Chapter 10
Infrastructure Vulnerability to Disruption: A Particularly Pacific Problem

Matt Blacka, Fiona Johnson, and Ron Cox

Increasing the climate resilience of infrastructure is vital for Pacific communities to support daily living and disaster response.

Abstract Infrastructure and climate have important roles in driving the water-energy-food nexus in the Pacific region. The significance of infrastructure is woven throughout the United Nation's 2030 Agenda for Sustainable Development, with Sustainable Development Goals relevant to infrastructure and its links to the water-energy-food nexus. Pacific Island Countries and Territories (PICTs) differ from larger developed neighbouring countries in Oceania such as Australia and New Zealand, bringing about a unique set of challenges for infrastructure. Physical characteristics include small, remote populations and small land masses, and susceptibility to natural hazards. Institutional challenges such as governance, small economies, and limited infrastructure expertise are prevalent. Yet, despite all these challenges, climate change is perhaps the largest. This chapter considers the interconnectivity of infrastructure and the water-energy-food nexus, and the importance of building climate resilience within the infrastructure sector reflected through the lens of three key infrastructure areas namely maritime transport, coastal protection, and Water, Sanitation and Hygiene (WaSH) infrastructure.

Keywords Infrastructure · Water supply · Sanitation · Ports · Maritime · Transport · Coastal · Adaptation

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10.1 Introduction

The United Nations (2015) identifies the central role of infrastructure through the Sustainable Development Goals (SDGs) and its links to the water-energy-food nexus. SDG 6 and SDG 7 relate to water and energy respectively and SDG 9 aims to “build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation.” These SDGs are relevant across the Pacific region but have particular importance for the Pacific Island Countries and Territories (PICTs) which are predominantly classified as lower and upper middle-income economies and include four of the world’s least developed countries (Kiribati, Solomon Islands, Timor Leste, Tuvalu) (United Nations 2021). The challenges facing these communities is reflected in SDG 9a, which focuses specifically on resilient infrastructure for small island developing states.

At a national level, the SDG infrastructure-related goals are echoed through the sustainable development plans of many, if not all, PICTs. For example, Infrastructure and Technology is one of five National Outcomes of the Tonga Strategic Development Framework 2015–2025 (Government of Tonga 2015), and Building Resilient Infrastructure is a National Development Goal of the Cook Islands National Sustainable Development Plan 2016–2020 (Government of Cook Islands 2016). World Bank (2006) similarly identifies infrastructure-related development goals for Fiji, Kiribati, and Solomon Islands within their national development planning agendas.

However, the PICTs are diverse in geography, culture, climate, and have unique development challenges. The small land masses, remote geography, rapid urbanization, and important role of the ocean in terms of infrastructure sets the PICTs apart from their larger neighbouring countries of Australia and New Zealand. This chapter, therefore, focuses on the relationship between infrastructure and climate change impacts on the water-energy-food nexus in the PICTs.

10.2 Infrastructure Functions in the Water-Energy-Food Nexus

Infrastructure in the PICTs can broadly be considered to support three principal outcomes (Baker and Week 2011), or a combination of them:

- Basic well-being of the population;
- Delivery of Government services; and
- Enabling economic activity.

Figure 10.1 maps different infrastructure categories to their intended principal outcome (or outcomes), from which it can be seen that basic well-being of populations is a fundamental outcome supported by most infrastructure types, and indirectly supported (through income generation, for example) by all types. In most instances, infrastructure supports the basic needs and well-being of communities through its role in the provision of clean water, stable energy, or secure food supplies—fundamental components of the water-energy-food nexus.

What differentiates infrastructure within the Pacific region from many other areas of the world, are the geographical and geophysical characteristics of the island nations that characterize the region, combined with the social and cultural characteristics of human populations. Dominated by dispersed island communities spread over vast areas of ocean, and with many communities inherently restricted to the coastal margin, there are strong traditional cultural ties, as well as modern needs associated with the ocean and coasts. Capital and maintenance costs for infrastructure services in the PICTs are comparably high, for a number of reasons, including the often small, dispersed, and remote settlements and inherent vulnerability to natural disasters (World Bank 2006).

To holistically consider climate impacts on infrastructure and subsequently the water-energy-food nexus, we need to look beyond the direct impacts on infrastructure itself, considering also the impacts on interdependent sectors supported by infrastructure (Baker and Week 2011). For example, a seaport is not only directly impacted

