

Invited Review Paper

Climate change and hydrological risk in the Pacific: a Humanitarian Engineering perspective

Fiona Johnson, Philippa Higgins and Clare Stephens

ABSTRACT

Pacific Island communities have adapted to floods, droughts and cyclones over many generations. Small and low-lying islands are particularly exposed to natural disasters, and many countries have limited access to water resources. Anthropogenic climate change is expected to further increase these environmental pressures. Any associated engineering response needs to consider the cultural, societal and historical context, and prioritise the agency of local communities to determine their preferred outcomes. It follows that Humanitarian Engineering, a discipline centred around strengths-based and context-appropriate solutions, has an important role to play in climate change adaptation. In this review, the interplay between hydroclimatology, geography and water security in the Pacific Islands is described and projected climate shifts summarised to highlight future adaptation challenges. A key source of uncertainty relates to the dynamics of two convergence zones that largely drive weather patterns. A broad overview of societal factors that present challenges and opportunities for Humanitarian Engineers is given. Finally, actions are recommended to inform climate change adaptation given the scientific uncertainty around hydrologic risks, and outline lessons for best practice Humanitarian Engineering in the Pacific. Enhancing data sharing, building resilience to climate variability and integrating traditional knowledge with convention engineering methods should be key areas of focus.

Key words | adaptation, climate change, Humanitarian Engineering, Pacific Islands

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HIGHLIGHTS

- Water resource climate change adaptation options are reviewed using a Humanitarian Engineering lens for the Pacific.
- Large uncertainties in future changes to the ITCZ, SPCZ and ENSO have major implications for adaptation in the Pacific.
- Hydroclimatology research gaps include the relationship between island geography and changes to rainfall extremes, and changes in evapotranspiration for drought assessments.
- Scenario-based approaches to understand system thresholds under climate change are promising, but require access to long-term data records.
- Appropriate climate adaptation options need to be developed using a strengths-based approach, considering cultural values, land tenure arrangements and institutional structures.

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INTRODUCTION

Pacific Island Countries (PICs) are small island states, with limited land to naturally buffer the intersection of their populations with climate variability. They are highly susceptible to natural disasters and extreme events, including tropical cyclones, droughts, floods and inundation from high tides (Houghton *et al.* 2001; Griffiths *et al.* 2003; IPCC 2007). With climate change leading to changing rainfall patterns, more intense rainfall and increased sea levels, these risks will be further amplified. Hydro-meteorological disasters already cause most disaster-induced economic loss in the Pacific region (World Bank 2016). Average GDP per capita in the PICs is less than 40% of global average. Therefore minimising the future costs of hydro-meteorological hazards is vital. The United Nations (UN) Sustainable Development Goals (SDGs) provide a framework to highlight the important role of water in ensuring that the development in the PICs is sustainable and equitable, particularly considering climate change (SDG13) and hydrological risk (SDG6).

In this review, the intersection of likely future hydro-meteorological changes with communities in the Pacific is considered through a Humanitarian Engineering lens. Humanitarian Engineering is a discipline that focuses on meeting the needs of communities in terms of development and disaster response (Mitcham & Muñoz 2010; Smith *et al.* 2017). It involves applying engineering knowledge to leverage the existing strengths of the local community (Mazzurco 2016), with a focus on sustainability and appropriate technologies. Humanitarian Engineering projects are generally conceptualised as a cycle with a number of guiding principles. The cycle starts with building relationships in the community through listening and understanding their needs. Next, the strengths and constraints (physical and social) of the community and the problem at hand are established. All engineers, and especially Humanitarian Engineers need to focus on developing sustainable designs. Sustainability means that the design meets the needs of the community, now and in the future, in terms of environmental, social and economic considerations (Mazzurco & Jesiek 2017).

A key part of sustainability for engineering solutions is that there is local capacity for operating and maintaining systems and infrastructure into the future, which to date has been a key limitation in the Pacific (Baker & Week 2011). The final step of the Humanitarian Engineering cycle is to evaluate the project and solutions, and potentially iterate to ensure that all the community's goals have been met. There are two main differences between Humanitarian Engineering and a more standard project approach to engineering or other approaches such as rational decision making. The first is an inherent and overarching focus on protecting and promoting human rights. Secondly, Humanitarian Engineering projects should explicitly aim to 'do no harm' by ensuring that projects do not have unintended consequences (CDA Collective 2020) and understanding that any intervention or action in a community will lead to changes in that community, whether planned or not.

As argued by Rubow & Bird (2016), 'climate change epitomises an interconnectedness between culture and nature by thinking across land, sea, sky and people'. Connecting climate change, water and Humanitarian Engineering provides researchers and practitioners with a holistic view of people, environment and infrastructure. Understanding all three together is vital if climate change adaptation is to be successful in the Pacific. This review is structured with background on the PICs, the role of the SDGs and the hydroclimatology of the Pacific along with a discussion of the links to water supply and flood planning. Next, the literature covering climate change impacts on the major drivers of floods and droughts in the Pacific is reviewed to identify outstanding knowledge gaps. Climate change impacts are then linked to distinct aspects of Pacific culture and society, highlighting how local contexts affect climate change adaptation and potential engineering solutions. Finally, recommendations are made to inform climate change adaptation in the Pacific in terms of hydroclimatological data needs, climate modelling approaches and Humanitarian Engineering practice.

BACKGROUND

Pacific nations and peoples – geography, culture, urbanisation

The tropical Pacific covers the area between the Tropic of Cancer and Tropic of Capricorn (23.5° north and south, respectively) (Figure 1). There are 21 countries and territories in the tropical Pacific region (Campbell & Barnett 2010) and an estimated total population of 11.8 million people (2018), of which over 8.5 million live in Papua New Guinea (PNG). Key industries include agriculture, fisheries and tourism, with a dependence on remittances and aid (McNamara & Farbotko 2017). Most islands have coral reefs which are very important in terms of their ecosystem services and environmental protection as well as sustaining fishing and tourism. Generally, the Pacific is divided into three regions – Melanesia, Micronesia and Polynesia (Figure 1) – based on the cultural heritage of the communities.

Best estimates suggest that the PICs are composed of more than 2,500 individual islands (Goldberg 2017) of which close to 700 are inhabited. There are four main island types in the Pacific (Nurse *et al.* 2014) ranging from low-lying atolls to high volcanic islands. Low-lying reef-carbonate islands (including atolls) have elevations just a few metres above sea level and are the most common island

type. Limestone islands, such as Tongatapu, Kingdom of Tonga, are composed of consolidated and often karstified limestone at the surface. They differ from atoll-type islands due to size and topography, with elevations tens of metres above sea level. On the other end of the scale are the high volcanic and composite (mixed type) islands such as New Guinea, which is the largest PIC landmass, divided between PNG (approximately 460,000 km²) and Indonesia. The mountain ranges in PNG have peaks up to 4,800 m. Volcanic islands such as Viti Levu in Fiji and Espirito Santo in Vanuatu have their highest elevations between 1,000 and 2,000 m.

Island size and type are the most important factors affecting climate and water resource availability. Atoll and limestone islands are highly permeable and often lack permanent surface water features, making them reliant on groundwater. Their small size and geographic isolation make them particularly vulnerable to natural disasters such as storm surges. Volcanic islands often have very steep slopes with limited land available for housing and agriculture, and much of the infrastructure is located close to the coast (Kumar & Taylor 2015). This geography can also cause rain shadows, leading to heterogeneous access to water and risks of drought (Pearce *et al.* 2018). The land area of many small islands is less than 10 km²; atoll islands are frequently less than 1 km² in area (Dijon 1983). Therefore, the ocean has a very strong influence on the climate

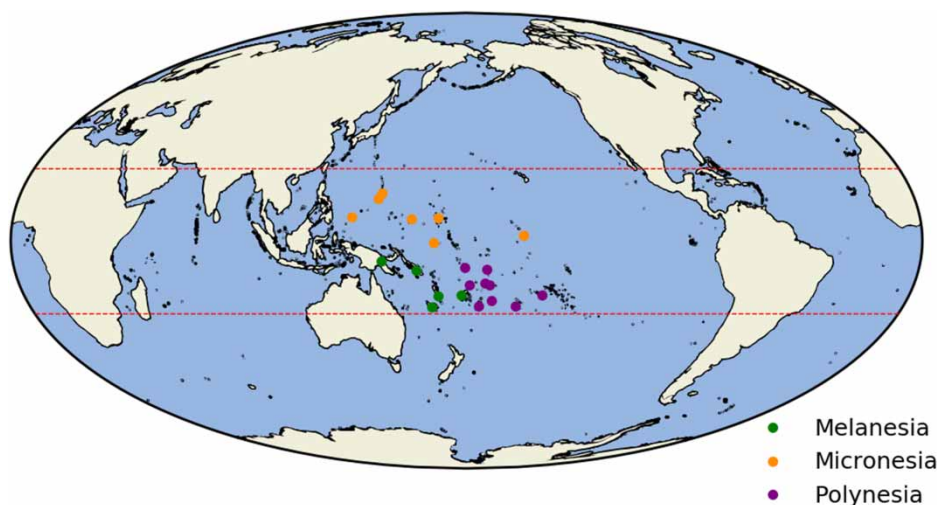


Figure 1 | Location of Pacific Island Nations.

and culture. The islands' small land areas also constrain estimates of weather and climate impacts in the region. For example, uncertainties in cyclone tracks are in the range of 300 km, but the maximum width of Viti Levu (main island of Fiji) is 150 km (Brown *et al.* 2018).

Weir *et al.* (2017) conclude that the geographical features of Pacific Islands constrain economic development, specifically the fragmented nature of physical and political structures as well as their remoteness and small size. For water resources and hydrological engineering, the small size is a challenge due to the reduced opportunities for diverse supply sources. Fragmentation also leads to increased access costs and fewer chances to build 'economies of scale' (Weir *et al.* 2017).

Communities in PICs vary from highly urbanised centres, to rural inland communities to remote, small communities on outlying islands. Urbanisation ranges from 13% in PNG to 100% in Nauru with a median of around 50% (Pacific Data Hub 2020). Urbanisation is increasing in the Pacific at a rate of approximately 0–4% per year/decade depending on the country (Pacific Data Hub 2020). Urbanisation occurs as people seek better employment and education opportunities (Weir *et al.* 2017; Anthonj *et al.* 2020). Informal settlements in the larger urban centres are also increasing, which suggests that estimates of urbanisation are probably too low (Trundle 2020). Informal settlements are often located in marginal land including floodplains and steep slopes, where floods and/or landslides are more likely, or low-lying coastal zones prone to seawater inundation from storm surges (Weir *et al.* 2017). They are, therefore, a vital consideration around the intersection of climate change, hydrologic risk and Humanitarian Engineering.

SDGs relevant to water and climate change in the Pacific

The SDGs were developed by the UN to mobilise international action to address global challenges and achieve a more sustainable future by 2030. Of relevance to this review are SDG6, which focuses on access to water and sanitation, and SDG13, which calls for urgent action to combat climate change and its impacts. A key tenet of the SDGs is the interlinked nature of the development

challenges that face the world. This means that SDG1 (no poverty) and SDG11 (sustainable cities) are also linked to climate change adaptation and Humanitarian Engineering because hydrological risks result from poor planning in informal settlements (Weir *et al.* 2017).

