PLOS CLIMATE

RESEARCH ARTICLE

Climate variability and water-related infectious diseases in Pacific Island Countries and Territories, a systematic review

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Citation: Hosking R, Smurthwaite K, Hales S, Richardson A, Batikawai S, Lal A (2023) Climate variability and water-related infectious diseases in Pacific Island Countries and Territories, a systematic review. PLOS Clim 2(10): e0000296. https://doi.org/10.1371/journal.pclm.0000296

Editor: Asif Qureshi, Indian Institute of Technology Hyderabad, INDIA

Received: May 4, 2023

Accepted: September 12, 2023

Published: October 18, 2023

Data Availability Statement: All data supporting the findings of this study are available within the article and its supplementary materials.

Funding: The authors received no specific funding for this work.

Competing interests: The authors have declared that no competing interests exist.

Abstract

Background

Climate induced changes in water-related infectious disease (WRID) transmission are a growing public health concern. The effects of climate on disease vary regionally, as do key socioeconomic modifiers. Regional syntheses are necessary to develop public health tools like risk maps and early warning systems at this scale. There is a high burden of WRID in the Pacific Island Countries and Territories (PICTs). There has been significant work on this topic in the PICTs, however, to date, there has been no regional systematic review of climate variability and WRID.

Methods

We searched the PubMed, Web of Science and Scopus scientific databases in September 2022 using a combination of disease, climate, and country terms. We included studies that evaluated the association between climate or weather variability and a WRID in the PICTs using a quantitative epidemiological design. We assessed risk of bias using validated tools. We analysed spatiotemporal publication patterns, synthesised the outcomes of studies in relation to the international literature and identified missing evidence.

Results & discussion

We identified 45 studies of climate and malaria, dengue, diarrhoea, leptospirosis, and typhoid, which represent major WRIDs of concern in the Pacific Islands. More than half of the studies were set in Papua New Guinea or Fiji. The number of studies published each year increased exponentially over time from the 1980s to present. We found few comparable outcomes per disease and setting across epidemiological studies which limited the potential for meta-analysis. However, we identified consistent increased incidence of diarrhoea, dengue, leptospirosis, and typhoid following extreme weather events, highlighting the necessity for adequate water, sanitation, and hygiene access across the PICTs.

Additionally, there were consistent positive associations between temperature and dengue incidence in New Caledonia, highly seasonal malaria in PNG, increased diarrhoea incidence with high and low rainfall, and positive associations between leptospirosis and rainfall. These findings are biologically plausible and consistent with the international literature. Future work on this topic in the PICTs can take advantage of increasingly available health and climate data to consolidate the field across a greater diversity of settings and apply these findings to strengthening climate resilient health systems.

Registration

This review is registered with the international prospective register of systematic reviews (PROSPERO CRD42022353853), in accordance with PRISMA guidelines.

Introduction

Water-related infectious diseases (WRID) are a global cause of morbidity and mortality, with disproportionate effects in developing countries. WRID are caused by a variety of pathogens including bacteria, protozoa, and viruses. They include waterborne diseases spread by inadequate water, sanitation and hygiene (WASH) (e.g. cholera, typhoid, cryptosporidiosis), and diseases with insect vectors that require water in their lifecycle (e.g. dengue, malaria) [1].

Climate and weather conditions affect WRID pathogen survival, reproduction and spread in the environment, and human interaction with the pathogens [2, 3]. The ways that climate variability affects disease outcomes depends on their transmission mode and relation to water [4]. For example, rainfall and ambient temperature may directly impact the duration of stages of a pathogen's lifecycle, or influence an insect vector's biting rates, breeding site availability and survival [2]. Global reviews have found that rainfall is a key driver of WRID transmission, with increased incidence and outbreaks occurring after rainfall extremes (very high or low rainfall) [2, 3, 5, 6]. Dry periods can concentrate pathogens in water sources and reduce water available for sanitation and hygiene [6, 7]. Extreme water-related events like floods, droughts and hurricanes can also affect WRID incidence by increasing human-pathogen interaction, damaging WASH infrastructure or affecting vector lifecycles and pathogen survival [7].

Concerns that climate change will affect infectious disease outcomes have been growing over the past two decades [8, 9]. To plan for climate induced changes in WRID transmission it is necessary to study associations between climate variability and WRID outcomes [10–12]. Global reviews have identified consistent associations between climate variables and WRID, and in some cases used these to forecast climate-induced changes in disease transmission under climate change scenarios [1, 2, 4, 7, 10, 11, 13].

However, the effects of climate change will not be uniform across the globe and nor will the effects on WRID transmission [9, 14]. Some regions are more vulnerable to the effects of climate change on health depending on their number of climate-sensitive endemic diseases, adaptive capacity, and geographic location [9]. The effects of climate variability on WRID outcomes are also modified by socioeconomic, behavioural, and environmental factors that vary regionally such as WASH access, healthcare access, population density and immunity [13, 15]. For this reason, outbreaks resulting from climate-induced changes in transmission are likely to have disproportionate effects in developing countries and exacerbate existing health inequalities [7, 16]. To implement local and regional public health responses and adaptations, such as climate based early warning systems (EWS) and risk maps, it is important to conduct regional assessments. There have been regional reviews and analyses of climate variability and WRID in Africa [17], Asia [18, 19], Europe [20, 21], the Arctic [22], and North America [23–25].

Climate-induced changes in infectious disease transmission are a priority health risk in the Pacific Island Countries and Territories (PICTs) [26, 27]. The PICTs are vulnerable to climate challenges due to their geography (small land size, isolation from larger economies), exposure to extreme weather, high natural disaster risk and resource constraints [27, 28]. Resource constraints include small populations, limited technical resources, and incomplete access to WASH facilities and supply. There is a high burden of WRID in the PICTs, especially in the under 5 and over 70 age groups [29, 30]. Ongoing efforts by governments and international organisations in the Pacific are directed towards strengthened public health surveillance, early warning system (EWS) development, WASH infrastructure improvement, promoting community engagement and developing climate resilient health systems [31]. Vulnerability assessments of climate change and infectious diseases have been conducted in some PICTs [32–34]. Kim et al. (2022) conducted a scoping review of climate and health research in the Pacific Islands [35]. However, to date, there has been no comprehensive systematic review of climate variability and WRID in the PICTs [31]. In light of this, the aims of this review are to synthesise the available literature on the effects of climate and weather variability on WRID in the PICTs to identify consistent patterns in the data and highlight gaps in current research. These outcomes are pertinent for climate and health adaptation policy stakeholders in the PICTs who are planning regional health and climate adaptation efforts.

Objectives

The objectives of this review are to (1) systematically search for and identify published literature, (2) synthesise and assess the quality of evidence and (3) identify gaps in the existing evidence base.

Methods

This systematic review was designed in accordance with the preferred reporting items for systematic reviews and meta-analysis (PRISMA) guidelines [36].

Search strategy

One author (RH) searched the databases Web of Science, Scopus, and PubMed in September 2022. Search terms included PICT names, climate and weather terms, and WRID terms described in Table 1. There were no restrictions by publication year or language. We also performed a targeted search of the World Health Organisation (WHO) and United Nations International Children's Fund (UNICEF) websites to identify grey literature. Forwards and backwards citation searching of included articles was undertaken using the citationchaser tool to identify additional literature [37].

Eligibility criteria

Articles were included in the review if they (i) were set in a PICT (member of the Pacific Community (SPC)) [40], (ii) evaluated the association between a climate or weather variable and a human WRID outcome, and (iii) had a quantitative epidemiological design. We examined WRID that were included in Nichols et al. (2018)'s review of climate change and WRID [1].