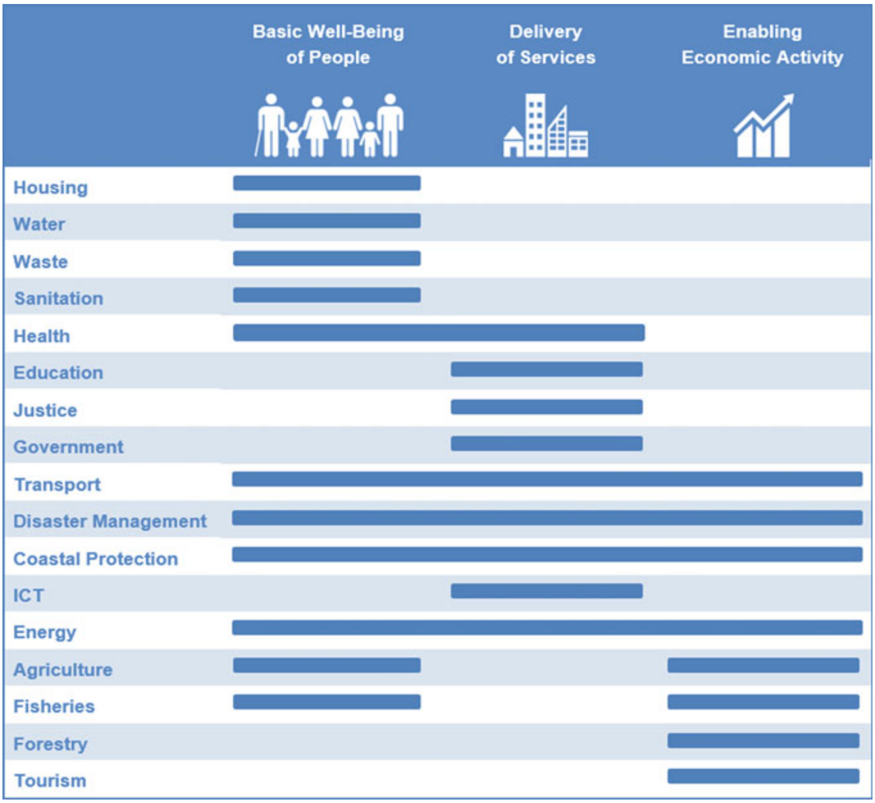

Fig. 10.1 Principal outcomes of sectors supported by infrastructure for PICTs

by rising sea levels and more extreme wave conditions, but also indirectly by climate change impacts on connected infrastructure. These indirect impacts occur on infrastructure such as the coastal protection structures that provide safe shelter for vessels, roads that service freight linkages, energy and fuel supplies that power operations, communications, and on local communities that require the import/export trade (Cox et al. 2013, 2014).

10.2.1 Maritime Transport Infrastructure

Communities across the PICTs have historically had (and continue to have) very close ties with the ocean. In addition to this strong cultural connectivity, maritime transport provides a fundamental link for international and inter-island freight, passenger travel, and is an essential component of both commercial and subsistence fisheries. Long distances between ports, low trade volumes, imbalanced exports/imports, and the widely varying standard of ports and their operations result in relatively high shipping service costs within the region (ADB 2007).

Each PICT has a number of ports with different functions. Typically, each country has just one or two major ports that process international trades, and these facilities are often government owned (ADB 2007). Secondary ports, typically located on outer islands or in provincial towns, provide domestic and inter-island freight and transport services. While these facilities are low-key and often under-maintained (Pacific Infrastructure Advisory Center 2013), they are the lifeblood of remote island communities through which essential supplies are received including food, medical supplies, building supplies, fuel, and gas. The secondary ports are sometimes owned and managed at an island or provincial government level (not national government), such as in the Cook Islands, introducing further funding and capacity constraints to maintain the assets and infrastructure.

Port infrastructure across the region varies vastly in operational standard and condition depending on the required functions. Even international cargo and bulk facilities in some countries (e.g., Cook Islands as shown in Fig. 10.2) comprise only a basic wharf, mooring, and water-side equipment, and completely rely on vessels to provide cargo handling equipment and personnel. In small, remote island communities, facilities are typically very basic timber or concrete wharves serviced by a narrow (and often dangerous) reef passage (Fig. 10.2). Small local barges and tenders pass through the reef and form a transfer link with larger freight vessels that remain offshore in deeper water during cargo transfer operations. In contrast, some countries with larger economies (French Polynesia and New Caledonia, for example) have major wharves and coastal protection infrastructure to support sophisticated facilities and cargo-handling that is of world-class standard (ADB 2007).

For maritime transport infrastructure such as seaports, the links between infrastructure and the water-energy-food nexus are strong within the PICTs due to a range of unique factors:

Fig. 10.2 A cargo vessel awaits to unload offshore of the reef at Arutanga Wharf, Aitutaki, The Cook Islands (©M. Blacka)

- All incoming fossil fuel supplies from international locations are either offloaded to storage facilities, often located on vulnerable land along the coast, or domestically transhipped through major ports. These fossil fuels are typically the dominant source of fuel used to produce energy in the form of electricity, which then powers water treatment and distribution infrastructure and refrigerates stored food.
- The imported fuels that pass through ports also drive land-based transportation networks that distribute food, bottled water, and other goods, and drive domestic shipping and recreational boating that underpins commercial and subsistence fisheries.
- Gas imported through ports forms a significant source of heat for cooking food and boiling drinking water.
- Jet fuel imported through ports is vital for air transport, and in particular supports the key economic role of tourism in the region.
- Ports provide for the extensive domestic and international commercial fisheries industries that are a significant component of local and regional economies, and a critical source of food for many countries.
- For countries with minimal arable land (atoll-dominated countries, for example), imported food via sea transport forms a major component of people's diet to supplement locally available produce.
- Domestic ports and harbours provide the opportunity for inter-island movement of food, both imported and exported from domestic agriculture, aquaculture, and

other primary producers, and for movement of other supplies and produce between remote communities.

- Domestic harbours are the safe base and hub through which many local fishermen access the seas surrounding their islands to undertake subsistence fishing.

10.2.2 Water, Sanitation, and Hygiene (WaSH) Infrastructure

Infrastructure for water supply and sanitation is varied across the Pacific, and access to both water and sanitation is uneven. Approximately 50% of the population of the PICTs have access to an improved water source (United Nations 2020). However, there are strong inter-country differences; for example Australia, Niue, and New Caledonia have close to 100% access to improved water sources, whilst Vanuatu and Tuvalu have less than 50% and Samoa only around 10% (United Nations 2020). Similarly access to safely managed sanitation (SDG 6.2.1) is highly variable across the Pacific ranging from approximately 30% for Kiribati and Tonga, close to 50% for Samoa, and up to 75–80% for Australia and New Zealand (United Nations 2020). There is limited data for many of the PICTs for sanitation coverage (see Chap. 2 for more details).