SDG6 assesses the proportion of a population using safely managed drinking water services and levels of water stress in communities. Access to safely managed water sources is uneven across the Pacific (Figure 2) and improvements have been gradual in most countries where data are available. Therefore, there is a strong need for better infrastructure and supporting institutional structures. The 'The intersection of climate change impacts with human–water systems' section considers typical water infrastructure adaptation options in the context of PIC culture and society. Typical of many hydrological assessments in the PICs, there is very little data available on water stress. Freshwater withdrawals are only between 0.1 and 0.3% of available freshwater in Fiji and PNG. However, these two countries have the largest islands and hence biggest catchment areas. For the smallest islands in the Pacific, it is very likely that the levels of water stress are much higher. Recommendations to address problems stemming from poor data availability in the PICs are provided in the 'What is

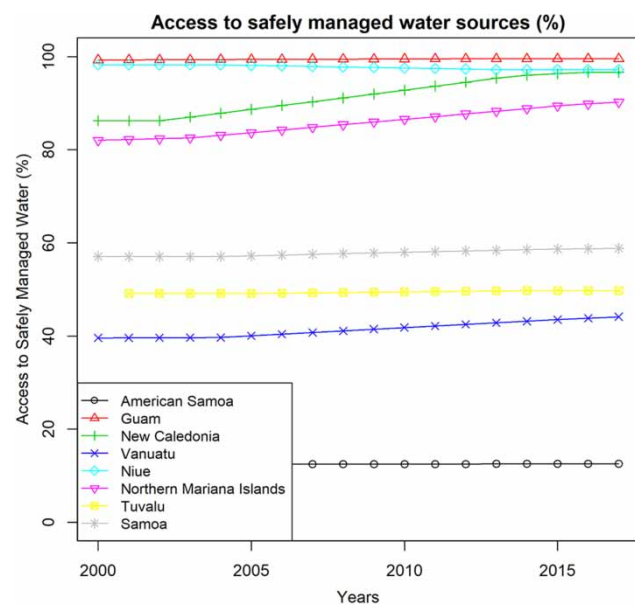


Figure 2 | SDG6.1 Proportion of population with access to a safely managed water source in PICs with available data (United Nations 2020).

needed to advance Humanitarian Engineering for climate change adaptation in the Pacific?’ section.

SDG13 measures how natural disasters affect sustainable development. Similar to earlier research by Strömberg (2007), the number of people affected by natural disasters in the Pacific is similar to other parts of the world, but deaths are significantly higher (Figure 3). SDG13 also considers how disaster risk reduction (DRR) strategies have been implemented based on the ten key elements of the Sendai Framework for DRR (2015–2030). A score of 1 reflects comprehensive implementation, 0.5 suggests moderate implementation, and 0 designates no implementation. Globally, the median score is 0.58 with the interquartile range between 0.25 and 0.83. National-level data on these indicators are scarce for Pacific Islands with data only available for Samoa (0.7) and Vanuatu (0) (United Nations 2020). Thus, there is considerable work to be done in most PICs to implement and report DRR strategies. The links between DRR and climate adaptation are discussed in the ‘Climate change adaptation for hydrological risks’ section.

Pacific hydroclimatology

Because of their location in the tropics, the PICs receive almost constant incoming solar radiation and hence low variability in annual air temperatures (CSIRO *et al.* 2015). Precipitation, on the other hand, has high spatial and temporal variability. Annual average rainfall ranges from 900 mm/year in eastern Kiribati in the dry equatorial Pacific to over 8,000 mm in elevated parts of the Federated States of

Micronesia (FSM), PNG and Solomon Islands (Falkland 2011). Rainfall across the tropical Pacific is largely dependent on the position, extent and strength of two large convective bands, the Intertropical Convergence Zone (ITCZ) and the South Pacific Convergence Zone (SPCZ).

The ITCZ is a zonal band of cloudiness and precipitation driven by the collision of the northerly and southerly trade winds near the equator (Byrne *et al.* 2018). The ITCZ moves across the equator following the seasonal solar insolation cycle. As a result, the Northern Hemisphere Pacific Islands (FSM, Kiribati, Marshall Islands, Nauru, Pulau and PNG) have their wet season from May to October and dry season from November to April (CSIRO *et al.* 2015).

The SPCZ is a persistent, convective cloud band that stretches from PNG in a south-easterly direction towards French Polynesia (Vincent 1994). In the north-western sector, the SPCZ merges with the ITCZ over the western equatorial Pacific warm pool. The SPCZ is most active during the austral summer, when the westerly duct is present over the equatorial Pacific (Matthews 2012; van der Wiel *et al.* 2016) leading to the wet (November to April) and dry (May to October) seasons being reversed for countries under its influence, compared with the Northern Hemisphere Pacific Islands.

On interannual time scales, precipitation is strongly influenced by the El Niño–Southern Oscillation (ENSO). As an example of ENSO impacts on hydrological risks, the 2015–2016 El Niño was one of the three strongest events since 1950 (Australian Bureau of Meteorology 2016). In PNG, 2.7 million people were affected by drought

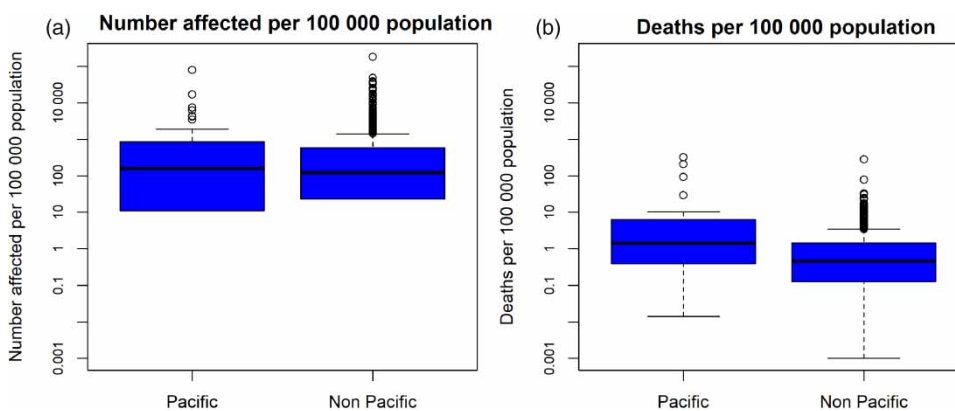


Figure 3 | SDG13.1 Statistics on the effects of natural disasters on countries in the Pacific compared with the remainder of the world: (a) number of people directly affected per 100,000 and (b) deaths per 100,000 persons (United Nations 2020).

and forest fires (FAO 2016). Below average rainfall was experienced across a large portion of the Pacific Ocean from New Caledonia to Kiribati, and the FSM, Marshall Islands and Palau declared a State of Emergency for drought impacts (FAO 2016).

The SPCZ and ITCZ tend to move towards the equator during El Niño events, resulting in dry conditions in the Southwest Pacific. Conversely, the SPCZ and ITCZ move away from the equator during La Niña events when zonal sea surface temperature (SST) gradients are strengthened, bringing dry conditions to the north-eastern Pacific Islands (van der Wiel *et al.* 2016; Werner *et al.* 2017). During strong El Niño events, the SPCZ can shift by up to 10° of latitude towards the equator (Cai *et al.* 2012). The Indian Ocean Dipole (IOD), an intrinsic interannual fluctuation in Indian Ocean sea surface temperatures, tends to occur synchronously with ENSO (Luo *et al.* 2010) and has been linked to the occurrence of extreme El Niño events (Hameed *et al.* 2018). Because there are very strong precipitation gradients near the convergence zones, small displacements in the mean position of the ITCZ and SPCZ can result in large changes to precipitation for South Pacific Islands (Vincent *et al.* 2011). Thus, whether higher or lower rainfall is experienced during ENSO phases depends on the location of each country and the type of ENSO event.

Tropical cyclones are responsible for many natural disasters in the Pacific Islands (Diamond *et al.* 2013; Magee *et al.* 2020), and their formation and trajectories are linked to the convergence zones (Vincent *et al.* 2011; Cao *et al.* 2012). Around 80% of tropical cyclones in the Western North Pacific form within or near the ITCZ (Cao *et al.* 2012) and cyclone formation in the South Pacific is favoured between the SPCZ and 10° to its south (Vincent *et al.* 2011). The SPCZ cyclone genesis area moves northeast during El Niño events, which are also conducive to a high rate of cyclone formation in the Southwest Pacific (Magee *et al.* 2020).

At longer time scales, the climate of the PICs is modulated by the Inter-decadal Pacific Oscillation (IPO), a low-frequency (approximately 15–30 years) variation in Pacific sea surface temperatures and basin-wide circulation (Folland *et al.* 2002). The IPO is the basin-wide expression of the North Pacific SST mode of variability known as the Pacific Decadal Oscillation (Mantua *et al.* 1997). Shifts in the

IPO have been linked to significant changes in climate regimes across the Pacific. For example, the rapid transition from a negative to a positive IPO phase during the mid-1970s was associated with a transition to an El Niño dominated period (CSIRO *et al.* 2015). In their study of precipitation records from 1951 to 2010, Ludert *et al.* (2018) noted more severe droughts southwest of the SPCZ and north of the ITCZ when the IPO was in its positive phase.

Typical infrastructure – water supply and flood mitigation

Most PICs have access to natural water resources that can be developed without highly complex technology (Falkland 2011). Permanent surface water features such as perennial rivers are a feature of high volcanic islands, where gravity-fed surface water systems and permanent springs are often important sources of freshwater, particularly for rural communities (Weber 2016). However, not all high volcanic islands rely on surface water; for example, the urban population of Port Vila, Vanuatu is predominantly supplied by groundwater (Carrard *et al.* 2019).

For most small Pacific Islands without ample surface water resources, rainwater harvesting and shallow groundwater are the main sources of drinking water (Werner *et al.* 2017). On atoll-type islands with sufficient land area and rainfall, as well as some limestone islands, groundwater is present as a freshwater lens, which floats atop saline seawater due to density differences (Werner *et al.* 2017). The nature of the freshwater lens is affected by many factors, including island size, permeability of the rock, and storm and tide-induced mixing; thickness can range from a few centimetres to 20 m (Weber 2016). Groundwater development to exploit freshwater lenses ranges from hand-dug vertical wells with bailers to low-pumping well fields and horizontal extraction systems such as infiltration galleries and skimming wells (Werner *et al.* 2017).

Rainwater harvesting from household roofs or community centres is often used to supplement groundwater sources during the wet season, but in some countries with high rainfall, such as Tuvalu, rainwater harvesting is the primary source of freshwater (Falkland 2011). Typical rainwater harvesting infrastructure consists of three components: a

catchment (usually a sheet metal or aluminium roof), a gutter-downspout system and a concrete or manufactured plastic storage tank (Bailey *et al.* 2018).

Non-conventional sources of water with higher technological demand, such as desalination, importation and treated wastewater, are limited in most countries. However, desalination using reverse osmosis (RO) is a primary source of drinking water in Nauru during droughts and a supplementary source during other times (Falkland 2011). Other countries have installed RO units for emergency use during droughts, but the long-term performance has been poor because operation and maintenance of the equipment is prohibitively expensive (Falkland 2011; Dahan 2018). Importation has also been used to supplement water supply during droughts, particularly for the outer islands of Fiji, PNG and Tonga (Falkland 2011), although water transfers between islands hundreds of kilometres apart are generally impractical and uneconomic (Duncan 2011).