Table 1. Database search strategy.

Databases	Web of Science, SCOPUS, PubMed	
Websites	WHO [38], UNICEF [39].	
Publication date	Up to September 2022	
Language restrictions	None	
Search to	Topic or Title & abstract	
Population (setting)	From SPC list of 22 PICTs	(Pacific Island* OR PICT* OR PICs OR 'American Samoa' OR 'Cook Islands' OR 'Federated States of Micronesia' OR Fiji OR 'French Polynesia' OR Guam OR Kiribati OR 'Marshall Islands' OR Nauru OR 'New Caledonia' OR Niue OR 'Northern Mariana Islands' OR Palau OR 'Papua New Guinea' OR 'Pitcairn Islands' OR Samoa OR 'Solomon Islands' OR Tokelau OR Tonga OR Tuvalu OR Vanuatu OR 'Wallis and Futuna')
Exposure (climate variables)	Climate and weather factors	(Climat* OR weather OR meteorol* OR season* OR temperature OR rain* OR precipitation OR humidity OR cyclone OR hurricane OR flood* OR drought OR 'El Nino' OR 'La Nina' OR ENSO OR heatwave)
Outcome (water-related infectious disease)	Based on Nicholls et al. classification of water-related infectious diseases [1].	(waterborne OR 'water-related' OR water OR 'infectious disease' OR notif* OR cholera OR dengue OR diarrh* OR hepatitis OR leptospir* OR malaria OR mosquito OR scabies OR trachoma OR typh* OR gastroenteritis OR campylobacter* OR 'eschericia coli' OR giardia* OR salmonell* OR shigell* OR norovirus OR rotavirus OR cryptosporidi*)

https://doi.org/10.1371/journal.pclm.0000296.t001

This includes waterborne infections, water-washed, water-based, and water-related insect vectors.

Articles were excluded if they (i) were not set in the PICTs, (ii) had no human-health outcomes (e.g. were entomological studies), (iii) were not focused on a WRID, (iv) had no climate or weather factors (v), studied damp-related, or waterborne chemicals/toxins, (vi) were not quantitative epidemiological studies including systematic reviews, conference or workshop proceedings, case reports, qualitative studies, descriptive studies or (vii) were mechanistic modelling studies. Full inclusion and exclusion criteria can be found in Table 2.

Selection process

One author (RH) conducted the database, grey literature and citation searches and removed duplicates. Two authors (RH, KS) independently screened record titles and abstracts. Both authors then independently undertook a full-text review of eligible articles. Reasons for

Table 2. Inclusion and exclusion criteria.

Inclusion criteria	Evaluate association between climate or weather variable and human water-related infectious diseases
	Set in a PICT, only 22 SPC members included
	Using an empirical quantitative epidemiological study design
	Published up to September 2022
Exclusion criteria	Non-Pacific Island setting: not Australia, New Zealand, or Hawaii
	Non-human health outcomes: animal diseases only, entomological studies or water quality testing
	Not a water-related disease pathogen: Not listed in Nichols et al. classification of water-related infectious diseases [1]. Non-infectious water-related diseases: toxins, and damp-related diseases not included
	No climate or weather factors included
	Alternate design: systematic review, conference/workshop proceedings, case reports, qualitative, descriptive, mechanistic modelling study
Search strategy limited to:	Date: Up to September 2022
	No language restrictions unless translation unavailable

https://doi.org/10.1371/journal.pclm.0000296.t002 exclusion were recorded. Conflicts were resolved by discussion with a third reviewer (AL). The titles and abstracts of the additional articles were screened for relevance and excluded using the same criteria.

Data extraction process

One author (RH) extracted data using an extraction table [41]: including bibliographic information (author, publication year, title, journal), design, setting, population/sample size, disease, study unit (outbreak or cases), outcome and data source, climate exposure variables and data source, temporal (coverage, lags, threshold, resolution), spatial resolution, analytical approach, and key findings related to climate exposures (S1 Table). Outcomes were considered for meta-analysis if (i) there were multiple comparable studies per disease (ii) with similar designs, populations and (iii) the ability to convert to a common effect measure.

Risk of Bias (ROB) and quality assessment

One author (RH) conducted a ROB assessment using validated tools. Time series analyses (TSA) were assessed using a tool developed by Chua et al. (2022) [42]. The tool includes domains: exposure assessment, outcome assessment, confounding bias, selection bias, selective reporting, and other bias. Options are 'low', 'probably low', 'probably high' and 'high' ROB for each domain. An additional table file shows the tool in more detail (S2 Table). TSA are assigned a 'low' overall ROB if none of the domains were assigned probably high or high risk, 'medium' if one or two domains were, and 'high' if three or more domains with probably high or high risk.

Other study designs were assessed using the Johanna-Briggs Institute Critical appraisal checklist for analytical cross-sectional studies [43]. This tool assesses sample inclusion criteria, subject description, exposure measurement, outcome criteria and measurement, confounding and analytical approach through yes or no questions. Studies are assigned an overall 'low' risk if 'no' was not answered for any domain, a 'medium' risk if no was answered for one or two domains and a 'high' risk if three or more domains were 'no'.