Centralized, piped water systems are common in the larger cities and can be fed by groundwater or surface water sources. For example, traditionally communities in Samoa settled around freshwater springs (Macpherson and Macpherson 2017), and aside from household personal water tanks, almost 100% of distributed water on Rarotonga (Cook Islands) is through intakes on upper catchment streams. Similarly, surface water provides 95% of water requirements in French Polynesia. For some islands, such as the atolls in the northern group of the Cook Islands, rainfall is the predominant potable water source, captured within both community and household tanks (Parakoti and Davie 2007). Purpose-built roofs can provide a catchment surface for larger community tanks (Fig. 10.3), though often community buildings such as churches, halls, and schools provide a roof catchment.

Fresh groundwater lenses are important water sources in low-lying atolls and limestone islands and basal aquifers can also occur along the coastal zones of volcanic islands (Falkland and White 2020). The sizes of these freshwater lens varies substantially. Investigations in Tonga and Niue, for example, show sustainable reserves while the small freshwater lens in Nauru disappeared completely during the 2008 drought (White and Falkland 2010). In some locations, water from freshwater lenses is used for non-potable or supplementary supplies because salinity levels are too high for drinking purposes.

Reverse osmosis (RO) for seawater desalination is used in some locations (see Chap. 8 for more information). Desalination in Nauru is used during drought periods and for supplementary supply at other times. Small-scale containerized desalination operates in Fiji, Kiribati, Solomons, Papua New Guinea (PNG), Nauru and Palau, among other PICTs in the region. Transportable desalination plants are becoming

Fig. 10.3 Community water tank and catchment roof on the atoll of Manihiki (©Melina Tuiravakai)

more common as a tool for rapid deployment to remote communities during emergency water shortages. For instance, such a system was used in the atoll of Penrhyn in the northern Cook Islands during the La Niña driven drought in 2020/2021 (Cook Island News 2021; Radio New Zealand 2021). Private desalination plants are operated by tourist resort owners in some PICTs. Desalination has now also been widely implemented for major cities around Australia, with multiple plants installed in Perth, western Australia due to the declining water resources in this region as a result of shifting rainfall patterns (Hope et al. 2006; Ummenhofer et al. 2008).

Informal settlements in urban and peri-urban areas are an increasingly important consideration in PICTs, where high urbanization rates are a result of migration for education and employment (Weir et al. 2017). Informal settlements are rarely considered in official urban planning and are under-served in terms of water and sanitation infrastructure (Anthonj et al. 2020). Sinharoy et al. (2019) note that globally unreliable or intermittent supplies in informal communities are associated with poorer water quality forcing householders to store more water, which can also lead to contamination. Access is often from shared community standpipes, which may be illegal connections or have higher tariffs (Schrecongost et al. 2015). Sanitation facilities in informal settlements are particularly problematic, with poor waste management and shared facilities leading to health and safety risks, particularly for women and girls (Sinharoy et al. 2019), and further deterioration of available water resources.

Examples of how WaSH infrastructure affects the water-energy-food nexus include:

- Alternative water supply technologies such as RO have high energy costs and if not using renewable energy, require fuel to be imported, providing further cross linkages with transport infrastructure.
- Similarly, energy, and therefore fuel, is required for water treatment plants and pumps for boreholes and surface water intakes. As highlighted above, energy supply disruptions can lead to households storing more water to mitigate against intermittent supplies. This can contribute to poorer water quality and health outcomes.
- Unsustainable groundwater use, leading to drawdown or salinisation of aquifers, requires higher energy inputs due to increased pumping and treatment requirements.
- Life on Pacific atolls can be “harsh and precarious,” due to their low agricultural productivity and highly porous soils, coupled with limited available land area, leading to food insecurity and the need to import food (Terry and Chui 2012). Attempts to improve productivity through fertilizers and pesticides risk contaminating the limited freshwater reserves and impacting adjacent coastal ecosystems.
- More research is required into safe rearing practices for livestock that better protects freshwater sources in the Pacific context (MacDonald et al. 2017). For example, the proximity of domesticated pigs to community water sources increases the risk of leptospirosis through contamination of freshwater by urine.

10.2.3 Coastal Protection Infrastructure

Whereas seaport and WaSH infrastructure can directly influence water-energy-food nexus outcomes, coastal protection infrastructure has a more indirect (though no less important) role. Many low-lying island communities rely on coastal protection infrastructure to reduce impacts from coastal erosion and inundation during extreme cyclones, large swell wave events (Hoeke et al. 2013), or king tide events (Lin et al. 2014; Davies 2015; Australia News Network 2014). In some cases the need for coastal protection is not driven by climate event extremes, but instead linked with other underlying climatic and physical processes, including degradation of coral reef health, longer-term climate cycles that influence waves and currents, removal of coastal sands by mining of beaches, and the trapping of sediment by rivers and other coastal structures (PRIF 2017).

Coastal protection works can or do mitigate risks to water, energy, or food systems. For example:

- For many island communities agricultural crops, in particular taro crops grown in low-lying freshwater wetlands, form staple food sources but can be destroyed by saline ocean water from wave overwash and storm surge processes, or damaged through erosion (e.g., impacts from Cyclone Pam on outer islands of Tuvalu) (Taupo and Noy 2017).

- Freshwater lagoons, wetlands and shallow groundwater aquifers that form drinking water reserves can become contaminated with salt water (Storlazzi et al. 2018), destroying their viability for decades into the future (e.g., impacts from Cyclone Percy on the atoll of Pukapuka in the northern group of the Cook Islands) (Terry and Falkland 2010).
- Protection of other infrastructure within the coastal zone that supports the water-energy-food interdependencies, including water distribution infrastructure, transport infrastructure (road, port, and air), power supply infrastructure, fuel storage etc., from the impacts of these extreme ocean events.