As highlighted in Figure 2, only half the population in the Pacific region uses improved drinking water sources (World Health Organization & United Nations Children's Fund 2017). There is a large disparity between water supply systems for urban and rural communities; 67% of urban communities (excluding informal settlements) have access to improved water piped to the premises, whereas only 9% of the rural population has the same service delivery (United Nations Children's Fund & World Health Organization 2019). Community-managed water systems are the dominant means of supply in rural communities due to a lack of governmental oversight and private sector development (Hadwen *et al.* 2015). Small rural communities are commonly too remote and therefore too expensive to equip with improved water and sanitation (Poustie & Deletic 2014).

Information about water supply infrastructure in informal settlements in the PICs is scarce. The characteristics of informal settlements vary across the Pacific, but work in Melanesia points to insufficient and unpredictable water supply, illegal connections or unimproved sources such as dug wells (Schrecongost *et al.* 2015). In many countries, utilities do not have an obligation to extend water and sanitation services to informal communities (Schrecongost *et al.* 2015).

Floods are a frequent occurrence in many PICs. Intense tropical storms and steep topography can produce floods

with high depths, velocities and sediment loads on high volcanic islands. Flood risk management measures are largely informal, although some structural measures such as levees and river dredging have been implemented in Fiji and Samoa, and flood mitigation dams are being considered in the Solomon Islands (Yeo *et al.* 2017). Urban drainage has also been improved in some countries, including Vanuatu and Samoa. Risk-informed land-use planning is a challenge for many countries due to land tenure arrangements (see the 'Pacific links between cultural, historical and community values with adaptation options' section) and increases in informal settlements (Yeo *et al.* 2017).

Both hard and soft engineering measures are used to protect Pacific Islands from coastal flooding. Hard engineering structures including seawalls, causeways and groynes are common across many countries. Protecting existing mangrove forests and reforestation of the coastal zone is the most common soft engineering protection measure (Paeniu *et al.* 2015).

WHAT IS KNOWN AND NOT KNOWN ABOUT CLIMATE CHANGE IMPACTS ON THE PACIFIC

Climate change projections are uncertain across the Pacific, and there is a lack of specific information for some countries. Sea level and extreme rainfall are likely to increase across most of the region, but there is regional variation in projections of future droughts, average rainfall and tropical cyclones, related to predicted shifts in the convergence zones and ENSO (see the 'Changes in the SPCZ, ICTZ and ENSO' section). Projections for individual countries are given in Table 1, with further details in the following sections.

Changes in the SPCZ, ICTZ and ENSO

The 'Pacific hydro-climatology' section established the importance of the SPCZ and ITCZ on Pacific hydroclimatology. Unfortunately, biases in SST gradients detrimentally affect their simulation in climate models (Widlansky *et al.* 2013; Grose *et al.* 2014). The SSTs along the equatorial Pacific are often too cold, and there is a region south of the equator where excessive rainfall is simulated; these two biases are

Table 1 | Qualitative future changes in drought, flood and tropical cyclone risk predicted for Pacific Island nations

Country	Population	Description	Future change in drought risk	Future change in average rainfall	Future change in tropical cyclone risk
Cook Islands	15,000	15 dispersed islands, low coral atolls to the north and volcanic islands to the south	Slight increase in the north and decrease in the south under a very high emissions scenario ^a	Little change, possible decrease in dry season in the north ^b	Decreased frequency but increased average intensity ^{a,b}
FSM	105,000	Over 600 islands ranging from mountainous volcanic islands to low coral atolls	Decrease ^a	Increase ^b	Decreased frequency but increased average intensity ^{a,b}
Fiji	887,000	2 large and over 300 smaller volcanic islands	Slight decrease ^a	No consensus, with model results spanning moderate decreases to large increases ^c	Decreased frequency but increased average intensity ^{a,b}
French Polynesia	277,000	Over 100 islands with mixed terrain	No country-specific projections found	No country-specific projections found	No country-specific projections found
Guam	173,000	One volcanic island (544 km ²)	Uncertain, but may increase if El Niño events become more intense ^d	Moderate increase ^e	Less frequent weak cyclones and more frequent strong cyclones, track location may move poleward ^{e,f}
Kiribati	115,000	34 widely dispersed, mostly low coral islands	Overall slight decrease, but increased duration of extreme droughts under a very high emissions scenario for the Line Islands ^a	Increase ^b	No country-specific projections found
Marshall Islands	55,000	34 small, low-lying islands	Decrease ^a	Increase ^b	Decreased frequency but increased average intensity ^{a,b}
Nauru	11,000	One small raised coral atoll (21 km ²)	Overall decrease, but frequency of mild droughts may increase slightly under a very low emissions scenario ^a	Probable increase, with models spanning slight decrease to very large increase ^c	No country-specific projections found
New Caledonia	272,000	One large and five smaller islands with varying geography	No country-specific projections found	No country-specific projections found	No country-specific projections found
Niue	2,000	One raised coral atoll (269 km ²)	Decrease under a very high emissions scenario ^a	No consensus ^b	Decreased frequency but increased average intensity ^{a,b}
Northern Mariana Islands	56,000	14 small islands, volcanic to the north and limestone to the south	No country-specific projections found, but outlook for (nearby) Guam is uncertain ^d	No country-specific projections found, but moderate increase projected for Guam ^e	No country-specific projections found, but less frequent weak cyclones and more frequent strong cyclones projected for Guam, track location may move poleward ^{e,f}

(continued)

Table 1 | continued

Country	Population	Description	Future change in drought risk	Future change in average rainfall	Future change in tropical cyclone risk
Palau	18,000	8 large and >300 smaller islands, ranging from high volcanic to low coral islands	Decrease ^a	Increase, especially in the wet season ^b	Decreased frequency but increased average intensity ^{a,b}
PNG	8,559,000	>150 mostly mountainous islands, includes eastern half of New Guinea	Overall decrease, but frequency of mild droughts may increase slightly under a very low emissions scenario ^a	Increase in most areas ^b	Decreased frequency but increased average intensity ^{a,b}
Samoa (and American Samoa)	253,000	2 main and 20 smaller islands (Samoa), 1 main and 6 smaller islands (American Samoa), volcanic archipelago	Slight decrease ^a	Little change projected by most models although some show moderate increases/decreases ^c	Less frequent weak cyclones and more frequent strong cyclones under moderate emissions scenarios but less frequent strong cyclones under high emissions scenario ^f
Solomon Islands	681,000	Archipelago with around 900 volcanic islands and small atolls	Decrease ^a	Slight increase ^b	Decreased frequency but increased average intensity ^{a,b}
Tokelau	2,000	Three small, low-lying coral atolls	No country-specific projections found, but slight decrease projected for nearby countries ^a	No country-specific projections found, no consensus for nearby countries ^{b,c}	No country-specific projections found but decreased frequency and increased average intensity projected for nearby countries ^a
Tonga	100,000	169 islands, volcanic to the west and mostly low coral limestone to the east	Slight decrease ^a	No consensus ^b	Decreased frequency but increased average intensity ^{a,b}
Tuvalu	10,000	Three reef islands and six atolls, low-lying	Decrease ^a	No consensus ^b	Decreased frequency but increased average intensity ^{a,b}
Vanuatu	282,000	Over 80 islands of volcanic origin	Slight decrease ^a	No consensus, ensemble mean close to zero but some individual models predict moderate increases/decreases ^c	Decreased frequency but increased average intensity ^{a,b}
Wallis and Futuna	12,000	Two main volcanic islands	No country-specific projections found, but slight decrease projected for nearby countries ^a	No country-specific projections found, no consensus for nearby countries ^{b,c}	No country-specific projections found but decreased frequency and increased average intensity projected for nearby countries ^a

^aAustralian Bureau of Meteorology & CSIRO (2014).^bCSIRO *et al.* (2015).^cEvans *et al.* (2016).^dPREL (2014).^eKeener *et al.* (2015).^fWang (2016).

related such that both tend to be more or less severe in the same model (Samanta *et al.* 2019). Most of the general circulation models (GCMs) from the Coupled Model Intercomparison Project (CMIP5) locate the ITCZ slightly north of its observed position, and the simulated ITCZ is unrealistically wide and intense (Stanfield *et al.* 2016). Brown *et al.* (2013b) note that simulations of the SPCZ tend to underestimate its diagonal slope (i.e. the band is too zonal). In addition to these known modelling issues, many islands in the Pacific are too small to be well represented in GCMs, which typically have grid cell sizes in the order of 100 km² or larger, and downscaling efforts are hampered by a lack of reliable long-term climate data (Nurse *et al.* 2014).

Individual models disagree on the magnitude and direction of future shifts in mean SPCZ and ITCZ positions (Brown *et al.* 2013b; Byrne *et al.* 2018). While this lack of consensus tends to produce little shift in the ensemble average, it reflects a wide range of possible futures and should not be interpreted as a prediction that the convergence zones will not move (Evans *et al.* 2016). In recent decades, the ITCZ has narrowed and its precipitation rate has intensified (Wodzicki & Rapp 2016). GCM simulations suggest that these changes will continue as the climate warms (Lau & Kim 2015).

Recent research points to more frequent and intense ENSO events under high emissions scenarios, and some studies suggest that warming-induced changes have already begun. For example, satellite observations show that the intensity and frequency of El Niño events are increasing in the central-equatorial Pacific (Lee & McPhaden 2010). CMIP5 models suggest both the frequency and intensity of ENSO events have increased since the pre-industrial age (Power *et al.* 2017). The underlying mechanisms driving El Niño development may be shifting as the ocean warms variably across the Pacific. Wang *et al.* (2019) suggest that initial warm SST anomalies are increasingly likely to emerge in the west and propagate east, which is associated with strong El Niño events. Cai *et al.* (2012) analysed results from CMIP5 and the earlier iteration CMIP3 models, concluding that zonal SPCZ events (associated with strong El Niño events, like the extreme 1997–1998 El Niño) would probably become more common in a warmer world, although this conclusion was not supported by the regional climate

model (RCM) simulations of Evans *et al.* (2016) that used bias corrected sea surface temperatures.

Future climate projections for the Pacific Islands are highly uncertain, firstly because of the deficiencies in model simulations of the ITCZ, the SPCZ and ENSO, and secondly because small shifts in these convergence bands have large implications for water availability in small islands. However, in a warmer climate, the detrimental impacts of ENSO-related droughts may worsen even if the ENSO events themselves do not change (Fasullo *et al.* 2018).

Changes in drought risk

Droughts can have detrimental impacts on small island nations, compromising freshwater availability, groundwater resources, food security, public health and economic activity (Annamalai *et al.* 2015; Barkey & Bailey 2017). Drought in the Pacific Islands is strongly influenced by ENSO-related shifts in the convergence zones (Ludert *et al.* 2018). Prolonged ENSO-related droughts, which can be several years in duration, result in substantial contraction of freshwater lenses. In countries with low annual rainfall, like Kiribati, severe droughts have caused very small islands to be abandoned due to the loss of groundwater resources (White *et al.* 2008).