Results & discussion

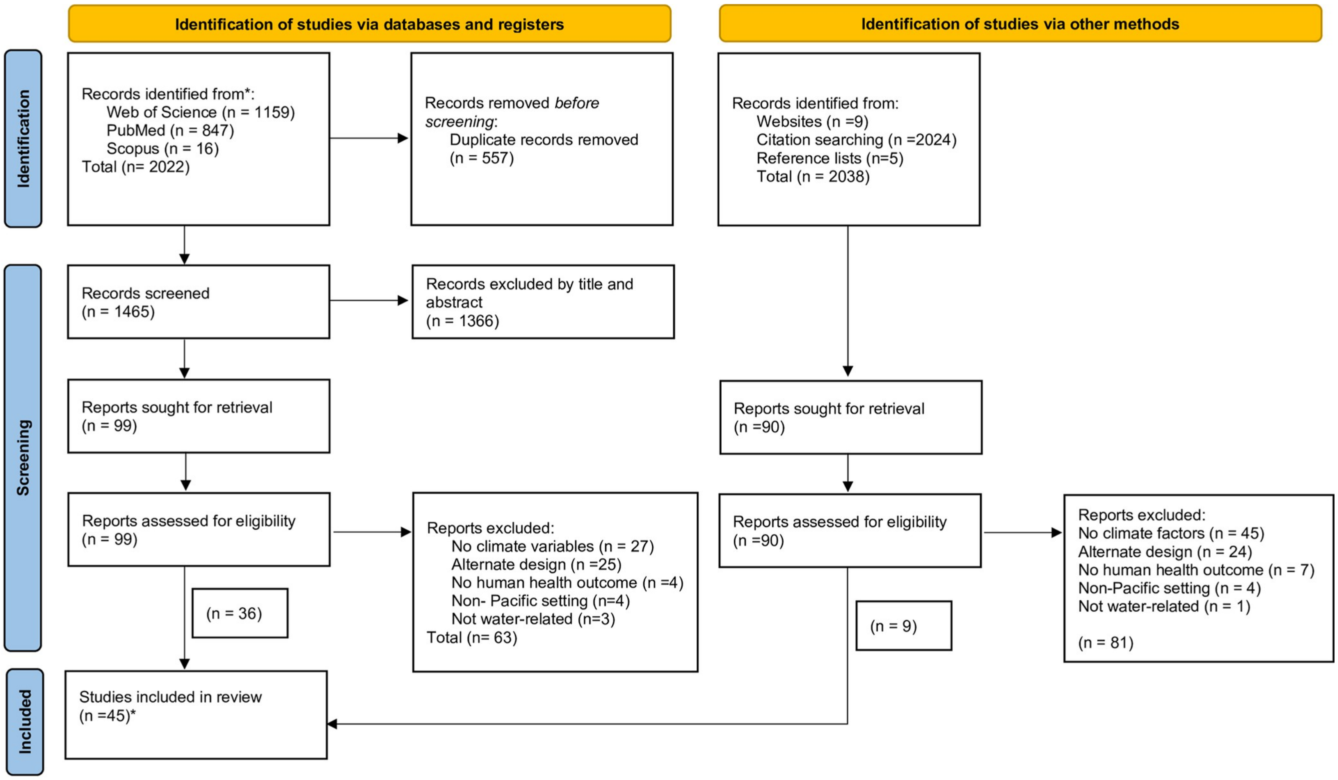
Study selection

The initial database searches yielded 2022 records, 1465 remained after duplicate removal. We excluded 1366 records in title and abstract screening, the remaining 99 records were sought for retrieval. Then, 99 full texts were assessed for eligibility, 36 met the inclusion criteria and were included in the review. An additional 2029 records were identified through forwards and backwards citation searches and nine through grey literature search. Nine full-texts were included after screening, for a total of 45 studies included in the review (Fig 1).

We excluded studies that described patterns in data but did not quantify the association between climatic factors and infectious disease outcomes [33, 44, 45], or were mechanistic modelling studies [46–48].

Study designs and spatiotemporal trends

The 45 studies of climate and WRID set in the PICTs comprise a small fraction of the global literature on this topic [49]. They are studies of malaria, dengue, diarrhoea, leptospirosis, and typhoid, which represent some of the major climate sensitive WRID of concern in the Pacific Islands [29, 50]. We did not identify studies of chikungunya, cholera, hepatitis A, or Zika despite their potential sensitivity to climate and status as public health concerns in the PICTs



*45 separate publications including a meta-analysis of 7 studies

Template From: Page MJ, McKenzie JE, Bossuyt PM, Boutron I, Hoffmann TC, Mulrow CD, et al. The PRISMA 2020 statement: an updated guideline for reporting systematic reviews. BMJ 2021;372:n71.

Fig 1. Search and screening strategy and results.

https://doi.org/10.1371/journal.pclm.0000296.g001

[51–53]. Filho et al. (2019) refer to a project, 'Climate Change and Prevalence Study of Zika Virus Diseases in Fiji', however, no related peer-reviewed articles were found [53].

Most included studies were TSA. Other designs included outbreak investigations, semi-ecological studies, spatial analyses, longitudinal cohort, and cross-sectional studies. The earliest published studies included were in 1986 [54, 55]. In the decades that followed, the number of quantitative studies of climate and WRID increased exponentially (Fig 2). This trend aligns with a global increase in climate and infectious disease research and improvement in statistical analytical methods [56, 57]. Most examined the effects of temperature and rainfall, or the impacts of extreme events like flood, drought, and cyclones on disease outcomes. Some also included measures of El Niño Southern Oscillation (ENSO), a coupled ocean-atmosphere phenomenon that drives inter-annual climate variability in the Pacific [58, 59]. The ways these variables were measured and aggregated (e.g. average, cumulative, maximum, minimum, thresholds) varied across the studies depending on modelling strategy and data availability.

More than half of the studies were set in Fiji and Papua New Guinea (PNG) (Fig 3). These countries have the highest populations and maintain more complete health and meteorological records than other PICTs [29, 60]. Researchers may also have relationships with governments, academic institutions and other organisations in these countries that allow them to obtain data. Research in PNG has been entirely on malaria. Other settings included American Samoa, Federated States of Micronesia (Micronesia), Wallis and Futuna, New Caledonia, Solomon Islands, Vanuatu, Guam, and the whole South Pacific Region. We did not identify any studies

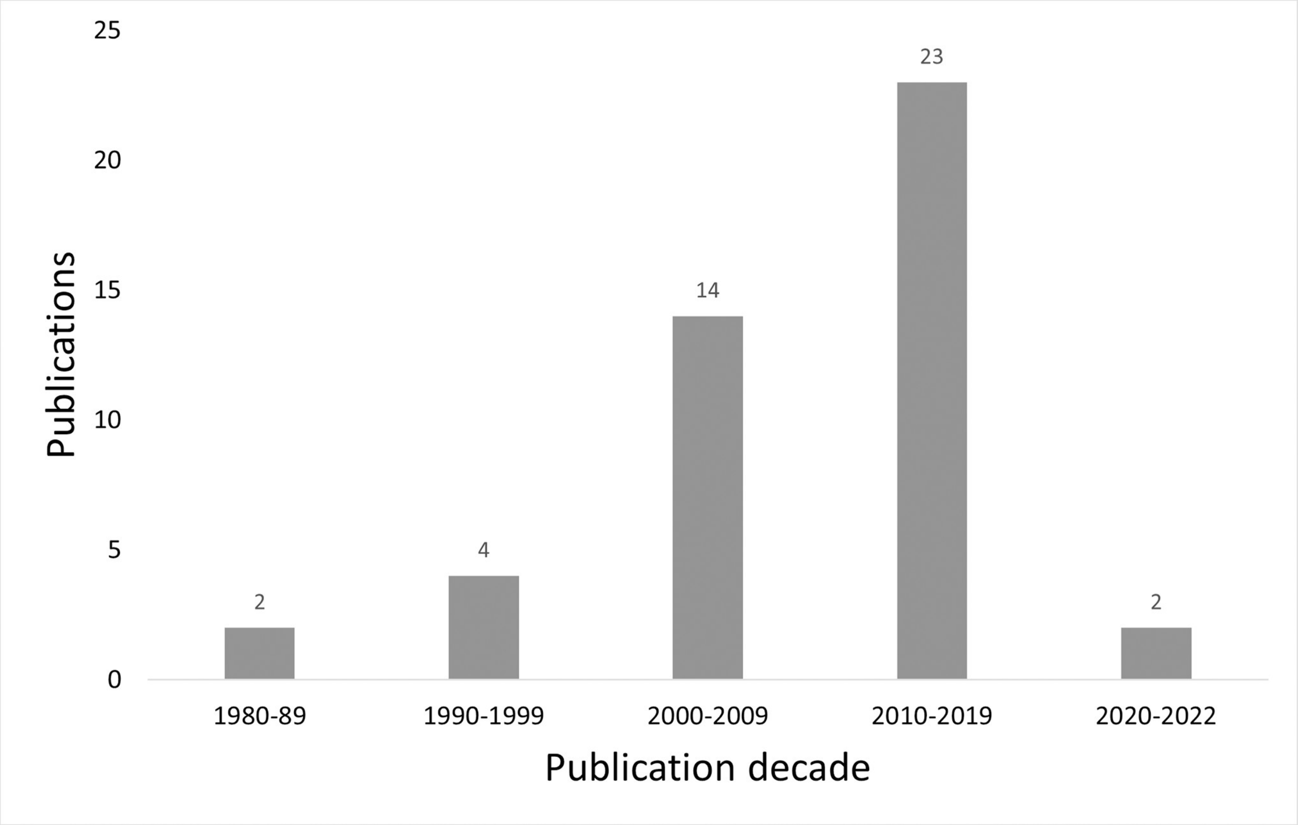


Fig 2. Number of studies of climate variability and water-related infectious diseases set in the Pacific Island Countries and Territories published by decade from 1980 to present.

https://doi.org/10.1371/journal.pclm.0000296.g002

in the Cook Islands, French Polynesia, Marshall Islands, Nauru, Niue, Northern Mariana Islands, Palau, Pitcairn Islands, Samoa, Tokelau, or Tonga.

