Water and Food Security in the Pacific

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1 Introduction

The aim of this briefing paper is to provide a summary of the fresh water and food production nexus in atolls and low-lying islands in the Pacific. It draws from academic and grey literature, including existing databases and recent projects undertaken by the SPC, to identify possible areas of intervention to support integrative water and agriculture development to support atolls' sustainable development.

Atolls are unique in the world given their isolation, relatively high population density, poor freshwater access and dependence on imported food (J. Campbell, 2020; Goldberg, 2016). Atoll communities are increasingly at the forefront of climate change threats, which exacerbates other underlying risk factors to water and agriculture, such as a narrow genetic base for crops and scarce freshwater resources (McLean & Kench, 2015; White, Falkland, Metutera, et al., 2007). Sustaining current and immediate future livelihoods require strategies that work within the biophysical and socio-cultural systems that influence agriculture and water management.

The Pacific is home to four countries that have a large number of atolls with population: Kiribati, Marshall Islands, Tokelau and Tuvalu (see Table). Tokelau is a dependent territory of New Zealand, and the other three are independent sovereign states. The countries have Micronesian and Polynesian cultural histories and governance systems. While these countries largely lie outside the cyclone belt, they are extremely vulnerable to climate change–induced sea level, overtopping and changes in rainfall patterns. There are also other Pacific sovereign nations that have a high proportion of low-lying carbonate islands within them, for example, the Solomon Islands (62% low-carbonate islands) and Papua New Guinea (PNG; 46% low-carbonate islands, based on Dixon-Jain et al., 2014). Planning water–food nexus interventions for atolls, thus, requires an initial understanding of the countries' contexts and political economies. For example, a small population atoll such as Tuvalu is more likely to have general issues that affect the 10,000 inhabitants, meaning their national policy frameworks can plan to target full populations that share similar bio-geophysical living conditions. Contrastingly, in PNG, it is estimated that 90,000 people live on very small islands (Bourke, 2000). For a very large complex island country such as PNG, geographic granularity and design of interventions is important to differentiate the national frameworks to the specific island contexts.

The water–food production issues highlighted in this briefing paper provide an initial overview for future researchers, consultants and practitioners seeking to contextualise water–agriculture linkages in atolls. While atolls are unique, they share some similarities to low-lying islands (some of which might be limestone or patch reef carbonate), so the analysis here may prove useful to other low-lying islands. There are some inhabited atoll islands and low-lying islands that lie within the cyclone belt in countries such as the Solomon Islands, PNG and Vanuatu, which makes adaptation strategies to support water and agriculture in these landscapes important.

Table 1. Summary of atoll characteristics (Nunn et al., 2016), JMP Data and SPC Water Diagnostic Reports

Country	Number of islands	Population size ('000)	Total area of islands (km^2)	Average island total area (km^2)	Average island maximum elevation (m)	Nutritional context	Basic water access	Annual rainfall averages
Kiribati	33	111	995	30	6	Overweight % (77 male / 81 female) Obesity % (42 male, 50 female)	78%	1300–2000 mm in Gilbert Islands, over 3200 mm in Northern islands, less than 1000 mm in eastern Line islands.
Marshall Islands	34	54	286	8	3	Stunting (34%) Overweight % (82 male, 84 female) Obesity % (57 male, 48 female)	89%	4000 mm in southern atoll, 2000 mm in northern atolls.
Tokelau	3	1.2	16	5	5	ND	100%	Not able to source with confidence.
Tuvalu	10	11	44	4	4	Stunting rate (10%) Overweight % (80 male, 84 female) Obesity % (47 male, 56 female)	100%	2700–3500 mm.