The use of rock armoured seawalls is widespread throughout the PICTs, as well as a host of other formal and ad-hoc coastal protection systems, including vertical concrete walls, grouted stone and coral boulder walls, sand and grout-filled bags, gabion baskets, and materials of opportunity such as rubber tires, tree trunks, scrap metal and machinery, and drums that are filled with concrete. While concrete armour units have been used, they are generally limited to ports or other areas of higher value. Table 10.1 identifies the length of coastline for most countries in the Pacific region, along with the types of human-created coastal protection in place around each country (including both nature-based and engineered coastal protection works).

Natural systems also provide significant coastal hazard protection to island communities throughout the Pacific region. On high-energy coastlines, coral reefs act as a natural dissipator of waves (Ferrario et al. 2014), regulating the wave energy that eventually reaches the shorelines. Healthy reef ecosystems also generate sediment that sustains the beaches of many islands providing further coastal protection value for communities. In low-energy coastal environments, mangroves also provide natural dissipation of wave energy and protection of communities from coastal flooding hazards (Gilman et al. 2006).

10.3 Climate-Related Vulnerabilities

The major intersections of current and future climate with infrastructure centre on rainfall patterns and sea levels (see further description of Pacific climatology and its future changes in Chaps. 1, 2 and 5). Extreme weather events, specifically tropical cyclones, are the major disrupting force for all infrastructure types. They lead to large rainfall totals, high intensity rainfall, and storm surges, which all contribute to flooding and can impact the efficient operation of infrastructure and potentially lead to infrastructure damage. At longer time scales, variability is primarily driven by the El Niño Southern Oscillation (ENSO) (see Chap. 5 for details), and water supply and food production are particularly at-risk during ENSO-induced droughts. The impacts of anthropogenic climate change on floods and droughts and key uncertainties and their links with hydrologic infrastructure in the Pacific are described in Johnson et al. (2021). Considering the infrastructure categories summarized in Fig. 10.1, these climatic intersections and vulnerabilities impact infrastructure across almost

Table 10.1 Coastline lengths and coastal protection types used in selected PICTs

Country	Coastline length (km)	Reported coastal protection types
Cook Islands	120	Concrete sea walls, rock boulder revetments, groynes, rock breakwaters, grouted coral sea walls, geotextile sandbag revetments, gabion baskets, beach planting, beach replenishment
Fiji	1,129	Mass concrete seawalls, reinforced concrete seawalls, rock revetments, rubber tires, gabion baskets, mangrove planting
Federated States of Mirconesia	6,112	Grouted coral seawalls, stacked coral boulders
Kiribati	1,143	Small-stacked sandbags, grout-filled and mortared sandbags, reinforced concrete, grout mattress, tetrapod armour units, rock revetments, gabion baskets, stacked coral, grouted coral, planted mangroves
Republic of Marshall Islands	370	Rock rip-rap revetments, sandbags, vertical concrete block or cemented coral walls, concrete armour units, gabion baskets filled with coral gravel, stacked tires, scrap metal and old heavy machinery
Niue	64	Concrete seawalls
Nauru	30	Coral boulders, concrete seawalls, rock seawalls
Palau	1,519	Rock riprap, grouted rock, vertical concrete
Papua New Guinea	20,197	Stacked rock, bricks, sandbags, tree trunks, gabion baskets, concrete filled tires
Samoa	403	Grouted stone walls, rock revetments, groynes, beach replenishment, mangrove planting
Solomon Islands	9,880	Rock revetments, stacked rock behind wooden piles, mangrove planting, vertical concrete walls, concrete armour units (tetrapods), gabion baskets

(continued)

Table 10.1 (continued)

Country	Coastline length (km)	Reported coastal protection types
Tonga	419	Limestone/coral boulders, mangrove planting, grout-filled bags
Tuvalu	24	Vertical concrete walls, gabion baskets, concrete cubes, steel drums filled with concrete
Vanuatu	2,528	Vertical concrete walls, stacked coral, grouted coral, gabion baskets, revegetation
Timor Leste	735	Rock revetments, concrete armour units, mangrove planting, coastal and marine protected areas

Modified from PRIF (2017), Paeniu et al. (2015)

all sectors and are particularly vital to understand in the water-energy-food nexus. Infrastructure vulnerabilities differ from high islands to low atolls, nevertheless, even on high islands the majority of infrastructure tends to be clustered within the coastal zone due to the often rugged and mountainous nature of inland areas (Fig. 10.4), which is particularly sensitive to disruption by climatic and environmental drivers, and the impacts of climate change. Close to 60% of built infrastructure for 12 PICTs is located within 500 m of their coastlines (Kumar and Taylor 2015), amounting to a total replacement value of USD 21.9 billion (World Bank 2016).