Overview of climate variability and WRID in the PICTs

Overall, we found few comparable outcomes per disease and setting on consistent spatial or temporal scales across the epidemiological studies, which limited the potential for meaningful meta-analysis. Instead we synthesised the results by identifying consistencies and divergences in associations for each disease and climate variable and highlighting gaps in the literature.

Dengue

Dengue is an arbovirus transmitted by mosquitoes of the *Aedes* genus. Symptoms of infection range from mild fever to severe haemorrhagic fever and death. It is the most commonly reported arbovirus in the PICTs [50]. Global systematic reviews have identified temperature, rainfall, and humidity as key drivers of dengue transmission [61, 62]. We identified nine studies of dengue and climate variability in the PICTs and a tenth study of syndromes related to dengue [63].

Temperature has been shown to increases the replication rate and shorten the extrinsic incubation period of the dengue virus [64]. Three studies in New Caledonia at low risk of bias consistently found positive associations between temperature and dengue [65–67]. Descloux et al. (2012) found a significant correlation between mean annual temperature and annual

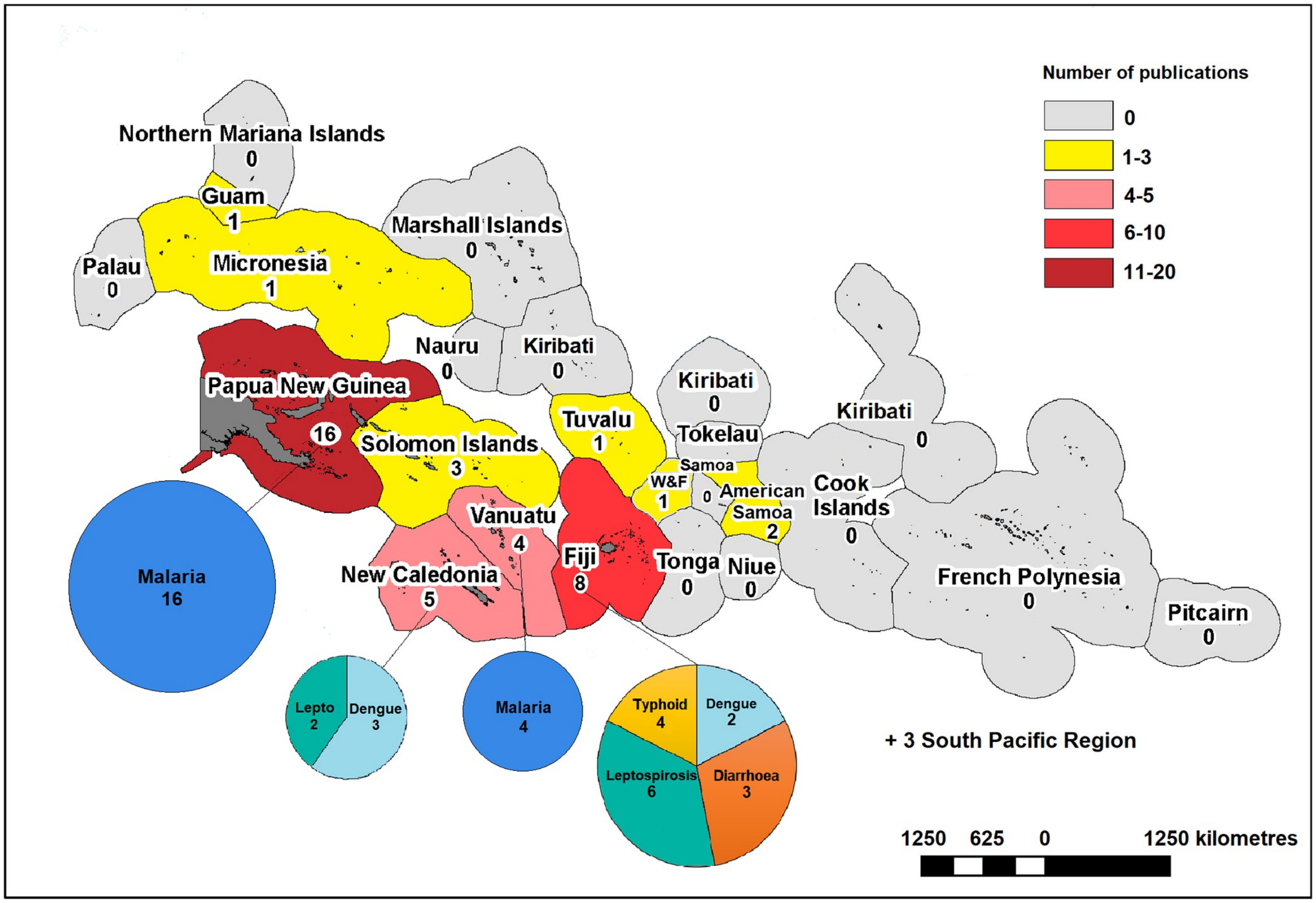


Fig 3. Distribution of studies of climate variability and water-related infectious diseases across the Pacific Island Countries and Territories. Base layer (Pacific Data Hub 2019) https://pacificdata.org/data/dataset/pacific-island-countries-and-territories-exclusive-economic-zones.

https://doi.org/10.1371/journal.pclm.0000296.g003

dengue incidence (Rho = 0.436, p = 0.007) [65]. Within years that high overall incidence (epidemic years), warm temperatures preceded weekly and monthly increases in dengue incidence and controlled the spatial distribution of dengue [65–67]. These findings align with those of a global meta-analyses of dengue incidence, which found that the risk of dengue infection increases by 7–13% per 1˚C increase in high temperatures, and as much as 20% in humid subtropical areas [68].

Findings for rainfall and dengue in the PICTs were mixed, with either no association or positive associations found (Table 3), echoing the international literature [61, 62, 69]. Unlike temperature, rainfall does not directly influence the virus, rather it affects the lifecycle of the mosquito vector by altering the availability of mosquito breeding sites [62]. The relationship is complex because increased rainfall may increase the number of available breeding sites, but human activities (such as storing water) may have a greater influence on dengue than the amount of rainfall. Rainfall does, however, affect humidity, which has been shown to affect mosquito survival and dengue incidence [61]. However, only one study examined humidity and found a positive association. Future studies of climate variability in the PICTs should consider humidity in addition to other local weather variables.

There is evidence that ENSO drives variability in inter-annual dengue incidence in the Asia-Pacific and South America [69–71]. ENSO is a strong driver of inter-annual weather

Table 3. Summary of studies of dengue and climate variability in the Pacific Island Countries and Territories, by exposure variable, setting and year of publication.