1.1 Atolls and their unique water and food context

Atoll islands consist of a circular to elliptical chain of small coral islets that surround a shallow lagoon. Atolls are low-lying carbonate islands with the highest average elevation of no more than 6 metres. Most of the world's atolls are located in the Pacific and Indian Oceans. Fresh water in atolls is available largely from rainfall or freshwater lenses. When precipitation across an atoll is high, freshwater lenses are created where freshwater floats above denser saline groundwater. Societies have lived in atolls for centuries and have heavily relied on a combination of rainfall and groundwater resources drawn from shallow freshwater lenses for their livelihoods (Werner et al., 2017). Food production on atolls is limited and relies on these same water sources. Atolls have highly porous and low-quality soils with limited fertility for growing crops. A combination of drought, variable rainfall, poor soils and isolation makes diversifying and up-scaling food production a challenge (Halavatau, 2018). The limited availability of fresh food means that atoll countries rely predominantly on coastal fishing from lagoons as a main source of livelihood and nutrition. Fresh goods include swamp taro, some leafy greens, coconuts, yams and cassava. For example, Kiribati has the highest per capita consumption of fish in the Pacific, at 82 kg per person per year (Gillett, 2016). With globalisation and international trade, atoll countries have increased food imports, which has meant higher availability of imported food, usually highly processed and packaged to last a long time on the shelves of local shops (Sievert et al., 2019; Snowdon et al., 2013).

Geologically speaking, atoll islands are quite recent—some are as young as 8000 years old (Wooroffe & Falkland, 2004). They are unique because they are generally composed of overlying aquifer formations made up of poorly consolidated sediments deposited over limestone reef deposits (Werner et al., 2017). Populations are relatively small, but population density can be very high due to limited land and distance between islands. For example, Ebeye island in the Kwajalein atoll of Marshall Islands has a population density of 40,000 inhabitants per square metre. The growing young population has increasingly put pressure on water supply systems, sanitation and waste management and has created environmental risks (United Nations Population Fund, 2014). Historically, atoll communities have managed the oceans and landscapes using customary governance and resource management practices, which have provided ways of managing resource scarcity and environmental change (Barnett, 2011). Recent discussions for the United Nations Food Systems Summit have emphasised the crucial need to enable resource management systems that balance Indigenous and traditional knowledge with internationally funded interventions (SPC, 2021). Traditional management approaches are highly context specific; for example, in the geographically vast Kiribati, one island may have different hierarchies and decision-making structures than another. Some islands within countries have management plans, for example, the Abaing Drought Management and Response Plan, which highlights governance of drought at the island level (Sutton, 2016). These island-specific plans often involve different members of the community, are facilitated by external funding and allow the interaction of 'Western' science and place-based, context-specific knowledge.

1.1.1 Climate change and its impact on water and food

The climate impacts on atoll islands will be caused by a combination of sea level rise and overtopping, changing ocean temperatures, changes in groundwater and rainfall, and changes in food production conditions. Cyclones will impact atolls, for example, in cyclone-prone countries such as Tuvaly and Tokelau, and will be exposed to increasingly extreme cyclones. Kiribati, on the equator, is rarely affected by cyclones and will face different issues associated with rainfall variability and intensity. The Marshall Islands, despite not lying in the South Pacific convergence zone, will also be impacted by cyclones (CSIRO [Commonwealth Scientific and Industrial Research Organisation] & SPREP [Secretariat of the Pacific Regional Environment Programme], 2021b).

Sea level rise's impacts on groundwater are expected to lift the freshwater lens in atoll countries closer to the land surface. This may have implications for evapotranspiration and a reduced 'barrier' for the mitigation of water table contamination. There is potential for the existing infrastructure of wells and galleries to be located in a more brackish part of the freshwater lens, especially during drought, in response to the water table uplift. While there is much uncertainty in climate projections, annual rainfall will increase in some areas and decrease in others. Some parts of Kiribati, such as Tarawa, may actually see an increase in rainfall over the next 50 years. Overall, there is general agreement that the intensity of extreme rainfall will increase with climate change (CSIRO & SPREP, 2021c; IPCC, 2021).