There is a perception of increased drought in many Pacific Island nations over recent decades (McGree *et al.* 2016), but it is unclear whether this relates to climate change or natural variability. Deo (2011) showed statistically significant decreases in the Standardized Precipitation Index (SPI) in Fiji between 1949 and 2008, but this was mainly driven by drying between 1969 and 1988. A subsequent recovery still left annual rainfall totals in 1989–2008 below those of 1949–1968, leaving the possibility of a long-term drying trend open but unconfirmed. McGree *et al.* (2016) found statistically nonsignificant and spatially mixed increasing trends in drought frequency, magnitude and duration at most locations between 1951 and 2010.

Limitations in GCM simulations of the ITCZ, SPCZ and ENSO (see the ‘Changes in the SPCZ, ITCZ and ENSO’ section) lead to high uncertainty in future projections of drought risk. Low-frequency oscillations (e.g. IPO) remain poorly understood, and it has recently been suggested that they may be driven by external forcing rather than intrinsic

cycles (Mann *et al.* 2020). It follows that the outlook for the IPO under climate change is unknown. The available knowledge on future drought risk for each country is provided in Table 1 and mapped in Figure 4. In most cases, a decrease in drought risk is projected, associated with an increase in average rainfall (see the ‘Changes in extreme rainfalls, antecedent conditions and flood risk’ section). It should be noted that most of these projections are based on SPI, which is limited because it considers rainfall only and not changes in temperature or evaporative demand (Vicente-Serrano *et al.* 2010; Zarch *et al.* 2015; Homdee *et al.* 2016). It is possible that rising temperatures will drive higher vapour pressure deficits in the future, increasing evaporative demand (Stephens *et al.* 2018b) and increasing drought risk.

Changes in extreme rainfalls, antecedent conditions and flood risk

Extreme rainfall (excluding tropical cyclones, covered in the ‘Changes in tropical cyclones’ section) is expected to increase over the Pacific Islands, even in those regions where average rainfall is projected to decrease. Modelling results suggest that rainfall events that currently have a 5% Annual Exceedance Probability (AEP) may become more frequent, reaching a 10–20% AEP by 2090 depending on the emissions scenario (Australian Bureau of Meteorology & CSIRO 2014). Theoretically, a general increase in extreme

rainfall globally is expected as atmospheric moisture holding capacity increases with warming (Utsumi *et al.* 2011), and some (limited) observational records support this expectation in the Pacific (CSIRO *et al.* 2015). However, high natural variability – especially at decadal scales – hampers efforts to detect significant trends.

The links between rainfall changes and flood risks are not straightforward. Whether increases in extreme rainfall translate into heightened flood risk depends on antecedent catchment conditions. Decreases in average rainfall, leading to (typically) drier antecedent conditions could mitigate increases in flooding due to more intense extreme rainfall (Hettiarachchi *et al.* 2019). Alternatively, wetter average conditions could amplify increases in extreme rainfall and further increase flood risk. As such, understanding future flood risk requires both extreme and average rainfall changes to be considered. The geography of the PICs will also affect the links between extremes and antecedent conditions. For example, on high volcanic islands, with steep catchments and high rainfall intensities, antecedent conditions may only have limited impact on floods due to limited infiltration. In limestone islands, changes in extreme rainfalls may not lead to any changes in flood risk, due to the high permeability of the catchments and general lack of surface water. Even within one country, there can be substantial variability between different islands or parts of the same island in terms of soil permeability and its influence on

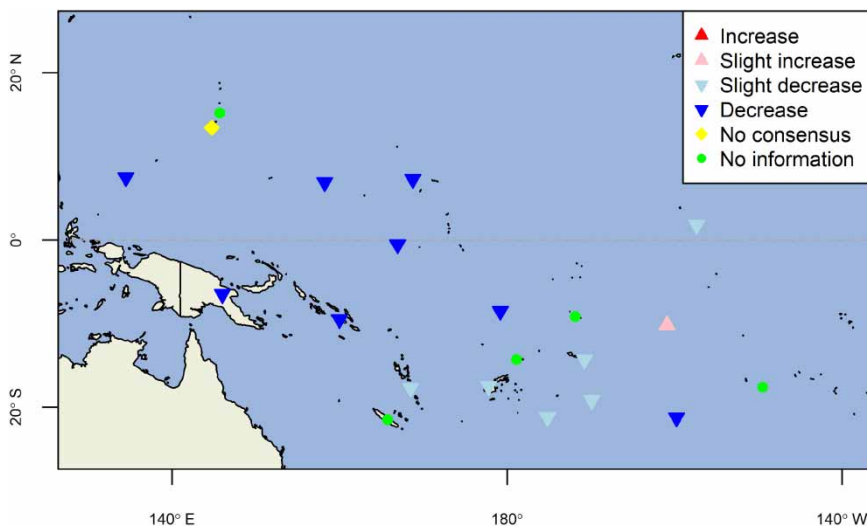


Figure 4 | Predicted future changes in drought risk for each PIC based on available information.

surface water (Macpherson & Macpherson 2017). McAnaney *et al.* (2017) analysed a long flood record for Ba River (Fiji) and found no significant change in flood risk.

PICs located within the convergence zones are broadly projected to see increases in mean annual rainfall, associated with increased moisture convergence due to warmer air temperatures (Australian Bureau of Meteorology & CSIRO 2011; CSIRO *et al.* 2015). However, temporal and spatial variation is likely. Widlansky *et al.* (2013) analysed a multi-model ensemble containing 76 different warming experiments and found that moderate warming (i.e. 1–2 °C) would likely decrease rainfall in the southwest SPCZ, while intense warming over 3 °C could drive wetter conditions. These findings were backed up in a later study that used a set of dynamically downscaled RCM results (Evans *et al.* 2016).

Peer-reviewed research describing future rainfall changes for individual small island nations is only available for a few countries (Brown *et al.* 2013a; Evans *et al.* 2016). However, a report released in 2015 by Australian government agencies provides qualitative information on likely future rainfall changes across the Pacific Islands (CSIRO *et al.* 2015). Based on the available information, Table 1 summarises future average rainfall expectations for small Pacific Island nations. Together with rainfall changes, sea-level rise will influence river tailwater conditions and potentially increase fluvial flooding in coastal areas (see the ‘Sea-level rise’ section).

Changes in tropical cyclones

Tropical cyclones are behind many climate-driven catastrophes, including three-quarters of natural disasters in the Southwest Pacific (Diamond *et al.* 2013; Magee *et al.* 2020). Even from a distance, they can cause severe coastal impacts due to propagating waves (Nurse *et al.* 2014). At the global scale, a decreased frequency but increased intensity of cyclones is projected (Knutson *et al.* 2010; Peduzzi *et al.* 2012; Knutson *et al.* 2015), but the results vary between regions. A decrease in the number of cyclones is (perhaps unintuitively) expected because the minimum SST required for deep convection, a precursor to cyclone development, is likely to increase in a warmer climate (Walsh *et al.* 2012). This minimum threshold already appears to be rising

based on satellite observations (Johnson & Xie 2010). For the South Pacific, simulations presented by Walsh *et al.* (2012) suggest decreased frequency of tropical cyclones, with results encompassing large decreases (>50%) through to slight increases. Decreased cyclone frequency is also projected for the Northwest and Southeast Pacific basins, but with low confidence in projections for the Northwest basin (Australian Bureau of Meteorology & CSIRO 2011). The average intensity of cyclones in the Southwest Pacific may decrease (Knutson *et al.* 2015), although some studies report wide-ranging model results including increases and decreases (Walsh *et al.* 2012). Increased cyclone intensity is likely in the Northwest Pacific (Knutson *et al.* 2015).

Sea-level rise

Currently, the global sea level is rising at around 3–4 mm/year. Sea-level rise is projected to range from 0.3 to 2.0 m by 2100, depending on methodology and emission scenarios, due to increased melting glaciers and ice sheets and thermal expansion of the oceans (Oppenheimer *et al.* 2019). Coastal erosion and inundation due to sea-level rise threaten existing infrastructure and freshwater supplies on Pacific Islands. Shoreline regression due to long-term sea-level rise results in a thinner freshwater lens, which can result in a significant decrease in freshwater availability for atolls and limestone islands. In general, small islands are more vulnerable than larger islands, due to relative thinness of the freshwater lens, and less ability for a compensatory rise in the groundwater table (Werner *et al.* 2017). For volcanic and composite islands with coastal aquifers, saltwater intrusion and the landward movement of the fresh–saltwater interface increase the likelihood of salinisation of coastal bores and the availability of freshwater for coastal communities.

Due to their low topography and geographic isolation, coral atolls are highly vulnerable to overtopping from storm surges, high tides associated with tropical cyclones, and tsunamis. Overtopping events contaminate the freshwater lens with saltwater leading to a temporary decrease in freshwater availability, destroying crops and causing water to be unsuitable for drinking for 6–12 months (Weir *et al.* 2017; Connell 2018).

Year-to-year variability in Pacific sea level can be up to 0.2 m, largely due to ENSO-related changes in temperature,

pressure and wind patterns (CSIRO *et al.* 2015). During La Niña events, strengthened trade winds cause higher than normal sea levels, which can lead to higher storm surges in the Western Pacific (CSIRO 2015; Connell 2018). Sea-level rise is expected to amplify the effects of extreme sea levels, increasing coastal flooding. For example, widespread inundation of Pacific Islands in 2008 resulted from remotely generated swell waves that were greatly amplified by anomalously high sea levels caused by sea-level rise and ENSO (Hoeke *et al.* 2013). Flooding is likely to be further amplified by the increase in coastal groundwater levels which reduces available soil storage (Habel *et al.* 2017). The high risk and severe consequences of saltwater contamination to low-lying islands are reflected in the large volume of the recent literature on the topic (e.g. Terry & Falkland 2010; Bailey & Jensen 2014; Holding & Allen 2015).

THE INTERSECTION OF CLIMATE CHANGE IMPACTS WITH HUMAN-WATER SYSTEMS

This section focuses on how climate change adaptation for water supply and flood protection systems in the Pacific

(discussed in the ‘Typical infrastructure – water supply and flood mitigation’ section) could be approached using principles of Humanitarian Engineering. Figure 5 shows links between the climate change impacts identified in the ‘What is known and not-known about climate change impacts on the Pacific’ section and how these relate to water supply and flood planning in the Pacific context. Each of the identified cultural and social factors will influence climate change adaptation. The principles of Humanitarian Engineering guide how adaptation projects should be approached with a focus on empowering communities. This section is structured to give a brief overview of the expected resilience of typical climate change adaptation options for water systems in the Pacific, and then, a strengths-based approach is outlined that considers how the culture, history and geography of the Pacific Islands can be used to inform robust climate change adaptation options.