	Setting	Design	Outcome	Resolution, coverage	Significant association	ROB
Temperature						
Descloux et al. 2012	NC	TSA	IR	Daily climate 1971–2010	Positive	Low
Teurlai et al. 2015	NC	TSA	IR	Daily 1995–2012	Positive	Low
		Spatial	IR	Commune (Municipality of NC)	Positive	Low
Ochida et al. 2022	NC	TSA	Cases	Monthly Cases, Daily climate 1970–2020	Positive	Low
McIver et al. 2015	FSM	TSA	Cases	Daily 2003–2010	None	Med
Rainfall						
Descloux et al. 2012	NC	TSA	IR	Daily 1971–2010	None/unclear	Low
Teurlai et al. 2015	NC	TSA	IR	Daily 1995–2012	Positive	Low
		Spatial	IR	Commune (Municipality of NC)	None	Low
Ochida et al. 2022	NC	TSA	Cases	D climate, M cases 1970–2020	Positive	Low
McIver et al. 2015	FSM	TSA	Cases	Daily 2003–2010	None	High
McIver et al. 2012	Fiji	TSA	IR	Monthly, annual 1995–2009	None	High
ENSO						
Descloux et al. 2012	NC	TSA	IR	Daily 1971–2010	None	Low
McIver et al. 2015	FSM	TSA	Cases	Daily 2003–2010	None	Med
Hales et al. 1996	S Pac	TSA	#epidemics	Annual 1970–1996, whole region	Yes (SOI)	High
Hales et al. 1999	S Pac	TSA	Cases	Monthly 1973–1994, country	Yes, by country (SOI)	Med
Relative humidity						
Descloux et al. 2012	NC	TSA	IR	Daily climate 1971–2010	Positive	Low
Drought						
McIver et al. 2012	Fiji	TSA	IR	Monthly 1995–2009	Positive	High
Flood						
Natuzzi et al. 2016	Sol Is	TSA	IR	Weekly 2013–2015	Negative	
McIver et al. 2012	Fiji	TSA	IR	Monthly 1995–2009	Positive	High

FSM = Federated States of Micronesia, NC = New Caledonia, Sol Is = Solomon Islands, S Pac = South Pacific, TSA = Time series analysis, IR = Incidence rate, SOI = Southern Oscillation Index

https://doi.org/10.1371/journal.pclm.0000296.t003

variability in the PICTs, [72] but few studies have explored its association with dengue. Hales et al. (1996) found that the annual number of epidemics initiated across the South Pacific region correlated with Southern Oscillation Index (SOI), an ENSO measure (Rs = 0.58, p = 0.002) [73]. Findings on the presence, direction, and strength of associations between SOI and dengue incidence at national or sub-nation levels varied in a later study [74]. This is unsurprising, given that the strength and effects of ENSO on local weather varies between PICTs, depending on their location [72].

Two studies examined dengue incidence after extreme weather events [75, 76]. Reviews have found that the incidence of mosquito-borne diseases drops may drop immediately after floods as breeding sites are washed away [77, 78]. Natuzzi et al. (2016) found that weekly case numbers were significantly lower than previous years following successive floods in the Solomon Islands [75]. As water stagnates and breeding sites are re-established, disease incidence may rise. This was seen by McIver et al. (2012) who found that the odds of a dengue outbreak increased in the month after floods (OR 10.57) and droughts (OR 5.17) (no confidence intervals provided) in one of the medical subdivisions of Fiji [76]. However, the certainty of these findings is limited by the completeness of the disease data and low occurrence of flood or drought outcomes. The relationship between flood and mosquito-borne disease is complicated by vector control responses [79].

Malaria

Malaria is a mosquito-borne disease caused by the *Plasmodium* parasite. Several species of *Plasmodium* cause malaria but *P. falciparum* and *P. vivax* are the most common in the PICTs. Malaria can cause fever, headache and vomiting and, if left untreated, is life threatening. It has consistently ranked in the top five diseases for years of life lost and disability-adjusted life years in the PICTs, and is endemic in PNG, Solomon Islands and Vanuatu [29, 80]. All climate and malaria research in the PICTs has been conducted in these settings, with most set in PNG (Fig 3).

Seasonality in *P. falciparum* malaria transmission has been found across the globe, with local variation in key climate drivers and lags [81]. Climate variation contributes to malaria seasonality, along with human behaviour, population dynamics, immunity, and vector abundance [81]. Seven studies in PNG, including a meta-analysis of seven cross-sectional survey studies, consistently found seasonality in *P. falciparum* infections [82–88] (Table 4). The timing of the seasonal peaks varied between studies, which were conducted in different provinces of PNG (for details see S1 Table). Most of the studies gathered incidence or prevalence data through repeated cross-sectional surveys in the wet vs. dry seasons. Differences in the timing peaks are due to variation in the timing and frequency of data collection, as well as true inter-annual and regional differences influenced by local climate variation and non-climatic factors.

Global reviews have found non-linear associations between rainfall and malaria seasonality and incidence [81, 89]. Rainfall influences mosquito density by controlling the availability of stagnant water breeding sites, the relationship is mediated by land type and human activities like water storage and vector control [81, 89]. All studies of monthly rainfall and malaria found it was significantly associated with malaria outcomes, but the direction and strength of association varied over time and space [86–88, 90–92] (Table 4). In PNG, rainfall in the three driest months of the year significantly affected the spatial distribution of malaria [87]. Over time, associations between rainfall and malaria varied in magnitude and direction by province, with different patterns in coastal versus highland regions [86, 90]. In the Solomon Islands, a TSA of monthly data found significant negative associations between rainfall and malaria in the Northern province ($R^2 = 0.74$: 95%CI 0.32–0.88) [92].

Temperature is a key determinant of the global distribution of malaria [93, 94]. This is because temperature affects the extrinsic incubation period of the *Plasmodium* pathogen and the lifecycle and survival of the mosquito vector. Three of four TSA of malaria and climate in the PICTs found that temperature was associated with incidence. In PNG, the direction and strength of associations varied sub-nationally but were positive in the Highland regions [86, 90]. The association was also positive in Vanuatu, with temperatures leading seasonal incidence [88]. Both spatial studies, one in PNG [87] and other in Vanuatu [95], found significant associations between temperature (or proxy variables altitude or distance to coast) and the spatial distribution of malaria.

There is limited available evidence on malaria and extreme weather events in the PICTs. A single study of malaria post floods in the Solomon Islands found case numbers were significantly lower than usual for six months [75]. Reviews have found that malaria incidence, like dengue, initially drops as breeding sites are washed away in floods and then rises again rapidly as water stagnates, but the relationship is also complicated by vector control responses [77, 79].

Leptospirosis

Leptospirosis is a bacterial zoonosis with a high incidence in the Pacific Islands [103]. Major animal reservoirs include rodents and domestic mammals like livestock and dogs [104]. It is

Table 4. Summary of studies of malaria and climate variability in the Pacific Island Countries and Territories, by climate exposure, setting and year of publication.

