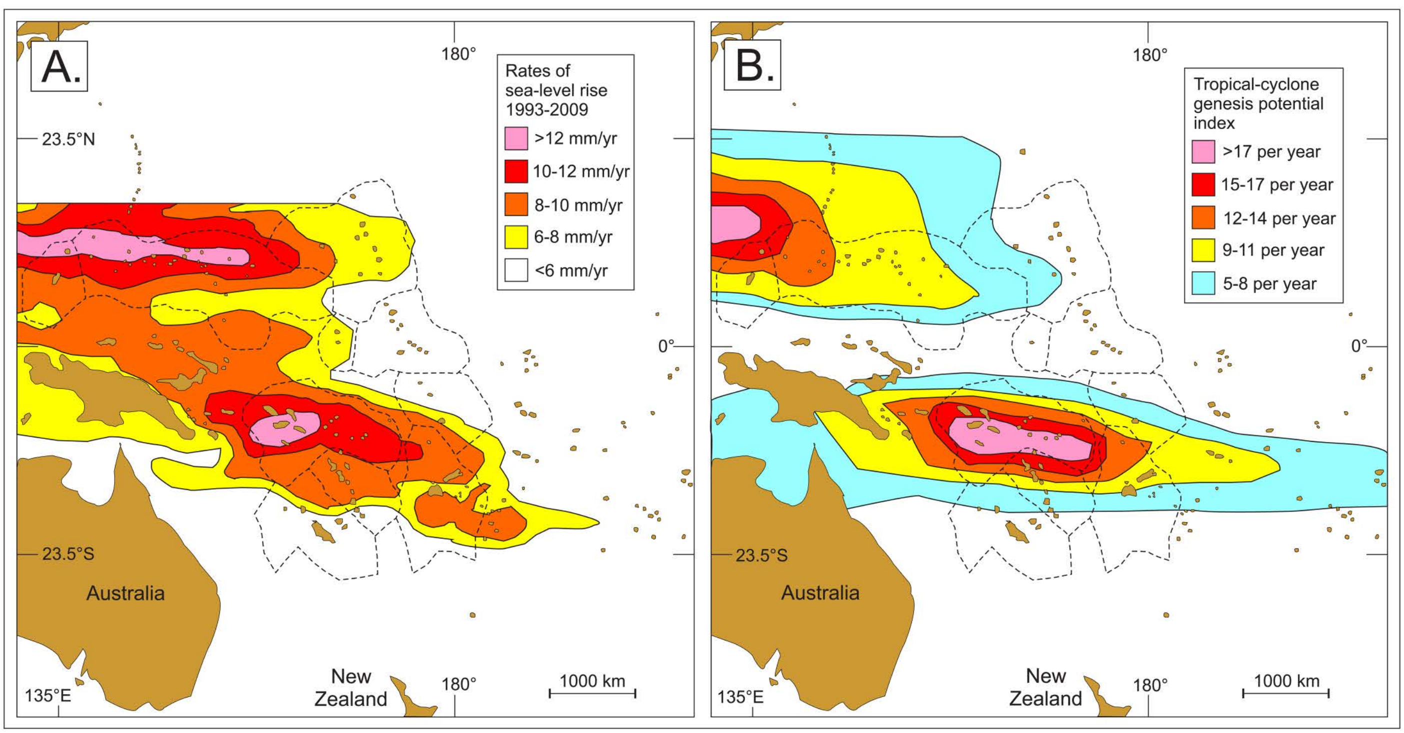

Fig 2. A: The Western Pacific showing altimetry-based sea-level trends [after Becker et al., 2012]. B: The Western Pacific showing tropical-cyclone genesis potential index (GPI) based on ERA-Interim data [after 36]. See Fig 1A for names of island groups.

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Other island nations in the Western Pacific have also been affected for several decades by these anomalously high rates of sea-level rise, including Fiji, New Caledonia, Palau and Vanuatu. There have been studies of associated (rapid) shoreline erosion in the first two countries, including from the Loyalty Islands of northeast New Caledonia [40] and throughout the Fiji archipelago [41–43]. There have been fewer such studies in Palau and in Vanuatu where coastal exposure to sea-level rise is influenced by active tectonics, as shown by the example of settlement relocation on Tegua Island in the Torres Islands in the north of the group. Widely and popularly heralded as a climate-driven relocation, the influence of tectonics on land level clearly dominates the effects of sea-level rise in this part of Vanuatu [44,45]. More compelling studies of shoreline erosion driven by rapid sea-level rise have been conducted in more stable parts of Vanuatu [46].