Taking into account emissions beyond 2020, the sea level is projected to rise by between 35 cm to 120 cm by 2100 in atoll countries, depending on the emissions scenarios used (CSIRO & SPREP, 2021a, 2021c). Impacts of sea level rise will include the inundation of coastal areas, erosion, the uprooting of mangroves and freshwater lens infiltration. Given that 100% of atoll populations live less than 1 km from the shore (Andrew et al., 2019), sea level rise is likely to displace people and impact infrastructure. Increased CO_2 and the associated decline in seawater pH will impact coral reefs and fish species, which poses a long-term food security risk for the population.

Despite relying on imported food, traditional crops continue to play important cultural roles and provide subsistence food for atoll communities. Saltwater intrusion, overtopping and lost land to sea level rise will impact the traditional food systems of atoll islands (Taylor et al., 2016). Prolonged drought and rainfall variability will also limit food production. This is already impacting food and water security. For example, the 2016 drought in Marshall Islands led to 11,000 people suffering from food and water shortages. The 2016 drought is considered one of the strongest on record, as rainwater in rooftop catchment systems was depleted and groundwater wells became brackish, which led to severe water rationing across the nation. Table provides a summary of projected rainfall in selected countries with atolls and low-lying islands.

Table 2. Summary of projected per cent rainfall change, from 1986–2005 averages, for RCP4.5 and RCP8.5 for 2090 for PICTs (Taylor et al., 2016)

Country	Station	RCP4.5 November–April	RCP4.5 May–October	RCP8.5 November–April	RCP 8.5 May–October
Kiribati	Gilbert Islands	23% (–11% to 77%)	44% (11% to 110%)	42% (–8% to 128%)	78% (7% to 169%)
	Line islands	12% (2% to 22%)	8% (–4% to 18%)	18% (5% to 35%)	14% (–3% to 29%)
Marshall Islands	Central	8% (–5% to 26%)	4% (–6% to 21%)	18% (–4% to 52%)	13% (–6% to 44%)
	South	2% (–11% to 14%)	5% (–5% to 16%)	5% (–11% to 31%)	11% (–6% to 26%)
Tokelau		NMA	–5% to 10%	NMA	–5% to 10%
Tuvalu		4% (–10% to 15%)	4% (–7% to 19%)	8% (–25% to 36%)	3% (–26% to 24%)

Note. NMA = No Model Agreement, PICTs = Pacific Island Countries and Territories, RCP = Representative Concentration Pathway.

1.2 Governing water and food in Pacific atolls

Governing water and agriculture in the Pacific is challenged by the fact that the sectors are managed through a combination of traditional and Indigenous knowledge with Westernised institutional structures. Societies in PICTs have been governed for thousands of years through traditional institutions and value systems, but colonialism and globalisation in the past two centuries have led to the establishment of Westernised governance systems (Hassall & Tipu, 2008). Modern-day governance of PICTs is facilitated through a blend of nation-statehood (or dependent territories of a nation-state) and traditional systems that have varying levels of power and legal recognition across the region (Hassall et al., 2011). As a result, central governments dictate policy for natural resource management and use for the country or territory. However, land tenure and stewardship, particularly in rural areas, and atolls outside the capital are often customarily held by traditional owners (Hassall & Tipu, 2008; Hassall, 2019). In urban centres, formal governments are more present in governing natural resources, but traditional systems exist there as well (Jones, 2016). Further, as a product of relatively new institutions since independence throughout the region, PICTs are formally governed by line ministries with limited opportunities for cross-ministry collaboration and policy incentives for cross-sectorial alignments. While Integrated Water Resources Management (IWRM) grew as a topic of interest in the region in the early 2000s, the very challenging geography and diverse governance systems have made the reality of implementation challenging (Dahan, 2018). The *Report 1: Policy Review* written for this research activity, which discusses framings of the water–food nexus, indicates that there are windows of opportunity to use national policy strategies and priorities to enable cross-ministerial projects and collaboration; however, context-specific capacity and co-development of initiatives are required.