10.3.1 Maritime Transport Infrastructure

For seaports in the Pacific, typical day-to-day weather fluctuations have minimal impact for port infrastructure but do impact port operations. Vessel navigation to enter, berth, and depart a port (be it larger scale international freight and bulk vessels through to smaller personal fishing boats) is sensitive to wind speed and direction, wave conditions, and ocean currents. Likewise, cargo handling operations (cranes, for example) are impacted by wind and wave conditions (Cox et al. 2013; Dyer 2019). Energy consumption for powering port operations is also sensitive to air temperature changes (UN Trade and Development Board 2014). For larger islands with reasonable land mass, intense wet-season rainfall events can cause localized flooding that can overtop wharf areas and impact landside infrastructure (PIANC 2020). The influence of these weather fluctuations can translate to operational disruptions, which differ both between seasons and with longer-term climate drivers such as ENSO. For smaller domestic outer island and provincial harbours, seasonal climate fluctuations and longer-term climatic fluctuations influence the frequency at which their intermittent cargo services are disrupted, or missed entirely, due to inclement conditions

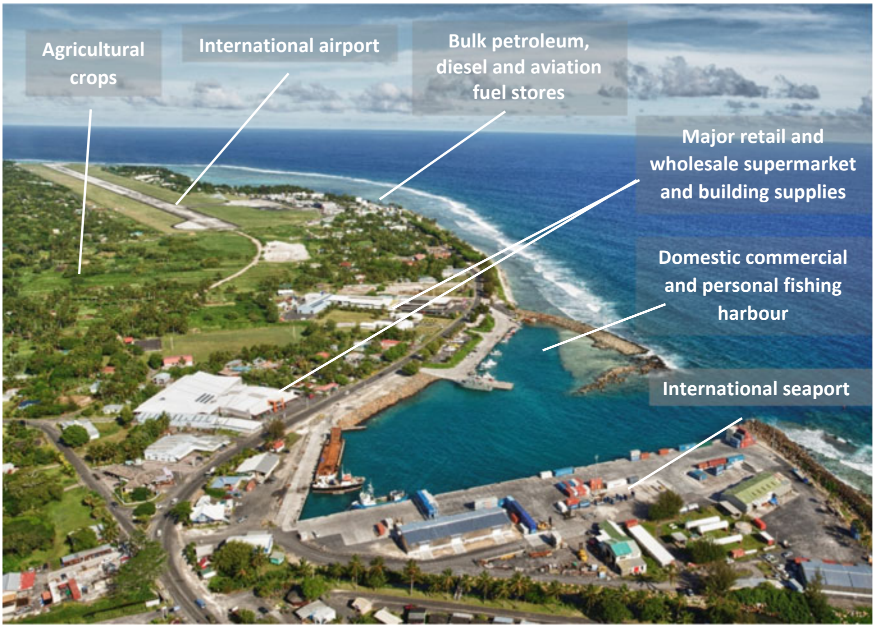

Fig. 10.4 Rarotonga, the main island of the Cook Islands, has a high mountainous interior, yet infrastructure is clustered along the coastal fringe (*Source* Cook Islands Ports Authority)

that prevent ship unloading (UN Trade and Development Board 2014; Cook Island News 2013 for example). When operational disruptions result in shortages of food, fuel, medical supplies, and other essential goods that can last many months, this can translate to significant health and social impacts for remote communities.

Tropical cyclones can have a significant impact on both port infrastructure and operations, predominantly through damage from storm surge and large waves to both waterside and landside assets. Due to the inter-connected nature of ports with other infrastructure and links with water, energy, and food as previously described, these disruptions can be extensive and last many years or decades beyond the event, and result in economic impacts that stretch much further beyond the re-build costs. Given that ports form the primary transport links with other parts of the world, damage to port and harbour infrastructure can also have a significant impact on emergency response in the period immediately following an event due to delays in providing required materials for infrastructure repairs as well as emergency food, water, and shelter supplies.

Over the long term, the highest risk impacts from climate change for port infrastructure in the Pacific are generally related to sea level rise and waves. Changes to both of these environmental variables will impact the day-to-day operations of ports, and exacerbate damage sustained during cyclone events. In the majority of ports (small and large), facilities such as wharves and boat ramps are constructed for current sea levels and tide ranges, such that they function with quite specific freeboard. Increase in mean sea level effectively reduces this freeboard and will eventually result in these facilities becoming increasingly unsafe to operate and losing functionality.

Small scale port and harbour facilities typical in the outer islands of many PICTs have very limited engineered protection from waves, often relying on the sheltering provided by the island itself and the dissipation of wave energy by fringing reefs. As sea levels increase relative to reef topography, the effectiveness of this natural wave dissipation will be reduced, and these harbours will be subject to increasing wave energy. Where breakwaters are present, they are typically low-crested and have limited to no maintenance, therefore vulnerable to this climate-change phenomenon (Fig. 10.4). For these low-key and often remote facilities, the effects of sea level rise and increased nearshore wave heights represent an extreme risk to public safety, including:

- More regular overtopping of the wharves, breakwaters, and ancillary facilities, making them unsafe or undesirable for use by the community;
- Reduced high-tide freeboard for vessels at berth, compromising the ability to safely load and unload cargo;
- Permanent inundation of the shoreline connections and/or wharves, making the infrastructure unsafe or unusable; and
- Increased maintenance requirements due to increased nearshore wave heights and cyclonic activity.

Larger ports in the region are not immune to these long-term issues, and in time will require significant adaptation to reduce climate-related risks. Wharf decks will need to be elevated, as discussed in ADB (2014) for Avatiu Port in the Cook Islands, and breakwater structures that provide wave protection will need to be strengthened, as discussed in ADB (2018) for Apia Port in Samoa. These being just two examples of the significant investment that will be required to reduce indirect climate-related impacts on the water-energy-food nexus that will result through impacts on the maritime transport sector.

10.3.2 WaSH Infrastructure

Most PICTs have strong wet and dry seasons (Chap. 5), and these annual cycles can lead to regular water shortages, particularly towards the end of the dry season for communities that rely on rainwater tanks or shallow groundwater-fed systems (MacDonald et al. 2017). On islands where they are present, perennial rivers can become much more important sources during the dry season (Elliott et al. 2017).