Few authors appear to have made a connection between anomalously rapid rates of sea-level rise in the Western Pacific and the disproportionate exposure of coastal communities. Yet it would be expected that in those parts of this region where sea level is rising fastest, the existence of livelihood stress among coastal peoples would be greatest. Several studies of coastal communities suggest this to be the case. For example, in East Kwaio (Malaita, Solomon Islands) in response to worsening inundation inhibiting the movement of people between Abitona and Wyfolonga villages, community members took the initiative to build a raised walkway, something hailed as a good example of autonomous adaptation [47]. A comparable example comes from coastal Navunievu Village (Vanua Levu, Fiji) where increasingly frequent flooding at high tide led to a community decision to build all new dwellings upslope behind the existing village, an autonomous adaptation to rising sea level that will see the entire community gradually relocate itself at minimal financial cost over the next few decades [48].

Anomalously rapid rates of sea-level rise in the Western Pacific are expected to continue for the next few decades. After this time, a probable decline in interdecadal water transfer (from the East to the West Pacific) is likely to be offset by an acceleration in the rate of global mean sea-level rise [34,49], making little practical difference to the ongoing ocean-driven exposure of coastal communities. The continuation of such comparatively high rates of sea-level rise in parts of the Western Pacific region contributes to the 'perfect storm' described below for parts of this region.

Strengthening tropical cyclones in the Western Pacific

Also called hurricanes or typhoons in this region, tropical cyclones commonly affect the tropical Western Pacific more than the central or eastern parts of the Pacific Basin. In line with predictions of the influence of sea-surface warming on tropical-cyclone intensity (strength) and frequency, there is clear evidence that in the past 15 years there has been a decrease in tropical-cyclone frequency but an increase in average tropical-cyclone intensity in this region [50,51]. These changes in frequency and intensity are expected to continue with future warming [52].

Two of the key tropical cyclones (TCs) to have brought this intensity increase to the attention of planners and government officials in Western Pacific Island countries were TC Pam (March 2015) and TC Winston (February 2016). TC Winston was the strongest cyclone ever recorded in the southern hemisphere with winds reaching 278–352 km/hour [53]. TC Pam affected all islands in Vanuatu, its economic impact exceeding 60% of national Gross Domestic Product (GDP), while TC Winston was at its most destructive in Fiji where damage amounted to 20% of GDP [54].

Historical data on Western Pacific tropical-cyclone development and impact (Fig 2B) show that west of the 180° meridian, the most intensely affected subregions lie 5–25°N, a region including the main parts of FSM, Marshall Islands and Palau, and 5–18°S, which covers the main parts of Fiji, Solomon Islands and Vanuatu [55]. Assuming that the geography of these subregions remains little changed in the future, then it can be seen that the cyclone-exposed parts of these island countries are likely to experience a higher level of cyclone intensity and damage in the future.

Other climate-linked livelihood stressors in the Western Pacific

There are several other climate-linked livelihood stressors applicable to an understanding of Western Pacific island futures but, while these are not trivial, they do not contribute significantly to the uneven geographical distribution of these stressors, so are mentioned only briefly in this section.

Perhaps the most widespread is the temperature rise which drives sea-level rise and is implicated in the changes observable in tropical-cyclone frequency and intensity in this region. Warming is also forcing changes to fisheries, vegetation and agriculture, shown by the low thermal tolerance of key staple crops but also in terms of agricultural practice, there having been numerous anecdotal examples of farmers from across the Western Pacific islands unable to work in the hottest parts of the day as they once did [56–59]. Effects of sustained weather changes have also affected the health and wellbeing of Pacific peoples [60,61].

For Pacific peoples living along island coasts, one of the most impactful effects of long-term warming has been coral bleaching which in many places has devastated nearshore sources of marine food on which coastal subsistence-oriented communities depend. Incidences of coral bleaching during marine heatwaves in the tropical Western Pacific have been increasing in frequency since the 1970s and it is projected that bleaching will become an annual occurrence by around the year 2050, largely depriving Pacific peoples of this critical food-production system [62,63]. Marine food supply is expected to be further reduced over the next few decades by the effects of increasing ocean acidification, attributable to increased oceanic uptake of CO_2 emissions [64], and to ocean-water deoxygenation, likely to be a direct consequence of anthropogenic forcing [65,66].

The nature of the 'perfect storm'

A 'perfect storm' is brewing in the island nations of the Western Pacific arising from their varying geographical exposure to climate-driven and other potential livelihood disruptors as well as their varying population distributions both within and between countries (see previous section). Within the Western Pacific region (illustrated in Fig 1A), the largest-sized and most populous island nations are those in the southwest Pacific, namely Fiji, Solomon Islands and Vanuatu; we recognize that New Caledonia could be included on this list but exclude it from further discussion here on the grounds that its status as a French Territory make it exceptional. With the inclusion of FSM in the northwest Pacific, these three countries are also those where the sea level is currently (and has recently been) rising fastest. These countries are also those most affected by tropical cyclones, which have been increasing in average intensity over the past decade or so.