2 Water and agriculture in atolls: A summary

2.1 Water resources in atolls and their common uses

Atoll hydrogeology

Atolls are geologic structures derived from basaltic volcanoes that have subsided. Reef growth results in a cap of calcium carbonate minerals that extend from the sea surface to the top of the submerged volcano. Chemical alteration and weathering of these carbonate minerals, induced by precipitation and sea level changes, govern the shallow subsurface geology and hydrogeology. Fresh groundwater in atolls occurs as a thin lens buoyantly supported by dense underlying saline water. As rainwater infiltrates the ground, a freshwater lens is formed within the top unconsolidated (Holocene) sediments due to suitable hydraulic conditions. The groundwater table is generally encountered at shallow depths (1.5–2.5 m), while a zone of transitional salinity typically exists between the fresh groundwater and the underlying saltwater (White, Falkland, Perez, et al., 2007). This zone is formed by the mixing of the two water types, which is promoted by tidal forces. Its thickness largely depends on the hydraulic properties of the aquifer sediments and the depth of the underlying karstified (Pleistocene) limestone, which sets a limiting factor for freshwater lens development (Werner et al., 2017; White, Falkland, Metutera, et al., 2007). The hydraulic properties of the Holocene sediments strongly depend on the island's position with respect to the prevailing winds. These sediments tend to acquire a coarse structure on islands that are in the direct path of the prevailing winds and their associated high-energy waves. In contrast, sediments on the partially protected leeward side of atolls tend to acquire a finer structure, more suitable for the development of thicker freshwater lenses.

Climate and droughts

Rainfall within an atoll is fairly uniform due to the absence of landforms creating orographic effects and variable rainfall patterns. Rainfall is governed by the regional climatic patterns, which are dictated by three major wind convergence bands and their periodical shifting associated with El Niño events. Average annual rainfall varies considerably between islands in the tropical Pacific Ocean, with variations between annual rainfalls of more than 4,000 mm to less than 500 mm.

El Niño events have the potential to cause catastrophic droughts in the Pacific region, such as in PNG, the Federated States of Micronesia (FSM) and the Republic of Marshall Islands (RMI). The reverse condition, popularly known as La Niña, can cause below-average rainfall in the low-equatorial islands of western Kiribati, Tuvalu and Tokelau.

These periods of drought pose serious risks to communities that are reliant on rainwater harvesting as a primary source of fresh water. The effects of droughts on groundwater (i.e., increasing salinity) take longer to manifest themselves, so groundwater is considered much more resilient compared to harvested rainwater supplies. Nevertheless, a prolonged drought can promote the shrinking of freshwater lenses driven by the upward movement of the freshwater–saltwater interface resulting in increased salinity of the groundwater abstracted from shallow wells. With limited capture and storage capacities for rainwater and shallow groundwater aquifers, these atoll islands require careful management of their water resources.

Water supplies

Rainwater harvesting has been traditionally practised in the Pacific atolls long before the widespread introduction of rainwater tanks. One example of this traditional management system is shown here.

People all around the Marshall Islands have been practising methods of harvesting fresh water for a long time. Two of these, according to Dustin Langidrik (University of South Pacific), involved palm trees and pandanus trees. ‘The palm tree method is called in the Ralik Chain “mammak” and in the Ratak Chain it’s known as “emmak”.’ The harvester uses a very young palm tree of the type that will have a slope to its trunk and carves out a hole in the tree’s base. As the tree grows, the hole gets larger. When it rains, the water drizzles down the tree and into the hole. ‘I’ve seen “bowls” in old trees, maybe 40 or 50 years old, that can collect two or even more gallons of water.’ Figure 1 shows an example of the Mammak/emmak palm tree water collection method.

Figure 1. Traditional palm tree water collection method. (Source: Authors)

Nowadays, Tuvalu, Marshall Islands, Kiribati and Tokelau use a combination of groundwater, rainwater, imported water and desalinated water to meet varying needs. For example, research in the Marshall Islands found that households dynamically access multiple water sources for different purposes across the dry and wet seasons (Elliott et al., 2017). Surface water is usually non-existent or available only temporarily or in small quantities.