At longer time scales, the major ongoing risk for WaSH infrastructure comes from the influence of ENSO (Chap. 2) on water resources systems across the Pacific. ENSO-induced droughts are a major challenge across the Pacific (Chap. 5) directly impacting the security of the water-energy-food nexus. For example the 2002/2003 drought in Samoa led to electricity shortages because there was insufficient water for hydro-electricity generation (Kuleshov et al. 2014). The 2011 drought in Tuvalu led to water rationing and required deliveries of fresh water supplies and portable desalination equipment from overseas (Kuleshov et al. 2014).

The primary cause of the largest flood events in the Pacific is tropical cyclones, although tropical depressions and flash flooding induced by short duration, high intensity rainfall events also contribute substantially to flood risk and associated devastating impacts on infrastructure. Cyclone Val in 1991 caused USD 200 million damage in Samoa alone, to energy, water, and telecommunications infrastructure as well as private and government buildings (Kuleshov et al. 2014). Importantly, there is substantial traditional knowledge in PICTs in terms of household level preparation for cyclones that should be drawn on to support climate resilience, including food storage techniques and traditional housing construction that enable rebuilding with local materials following a cyclone (Weir et al. 2017). Equally resilient designs are required for infrastructure. Community-wide piped water systems are considered very vulnerable to potential disruptions (Howard et al. 2010). For example, water treatment plants can be overloaded by high sediment loads in source water following extreme rainfall events or power losses can lead to lack of treatment, highlighting the importance of understanding the water-energy-food nexus. Back-up rainwater tanks are one solution that can be used to mitigate these risks (MacDonald et al. 2017) and in Samoa unused springs have been reinstated following extreme weather events (Macpherson and Macpherson 2017).

Rising sea levels, as well as increasing rainfall extremes and increased intensity for tropical cyclones from climate change will magnify existing vulnerabilities in water infrastructure. Extensive research has been undertaken in Australia to understand the potential impacts of climate change on water supply (Khan et al. 2015) and water resources infrastructure (Chiew et al. 2011). Some recommendations have been developed for floodplain management and infrastructure design (Bates et al. 2016), although there remain outstanding questions regarding modelling approaches (Stephens et al. 2019) and how changes in catchment wetness will interact with increasing rainfall intensities (Stephens et al. 2018). Similar research is urgently required for PICTs although data availability is a constraint (Johnson et al. 2021).

The risk of saltwater intrusion into groundwater systems will increase with climate change (Weir et al. 2017; Terry and Chui 2012). Given that freshwater lenses are entirely rainfall fed, any changes in rainfall patterns will also affect their recharge rates and therefore sustainability (Terry and Chui 2012). Higher temperatures are likely to amplify existing problems with algae growth in water supply reservoirs (Paerl et al. 2016; Ministry of Health 2018). Johnson et al. (2021) adapted the global qualitative review of Howard et al. (2010) on the resilience of different water supply and sanitation options, considering the applicability of a range of WaSH options in PICTs. They found that increasing the resilience of water supply options in the Pacific for climate change adaptation is challenged by under-resourced institutions, remote geography, and high rates of urbanization.

10.3.3 Coastal Protection Infrastructure

Sea level rise represents the most significant climate change challenge for coastal protection infrastructure in the Pacific region (Shand and Blacka 2017). World Bank (2016) suggest that the highest adaptation cost for PICTs by 2040 will be coastal protection works. Increases in sea level will directly result in increased frequency and magnitude of waves breaking over coastal protection infrastructure, and thus increased inundation (Quataert et al. 2015; Beetham and Kench 2018). Sea level also modulates incoming wave heights at the reefs along the coastlines of many islands of the Pacific (Monismith et al. 2013). Therefore, higher sea levels will also result in larger waves impacting coastal defences. Ocean water level and sea level rise has also been shown to have a significant impact on hydrodynamics of reef and lagoon systems of PICTs (Hoeke et al. 2011; Blacka et al. 2019). This will result in significant long-term changes in sediment transport and morphology of coastlines (Webb and Kench 2010; Masselink et al. 2020), further impacting built coastal protection structures such as seawalls through processes such as undermining (supporting sand removed from under foundations of structures) and out-flanking (supporting sand removed from around ends of structures), and natural protection offered by vegetation.

Increases in wave energy reaching the coastline (either through more intense cyclone events or through reduced nearshore wave breaking due to higher sea levels) may also have a significant impact on coastal protection structures. The required mass of rock or concrete armouring for seawalls and breakwaters for example, has a cubic power relationship to wave height (USACE 2002)—a 15% increase in wave height requires a 50% increase in the mass of coastal protection armour. Increases in demand for local rock adds further pressure both on local quarries and a finite extractable resource. This is especially true on small or non-volcanic islands, with increased sedimentation and deterioration of local waterways associated with such activities. With concrete production itself being a major contributor to global CO_2 emissions (Habert et al. 2010), increasing demand for this is also counterproductive, and suffers the same finite supply limitations due to limits on locally available aggregates.

10.4 Management and Adaptation

10.4.1 Infrastructure Adaptation Options

There are a range of solutions to the infrastructure vulnerabilities discussed above, summarized in Table 10.2 for each of the focus infrastructure areas. The major difference between the three classes of infrastructure and the adaptations that could be employed is the spatial scale and extent of the communities that they serve. Nevertheless the interconnectedness of infrastructure across the water-energy-food nexus means that it is vital that these potential adaptations are not considered in isolation. Maladaptation is a real risk from isolated adaptation approaches, for example sea walls that do not accommodate increased rainfall and flood risk can trap water on the landward side (McNamara et al. 2020; Piggott-McKellar et al. 2020). In the context of the water-energy-food nexus, there is limited benefit from adaptation of port facilities if internal road infrastructure servicing the port does not have a similar level of resilience to climate change or extreme events. Failure of coastal infrastructure to prevent overtopping and erosion on shorelines will result in negative impacts on local food (household gardens, taro crops in low-lying areas) and water (shallow aquifers) resources.