Projections suggest that the drivers of this uneven vulnerability will continue into the future. Populations in the year 2050 will also be far higher than those in other Western Pacific countries (see growth rates in Table 1). The currently above-average rates of sea-level rise in Fiji, Solomon Islands and Vanuatu are expected to remain higher than the rest of this region, the disparity likely becoming amplified by the projected acceleration in the rate of global mean sea-level rise throughout the 21st century [67]. The disproportionately-high impacts of increased-strength tropical cyclones in these three countries are also expected to continue, as is also the case in the northwest Pacific [68,69].

More so than any other island nations in the Western Pacific, human systems in Solomon Islands and Vanuatu are also periodically and often quite profoundly affected by non-climate stressors, especially earthquakes, tsunamis and volcanic eruptions associated with these islands' locations along the actively-converging boundary between the large Australian and Pacific lithospheric plates [70]. This represents an additional factor contributing to the disproportional exposure of livelihood disruption of people living in this part of the Western Pacific, as exemplified by studies of the impacts of the 2017/2018 eruptions of the Manaro Volcano on Ambae Island in Vanuatu that involved evacuation of residents to places where they had to compete with others to secure their subsistence livelihoods [71,72]. More generally in Pacific Island countries, volcanic and seismic phenomena, especially tsunamis, have caused "destruction and damage of infrastructure including water supply systems and temporary salinisation of groundwater resources" [73: 2]; the critical nature of wave overwash on atoll islands, as is commonly associated with tsunamis, can have severe consequences for their residents [74].

Current exposure for eight risk factors is summarized in Fig 3 for the ten countries of the Western Pacific region; details of data and analyses in S1 Data.

Population densities are a common measure of exposure to livelihood stressors like climate change but in Fig 3A are better interpreted as the degree to which Western Pacific island nations can accommodate climate change without