	Setting	Design	Outcome	Resolution, coverage	Associations	ROB^
Seasonality					**(For P. falciparum)**	
Cattani et al. 1986	PNG	CS	Fev/SE	Wet vs dry, 1981–83	None, (fever positivity)	Low
Cox et al. 1994	PNG	LC	IR/PR	Wet vs dry 1990–1991	Max: Jan- Mar Min: Jul-Sep	Low
Lin et al. 2010	PNG	LC	IR	Wet vs dry 2006	Max: Aug-Sep, Min: Apr-May	Low
Betuela et al. 2012*	PNG	MA	PR/Epis	Wet vs dry, 2000–2005	>1200m, Max: Mar-Jul	Low
Dimitrov et al. 2013	PNG	TSA	# cases	Wet vs dry 1987–1996	Max: May-June, Min: Sep-Oct	Med
Park et al. 2016	PNG	TSA	IR	Monthly, 1996–2008	Yes, timing changed coast vs highland	Med
Cleary et al. 2021	PNG	STA	PR	Monthly 1950–2000, 1km^2	Max: Mar-May Min: Nov-Feb	Low
Maitland et al. 1996	Vanuatu	CS	IR	Weekly 1992–1994	None	Low
Chaves et al. 2008	Vanuatu	TSA	IR	Monthly 1983–1999	Max: Jan-Mar, Min: Jul-Sep	Low
Rainfall						
Imai et al. 2016	PNG	TSA	IR	Monthly, 1996–2008	Yes, direction change by region	Med
Park et al. 2016	PNG	TSA	IR	Monthly, 1996–2008	Yes, direction change by region	Med
Cleary et al. 2021	PNG	STA	IR	Monthly 1950–2000, 1km^2	Yes, in driest months	Low
Smith et al. 2017	Sol Is	STA	PR	Monthly 1988–2013	Yes, direction change by region	Low
Chaves et al. 2008	Vanuatu	TSA	IR	Monthly 1983–1999	Yes, inter-annual cycles	Low
Gilbert & Brindle 2009	Vanuatu	TSA	IR	Monthly, annual 1995–2005	Positive	Med
Temperature						
Imai et al. 2016	PNG	TSA	IR	Monthly, 1996–2008	Yes, changed by region	Med
Park et al. 2016	PNG	TSA	IR	Monthly, 1996–2008	Yes, changed by region	Med
Cleary et al. 2021	PNG	STA	PR	Monthly, long term average, 1950–2000, 1km^2	Positive (negative with altitude)	Low
Smith et al. 2017	Sol Is	TSA	IR	Monthly 1988–2013	None	Low
Chaves et al. 2008	Vanuatu	TSA	IR	Monthly 1983–1999	Positive, seasonal cycles	Low
Reid et al. 2010	Vanuatu	Spatial	PR	Infra red 60m grid 2008	None (but negative associations with altitude, distance to coast)	Med
ENSO						
Imai et al. 2016	PNG	TSA	IR	Monthly, 1996–2008	Yes, changed by region	Med
Smith et al. 2017	Sol Is	TSA	IR	Monthly 1988–2013	None	Low
Gilbert & Brindle 2009	Vanuatu	TSA	IR	Monthly, annual 1995–2005	None	Med
Chaves et al. 2008	Vanuatu	TSA	IR	Monthly 1983–1999	None	Low
Flood						
Natuzzi et al. 2016	Sol Is	TSA	IR	Weekly, 2013–15	Negative, significantly lower following floods	Low

CS = cross-sectional, LC = longitudinal cohort, MA = meta-analysis, PNG = Papua New Guinea, Sol Is = Solomon Islands, STA = spatiotemporal analysis, TSA = time series analysis, IR = incidence rate, Fev = Fever positivity, PR = Prevalence rate, SE = splenic enlargement, Epis = Epidemics, ROB = Risk of Bias

* Meta-analysis of Mueller et al. 2003a [96], Mueller et al. 2003b [97], Mueller et al. 2004 [98], Mueller et al. 2005 [99], Mueller et al. 2006 [100], Mueller et al. 2007a [101], Mueller et al. 2007b [102].

https://doi.org/10.1371/journal.pclm.0000296.t004

spread to humans through contaminated water and soil or direct contact with infected animals. We identified nine studies that quantified the association between climate variables and leptospirosis in the PICTs [76, 105–113].

Rainfall has been found to be a key determinant of leptospirosis transmission [114, 115]. Rainfall was a significant predictor of the number of leptospirosis cases or incidence rates in four TSA conducted in Fiji, Wallis and Futuna, and New Caledonia (Table 5). The association was positive in three of these studies, while the direction of the association was not provided in the fourth study in Fiji due to missing outcome data. Additionally, Berlioz-Arthaud et al.

Table 5. Summary of studies of leptospirosis and climate variability in the Pacific Island Countries and Territories, by exposure variable, setting and year of publication.

Rainfall	Setting	Design	Outcome	Resolution, coverage	Significant associations	ROB
Lau et al. 2012a	AmSam	CS	Sero+	Annual 2010	None	Med
Lau et al. 2012b	AmSam	CS	Sero+	Annual 2010	None	Med
McIver et al. 2012	Fiji	TSA	IR	Mon/An, 1995–2009	Yes, (direction np)	High
Lau et al. 2017	Fiji	CS	Sero+	Annual 1971–2000	Positive	Low
Mayfield et al. 2018a	Fiji	Spatial	Sero+	Annual 1971–2000	Yes, by region	Low
Mayfield et al. 2018b	Fiji	Spatial	Sero+	100m raster	None	Low
Massenet et al. 2015	W & F	Retro surveillance	# cases	District, 2004–2014	Positive	Med
Weinberger et al. 2014	NC	TSA	# cases	Monthly 2000–2012	Positive	Low
Temperature						
McIver et al. 2012	Fiji	TSA	IR	Monthly, 1995–2009	Direction np	High
Berlioz-Arthaud et al. 2007	NC	TSA	# cases	Monthly 2001–2005	Direction np, at 2-3m lag	Med
Weinberger et al. 2014	NC	TSA	# cases	Monthly 2000–2012	None	Low
Flood						
Lau et al. 2012a	Am Sam	CS	Sero+	2010 annual	None	Med
Lau et al. 2012b	Am Sam	CS	Sero+	2010 annual	None	Med
Lau et al. 2017	Fiji	CS	Sero+	Annual 1971–2000	Positive	Low
Togami et al. 2018	Fiji	Outbreak	# cases	Weekly 12/2011–5/2012	Positive	Low
ENSO						
Berlioz-Arthaud et al. 2007	NC	TSA	# cases	Monthly 2001–2005	Yes	Med
Weinberger et al. 2014	NC	TSA	# cases	Monthly 2000–2012	Yes	Low

Am Sam = American Samoa, NC = New Caledonia, W & F = Wallis and Futuna, CS = Cross-sectional, TSA = Time series analysis, Mon = monthly, An = annual, Sero+ = seropositivity, np = not provided

https://doi.org/10.1371/journal.pclm.0000296.t005

(2007) reported that confirmed cases of leptospirosis in New Caledonia were four times greater during a La Niña (wetter) period than an El Niño (drier) period, but other potential confounders were not accounted for [105]. Cross-sectional studies in Fiji and American Samoa had mixed findings. High maximum rainfall in Fiji's wettest months (275-789mm), was positively associated with the presence of Leptospira antibodies (OR 1.003 for a 1mm increase in rainfall) [106]. In American Samoa, average annual rainfall was not significantly associated with seropositivity or a driver of its spatial distribution [107, 108], possibly due to limited exposure contrast caused by high levels of rainfall across the study sites.

Warmer temperatures have been found to increase leptospirosis incidence by promoting the growth and survival of the bacteria [114, 115]. However, there were a limited number of studies of temperature and leptospirosis in the PICTs, as most research has focused on rainfall. In New Caledonia, leptospirosis incidence peaked 2–3 months after the highest mean monthly temperatures, but rainfall was not directly considered, and an effect estimate was not provided [105]. Similarly, in Fiji, temperature was associated with leptospirosis incidence, but the direction of the association was not specified [76]. Further studies are needed to better understand the relationship between temperature and leptospirosis in the PICTs.

Leptospirosis outbreaks have been linked to flood events in tropical developing countries [114]. In Fiji, Togami et al. (2018) found cases spiked in the 2–6 weeks after successive floods [109]. In Fiji, Lau et al. (2017) found a distance of <100m between a major river or creek and home as a proxy for flood risk increased risk of seropositivity (OR 1.41 (95% CI: 1.09, 1.83)) [106]. Two cross sectional studies in American Samoa found no association between living in a "flood risk zone" and seropositivity [107, 108]. However the authors indicated that flood risk was based on insurance maps that were inaccurate indicators of actual flooding based on reported participant experiences. Collection of health data post-flood event is difficult but represents a research gap for leptospirosis and climate studies in the PICTs.