On most atolls, rainfall and groundwater (from shallow wells) are the two primary freshwater sources, although some smaller atolls do not have substantial groundwater. In some areas, there is limited rainwater harvesting infrastructure, which makes groundwater a crucial freshwater resource. For example, in the atolls of Kiribati, people rely on groundwater for their potable water because of the low rainfall they receive throughout the year, a trend that is remarkably reflected in the majority of thatched roofs still present. Recent technology and trade have made desalination and imported water an important source of water on some atolls, but these are usually secondary sources (although desalinated water is the primary source of fresh water on some atolls, such as Ebeye island, Marshall Islands).

Rainwater is usually collected at both household and community levels. Community buildings such as schools and churches are frequently equipped with rainwater harvesting systems that collect rainwater for use by the community. Depending on the local management scheme, community tanks can be used:

i) during dry periods when private tanks are running low;
ii) by disadvantaged members of the community who do not own private rainwater harvesting systems;
iii) to cover the water demands of the particular building (e.g., a school); and
iv) by community members at any given time.

Groundwater is usually abstracted through shallow wells dug just below the water table to access the freshest portion of the groundwater. These wells are usually private and serve the primary and/or secondary water requirements of individual households. In certain cases, community wells are used as emergency water collection points during droughts. Larger-scale groundwater development for public water supply only exists in South Tarawa (Kiribati), Kiritimati (Kiribati) and Majuro (RMI) atolls. Groundwater in these atolls is abstracted through a network of horizontal wells (infiltration galleries) constructed just below the water table and skimming the freshest part of the lens. Development of these aquifers requires careful management guided by suitable monitoring of rainfall in conjunction with groundwater salinity to maximise their yield without compromising their quality and health.

Water resources in atolls are typically limited and fragile. Rainfall patterns can be irregular, which leads to prolonged dry spells. Groundwater is the most reliable water resource on many atolls, but because it exists as a shallow lens, it is susceptible to depletion and salinisation from over-abstraction and natural causes and contamination from human activities (e.g., pit latrines and septic tanks; White & Falkland, 2010). Desalinated and imported water are relatively expensive and generate waste (concentrated brine from desalination technologies and plastic waste from imported water) that is harmful to sensitive ecosystems on atolls.

To meet water needs, people living on atolls use a combination of water supplies that draw on these resources. These water supplies and their common uses are summarised in Table3.

Table 3. Water supplies in atolls and their common uses (Falkland & White, 2020; Werner et al., 2017)

Water supply	Description	Common uses of water
Privately owned electric and hand pumps and wells	Abstraction of shallow groundwater through wells using hand pumps, electric pumps or buckets. These systems are owned by individual households or communally by the village.	Domestic purposes such as cleaning and washing. It may also be used for potable water, although health authorities encourage treating the water before consumption because of the high risk of contamination. It may also be used to feed livestock.
Rainwater harvesting systems	Systems that collect rainwater into a storage container for later use. These include privately owned domestic systems that collect rainwater off household rooftops, communal systems that collect rainwater from communal building rooftops and rainwater collected off of ground surfaces, such as the concrete runway on Majuro atoll, Marshall Islands.	On small atolls with limited water resources, this may be the primary source of fresh water for all uses. On larger atolls with groundwater, it is primarily used where domestic potable water is needed.
Piped schemes	Reticulated piped systems that distribute water to multiple locations. These generally exist on larger atolls and are managed centrally by governments or utilities. The water source is usually groundwater abstracted by infiltration galleries or desalination plants.	Used for all domestic, commercial and other productive purposes.
Desalination	Technologies that remove minerals from seawater make the water suitable for potable and agricultural purposes. Desalinated water may be a source for piped schemes. Small-scale (sometimes solar-powered) desalination units provide water that is collected in containers on-site and carried to the point of use.	Larger-scale desalination systems that provide water for piped schemes may be a primary source of water for all uses (e.g., some atolls in Marshall Islands) or for emergency use during drought (e.g., in Funafuti, Tuvalu). Water from small-scale desalination units is usually used for potable purposes only.
Imported water	Packaged water (e.g., bottled water) or larger volumes of water shipped from locations outside the atoll.	Packaged water is primarily used for drinking. Larger volumes of water are shipped in during water scarcity emergencies and prioritised for potable purposes and other emergency uses.