Although a strengths-based approach to potential solutions is vital, it is also important to understand that existing vulnerabilities of Pacific Islanders may be magnified by climate change. Specific vulnerabilities include population growth and rapid urbanisation, pollution and unsustainable resource use (Weir *et al.* 2017). The

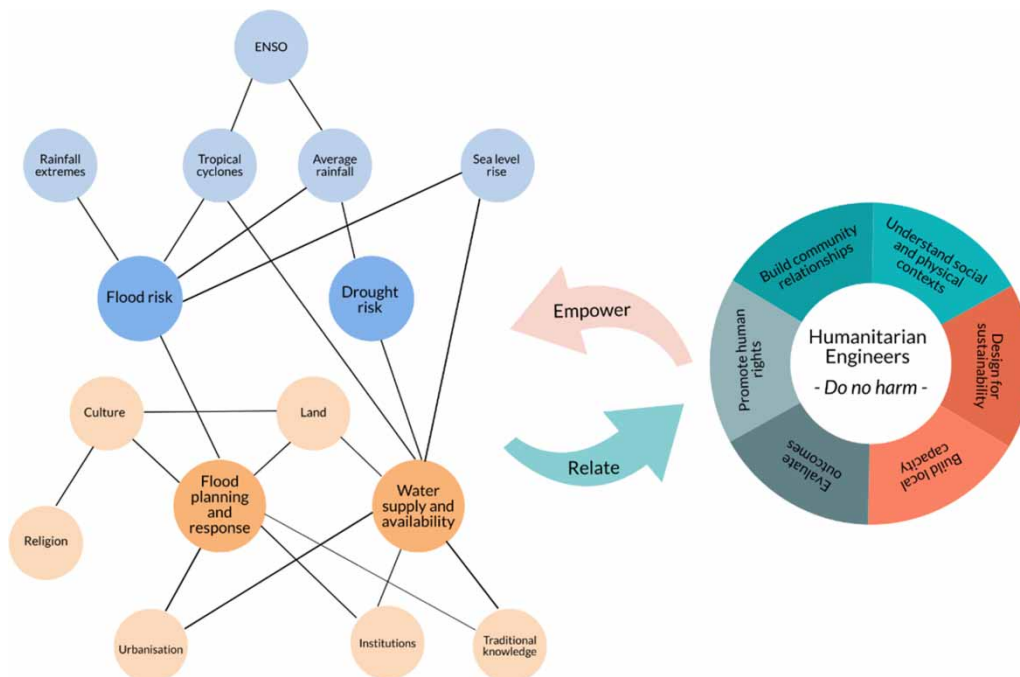


Figure 5 | Influence diagram of climate change impacts on water availability and flood planning and responses in the Pacific. Arrows represent influences and not causation.

intersection of urbanisation with climate change and hydrological risk is covered in the 'Urbanisation' section.

Land degradation is another existing stress in the Pacific (Weir *et al.* 2017) that can directly influence hydrological risk. A clear illustration of this interaction is provided by the case study of Yadua Island, Fiji (Martin *et al.* 2018) where land clearing on unstable volcanic slopes led to a landslide after heavy rainfall destroying part of a village. The village had earlier been relocated from its original coastal location due to ongoing shoreline erosion because of mangrove clearing and the damaging impacts from Tropical Cyclone Evan in 2012, which destroyed most of the remaining dwellings in the village.

Climate change adaptation for hydrological risks

The IPCC defines adaptation as 'adjustment to actual or expected climate and its effects' in natural or human systems which moderates harm or exploits beneficial opportunities (IPCC 2014). There are many approaches to climate change adaptation. One that aligns well with the general goals of Humanitarian Engineering is community-based adaptation (CBA). CBA emphasises indigenous resources and institutions and empowers vulnerable groups. CBA aims to raise awareness of climate change and incorporate future climate risks into project design activities. Other similar community-based approaches include participatory development, community-based natural resource management and community-based disaster risk management. CBA does not reject the use of external scientific information and experts but Dumaru (2010) recommends that 'community-based approaches can include engineering and engineering-based approaches should include communities in decision making and implementation'.

Table 2 summarises some typical climate change adaptation options that may be appropriate for the Pacific (based on Weir *et al.* (2017); Brown *et al.* (2018); McNamara *et al.* (2020)) and links them to the specific climate change impacts identified in the 'What is known and not-known about climate change impacts on the Pacific' section. The relationship between these options and the cultural and social dimensions of Pacific society are explored in the following sections. Given that the focus of this review is on the intersection of Humanitarian Engineering with climate

and water adaptation, only options listed in Table 2 specifically related to engineering are explicitly discussed.

A qualitative assessment of the climate resilience of drinking water infrastructure in developing countries was carried out by Howard *et al.* (2010). However, the remote geography and sparse population distribution of the Pacific Islands leads to a very different context for infrastructure choices compared with, for example, Africa or South East Asia. Therefore in Table 3, the recommendations of Howard *et al.* (2010) have been revisited to provide more insight into the needs around water supply in the PICs. There are clear distinctions in remote communities between water sources used for consumptive and non-consumptive uses (Elliott *et al.* 2017). Thus, the discussion in Table 3 is mainly focused on drinking water supply. These infrastructure choices are discussed further in the following sections with respect to culture and social perspectives in the Pacific.

Many of the options listed in Table 2 have been traditionally used by communities to manage hydrological risks for many generations. The strengths-based approach of Humanitarian Engineering explicitly uses this knowledge in engineering solutions. For example, Tables 2 and 3 provide specific ideas of how Humanitarian Engineering practice in the Pacific can use a strengths-based approach to infrastructure design, for example house raising rather than relocation, the use of local materials to allow quick repairs following natural disasters or through improved understanding of consumptive water use patterns to enable resilient rainwater tank design. Brown *et al.* (2018) suggest that the adaptation options included in Table 2 are reasonably well understood, but that there is a bigger gap around strategies for institutional and social dimensions of adaptation. The additional challenge of climate change is that the risks can no longer be considered stationary and hence the resilience of some adaptation options in the face of larger future changes is uncertain. In addition, it may not be possible to adapt to some extreme climate impacts and more fundamental societal changes may be required (Weir *et al.* 2017).

As discussed in the following section, adaptation options that do not consider the cultural and societal contexts of communities may not be successful. Even worse, they may lead to maladaptation, whereby unintended consequences of the project lead to more perverse outcomes for

Table 2 | Climate change adaptation options and links to specific climate impacts

Adaptation option	Climate change impact	Links to Pacific context
<i>Infrastructure</i>		
Protective infrastructure such as levees, tidal gates and sea walls	Increased flood risk, sea-level rise	Steep catchments and sparse population densities unlikely to provide good cost benefit ratios in many catchments. Risks of maladaptation if not properly designed (Piggott-McKellar <i>et al.</i> 2020)
Climate resilient drinking water infrastructure	ENSO, flood risk, drought risk, sea-level rise	Refer to Table 3
<i>Household</i>		
Building houses on stilts to reduce vulnerability to flooding	Flood risk	This option is likely to align well with importance of ancestral links to land in Pacific cultures (see 'Culture' and 'Land' sections)
Local materials for houses to allow quick rebuilding after disaster and/or designed to not be damaged in a cyclone	Tropical cyclones, flood risk	'Modern' houses may be preferred and require money and time for rebuilding and there is limited building insurance (Weir <i>et al.</i> 2017). Need to be properly designed for resilience. Use of local materials important for ongoing maintenance (McNamara <i>et al.</i> 2020) particularly post-disaster
Innovative water storage practices	ENSO and drought risk	Refer to Table 3
Rainwater tanks provide buffers against seasonal (or longer) droughts	ENSO and drought risk	Refer to Table 3
Preparing for extreme weather events by using particular planting ^a	Tropical cyclones	Rural communities are often based around subsistence farming and hold deep TK regarding these practices. Urbanisation pressures in the Pacific mean that younger generations may not have the same knowledge (Weir <i>et al.</i> 2017).
TK of diversity of crops with some having drought resistance and others prolonged dry spells ^a	ENSO and changes in seasonal rainfall patterns	Rural communities are often based around subsistence farming and hold deep TK regarding these practices. Urbanisation pressures in the Pacific mean that younger generations may not have the same knowledge (Weir <i>et al.</i> 2017).
New crops and agricultural products (e.g. pigs, chickens and beehives)	ENSO, increased rainfall, tropical cyclones	Diversity of income for subsistence farmers to protect climate extremes. Reported perverse outcomes from pig projects due to high status linked to their ownership (McNamara <i>et al.</i> 2020) and poor understanding of cultural context
Preservation of crops – fermentation or storage ^a	Tropical cyclones	Rural communities are often based around subsistence farming and hold deep TK regarding these practices. Urbanisation pressures in the Pacific mean that younger generations may not have the same knowledge (Weir <i>et al.</i> 2017)
<i>Land-use change</i>		
Managed retreat and relocation, floodplain planning	Increased flood risk, sea-level rise	Strong ancestral links to land and land tenure structures affect the viability of this option (see the 'Land' section). Rapid urbanisation and poor institutional planning around informal settlements pose particular risks for floodplain planning (see the 'Urbanisation' section)

(continued)

Table 2 | continued

Adaptation option	Climate change impact	Links to Pacific context
<i>Institutional</i>		
ENSO prediction (seasonal forecasting)	ENSO	TK of climate variability in the Pacific can be leveraged in improving communication of seasonal forecasts and understanding local impacts (see the 'Traditional knowledge' section)
Flood forecasting systems	Increased flood risk, sea-level rise	Collective nature of Pacific culture can improve understanding of exposure to hydrological hazards and estimates of risk (see the 'Culture' section). TK, e.g. environmental changes seen prior to imminent rain can be leveraged in improving community preparedness (see the 'Traditional knowledge' section)
Tropical cyclone outlooks	Tropical cyclones, sea-level rise	Example of TK of tropical cyclones and resulting better preparation attributed to low death rate from Cyclone Pam in Vanuatu (see the 'Traditional knowledge' section)

^aNon engineering option not considered further in the 'Pacific links between cultural, historical and community values with adaptation options' section.

the community than even the status quo (Piggott-McKellar *et al.* 2020). Projects where sea walls have trapped water on the landward side are examples of such maladaptation (McNamara *et al.* 2020; Piggott-McKellar *et al.* 2020).

It is often argued that DRR and climate adaptation should be complementary activities, with seminal work on the theoretical links between development, adaptation and disaster response developed by Schipper & Pelling (2006). As evident in the 'What is known and not-known about climate change impacts on the Pacific' section, climate change impacts in the Pacific are often linked to extreme events such as cyclones, floods and droughts. Therefore, DRR needs to be central to climate change adaptation. However, often different institutions are involved and the scales of impact may be different (local versus global); in both cases, coordination across policy and legislation could be improved (Gero *et al.* 2011). As identified in the 'SDGs relevant to water and climate change in the Pacific' section, there is limited data available at a national level on DRR, although this may reflect the challenges of sparse populations and under-resourced institutions (e.g. the 'Institutions' section), with local projects not nationally reported. Humanitarian Engineers can play a part in both disaster response and ongoing development projects linked to climate adaptation given there is often potential to address both immediate and long-term risks synergistically. In such cases, designs need to be resilient to, for example,

increased rainfall extremes as well as changed seasonal or interannual patterns of rainfall.

Pacific links between cultural, historical and community values with adaptation options

Weir *et al.* (2017) provides a general overview of the social and cultural issues raised by climate change in PICs. They note that climate-related disasters in the Pacific are not new and the importance of traditional knowledge (TK) around this is discussed in the 'Traditional knowledge' section. Climate change impacts that are unprecedented in recent history include changes in rainfall extremes due to intensification of the hydrological cycle, sea-level rise and ocean acidification (not covered in this review). All these climate hazards impact food (fisheries and crops), water supply, tourism and infrastructure, particularly on the coast. Weir *et al.* (2017) identify equity issues that are important to consider when planning for and responding to climate impacts. Like in the SDGs, equity around gender, education, health and age is emphasised. Of particular relevance to PICs is the importance of integrating place and land into climate change responses. Differences between inner and outer islands, urban and rural communities and landowners, leasees and informal communities need to be acknowledged. These issues are covered in the 'Land' and 'Urbanisation' sections.