Diarrhoea

Diarrhoea is a leading cause of global death and morbidity, with a high burden in the Pacific, especially in the under 5 and over 70 age groups [29]. Diarrhoea can be caused by bacteria, protozoa, viruses, or toxins spread through contaminated food, water or person-person contact [15]. Associations between climate and diarrhoea are complex and can vary based on pathogen-specific responses and local environmental conditions, so examining general patterns of diarrhoea may yield different results to pathogen-specific approaches. There were nine studies of diarrhoea outcomes and climate in the PICTs, including two that were pathogen specific: a study of non-typhoidal salmonella [55] and an outbreak investigation in the Solomon Islands that typed diarrhoeal pathogens [116] (Table 6).

Global reviews have found positive associations between ambient temperature and all cause diarrhoea [4, 117, 118]. Singh et al. (2001) analysed data from 18 PICTs and found a positive correlation between average annual temperatures and diarrhoea counts ($R^2 = 0.49$, $p<0.05$) [119]. There are a limited number of national analyses of diarrhoea and climate with higher resolution data in the PICTs, only one provided effect estimates. Singh et al. (2001) also conducted a TSA of monthly infant (<1 year) diarrhoea in Fiji (1978–1998) and found a 1˚C temperature increase led to a 3% (95%CI: 1.2–5.0%) increase in cases in the following month and higher diarrhoea rates at rainfall extremes (U shape relationship) [119]. This finding is similar to a global meta-analysis of 26 studies of all cause diarrhoea and ambient temperature, which found an incidence rate ratio of 1.07 (95% CI: 1.03,1.10) [120]. A later TSA (1995–2009) of monthly diarrhoea in Fiji found associations in some states over time lags (pseudo R^2 0.06–0.10) but the direction of these associations was not provided [76]. A study of weekly syndromic surveillance data in Fiji found temperature did not influence variation in bloody and watery diarrhoea [63].

The relationship between rainfall and diarrhoea is complex and non-linear. International studies have reported U-shaped associations with increased rates at rainfall extremes [15, 120]. Studies in the PICTs of rainfall and diarrhoea echoes these findings (Table 6). Two TSA studies found U-shaped relationships between monthly diarrhoea incidence and rainfall in Fiji at one-month lags [76, 119]. Nelson et al (2022) found that rainfall explained the most variance in watery and bloody diarrhoea across Fiji, with cases peaking several weeks after rainfall [63]. The timing of these peaks is likely to be pathogen specific. One study in FSM did not find any associations with rainfall, but substantial gaps in the disease data were reported by the authors [32].

Diarrhoea outbreaks have occurred after extreme events in the PICTs. Diarrhoea rates have been found to spike after flooding, where pathogens are washed into water sources and WASH infrastructure is overwhelmed [120]. Two outbreak investigations in the Solomon Islands confirmed higher case numbers in the weeks following a 2014 flood compared to previous years [75, 116]. In Fiji, McIver et al. reported an increased risk of outbreaks in the month following a flood (OR 3.5), (no confidence intervals provided) [76]. At the other extreme, drought may concentrate diarrhoeal pathogens in water sources and reduce the quantity of water available for hygiene and sanitation [121]. In Tuvalu, weekly diarrhoea cases exceeded 2 standard deviations above historical means during a drought linked to a La Niña event in 2011 [121]. Through a case-control study the authors also found that low water tank reserves and decreased handwashing were significantly correlated with diarrhoea ($p<0.01$).

Table 6. Summary of studies of diarrhoea and climate variability in the Pacific Island Countries and Territories, by exposure variable, setting and year of publication.

	Setting	Design	Outcomes	Resolution, coverage	Associations	ROB
Temperature						
Singh et al. 2001	S Pac	TSA	# cases adult	Annual, 1986–1994	Positive	Med
	Fiji	TSA	# cases infant	Monthly, 1978–1998	Positive at 1m lag only	Low
McIver et al.2012	Fiji	TSA	IR	Monthly,1995–2009	Yes	Med
Nelson et al. 2022	Fiji	TSA	IR	Weekly 2016–20	None	Low
McIver et al. 2015	FSM	TSA	# cases	Daily 2003–2010	U Shape	Med
Emont et al. 2017	Tuvalu	TSA	AR	Weekly 2000–2013, monthly 2008–2013	None	Med
Rainfall						
Singh et al. 2001	Fiji	TSA	# cases child	Monthly, 1978–1989	U shape	Low
McIver et al.2012	Fiji	TSA	IR	Monthly,1995–2010	U shape at 1m lag	Med
Nelson et al. 2022	Fiji	TSA	IR	Weekly 2016–2020	None	Low
McIver et al. 2015	FSM	TSA	# cases	Daily 2003–2010	None	Med
Haddock & Malilay 1986	Guam	TSA	Salmonella IR	Monthly 1977–1984	Yes, annual /monthly	High
Jones et al. 2016	Sol Is	OBI	IR, MR	Outbreak 2014	Positive	Low
Emont et al. 2017	Tuvalu	OBI	AR	Weekly 2000–2013, monthly 2008–2013	Negative	Med
ENSO						
McIver et al. 2015	FSM	TSA	# cases	Daily 2003–2010	U shape, one state	Med
Drought						
McIver et al. 2012	Fiji	TSA	IR	Monthly,1995–2009	Positive	Med
Emont et al. 2017	Tuvalu	TSA	AR	Weekly 2000–2013, monthly 2008–2013	Positive	Med
Flood						
McIver et al. 2012	Fiji	TSA	IR	Monthly,1995–2009	Positive	Med
Jones et al. 2016	Sol Is	OBI	IR	2014 Outbreak	Positive	Low
Natuzzi et al. 2016	Sol Is	OBI	IR	2014 Outbreak	Positive	Low
Other						
McIver et al. 2012	Fiji	TSA	IR	Monthly,1995–2009	Humidity: None	Med
Nelson et al. 2022	Fiji	TSA	IR	Daily clim, weekly d 2016–2020	Seasonality: Mar- Apr	Low

ROB = risk of bias, Sol IS = Solomon Islands, FSM = Federated States of Micronesia, OBI = outbreak investigation, IR = incidence rate, AR = attack rate

https://doi.org/10.1371/journal.pclm.0000296.t006

Typhoid fever

Typhoid fever is an infection transmitted by ingestion of food or water containing faeces with Salmonella enterica serovar *Typhi* bacterium. It is endemic in some PICTS, including Fiji [122]. Outbreaks have been described after cyclones and floods [123], but only three studies in Fiji, conducted at different spatial scales, quantified associations between climate and typhoid outcomes [76, 124, 125] (Table 7). An additional study analysed syndromes related to typhoid in Fiji (watery diarrhoea, bloody diarrhoea and prolonged fever) but not confirmed cases [63]. Two spatial analyses in Fiji found that "flood risk" areas (based on topography, hydrology, distance to water and elevation) had higher typhoid incidences [124, 125]. Findings of these studies for weather variables were mixed. A lack of climate variability and typhoid studies represents a research gap in the PICTs.

ROB and quality assessment

Most of the included studies were at a low or medium overall ROB. Studies were at a medium or high of bias due to concerns in exposure or outcome assessment, or inadequate accounting

Table 7. Summary of studies of typhoid fever and climate variability in the Pacific Island Countries and Territories, by exposure variable, setting and year of publication.