2.2 Food production systems

For atoll communities, subsistence agriculture and coastal fishing are the main sources of both food and income, largely through domestic markets (Halavatau, 2018). Some export crops—notably copra—provide some income, but the sector is declining due to senile coconuts. The value of exports to imports is very low (6% in Kiribati between 2003 and 2010), and this imbalance is offset through a combination of foreign income remittances, aid inflows and, in some cases, tourism (Taylor, 2016). Atoll countries such as Kiribati, Tuvalu and Tokelau receive a large proportion of government revenue from fisheries access fees (Gillett, 2016). Due to poor soils, regular consumption of fruit and vegetables is low. For example, in Kiribati, only 130 g per day of fruit and vegetables is consumed, which is well under the 400 g recommended by the WHO. Poverty is a major driver of food insecurity; 22% of the population lives below the poverty line, and 41% of people experience moderate to severe levels of food insecurity (FAO, 2021).

The predominant constraint in atoll islands for agriculture is arable land availability and fresh water. With projected increases in rainfall due to climate change, freshwater capture could be managed to support fresh food production in the future. Poor-quality soils are a major barrier that requires novel interventions and research into the types of soil production systems that could generate sufficient nutrients to support plant growth in saline conditions. There has been a growing number of livestock (pigs, poultry) throughout the country. These are important sources of protein, yet they create a pollution risk for the limited freshwater resources (Alik et al., 2010). Food crop production is constrained to the coast and to small, community-owned farms less than an acre in area, but still make a valuable contribution to household self-sufficiency. For example, around 20% of household income in Tuvalu comes from home gardens and the products they produce (Taylor, 2016).

Multiple crops are still grown on atolls, as they hold important traditional and food consumption value. Swamp taro (called *babai* in Kiribati and *pulaka* in Tuvalu) is an important traditional crop that holds important cultural value (Halavatau, 2018). Swamp taro has been cultivated traditionally in hand-dug water table level pits (in many Kiribati atolls, only 1–2 m below the surface), and while many of these pits are now neglected, they provide a strong connection to both culture and fresh groundwater (Halavatau et al, 2020). Coconut, from which copra is produced, is a major agricultural export, albeit limited in production (Halavatau, 2018). Production of copra is government subsidised to enable employment for the outer islands population and minimise people moving to already overcrowded centres (e.g., Tarawa in Kiribati).

Having extremely limited surface water resources means that agriculture relies almost completely on fresh groundwater resources. Storage and availability are constrained by very small land areas, aquifer geology, demand from both human settlements and agricultural activities and waste disposal issues (Taylor, 2016). A combination of drought conditions and highly variable rainfall will affect the ability of atolls to reliably produce food. Understanding long-term variability and capacities to adapt water management practices will be important strategies for future food production. Salinisation of groundwater, storm surges and land lost due to coastal erosion will also affect food production. Soil fertility is low in the atoll countries characterised by porous and alkaline soils, which is a major barrier to improving food production. While not comprehensive, we have synthesised material from different studies to provide an overview of the main crops and current water conditions for key atoll commodities (see Table). The complementing *Report 2: Nexus briefing paper* provides additional analysis for selected crops and models implications for water use in light of climate and population growth.