Table 3 | Links between water supply system alternatives and climate change risks in the Pacific (adapted from Howard *et al.* 2010)

Infrastructure	Key threats (globally)	Pacific context
Boreholes	Drying and salinisation may be issues, but boreholes have high adaptability.	Remote outer islands are difficult to access with drill equipment. There is a difference between community and household boreholes, with the former more likely to be deeper and provide more reliable supply during periods of drought (Chan <i>et al.</i> 2020).
Dug wells	Microbial pollution and year-round availability already a problem. Increased drying and salinisation with limited adaptation options.	Salinisation due to overtopping events on atoll islands. High permeability and shallow groundwater tables mean atolls are at high risk of contamination from landfill, sewage and agriculture (Werner <i>et al.</i> 2017).
Protected springs	Reduced flow in drying environments or in dry seasons	Spring water is used by over 20% of households for drinking water in some communities in Solomon Islands (Elliott <i>et al.</i> 2017), with increasing importance in the dry season when tanks are used less.
Household rainwater harvesting	Increasing variability and intensity of rainfall may not provide year-round supply.	Tanks may not be big enough to provide all water needs (McNamara <i>et al.</i> 2020). There is a gap in understanding how water use needs are prioritised at such times (MacDonald <i>et al.</i> 2017).
Gravity-fed river systems	Not discussed	Catchments in the Pacific tend to be relatively small and rainfall seasonal, so river-based systems are already not appropriate in some locations. Many islands do not have permanent surface water resources. However, in some locations, e.g. Solomon Islands, up to 90% of households use river water, although relatively rarely for consumptive use (6–11%) (Elliott <i>et al.</i> 2017).
Treatment processes	Processes are resilient but climate change may increase treatment requirements	Remote and distributed geography increases cost and potential for maintenance delays, particularly following extreme events/disasters. Maintenance can be affected by lack of resources in water authorities. Back-up rainwater tanks are suggested as one alternative for mitigating such risks (MacDonald <i>et al.</i> 2017).
Piped water	Damage to systems can impact large populations. Highly complex systems, with options for more robust design and operation – depends on management and the financial position of the water authority.	May be strongly groundwater dependent in some parts of the Pacific so sustainability of use and impacts of climate change on recharge need to be considered (Carrard <i>et al.</i> 2019).
Alternative sources	Not discussed	Population densities unlikely to be high enough for desalination to be cost efficient. Access to parts and maintenance needs to be considered (cost and availability). Although not specific to alternative water sources, examples of poor project outcomes due to parts not being easily available are described in McNamara <i>et al.</i> (2020). Bottled water is used by 3–6% of households (Elliott <i>et al.</i> 2017). Some households in outer regions of the Republic of the Marshall Islands report cooking with seawater (Elliott <i>et al.</i> 2017).

Culture

Adger *et al.* (2013) describe culture as ‘the symbols that express meaning, including beliefs, rituals, art and stories that create collective outlooks and behaviours, and from which strategies to respond to problems are devised and implemented’. It involves the distinctive features of a society including spiritual, material, intellectual and emotional aspects (Kuruppu 2009). Crook & Rudiak-Gould (2018) caution that ‘such Eurocentric terms are poor substitutes for particular Oceanic conceptualisations, and merely proxies for specific indigenous references and philosophies’. It is these ‘references and philosophies’ that are vital for Humanitarian Engineers to work with when approaching climate change adaptation around hydrological risk.

Culture is dynamic and is therefore also shaped by climate change (Adger *et al.* 2013). Where culture can change, this can lead to beneficial changes in response (Adger *et al.* 2013). Changes in culture may consider new narratives or alternative meanings, for example as explored by Fair (2018) with respect to the links between story of Noah and climate change thinking (see the ‘Religion and spirituality’ section). Climate change responses that ‘focus on physical risks ... are likely to fail without a cultural understanding of risk’ (Adger *et al.* 2013). This point is further highlighted by Nunn *et al.* (2016) who suggest that failure over the last 25 years in communicating climate change in the Pacific can be attributed to ‘acultural, secular’ messaging. Further than just communication, cultural values need to be integrated into planning and management of water and climate change adaptation (Kuruppu 2009). In a review of 32 CBA initiatives in the Pacific across 14 case study sites, McNamara *et al.* (2020) found that in some cases, low-performing initiatives may have been associated with poor alignment of the projects with the culture. High-performing projects were more likely to be appropriate to the local context, with these projects proportionally more often locally funded and/or implemented by NGOs, further emphasising the importance of understanding local culture in implementing successful projects.

Globally, and particularly in the Pacific, culture is tied to place – such that physical locations have community meaning. Changes in place due to climate change may, therefore, be perceived as a loss if culture is changed as a result (Adger

et al. 2013). The links between place and land and its intersection with climate change impacts are explored further in the ‘Land’ section. Place attachment has been shown to increase flood preparedness because people are socially and economically invested in a region (Adger *et al.* 2013). There are also distinctively Pacific ideas of time. Islanders may express a ‘waiting’ faith in the unfolding future which is very different from the approach recommended in risk and vulnerability assessments (Rubow & Bird 2016). This ‘waiting’ faith can often be construed as fatalism. This is relevant to planning for natural disasters such as flood and cyclones and needs to be considered in how messages around risks are communicated.

Collectivism is central to Pacific culture, which includes ‘notions of interconnectedness, belonging, sharing and reciprocity’ (Rubow & Bird 2016). For example, in Kiribati belonging to a community group (e.g. a village or church) is a priority (Kuruppu 2009). The impact of this collectivism on how climate change adaptation should be approached is illustrated by the work of Brown *et al.* (2018) who examined the relationship between responses to Tropical Cyclone Evan (2012) and the cultural background of the affected communities in Fiji. They found that the collective nature of iTaukei society means that even those who were not struck by the cyclone were affected, which impacted their future decision making. Brown *et al.* (2018) also found that risk-sharing networks and land tenure systems enable iTaukei society to better absorb natural shocks. It is important to understand how individuals change their risk perceptions after experiencing natural hazards (Brown *et al.* 2018) because it is likely that natural hazards will become more frequent and/or more severe under climate change. Although there is increasing research into the effects of natural hazards on risk attitudes, perceptions and behaviour, this has been primarily focused on developed countries and further research is required in areas like the Pacific.

Kinship and hierarchy are important concepts in the Pacific. Hierarchy has traditionally been based around seniority (Neef *et al.* 2018; Lee 2019), with older men holding positions of power and children and youth generally having low status. It has been suggested that leveraging traditional leadership structures can be useful in implementing climate adaptation in the Pacific (Fletcher

et al. 2013). However, two potential issues are also evident from the literature. Neef *et al.* (2018) point out that individual families may have constrained opportunities for determining their own adaptation options that differ from those supported by the community leaders. Secondly, Nunn (2009) suggests that inspiring climate action through school education may 'not bring about change in the position of societies on these issues as quickly as might be expected in other, less hierarchical societies' because of the lower status of children.

For Humanitarian Engineers around the world, a key tenet of successful projects is the importance of building strong relationships with communities. This aligns well with the Pacific context. *Talanoa* is a Fijian term, understood across the Pacific, describing the importance of 'inclusive, participatory and transparent dialogue' (United Nations Framework Convention on Climate Change 2018). This dialogue is based around storytelling and building relationships based on trust and respect. The *Talanoa* process may be perceived as time-consuming, but this engagement is vital for Humanitarian Engineers to ensure positive, sustainable project outcomes.

Other important aspects of culture in the Pacific with respect to Humanitarian Engineering and climate change adaptation are the role of TK in understanding and managing local environmental changes and religion in shaping the response of communities to risk and external changes. These issues are discussed in the 'Traditional knowledge' and 'Religion and spirituality' sections.

Traditional knowledge

Pacific Island communities have extensive knowledge of local environmental changes, gained over generations of observing weather, climate and impacts on the environment (Dumar 2010; McMillen *et al.* 2014). TK is 'location specific, acquired through long-term observation of (and interaction with) the environment, and transferred through oral traditions from generation to generation' (Ifejika Speranza *et al.* 2010). TK weather forecasts rely on close observation of the behaviour of plants and animals, and meteorological and astronomical phenomena and encompass a range of scales, from screeching kingfishers signifying imminent

rain, to early flowering of mango trees during the cyclone season of 2019 (Chand *et al.* 2014; Chambers *et al.* 2019).

Major environmental changes that Pacific Island cultures have survived and adapted to over generations are of similar magnitude to those expected from climate change (McNamara *et al.* 2020). Groups with oral histories of extreme natural events, such as in Fiji and PNG, may have better collective knowledge of the frequency and magnitude of natural disasters than groups without such traditions (Brown *et al.* 2018). This is important because it enables communities to estimate risk more accurately, and therefore plan and respond appropriately, to floods (Adger *et al.* 2013). TK, which often includes practical knowledge for enduring natural disasters, is therefore a strength for disaster response and climate adaptation (Weir *et al.* 2017; Brown *et al.* 2018).

The benefits of using TK to supplement western science are increasingly being recognised (Chand *et al.* 2014). In response to the impact of ENSO variability on Pacific climate, especially extremes, a considerable focus has been placed on producing robust seasonal meteorological forecasts. Seasonal forecasts enable water managers to plan for shortages. They are particularly important for atoll countries relying on freshwater lenses and form an important component of climate extreme early warning systems. However, even state-of-the-art seasonal forecasting systems have constraints, such as their inability to resolve small-scale phenomena, and the lack of *in situ* data for calibration and verification for many small islands. In addition, slow internet speeds, budget constraints and limited resources can limit the utilisation of forecasts by governments (Chand *et al.* 2014), and in general, there are low rates of uptake of contemporary forecasts amongst communities (Chambers *et al.* 2019). Participatory approaches that integrate TK with model predictions can improve the reception of forecasts by local communities in the Pacific and ensure forecasts are delivered in community-accessible formats, leading to improved decision making and disaster prevention (Chand *et al.* 2014). For example, the low death rate in Vanuatu following Category 5 Tropical Cyclone Pam in 2015 is attributed in part to the effectiveness of the locally appropriate early warning system combined with the use of TK by communities to prepare by storing water, cutting down banana palms and sheltering in cyclone-safe housing (Handmer & Iveson 2017). While other factors

like the slow movement of the cyclone also limited its impact, timely warnings with maximum reach, accompanied by preparedness training, are key strategies that can be applied to future events (Handmer & Iveson 2017).

The Pacific TK Database (Chambers *et al.* 2017) has been developed to preserve TK related to weather and climate and facilitate its use by national meteorological services (NMSs) whilst safeguarding culturally sensitive information. As of 2017, the TK Database was trialled in four PICs. Methods for combining traditional and contemporary forecasts, considering the potentially substantial differences between the two perspectives, are still under development (Plotz *et al.* 2017). Methods fall into either consensus approaches or science integration approaches in which TK is 'validated' to produce forecasting models. Both approaches have advantages and disadvantages, and differ in their requirements for human resources, historical data and community involvement, as well as in their cultural sensitivity (Plotz *et al.* 2017).