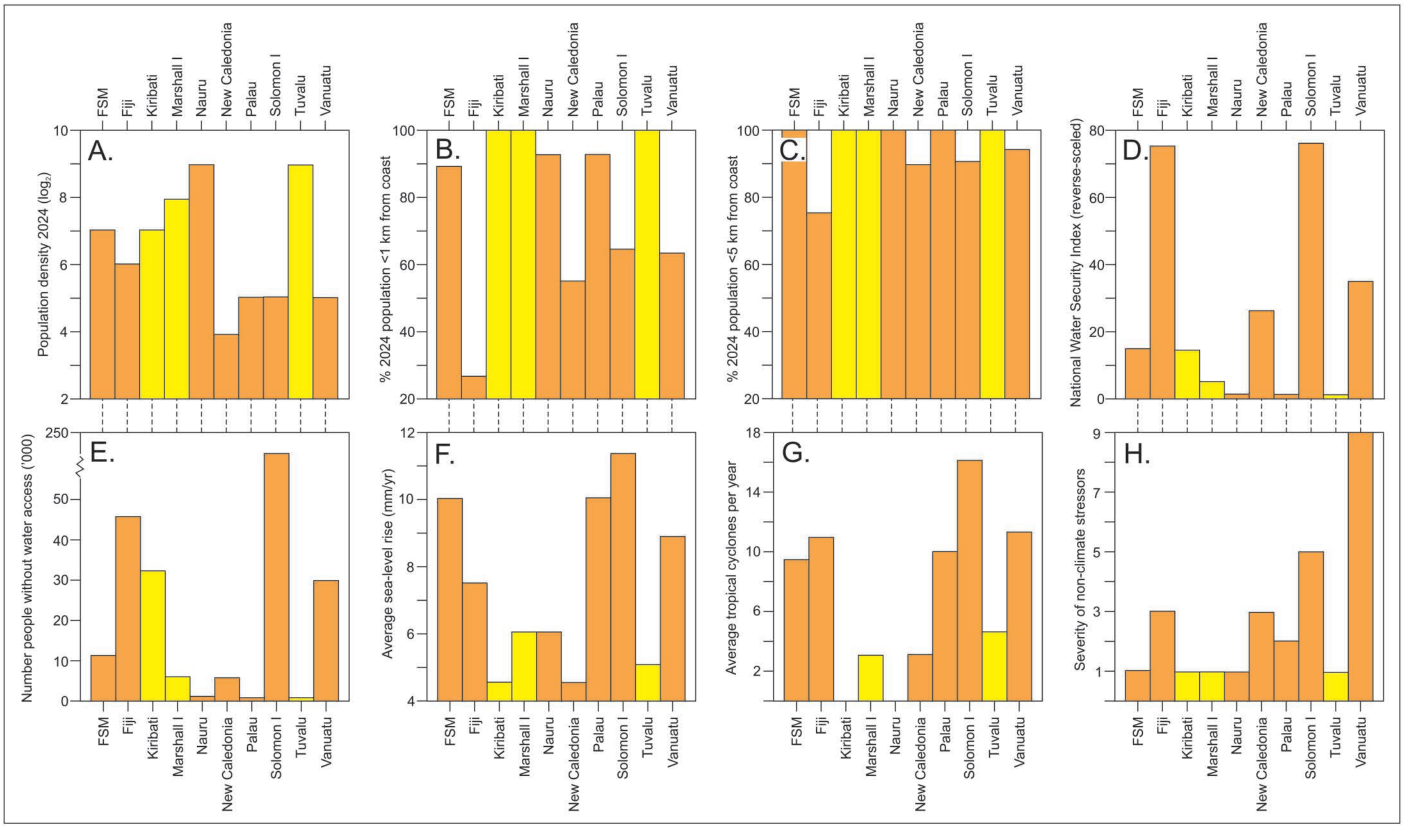

Fig 3. Comparison of the current vulnerability of the ten island countries of the Western Pacific using eight criteria (data and analyses in S1 Data). A: Population density 2024; B: % population living <1km from the coast in 2024; C: % population living <5km from the coast in 2024; D: National Water Security Indices (reverse-scaled); E: Number of people in 2022 without access to at least basic water (Solomon Islands data from 2015); F: average rates of sea-level rise 1993-2009; G: Average number of tropical cyclones forming per year 1991-2014; H: Severity of non-climate stressors. Atoll nations lighter shaded.

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needing to consider off-island or international migration. The graph shows that atoll nations (Kiribati, Marshall Islands, Tuvalu) are most exposed together with the single-island nation of Nauru, all countries where land is in short supply and relocation to less-exposed contexts in-country is far less viable than elsewhere. These challenges have been well-researched but (without trivializing these) involve only 202,788 people, less than 8% of this region's total (see Table 1). In contrast, the low population densities of the four higher-island nations in the southwest Pacific (Fiji, New Caledonia, Solomon Islands, Vanuatu) may seem to suggest lower exposure yet they involve 2.3 million people, over 87% of this region's population (see Table 1).

These contrasts in total people exposed to climate-linked livelihood stressors are illuminated further when the numbers of people living within 1 km of the coast (Fig 3B) and within 5 km of the coast (Fig 3C) are considered. While everyone in the atoll nations lives within 1 km of the sea, percentages are much reduced in most higher island contexts although numbers of people exposed here are far greater. For example, compared to a total of slightly less than 190,000 people in the three atoll nations, over 1.13 million people live within 1 km of the coast in the higher-island nations. Even though there is more accommodation space for communities on higher islands to relocate inland from coasts, the reality is that the concentration of infrastructure and services along the coasts (and the comparative lack inland) makes such localized relocation unattractive. Reliable and high-quality water sources are typically located on the coastal fringes in these higher islands in both surface and groundwater systems. Groundwater access is expensive and is often limited to coastal fringes which can be polluted by rising seawater incursion and/or bacterial contaminants from local sewage systems in the higher island settings. The exception in this regard is Fiji which, while having the same concentration of coastal development, has infrastructure in many inland contexts, typically along broad valleys (like those of the Sigatoka, Nadi and Labasa rivers), which helps explain why 24% of its population, the highest proportion of all Western Pacific nations, lives >5km from the sea (see Table 1).

The higher the reverse-scaled NWSI (Fig 3D), the greater the water-linked exposure of people in different island nations of the Western Pacific (see S1 Data). This form of exposure (water insecurity) is highest on average in Fiji and Solomon Islands, followed by Vanuatu and New Caledonia, the most populous island countries in this region. The NWSI is principally a measure of water security in both rural and urban areas, including the growing informal settlements along the fringes of the latter. It is also a measure of the comparative exposure of these countries to water insecurity following disaster, both climate and non-climate related; as this NWSI is reverse-scaled, the higher its value, the greater the national water insecurity.

The total numbers of people in each of the ten Western Pacific Island nations who lack access to 'at least basic' drinking water are shown in Fig 3E. Notwithstanding the fact that 2022 data for Solomon Islands (2015 data used instead) are unavailable, the disparity between higher and lower island nations is clear. The three independent island nations in the southwest Pacific where most people live on high islands (Fiji, Solomon Islands, Vanuatu) have far larger numbers of people without basic access to drinking water.