An adaptation case study

Avatiu Port on the island of Rarotonga (Figs. 10.4 and 10.5) is the main international seaport in the Cook Islands, processing 90% of total imported goods arriving via sea transport (ADB 2014), as well as visiting international yachts and cruise ships. In 2012–2013 an ADB-funded project led to infrastructure improvements targeted at building climate resilience for the port. Prior to the upgrade, the port was restricted to ships with a maximum length of 90 m and draft of 6 m (Youdale and Tou 2013). The main wharf and quay were deteriorating and had suffered periodic damage from cyclones prior to the upgrade (Blacka et al. 2013).

One of the key features of the upgrade was rehabilitating the wharf deck including modifying the design to improve drainage and allow for projected sea level rise. Importantly the new design ensured that future adaptation works could more easily be implemented (such as further raising of the wharf deck level). To address the risk of extreme waves, a new inner harbour rock revetment was constructed, and additional rock armour added to the breakwater to protect the northern end of the quay. Highlighting the interconnectedness of infrastructure with energy and food, the port works also included land-side improvements such as relocating and strengthening the stevedoring and cargo sheds and rearranging the petroleum handling pipes and hazardous materials area. The redevelopment of the port of Avatiu has undoubtedly improved the climate-security of supplies to the Cook Islands via seaborne cargo, which supports energy and food security of the country. Nevertheless, some climate risks to the facility remain and are still being identified.

10.4.2 Pacific Strengths and Barriers to Infrastructure Adaptation

Beyond technical aspects, the complexities in developing adaptive responses to mitigate climate change impacts on infrastructure vary across the Pacific region due to geophysical, cultural, social economic, and environmental differences between countries and islands. A ‘one-size-fits-all’ approach does not work for the region (World Bank 2016). Land tenure is a major consideration in providing infrastructure in PICTs. Communities have deep spiritual, cultural, and ancestral ties to land and water (Weir et al. 2017). There are examples of conflicts over water being based on land tenure in Kiribati where government control of land to create water reserves intersected with the interests of the traditional owners (White et al. 2008).

Table 10.2 Potential adaptation options for climate change impacts on infrastructure

Effect of climate change	Impact on infrastructure	Potential adaptation responses
Marine transport infrastructure		
Changes to seasonal climatology such as winds, air temperature, ocean currents, and waves	Implications for navigation and berthing of vessels	Altered operating rules for vessels entering port, modifications to navigation channels, and harbour wave protection structures
	More frequent occurrences when vessels cannot enter port or safely transfer cargo to island barges	Modify harbour facilities to provide additional shelter or safer passage during broader window of conditions, consider alternative/backup unloading facilities, increase storage of goods held on-island
	Implications for operation of cargo unloading equipment (such as cranes), cold storage, etc.	Alter operations to accommodate periods of down-time, adapt cargo-handling methods to accommodate higher winds or air temperature, improve efficiency of cold storage facilities
Sea level rise	More frequent inundation of wharf facilities	Structural changes to raise wharf deck levels and lift other infrastructure
	Increased wave conditions impacting port due to deeper water or increased winds	More frequent maintenance of wave protection structures
		Modifications to wave protection structures
	Landward retreat of adjoining coast	Protection of adjacent areas of coast (soft or hard), modifications to interface areas of wharves/surrounding terrain
More intense cyclones	More frequent and/or more intense storm surge inundation of wharves and other port infrastructure	Raise level of wharf decks and other infrastructure, adapt land-side facilities to tolerate short periods of inundation, modify coastal protection to reduce impacts of wave setup and infragravity waves, modify cyclone preparations to accommodate more severe conditions

(continued)

Table 10.2 (continued)

Effect of climate change	Impact on infrastructure	Potential adaptation responses
	Larger waves and higher water levels impacting on coastal protection structures	Raise and increase armouring of protection structures, increase maintenance top-ups of armouring, adapt protection structure designs to tolerate more intense conditions
	Additional wind damage on cargo handling and other land-side equipment/facilities	Strengthen cargo handling equipment and storage facilities, modify cyclone preparations to accommodate more severe conditions
WaSH infrastructure		
Changes to seasonal and annual rainfall cycles	Water shortages due to insufficient storage	Increase storage and catchment areas, more diverse water sources developed
	Reduced recharge for springs and freshwater lens	Sustainable yields identified, more diversity in sources
More intense rainfall events	Increased flood risk and damage to infrastructure	Diverse water supply sources
	Cross contamination of freshwater from sanitation infrastructure	Improved water sources with less exposure to surface water inflows, improved design and siting of sanitation infrastructure
Sea level rise	Increased saltwater intrusion for freshwater lens	Limited ability to adapt to this impact
More intense cyclones	Increased incidence of wave overtopping for freshwater lens	Limited ability to adapt to this impact
	Extreme rainfall and wind speed damage to infrastructure	Diverse water supply sources
Increased temperatures	Changes in microbial growth	Wider use of improved water sources, wider use of system or household disinfection systems
	Increases in algal growth	Improved catchment protection Mechanical and chemical treatment
Engineered coastal protection infrastructure		
Sea level rise causing increased water levels at protection structure	Increased frequency and volume of overtopping	Raise structure crest to reduce overtopping or adapt backshore areas to tolerate higher overtopping flows

(continued)

Table 10.2 (continued)