Table 4. Summary of key food products and water conditions in atolls

Food item	Overview	Vulnerability	Water context
Coconuts	• Products provide small but important source of income in RMI and Kiribati. • Exported as whole nuts, copra and coconut oil manufactured from copra or oil extracted directly from fresh coconuts. • Copra industry subsidised with the intention of supporting and providing rural livelihoods. • Tolerates neglect well and short periods of drought, saltwater intrusion, intensive rainfall and longer periods on well-drained soils. • Timing of harvest not critical.	• Copra production has high labour requirements relative to price. • Prolonged drought significantly delays nut production. • Sea level rise.	• Relative humidity should be more than 60%. • Ideally, the crop requires stable water conditions and not to be exposed to prolonged periods of drought or excess soil salinity. • Can tolerate higher rainfall if soils are well drained. Optimal rainfall is between 1000–2250 mm per annum.
Breadfruit	• Commonly grown and important in many atoll countries, such as RMI (Taylor, 2016). • In urban Majuro (Marshall Islands), more than 40% of households grow some breadfruit.	• Fungi can rot fruit and affect fruit, trunk and root. • Mango fly can attack breadfruit. • Coconut scale affects breadfruit in Tuvalu. • Prolonged drought can damage tree. • Some varieties do not tolerate salinity. • Susceptible to damage from storms (all points from Taylor, 2016).	Breadfruit requires well-drained soils, but some varieties have adapted to the sandy soils in atolls. It remains a culturally important carbohydrate in Kiribati. It grows best under warmer temperatures and high rainfall (1500–2500 mm per annum). While it requires high amounts of rainfall, it is also tolerant to long periods of drought after tree establishment. Some traditional varieties, such as Mejwaan in the Marshall Islands, are tolerant to brackish and saline soils. Similar varieties also exist in Kiribati (Te Maitairika and Te bukiraro).

Food item	Overview	Vulnerability	Water context
Pulaka (swamp taro)	• Important crop. • Tolerates swampy conditions and some salinity (genotype-dependent). • Significant cultural value. • Value as staple food crop declining. • Can survive a cyclone with limited wind damage.	• Saltwater intrusion from sea level rise and extreme high tides. • Drought will exacerbate impact of salinity.	• Pulaka requires low-salinity fresh water and relatively wet conditions. • Increasing salinisation on atolls could lead to the full disappearance of swamp taro by 2050.
Taro	• Staple root crop. • Irrigation essential for production. • Production has fallen dramatically with increased access to imported staples (Taylor, 2016).	• Lack of water restricts root development and limits photosynthetic ability, resulting in stunted crop (Halavatau, 2018). • Highly susceptible to cyclone damage and associated flooding (rotting of corm, thin leaves and stems susceptible to tearing in strong winds) (Taylor, 2016). • Colocasia taro susceptible to taro leaf blight. • Plant leaf hoppers, caterpillars and mites (Halavatau, 2018).	As taro is vulnerable to drought, simple irrigation may be essential for production. It requires a good supply of water for up to 20 to 25 weeks. Even a two-week drought may affect yield. Prolonged dry conditions will restrict root development and result in a stunted crop. When taro cultivation depends on rainfall, the timing of planting is critical. The crop must be planted at the start of the rainy season, which has to last long enough for the crop to mature (6–9 months). On atolls, it is essential to maintain soil organic matter to make the best use of the water supplied by rainfall.

Food item	Overview	Vulnerability	Water context
Cassava	• Tolerant of drought (Halavatau, 2018). • Can grow in relatively infertile soils (Halavatau, 2018). • Often used as final crop in rotations before land is left to fallow (Halavatau, 2018). • Competes well with weeds (Halavatau, 2018). • Come varieties tolerant of salinity (Taylor, 2016).	• Sensitive to shade (Halavatau, 2018). • No major pests of cassava except possibly rodents (rats) and pigs.	Cassava grows best when rainfall is around 1000–1500 mm annually. Too much rain can reduce tuber growth. The plant is tolerant of drought and can be grown in areas with an annual rainfall of around 500 mm, though yields will be lower.
Sweet potato	• Reasonable yields can be obtained with some varieties (Taylor, 2016). • Can be grown throughout the year (Halavatau, 2018). • Some varieties tolerant of salinity (Taylor, 2016). • Production has fallen dramatically with increased access to imported staples (Taylor, 2016).	• Soil nutrient deficiencies reduce crop growth rates and yield (Halavatau, 2018). • Sweet potato weevil and leaf scab (Halavatau, 2018).	Sweet potato is known as a relatively drought-tolerant crop. It is most commonly grown under suitable rainfall conditions or with irrigation in seasons where enough irrigation water is available for other crops as well. Sweet potato crops perform best when the soil is constantly moist. Moist conditions are required after planting until the root system is well developed. Plants can then tolerate brief dry spells, and they recover well when the soil is moistened again. However, long spells of dry conditions restrict the development of roots and limit photosynthetic ability, which produces a stunted crop with tubers likely to be shorter or misshapen.