The levels of exposure of people living close to the coast in these Western Pacific Island nations can be focused further by considering average rates of sea-level rise that affect the higher-island nations considerably more than the atoll-island nations (Fig 3F). In Solomon Islands and Vanuatu, which are affected by the fastest rates of sea-level rise, more than 700,000 people live within 1 km of the coast. Given the unmistakable impacts that this sea-level rise has had on coasts in these island groups recently, it is clear that this number of people will need to adapt far sooner than those elsewhere in this region and that their numbers considerably outweigh those similarly exposed in the northwest of the region; some 120,000 people live within 1 km of the coast in FSM and Palau where sea-level rise rates are also unusually rapid.

Exposure in the higher-island countries of the Western Pacific (FSM, Fiji, Palau, Solomon Islands, Vanuatu) is amplified even further by their disproportionately high exposure to tropical cyclones (Fig 3G), which cause flooding and landsliding and have been increasing in strength over the past decade or so. These countries are those with the highest exposure to tropical cyclones, typically several times higher than the degree of cyclone exposure in atoll countries.

Non-climate stressors, measured as explained in S1 Data, are shown in Fig 3H and affect the four high-island countries of the southwest Pacific considerably more than the rest, amplifying still further the exposure of these countries.

These eight sources of livelihood stress are plotted in a single exposure index which is compared in Fig 4A with the *per capita* amount of external funding for climate change that each country received 2008–2021 (S2 Data). There is a significant disconnect between the exposure and the assistance, atoll-island nations receiving in general far greater *per capita* aid than higher-island countries in the Western Pacific. Acknowledging that climate aid is often given for reasons other than the degree of exposure/need, there is still a significant shortfall in help for those countries that need it most, according to this analysis (S2 Data).

A similar pattern emerges in Fig 4B that refers specifically to water. Of the ten countries in the Western Pacific, the three with the greatest water-focused livelihood exposure are Fiji, Solomon Islands and Vanuatu where the calculated indices are respectively 3.3, 4.1 and 1.9 above average (mean = 5, see Table B in S2 Data).

We suggest that the situation shown in Fig 4 represents a 'perfect storm' brewing in the high-island countries of the southwest Pacific, arising from the disproportionately high exposure of their people and their livelihoods to imminent future disruption. This situation has implications for the sustainable future of the Western Pacific region. Specifically, this study shows that the largest numbers of people most exposed to livelihood insecurity in this region are those who have been among the least funded by outside agencies. If this situation remains unchanged, especially as climate-change impacts