	Setting	Design	Outcome	Resolution, coverage	Associations	ROB
Rainfall						
McIver et al. 2012	Fiji	TSA	IR	Monthly,1995–2009	Yes, direction np	Med
Jenkins et al. 2016	Fiji	STA	IR	Monthly 2013–2015 Sub-catchment	None	Low
De Alwis et al. 2018	Fiji	CS/spatial	Sero+	Community	Positive	Low
Temperature						
McIver et al. 2012	Fiji	TSA	IR	Monthly,1995–2009	Yes, direction np	Med
Jenkins et al. 2016	Fiji	STA	IR	Monthly 2013–2015 Sub-catchment	None	Low
De Alwis et al. 2018	Fiji	CS/Spatial	Sero+	Household	None	Low
Flood -						
Jenkins et al. 2016	Fiji	STA	IR	2013–2015 sub-catchment	Positive	Low
De Alwis et al. 2018	Fiji	CS/ Spatial	Sero+	Household	Positive	Low

TSA = Time series analysis, STA = spatiotemporal analysis, CS = Cross sectional, IR = incidence rate

https://doi.org/10.1371/journal.pclm.0000296.t007

for confounding (see S3 and S4 Tables). These potential biases are common in observational epidemiological studies of environmental exposures [18]. Potential confounders for TSA include long-term data trends and seasonality, or meteorological variables that are not controlled for [126]. For example, in some studies examining the association between rainfall and disease outcomes, temperature was not accounted for (or vice versa). Many studies also did not account for sociodemographic variables which can confound spatial associations with climate variables.

Further, several of the TSA used monthly climate data but did not provide information on the completeness of the data or reported substantial gaps in the data. Additionally, some studies used data from only one weather station, usually due to this being the only available data, as a proxy for an entire region or country. This renders it difficult to assess the accuracy of the exposure classifications and limits exposure contrast across the study sites.

Summary and applications

We identified 45 studies that quantified associations between climate variability and WRID outcomes in the PICTs. While the amount of research on this area in the PICTs has increased over the past decades, there were geographic restrictions in the scope. The studies were largely concentrated in PNG and Fiji, with a limited number set in other PICTs. Synthesis of the findings by disease and climate variable revealed the following consistent findings:

1. Positive associations between temperature and dengue incidence, and the potential for outbreaks post-drought and flood,
2. Highly seasonal malaria with associations with rainfall and temperature varying subnationally,
3. Increased diarrhoea incidence at high and low rainfall levels and post- drought and flood,
4. Positive associations between leptospirosis and rainfall and flooding,
5. Associations between typhoid and flooding.

These associations are all biologically plausible and supported by broader international literature [2, 56]. Given the high frequency of extreme weather events that occur in the PICTs

[127], these findings indicate that high alert for outbreaks of diarrhoea, dengue, leptospirosis, and typhoid is necessary during and post- disaster. Access to safe drinking water, rebuilding of WASH facilities and reduced contact with contaminated water are a priority to reduce public health burden. As climate change is predicted to increase the frequency of extreme weather events, ongoing investment in improved WASH access in the PICTs is necessary to buffer against the effect of climate change on public health [128].

Integration of climate and health data is a critical component of building climate resilient health systems [129]. In several cases where no associations were found, authors stated a lack of exposure contrast across their study sites (e.g. very high levels of rainfall) as potential a reason for this. In some cases, this may be because data were not available at a fine enough spatial or temporal resolution to detect associations (e.g. when data from only one weather station was used) [130]. In other studies, periods of missing health data were reported. Missing or inconsistent health or climate data is an ongoing issue in the PICTs where surveillance and collection resources can be limited [31, 60]. However, data is increasingly available and accessible through initiatives such as the Pacific climate change data portal [131], the Pacific Public Health Surveillance Network [132], and The Pacific data hub [133].

Geographic limitations in the scope of research underscore the need for future studies in diverse settings across the PICTs to enhance the applicability of the evidence for public health responses. Despite limitations, the patterns of consistent findings identified in this review indicate the potential for development of climate based EWS, risk maps and disease forecasting under climate change scenarios in the PICTs.

Climate-based EWS can alert communities and health authorities about the increased risk of disease outbreaks during specific climate conditions, allowing for timely interventions and preventive measures [28]. Climate-based EWS for infectious diseases are in place across the world, for example, there are ENSO-based EWS for hantavirus pulmonary syndrome, Rift Valley Fever, cholera, and dengue [134, 135]. The potential for climate-based EWS in the PICTs has been discussed and establishment frameworks proposed [136]. However, the authors are aware of one previously operational EWS in the PICTs, Malaclim, developed from the results of Smith et.al. (2017) for malaria risk in the Solomon Islands [137]. Further research may build on some of the consistencies identified through this review, like highly seasonal malaria in PNG, to enable the establishment of other EWS.

Associations between climate variables and WRID outcomes are also useful for the development of risk maps. Risk maps can be used by health authorities, policymakers, and other stakeholders to allocate resources. For example, Mayfield and colleagues developed risk maps for leptospirosis based on associations between climate variables, environment, and disease outcomes [112, 113]. The body of evidence identified in this review also offers the potential for projecting disease burdens and risk mapping under climate change scenarios. For instance, research on dengue in New Caledonia was used to project annual incidence and spatial evolution up to 2100 [65–67]. Future studies on climate and WRID in the PICT may incorporate updated emissions scenarios to forecast disease patterns using long-term climate and disease data.

Limitations

This review is limited to studies that quantified associations between climate variables and WRID. Mechanistic studies were excluded but are important for understanding transmission dynamics and designing control strategies. For examples of mechanistic climate and WRID research in the PICTs, see Henderson et al. (2021)'s study of Zika in Fiji [48] or Kucharski et al. (2018)'s of dengue transmission in Fiji [46]. We also excluded a considerable number of entomological studies in the PICTs, which are important for understanding how climate can impact the transmission dynamics of vector borne diseases.

Further, our search terms included broad terms and some, but not all, specific WRID terms (e.g. cholera, hepatitis). We did not find studies of Zika and chikungunya that matched or inclusion criteria, but these were not specific search terms. While it is expected the broader terms and full citation searches would identify literature on these diseases, it is possible that exclusion of these terms missed important literature. Finally, while we identify patterns of associations in light of potential biases, we did not conduct a meta-analysis. Limited data availability, and heterogeneity in climate indicators (measurements, aggregations, lags, and values) and analytical approaches precluded meaningful quantitative summaries within the scope of this review and is an area for future research.

Conclusion

We observed associations between climate variability and some WRID in the PICTs that were both biologically plausible and consistent with the international literature. Future research on this topic may take advantage of increasingly available data to consolidate the field across a greater diversity of settings and increase application of the evidence to the development of effective control strategies and interventions like EWS, forecasting and risk maps. Today, WASH access must be prioritised and strengthened across the PICTs to reduce the impacts of WRID on human health during and following extreme weather events.

Supporting information

S1 Table. Extracted information from studies of climate variability and water-related infectious diseases in the Pacific Island Countries and Territories, by disease, setting and year of publication.
(XLSX)

S2 Table. Risk of bias tool developed by Chua et al. (2022) in a review of climate variability and diarrhoea for assessment for time-series analyses.
(DOCX)

S3 Table. Risk of bias assessment for included time-series analyses, by disease and year of publication.
(XLSX)

S4 Table. Risk of bias assessment for included studies, cross-sectional designs, by disease and year of publication.
(XLSX)

S1 File. PRISMA checklist.
(DOCX)

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