Religion and spirituality

Understanding the way that risk is perceived by individuals and communities is vital in considering and communicating climate change adaptation options. Community responses to extreme weather and climate change are shaped by myth and religion (Fair 2018), and risk perception is also influenced by spiritual beliefs. Following colonialism in the Pacific, Christianity has become a strong system in PICs. Nunn *et al.* (2016) argue that secular messaging for climate change projects means that communities do not engage sufficiently with them and can even reject them. Religious organisations in the Pacific have significant financial, political and institutional power and, therefore, can have an influential role in climate change adaptation and advocacy. 'Churches are ... potentially important – and conflicting – actors in the cultural modelling of new time/place configurations of climatic changes' (Rubow & Bird 2016). However, because churches require large financial contributions from followers, they may impede climate adaptation if people are left with less material resources (Kuruppu 2009). There are limits to the role of the church because of monetary and technical constraints, as well as other more immediate threats in communities (Rubow & Bird 2016). One way to leverage the strength of religion in the Pacific in

Humanitarian Engineering and climate change adaptation is through the 'power and potency of religious ideas themselves' (Fair 2018).

Christianity is not the only religion in the Pacific and Hulme (2009) and Rubow & Bird (2016) highlight that religious heterogeneity needs to be considered. For example, Fair (2018) shows that although only 3.5% of the population in Vanuatu exclusively identify with indigenous knowledge and practice, it is still culturally very important and the conversion to Christianity has not led to a total loss of indigenous beliefs and practices. Similarly, in Kiribati, traditional spiritual beliefs are practised amongst families, despite widespread Christianity (Kuruppu 2009). The links between this TK and climate change adaptation for hydrological risks were explored in the 'Traditional knowledge' section.

Fair (2018) argues that Biblical stories have the 'potential for more-than-scientific yet not anti-scientific responses to climate change that are locally meaningful and morally compelling'. Adopting targeted approaches could help Humanitarian Engineers work effectively within religious traditions in the Pacific, particularly if they are used to working in more secular societies. Firstly, Humanitarian Engineers should understand and work within the existing power structures and ensure that communication and projects are compatible with the religion and spirituality of the PIC communities. This may involve including religious organisations in projects in ways that would not be considered in more secular communities. Secondly, Humanitarian Engineers need to avoid placing further burdens on organisations, including churches, that are already overcommitted. Overall, technical constraints in the Pacific need to be addressed through systemic capacity building as well as strong institutions (see the 'Institutions' section) that have adequate resources to maintain and nurture their personnel.

Land

Water infrastructure projects that do not consider the social and cultural context in which they are set, as well as the environmental and resource constraints, have little chance of success (White *et al.* 2008). For example, in Kiribati traditional land ownership includes possession of groundwater resources and is of fundamental importance

to the I-Kiribati people and a source of status (Kuruppu 2009). Population growth, groundwater pollution and public health issues in the densely populated capital of South Tarawa led the Government to declare ownership over large areas of the island for Water Reserves, which, despite land rights compensation, resulted in conflict with traditional land owners and vandalism of some water infrastructure (White *et al.* 2008).

Land tenure is of similar importance in Fiji, as land is the link connecting individuals with their social groups. The basic land-owning social units are the *mataqali* comprised of several family groups claiming descent from a common ancestor. *Mataqali* subdivisions own about 90% of the total land area in Fiji (Weber 2016). There have been several well-publicised disputes over land rights between the Fijian Government and *mataqali* traditional owners. In 1999, traditional owners closed the pipeline that brings water from the Varage Dam supplying Lautoka, Fiji's second biggest city, including the hospital (Weber 2016). Similar disputes have occurred over land leasing arrangements for hydro-electric plants, the airport and agricultural land.

Issues of land and water ownership are a significant stumbling block to providing water infrastructure in the Pacific (White *et al.* 2006). The development of water management policies and infrastructure projects must be compatible with sociocultural norms and include community participation at the national and local village levels. While stakeholder and community participation are essential for the success of water supply projects, they are rarely addressed in practice (Werner *et al.* 2017). In part, this is due to the reliance on aid funding from international governments and donor organisations who are over-reliant on technological solutions and unwilling to fund long-term projects (White *et al.* 2008; Werner *et al.* 2017). In addition, coordination between donors and international organisations is lacking (White *et al.* 2006).

Traditionally, floodplain managers may consider a range of policy and structural responses to reduce flood exposure. These may include channel modifications; levees or flood walls to protect infrastructure on the floodplain; removing choke points (e.g. by increasing the size of culverts or replacing with a bridge), and planning provisions that limit what types of development are permitted within different parts of the floodplain. Retrospectively reducing risk of flooding for

any community is difficult. One option is to move all or part of the community to lower risk areas. An example of such a response is provided in Grantham in South East Queensland, Australia following the devastating January 2011 floods which led to the deaths of 12 people. Flood-prone households in Grantham were offered a land swap, with the local government authority identifying a 380 ha parcel of land on a hill overlooking the existing town and as a result, 115 lots in the new housing estate were taken (Okada *et al.* 2014).

However, in the Pacific, even if such approaches are attractive from a technical point of view, a Humanitarian Engineering lens requires us to consider the cultural context within which such 'solutions' may sit. For example, Nolet (2018) describes attitudes to shifting a community in Narewa, on the Nadi River in Fiji, following the 2012 floods. In this community, relocation would break the community's links with their ancestral lands, a 'shameful abandonment'. These lands are considered to have spiritual power and the community has a responsibility to care for and protect them. There is no effective substitution or compensation for the loss of culturally significant sites (Adger *et al.* 2013).

Similar views on the cultural importance of land is evident in the work of Struck-Garbe (2018) with respect to the issue of sea-level rise and the fate of the Caretet Islanders in PNG. The idea of the spiritual connections with the land are prominent, as well as a prevailing sense of guardianship. Struck-Garbe (2018) states that land is an important issue across the Pacific with a close connection to identity: 'the land is part of me and I am part of the land'.

Urbanisation

Migration has been a part of life in the Pacific for generations (Weir *et al.* 2017), both in pre-colonisation times and more recently post-colonisation. In the Pre-European Pacific, there is evidence that 'people were mobile within and between islands at this time, able to adapt to localised environmental impacts' (Nunn & Campbell 2020). During colonial times, there was a shift towards more communities living along the coasts or lowlands to facilitate contact with churches and colonial authorities, as well as trade. Coastal living is now considered to be normal (Nunn & Campbell

2020). More recently, as noted in the ‘Pacific nations and peoples – geography, culture, urbanisation’ section, urbanisation is increasing in many parts of the Pacific. One of the issues around urbanisation in the Pacific is that peri-urban areas and informal settlements are generally not separately measured and are underserved in terms of water infrastructure (Anthonj *et al.* 2020). This makes it particularly difficult to identify the needs of these communities and design infrastructure appropriately. Future research efforts need to be focused on rectifying this situation.

The driver for most urbanisation is education and economic opportunities, and therefore, it has tended to be young adults leaving outer islands. This has implications for both the rapidly urbanising communities as well as the communities in rural areas and outlying islands. This leads to a higher than average percentage of elders in outer communities. A strength of these elders is that they are likely to hold TK that can be used in climate adaptation actions (Weir *et al.* 2017).

Anthonj *et al.* (2020) examine access to drinking water in the Solomon Islands and find distinct differences between urban and rural populations. Remote provinces are more likely to rely on rainfall and surface water, while urban populations and more central provinces tend to have piped water supplies. Urban populations can thus store more water, spend less time collecting water and are more likely to have access to at least basic drinking water infrastructure (World Health Organization & United Nations Children’s Fund 2017). As shown in Table 3, different water sources have different levels of resilience to climate change, both in terms of quantity of supply and also the impacts of climate variability on water quality (Guo *et al.* 2019). Therefore, the need for future investments in water supply will be spatially heterogeneous even within one country. Another consideration is that the sustainability of groundwater resources may not be taken into account, and in parts of the Pacific, urban areas have higher reliance on groundwater for drinking than rural areas (Carrard *et al.* 2019).

Informal settlements present particular challenges. Regulations around land tenure and informal settlements can be a barrier to improving access to water supplies (Sinharoy *et al.* 2019), and these issues need to be fully considered when planning and designing new systems. As with CBA (see the ‘Climate change adaptation for hydrological risks’ section), community participation and ownership are

important factors in the success of improving water supply infrastructure for informal communities (Sinharoy *et al.* 2019). This aligns with the general principles of Humanitarian Engineering and user-centred design.

Institutions

One of the key tenets of Humanitarian Engineering is that appropriate technology in and of itself is not enough to address the challenges faced in developing countries. In the context of climate change, the adaptive capacity of a community is governed by economic capacity, awareness and information, technology, skilled labour and infrastructure (Dumaru 2010). Thus, without the support of strong institutions, policies and experienced personnel, infrastructure and/or technology will not satisfactorily solve the challenges that Pacific nations face. For example, Anthonj *et al.* (2020) review how the Solomon Islands struggle with inadequate public administration and financial management as one of the poorest nations in the Pacific. It is hard to deliver services when this poverty is combined with small populations and geographical isolation (there are approximately 350 inhabited islands in the Solomon Islands).

Many archipelagic countries have small administrations who must manage the complexities of delivering services to main and outer islands without economies of scale (Duncan 2011). An extreme example is Kiribati, where Kiritimati in the Line Islands is over 3,000 km from the capital, Tarawa, with no direct flights (Spires *et al.* 2014). National-level DRR metrics, as discussed in the ‘Background’ section, may be less applicable to archipelagic countries because island geography and location affect disaster risk, and challenges around access, limited governmental support, and delays in disaster response also contribute to the vulnerability of outer islands.

It is important to note that PICs are managing numerous challenges with limited financial and human resources (Spires *et al.* 2014); climate change is only one. Many Pacific Island governments do not possess the resources to adapt to climate change without assistance. Often, government employees working on environmental matters are too overstretched to be able to develop and implement adaptation strategies (Nunn 2009). However, partnership approaches to adaptation are challenging, as coordination arrangements can be complex, especially when multiple organisations

with different objectives work together (Spires *et al.* 2014). The objectives of donor countries or organisations may not result in improved adaptive capacity. As described by Nunn (2009), international funding focuses on climate change policy development without appropriate resourcing for effective implementation of these policies. Project-based funding models can also be problematic, with many projects ending due to a lack of local financial and technical capacity once the grant funding runs out (Mcleod *et al.* 2019). Governments have an important role in both ensuring that international funding is channelled correctly, and that projects are sustained once funding ceases (Spires *et al.* 2014).

Pacific Island communities are adept at adapting to changes in environmental conditions. For example, in response to climate change and water contamination issues, communities on the island of Oneisomw, Federates States of Micronesia, are improving water security through revitalising traditional wells and negotiating access to privately owned wells during drought periods (Mcleod *et al.* 2019). However, such local actions require the support of state and national water policies which can provide a framework and funding for their expansion to other communities (Mcleod *et al.* 2019). Institutions also play an important role in securing community access to the resources, information and technologies required for adaptation (Cinner *et al.* 2018).

The lack of national water policies and legislation in many PICs and the lack of capacity to implement existing strategies contribute to water insecurity (Duncan 2011). This is especially true for informal settlements. A potential barrier to increased government investment in water services for informal settlements is the question of cost recovery. However, research shows there is high willingness to pay for water services (Sinharoy *et al.* 2019), which needs to be communicated to policymakers within Pacific institutions.

WHAT IS NEEDED TO ADVANCE HUMANITARIAN ENGINEERING FOR CLIMATE CHANGE ADAPTATION IN THE PACIFIC?