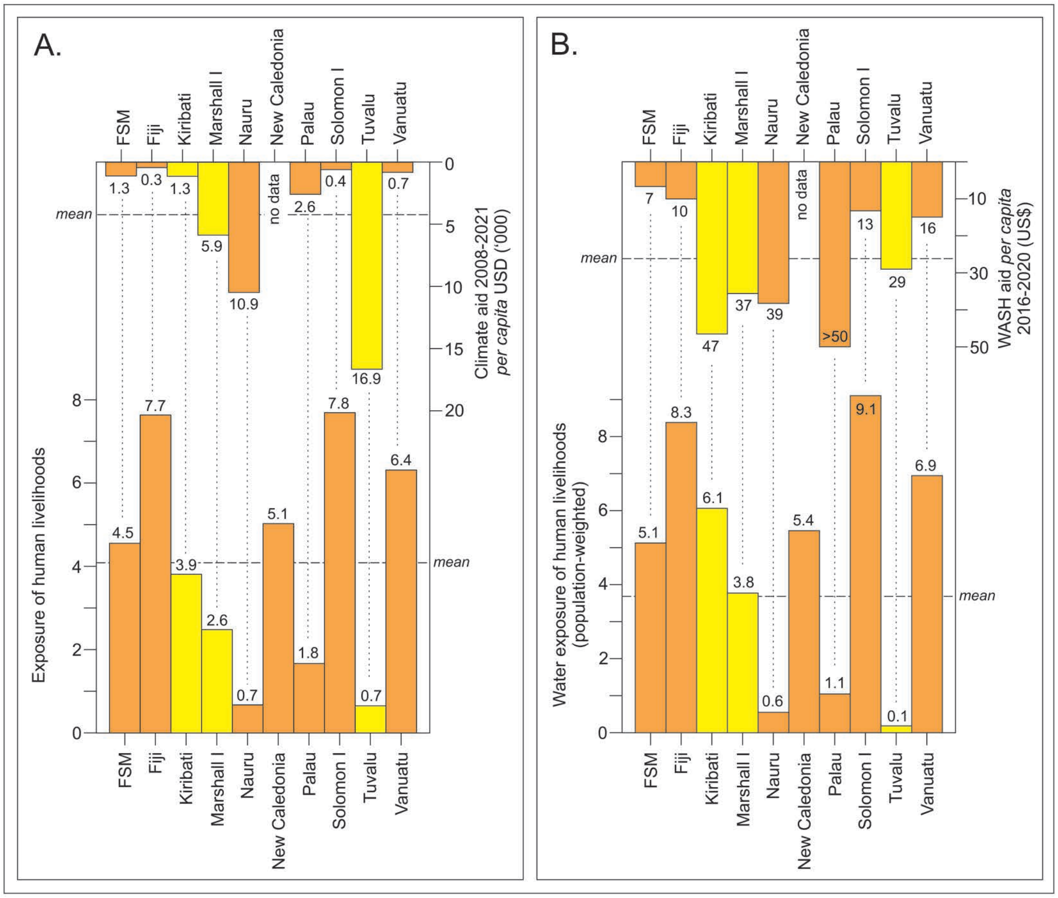

Fig 4. A: Exposure values of each ten Western Pacific countries compared to per capita climate aid. B: Water-linked exposure of these ten countries compared to per capita WASH aid. Conspicuous misfits between exposure (need) and aid appear in both graphs. Details of data and analyses in S2 Data.

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ratchet up over the next two decades or so, it will create a crisis – the ‘perfect storm’ – for residents of those countries as well as the rest of the Western Pacific region and neighboring countries. For unsustainable levels of livelihood insecurity in some parts of the region will have ‘knock-on’ effects within the rest of it, as well as spill-over effects beyond its borders. These effects may involve increased human mobility, both within and between countries, as well as increased conflict that impacts state security [75,76].

Coping with the ‘perfect storm’

The projected impacts of the ‘perfect storm’ that has been building in the high islands of the southwest Pacific can still be reduced with adaptation involving effective planning and, as several commentators have argued, with a shift in the donor-recipient and dependency-autonomy dynamics in this region and elsewhere [3,6,77]. While the precise nature of coping with the ‘perfect storm’ is beyond the scope of this study, this section highlights three issues that are considered fundamental to addressing it across the Western Pacific region. The first of these is the nature of both need and assistance – who is most exposed and how are they best aided. The second is the foundational issue of water – where and how should unfolding deficiencies in availability be best addressed. The third is the often controversial issue of relocation – should people move or stay. These are discussed separately in the following three subsections.

Need and assistance

Over the past decade and more, external funding for helping island nations in the Western Pacific grapple with the challenges of climate change has been disproportionately applied, countries that are generally less exposed receiving more *per capita* aid than those with the highest levels of exposure (see Fig 4A). We suggest that those countries which have become the traditional foci of climate aid are generally perceived by outsiders as being more 'vulnerable', principally because of their low-lying nature, while higher-island countries that appear to have plentiful 'unoccupied' land are generally perceived as less vulnerable for this reason. In addition, threats to the sovereignty of lower-island (atoll) nations and an associated cessation of livelihood possibilities are not shared by higher-island nations and may have influenced assessments of comparative vulnerability [78,79].

While we acknowledge that there are clear disparities in the geography and landforms of islands in the Western Pacific, as is measurable [13], these disparities are often amplified in the minds of outsiders who do not readily perceive the nature and resilience of island people's livelihoods [7,80–82]. Evidence for this can also be deduced from accounts of these islands (and their supposedly obvious frailties) in popular media, several analyses concluding that representations of lower-lying islands as being disproportionately vulnerable are not accurate [1,3,83,84].

The comparative lack of understanding of the exposure of the livelihoods of most inhabitants of the far more populous high islands in the southwest Pacific may be a result of this sustained focus on atoll nations and the undeniably alarming possibility that some may need to be abandoned entirely by their inhabitants over the next few decades as sea-level rise submerges most habitable land [18,85]. While the same will not be true of most people living on the (mostly) higher-island countries of the Western Pacific, a majority of their current coastal residents will be forced to move from low-lying coastal locations to higher ground over the next few decades, a move that for many will be equally as transformative and likely as traumatizing as for atoll dwellers forced to abandon entire islands that have been rendered uninhabitable.

The numbers of people involved show the contrasting scale of the associated challenges. As discussed above, a total of 626,351 people in the high-island nations of Fiji, New Caledonia, Solomon Islands and Vanuatu live within 1 km of the coast and are likely to be forced to relocate within the next 10–30 years if sea level rises as projected [4]. This total is more than three times the combined population of the three atoll nations of Kiribati, Marshall Islands and Tuvalu which may also need to relocate within the same time frame or perhaps longer given the slower rates of sea-level rise in this part of the region (see Fig 2A).