Effect of climate change	Impact on infrastructure	Potential adaptation responses
Larger waves caused by higher wind speeds or deeper water at protection structure	Higher wave loading on armour units	Place larger armour over existing units or create berm/beach in front of structure to induce early wave breaking and dissipation
	Increased frequency and volume of overtopping	Raise structure crest to reduce overtopping or armour backshore to tolerate higher flows or create berm/breakwater/beach in front of structure to induce early wave breaking and dissipation
Landward retreat of shoreline under rising sea level or faster lagoon currents	Erosion of sand from around ends of protection structures	Extend structure alongshore or re-align ends to accommodate new shoreline position
	Beach level lowers in front of structure	Extend or create deeper toe (base of protection structure) using additional armour material (rock, sand-filled geotextile bags etc.), sheet piling or concrete

Modified from Shand and Blacka (2017)

Pacific strengths around dialogue and the importance of relationships and reciprocity suggest ways to approach infrastructure adaptation. Brown et al. (2018) show that the collective nature of iTaukei communities in Fiji provides for better ability to recover from natural hazards, and Macpherson and Macpherson (2017) document success in government policies to manage water in Samoa, which was previously seen as a community owned resource. This success was attributed to the wide consultation process and emphasis on national interest, aligning with the importance of dialogue more broadly in PICTs. Similar experiences are occurring in the Cook Islands with major water supply and wastewater infrastructure development on the island of Rarotonga, again highlighting the importance of ongoing communication between government, donors, and other stakeholders. Chapter 11 covers traditional knowledge and its role in adaptation to the current climate change threats in the Pacific in detail.

Institutional arrangements in the Pacific affect infrastructure provision and adaptation. For example, informal settlements are often not included in the service areas for water supply authorities (Anthonj et al. 2020). Additionally the PICTs have some of the highest rates of non-revenue water in the Asia Pacific with rates between 30 and 60% (World Bank 2016). These high rates of non-revenue water also increase the operational expenditure, with particularly high rates in the Solomon Islands and Samoa leading to elevated costs of input water (World Bank 2016). Other institutional

Fig. 10.5 Cyclone damage to Avatiu Port from wave and storm surge impacts (Reproduced from Blacka et al. 2013)

barriers include the scarcity of experienced professionals, insufficient resources for operation and maintenance of existing infrastructure and poor infrastructure planning (Baker and Week 2011). For example, Falkland and White (2020) suggest that long term performance of RO units in the PICTs has been poor due to these types of barriers. Issues with operation and maintenance of infrastructure (PRIF 2014) have day-to-day impacts, as well as reducing the resilience of PICTs to natural disasters, which will likely become more severe with climate change (Pacific-Australia Climate Change Science and Adaptation Planning Program 2014).

One of the major constraints on infrastructure adaptation is that the ability to provide economies of scale through the Pacific is hampered by the geography of remote islands and distributed populations (Weir et al. 2017). Although tourism is an important part of the economies of many PICTs, most tourist infrastructure is private and of limited benefit to local communities (Baker and Week 2011; Pearce et al. 2018). Major public infrastructure investment relies on international donors and/or loans, which come with their own requirements and the priorities of donors (e.g., donor preferences may be for centralized infrastructure), and donor coordination can be poor (Baker and Week 2011). McNamara et al. (2020) found that the high performing adaptation projects tend to be delivered by local organizations and/or locally funded, highlighting the value that comes from sustainable community involvement in adaptation and the importance of decentralized/local infrastructure, regardless of the source of funding, particularly given the remote geography.

10.5 Conclusion

Infrastructure plays a vital role in the provision of water, energy, and food in the Pacific region. Significant investment is required to ensure the continued efficient operation of this infrastructure under a changing climate. Countries such as Australia and New Zealand may have sufficient economic and technical resources to achieve these outcomes. However, the physical and institutional challenges that face PICTs are substantial. Communities in the PICTs have a long history of living with climate variability and particularly distinctive aspects of Pacific culture, such as collectivism, the importance of building relationships, and strong traditional knowledge of the climate, oceans, and land, can support resilience. The water-energy-food nexus is a useful framework for exploring infrastructure interdependencies, as shown in this chapter, because of the extensive linkages between infrastructure that supports multiple social and economic outcomes. These linkages are important day-to-day to support the livelihoods of Pacific communities but become even more vital during disaster response and recovery. With climate change expected to increase the prevalence and/or intensity of coastal and hydrological extremes, improving the resilience of infrastructure must be prioritized to further promote social and economic resilience in the Pacific. There are a number of steps that could be taken to improve the resilience of infrastructure in PICTs, thereby reducing the vulnerability of the Pacific population to threats to their water, energy, and food security.

- Framing infrastructure investment using the water-energy-food nexus is vital to ensure that the interconnectedness of infrastructure is not missed and to prevent maladaptation. Ad-hoc or individual infrastructure improvements will not increase the resilience of PICTs.
- Building knowledge and capacity within the region to:
  - Mainstream climate risk considerations as part of the initial design of new, and adaptation of existing infrastructure, such that integration with natural environmental systems and local knowledge is captured within designs, and that expertise is retained;
  - Improve design standards for infrastructure; and
  - Support maintenance of infrastructure across its functional life.
- Continuing to close the gap in scientific knowledge and use traditional knowledge of island-specific processes, such that infrastructure interventions are fit-for-purpose in terms of their own longevity, the service they provide, and the impact of the site-specific environment within which they sit.

- Ensuring whole-of-life sustainability for infrastructure interventions and integration of engineering and nature-based solutions, such that climate adaptation works appropriately reflect the scale required, and due consideration is given to the specific environmental and cultural context.

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