A number of research and practice gaps were identified in the previous sections. These can be broadly summarised in three main areas, namely data availability, physical climate change

uncertainty and wider implementation of best practice Humanitarian Engineering. Progress is needed in all three areas to advance Humanitarian Engineering for climate change adaptations to hydrological risk in PICs. This section lists the research gaps in each area and recommends research and/or implementation approaches to address them.

Improving collection of and access to on-ground data

Data availability is a key need in improving climate change adaptation for hydrological risks. Specifically, data are essential for water supply planning, climate risk assessment, and to support drought and flood monitoring and early warning systems. Examples of data availability gaps include:

- lack of data to understand sustainable limits for freshwater use (e.g. to support monitoring of SDG6), particularly groundwater use,
- poor national level reporting of DRR policies (e.g. SDG13),
- insufficient long-term data to understand multidecadal climate variability, affecting drought risk (see the 'Changes in drought risk' section), and
- poor or non-existent data on informal settlements in general and hydrological risk and water use specifically (see the 'Urbanisation' section).

Pacific Island NMSs are primarily responsible for weather observations, climate services and seasonal climate outlooks (SPREP 2012). All NMSs are currently collecting and managing meteorological data and producing near real-time weather data, weather forecasts and warnings. However, many NMSs are operating with poor infrastructure, staffing constraints, and rely on external funding capacity (SPREP 2012). Gaps also remain in longer-term climatological records, although as noted below in some cases, this is due to data-sharing issues. In the absence of long-term records, paleoclimate data from the Pacific region (i.e. coral cores and speleothems), and remote paleoclimate proxies with strong teleconnections to the Pacific (e.g. tree rings) can be used to provide multidecadal to millennial context for hydroclimatic variables (Higgins *et al.* 2020). Remotely sensed data from satellites may also be useful; however, satellite-derived datasets generally contain substantial bias and there are limited recent assessments of their quality over the

PICs, particularly for sub-daily durations (Chen *et al.* 2013; Pfeifroth *et al.* 2013). Gauge sparsity will affect the accuracy of any blended satellite products over this region.

Compared with meteorological data, there is limited information on water resources in PICs (World Bank, 2018). In general, there is insufficient knowledge about water resources to understand how they respond to natural climate variability and to support climate risk assessment (Falkland 2011). Despite the high dependency on groundwater resources for many countries, monitoring data is rarely used to improve abstraction efficiency and maintain water quality (IGRAC, 2016). Additionally, there are data gaps around water usage in rural and informal settlements, particularly how water use varies across seasons and between water sources (Hadwen *et al.* 2015). Improvements are needed in monitoring and analysis of water resources, and in disseminating findings to local communities (Falkland 2011).

Limited data availability is not always the result of a lack of data in the Pacific. Despite considerable data digitisation efforts (e.g. Page *et al.* 2004) a lot of data pertaining to geology, hydrology and water quality are retained as paper records or within hardcopy reports. *Ad hoc* data collection by multiple national government departments and poor data-sharing processes prevent utilisation even when a large volume of data have been collected (Dahan 2018). Despite increasing global recognition of the need for open access to data for climate change planning and adaptation (Hanger-Kopp *et al.* 2012), data sharing between government departments is often minimal and sharing between governments and external stakeholders is poor to non-existent. Identified barriers to data sharing include the need to meet departmental cost-recovery requirements, concerns regarding misrepresentation of data and a lack of clear whole-of-government data-sharing obligations (Mackay *et al.* 2019). Strengthening collaboration and data sharing between meteorological and water resource services is a key goal for the *Pacific Islands Meteorological Strategy 2017–2026* (SPREP 2012).

Improving climate change physical science for the Pacific

Although global climate changes are the focus of extensive research, impacts on communities are local and future water planning typically relies on hydrologic modelling

and assessment at the catchment scale. There remain substantial gaps in process understanding at these scales. For the Pacific specifically, important gaps include:

- poor representation of the ITCZ and SPCZ in GCMs leads to substantial concerns about the validity of climate projections for the Pacific;
- there are substantial uncertainties with ENSO projections which is a key driver of Pacific hydrological risk;
- discrepancies in the spatial resolution of GCMs compared with the size of PICs;
- country-level projections of changes in annual average rainfall are not available for many PICs;
- interactions between changing rainfall extremes and Pacific Island geography are not well understood; and
- drought projections tend to focus on SPI which does not holistically consider all changes in future drought (e.g. both evapotranspiration and precipitation).

Due to the known problems in GCM simulations, along with the importance of topographic effects and the fact that many islands are much smaller than GCM grid cells, GCM outputs require effective bias correction and downscaling before they can be used as inputs to hydrologic models and analyses (Fowler *et al.* 2007).

Statistical downscaling involves modelling data-based relationships between large-scale drivers that are well captured by GCMs and point measurements of a target variable (for example, rainfall). Although statistical downscaling is computationally inexpensive (Benestad 2004), it still requires considerable expertise and resources to establish reliable models which may not be available in Pacific NMSs. More concerningly, if the ITCZ, SPCZ and ENSO are not correctly represented in GCMs, then the future changes of the large-scale drivers used in the downscaling remain questionable. Finally, reliable observational records over several decades are required to properly inform the underlying statistical relationships, which are not widely available (see the 'Improving collection of and access to on-ground data' section).

RCMs with grid cell sizes in the range of 1–60 km² (Tang *et al.* 2016) provide a second approach to resolve the spatial scale discrepancies between GCMs and PICs. RCMs can resolve smaller-scale processes and, if the resolution is fine enough ($\leq 1\text{--}2$ km), can explicitly model convection. RCMs can partially address known GCM problems in the Pacific

because biases in the driving GCM can be corrected. However, RCMs have their own biases, and spatial biases in GCMs around the positioning of climate features, for example, the ITCZ, cannot easily be corrected (Adachi & Tomita 2020). Because dynamical downscaling is highly computationally expensive, it is inaccessible to most resource-limited organisations, and even well-funded dynamical downscaling projects can generally only consider a small number of driving GCMs and scenarios.

An alternative approach for decision making under future climate uncertainty is scenario neutral assessment (Prudhomme *et al.* 2010; Brown & Wilby 2012; Stephens *et al.* 2018a). This method simulates incremental, hypothetical climate shifts to determine how much change would produce a detrimental impact. A key advantage is that a range of plausible future cases can be systematically covered, which is often more informative than a discrete set of results from an RCM that may not encompass all possibilities. However, scenario neutral assessments require several decades of observed data on key variables (generally rainfall and temperature) to characterise the baseline climate and form the basis for the perturbed future climate series. In many parts of the Pacific, limited data availability will be a barrier to these studies.

While data and resource constraints are a barrier to quantitative future climate assessments in parts of the Pacific, evidence-based adaptation is still available. The traditional ‘anticipatory’ adaptation approach, whereby climate changes are modelled and substantial investments are made to manage the impacts, could lead to wasted resources and lost opportunities where future climate uncertainty is high (Barnett 2001). A better strategy is flexible and resilience-focused, allowing initially local projects to gradually scale-up over time and resources to be reallocated in the face of emerging impacts or projections. In general, systems that are adapted to high climate variability are inherently resilient to climate change (Nathan *et al.* 2019). Even if the precise nature of future climate changes is unknown, communities can prepare by building their resilience to hydrological risks using knowledge gained from the Pacific’s inherent high climate variability (Tables 2 and 3). Such a strategy should place TK at its centre since island communities have been adapting to a highly variable climate for generations.

Best practice Humanitarian Engineering

Data and modelling can only partially contribute to climate adaptation in the Pacific. Many of the major opportunities and challenges to advance adaptation are centred on Pacific communities and their institutions. Best practice Humanitarian Engineering recognises that projects are rarely successful unless the infrastructure and systems that provide the context for a problem are also considered. To this end, identified knowledge gaps evident from this review include:

- research methods to integrate TK with contemporary climate and weather forecasts,
- Pacific-centric research on the relationship between natural hazards and risk perception,
- Pacific-centric research on the value of open data sharing,
- policies and planning that accounts for the needs of informal communities given high urbanisation rates in the Pacific,
- strengthened institutional frameworks for water policy and legislation,
- improved institutional processes around data sharing and data availability, and
- addressing resource and infrastructure constraints in the dissemination of warnings.

Some parts of the Pacific already have poor water security and the impacts of climate change will only magnify these vulnerabilities. Remote geography and sparse populations lead to particular challenges in installing infrastructure such as boreholes that are more common in other parts of the world, particularly given the institutional challenges discussed in the ‘Institutions’ section. High rates of urbanisation in larger population centres in the Pacific create a different set of challenges. A global focus by international partners and donors on ensuring the SDG6 targets are met in the Pacific is thus vital to addressing these inequalities in water access now and into the future.

Pacific Islands are overwhelmingly represented as extremely vulnerable in the face of climate change. While this discourse may have been helpful in leveraging international support, it also denies the agency, resilience and ability of Pacific Islanders to adapt to climate impacts (Campbell & Barnett 2010). Alternative framing, which considers climate

risk, but focuses on adaptive capacity is more likely to result in constructive outcomes (Campbell & Barnett 2010). A strengths-based approach, as advocated in Humanitarian Engineering practice and research, also provides a useful frame for developing the adaptive capacity of communities.

Research activities in PICs should be undertaken collaboratively in ways that support the academic development of local researchers and research organisations (Dahdouh-Guebas *et al.* 2003). Further, publication in open access journals will increase the accessibility of research findings for developing countries, which can aid science-based policy decision making (Tai & Robinson 2018).

Research and consultation fatigue are commonly reported by Pacific Island communities (David-Chavez & Gavin 2018; Nalau *et al.* 2018). Researchers, operating within a 'Western scientific framework' and not following local customs, extract information from communities for their research projects with no follow-up on research findings (Nalau *et al.* 2018). Reciprocity should be a fundamental pillar of research design for Humanitarian Engineers, with both research questions and outcomes framed with communities in mind. In their global assessment of Indigenous community engagement in climate research, David-Chavez & Gavin (2018) identify a number of ways in which researchers can improve scientific engagement with communities, including:

- on-site community workshops to develop research topics that are useful for communities and policymakers and to disseminate findings,
- community review of data prior to publication,
- locally produced and disseminated findings, which prioritise Indigenous language, are developed through participatory approaches, and use relevant multimedia tools (e.g. videos, photographs, podcasts and maps), and
- compensation for research participants.

CONCLUSIONS

Changes to the climate and their associated impacts on hydrological risks are major challenges facing communities and governments in the Pacific region. This review has

shown that there are a number of substantial gaps in understanding climate change impacts in the region, associated with short and spatially sparse historical data records and the poor ability of climate models to resolve the major drivers of regional variability in the Pacific. However, Pacific Island communities have a long history of adapting to climate variability and this strength provides opportunities for climate change adaptation projects going forward. Adaptation approaches in the Pacific need to account for the distinct cultures of the region, with the review highlighting the value of TK, as well as the importance of ensuring adaptation options are aligned with Pacific values including religion, spiritual and ancestral ties to land, and the vital time-building that goes into relationships. Such findings are also relevant to other cultures and societies around the world. However, particular challenges in the Pacific come from under-resourced institutional structures that need to deal with remote geographies and high rates of urbanisation. Options for water supply and hydrological risk adaptation have been identified and framed by their links to Pacific geography and culture. The value of this framing is to highlight how Humanitarian Engineering approaches can improve climate resilience and overall development outcomes for the Pacific.

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