It seems clear from the analysis above that these relationships between *per capita* exposure and place are not clear to many of those who decide priorities for climate assistance in the Western Pacific. The more immediate challenge by far lies in the higher-island nations of Fiji, Solomon Islands and Vanuatu where populations and sea levels are currently rising fastest, creating a crisis that might have been better managed by directing greater proportions of regional climate assistance towards these island countries. Of course, ethical aid management is premised on the idea that the needs of everyone, irrespective of where they live, are important. But in an environment where climate aid is limited and often delivered regionally (not nationally), future conversations about the distribution of assistance might usefully incorporate exposure measures such as those calculated for this study.

A final important consideration in this part of the discussion is around the likely levels of future climate assistance to countries of the Western Pacific (excluding the French territory of New Caledonia). At least one study has argued that, as the costs of domestic climate-change adaptation accelerate in donor countries, they will become less able to continue funding Pacific Island countries at the level to which many have become accustomed [86]. In fact, it seems abundantly clear that most island countries in the Pacific region have become dependent (and are becoming increasingly dependent) on external funding to adapt to the various challenges posed by climate change and non-climate change [87]. While inextricably linked to geopolitics in this region, the fact of (growing) dependency of Pacific Island Countries is likely to increase their future exposure to climate change, particularly as its impacts increase and external funding decreases. It would be in the better long-term interests of Pacific Island countries if trends of growing dependency were to be replaced by trends of growing autonomy, which would position island governments to cope far better with the effects of climate change over the next few decades [88–90].

Water

As in many ('small') island situations, the issue of water security is key to livelihood sustainability in the island nations of the Western Pacific, especially in their rural parts where there is no connection to reticulated supply systems [91–93]. Two distinct measures of water security in the Western Pacific were shown in Fig 3D and 3E and illustrate the magnitude of the existing challenge for this region. For example, 319,000 people in the high-island countries of the southwest Pacific (Fiji, New Caledonia, Solomon Islands, Vanuatu) lack access to 'at least basic' supplies of drinking water compared to 39,113 people in the atoll nations of Kiribati, Marshall Islands and Tuvalu (see Table 1).

As is the case for climate assistance more generally (see previous section), these geographical differences in water need are mismatched with external assistance provided for improving water access, as shown in Fig 4B. High levels of *per capita* aid for water are being provided to many countries where water security is relatively high. Conversely, those countries that exhibit relatively low levels of water security have generally received comparatively low levels of *per capita* aid for water. For instance, the generally water-insecure high-island countries of the southwest Pacific (Fiji, Solomon Islands, Vanuatu) received *per capita* WASH (Water, Sanitation and Health) aid funding averaging $12 below the average for the Western Pacific while three less-exposed countries (Marshall Islands, Nauru, Tuvalu) received *per capita* WASH funding $10 above average for the region in the period 2016–2020.

Access to enough water for the diverse needs of rural communities in the Western Pacific is key to their sustainability. The limitations of water availability in such contexts are vividly illustrated by examples from pre-globalization histories. For example, on comparatively remote Tikopia Island in the eastern outer Solomon Islands, people in the past might undertake *forau* or 'suicide voyages' when water was insufficient for the island's population, particularly as a result of drought [94]. Elsewhere in the tropical Pacific, water shortages are implicated in the abandonment of entire islands, plausibly during prolonged periods of decreased rainfall [95–97].

The future availability of water on islands in the Western Pacific is uncertain, most climate model-based projections being either contradictory or marked by low likelihood, especially in island groups affected by the South Pacific Convergence Zone (SPCZ) like those in the southwest part of the study region [98,99]. The future impacts of climate-driven changes on rural island dwellers in the Western Pacific will see many displaced by sea-level rise from the near-coastal places in which they currently live. For example in the high-island countries of the southwest Pacific (Fiji, New Caledonia, Solomon Islands, Vanuatu), 48.5% of the 2.3 million people live within 1 km of the sea and most are likely to be forced to relocate locally within the next 10–30 years as sea-level rise, at an average rate of 8 mm/year at present in these four countries (see S1 Data), reduces the amount of coastal land and impacts its habitability, especially through groundwater salinization and flooding of growing magnitude (depth and extent) and frequency.

Relocation

Over the next decade or so, it is expected that hundreds of coastal communities in the Pacific Islands will be forced to relocate, moving from places that have become increasingly exposed to seawater inundation to places where the risk of this is significantly diminished. On higher islands where island interiors are comparatively sparsely populated, this relocation is likely to be localized, communities moving from coastal lowlands to upland/inland sites that may be comparatively distant from the coast. On lower islands, where there is no/little high ground, it is likely that entire islands will be abandoned, their inhabitants resettled elsewhere to places where life in a climate-changed world is more sustainable [100–102].

The analysis in this paper shows that the first major group of involuntary coast-to-inland relocations in the Western Pacific are likely to occur on islands where near-coastal population densities are largest and where sea level is rising fastest. As discussed above, these will be the island countries of Fiji, New Caledonia, Solomon Islands and Vanuatu where more than one million people currently live within 1 km of the coast and where, if no-one moved, more than two million would live <1 km from the sea in 2050 (see Table 1). Sea level is currently rising fastest in this region, as much as an average 11.5 mm/year in parts of Solomon Islands and, as detailed in S1 Data, tropical cyclones and non-climate livelihood stressors also disproportionately impact this part of the Western Pacific region.

While acknowledging that upslope/inland settlement relocation is commonly an unpopular adaptation option for coastal communities, especially because of issues around land ownership, it is expected to become their most common adaptive response on higher islands in the Western Pacific seeking to relocate in the future. Part of the evidence comes from observations on many islands of partial or incremental relocations in which typically a few houses have been moved/rebuilt on higher ground at the back of the coastal flats [103–105].

We use the term 'Locally Relocated Coastal Communities' (LRCCs) to refer to communities that have or will relocate locally on the same island from a coastal to a (nearby) inland/upslope location. And since it seems clear that these LRCCs will become far more numerous over the next 10–30 years in the high islands of the Western Pacific, it is worth briefly reviewing two key issues around LRCC sustainability.

First is community autonomy, the self-belief of a community that they can make decisions about relocation for themselves and can drive the process of relocation without outside help. The alternative, which can be found in many situations, is that communities await top-down (government) direction and the (cash) funding that is considered necessary to relocate. The experience of some researchers on islands in the Western Pacific is that communities which exhibit high degrees of autonomy, commonly on island or archipelagic peripheries, are those that more successfully anticipate and respond to climate-linked livelihood challenges than those which are less autonomous [48,88,106]. The lesson for the future is that, as the 'perfect storm' unfolds over the next decade or so, governments and their donor partners are going to find it increasingly difficult to answer the demands of every community needing to relocate locally. Those communities with greater autonomous coping capacity are likely to fare better than those that lack this, especially if the level of donor support for Pacific Island countries declines, as seems probable over the next decade or so [86].

Second is the choice of site for local relocation, something that for most informal or partial relocations has been largely *ad hoc*, based on relocatee preferences, relationships and land rights [107,108]. Yet such processes will not always lead to sustainable LRCCs because, once more people move, the initial site may prove unsatisfactory [109]. The most widespread reason for this, we suggest, will be the inadequacy of water supply, so future research should focus on identifying generic pathways for community relocations that centre on water and wastewater management. This suggestion does not trivialize other issues, including the key issue for subsistence-oriented rural LRCCs about how their inhabitants will access sufficient food to satisfy both basic needs and nutritional aspirations. In this way, many LRCCs could learn valuable lessons from the experience of similarly-constituted settlements that relocated perhaps decades earlier, especially their successes and failures for sustaining subsistence-oriented livelihoods in what were once unfamiliar (inland) environments [110,111].

Conclusions

This study shows that there are mismatches between external assistance provided for water/WASH and climate-change adaptation in the countries of the Western Pacific region. This mismatch extends to their exposure to climate risk. This suggests a misapprehension on the part of global aid planners and donor agencies about where in the Western Pacific the need for assistance is greatest. More than that, this study suggests that 'a perfect storm' of circumstance is brewing in the high-island countries of the southwest Pacific (especially Fiji, Solomon Islands and Vanuatu) that will culminate in an unprecedented crisis, focused on water-centered livelihood sustainability, over the next decade or so. This situation requires to be addressed urgently although we note that it has also instigated successful autonomous adaptations in some situations [105,112].

Water security is regarded as critical to the successful weathering of this perfect storm, focused on relocation of exposed coastal communities to places where their water needs can be adequately met. There is a pressing need for evidence-based research to develop pathways that enable exposed communities to relocate to places where there is enough water to sustain community needs and accommodate community aspirations. The alternative is that the viability of rural livelihoods will become increasingly strained, leading to increased mobility and associated security issues.

A global lesson from this study is that, as the effects of climate change become increasingly visible and impactful, the importance of aligning available support with need becomes ever more critical. While it might be extreme to argue that climate assistance in the Pacific Islands region, as in other parts of the Global South, has been misdirected, evidence-based decision-making might have led to more equitable outcomes – and perhaps even prevented a 'perfect storm' from developing.

Supporting information

S1 Data. Data for the calculation of Fig 3.
(DOCX)

S2 Data. Data for the calculation of indices and aid.
(DOCX)

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