Food item	Overview	Vulnerability	Water context
Yams	• High-value food (Halavatau, 2018). • *D. esculenta* most commonly found (Taylor, 2016). • Easily grown and mature quickly in right soil conditions (Halavatau, 2018). • Good keeping qualities and may be harvested well before eating (Halavatau, 2018).	• Mildly drought tolerant but do not compete well with weeds for soil nutrients. • Anthracnose disease.	Yams are mildly drought tolerant. Most varieties of yams grow best in rainfall of >1500 mm/year and require a minimum 6-month growing season with well-distributed rainfall. Yams do not tolerate poorly drained soils or waterlogging. The best soils for growing yams are sandy clay loams.

Note. RMI = Republic of Marshall Islands.

3 Types of interventions in water for food on atolls

Atolls face unique natural resource conditions that make them vulnerable to global environmental and socio-economic change. Yet they also have long histories of communities adapting to migration, climate shocks, food availability changes and dynamic natural resource conditions. Because of the geographic spread of some atoll and low-lying countries, such as Kiribati, interventions require careful, island-specific design that speaks to the dual governance system that exists between traditional governance and national policies and frameworks (Hassall & Tipu, 2008). The recommendations here are an initial set of activities across different modalities that can support water governance and resource management for communities. They focus largely on issues related to geographic isolation and unique island conditions and are focused on farming practices, governance support and capacity building.

Contextualising interventions at island or community scales

Interventions to support future water and agriculture management in atolls require in-person planning and strong buy-in from relevant community groups. Importantly, given the small populations in some atoll countries, it is important not to 'overwhelm' communities with new activities. The continued dependence on international aid for agriculture and water infrastructure and overall governance support (Lowy Institute, 2020) means that some islands continue to interact with international agencies for the everyday management of their resources. This creates a strong asset for future interventions; there are community leaders and local experts throughout the atoll communities and islands in the countries that can champion and lead interventions. The commissioning of consulting activities, research projects and capacity-building programs can leverage these local experts and support them in championing work for their communities. Remote ways of working developed through the COVID-19 pandemic can be leveraged to shift towards more localised models of developing and conducting activities.

An important factor to consider is the remoteness and the public sector's capacity to attend or be involved in formal projects. Some remote islands may have very limited staff, and if that staff is called to events, policy development or project activities, other activities may be paused. Projects need to be designed with this staffing consideration in mind and consider alternative non-public sector staff (e.g., consultants or NGOs on different islands) who may be able to complement the capacities of official government.

Placed-based water governance

The reality of small island communities is that there are very localised ways of accessing, managing and distributing resources. Approaches to long-term climate change adaptation and socio-economic shocks are also likely to be very place-based. For example, one adaptation in Tarawa may not be the same as in Abaiang (Kiribati). Because freshwater is so scarce in most low-lying atolls, and islands have small but dense populations, localised approaches to resource management are crucial. The geographic and socio-cultural uniqueness of each island community creates an opportunity to learn how communities have managed water (and other) resources through history and how they are adapting to the current changes in demographics, diets, climate and natural resource conditions.

National governance support to adapt farming and water management systems

National governments still play a role in creating policy direction, providing funding through centralised systems to islands and tracking against global development objectives, such as the Sustainable Development Goals. This briefing paper has given an initial overview of the existing databases and grey literature materials on the past, present and future conditions of water and agriculture in atolls. There is much more limited work on which water and food governance mechanisms can enable adequate water use and variability monitoring, water use in specific crops in different seasons and water of traditional varieties. Technical support into specific aspects of building water and food production monitoring systems in the context of a changing climate (following a placed-based approach) can provide useful data and evidence for decision-making.

Traditional varieties and water use as alternative food production systems

Traditional knowledge of food production remains important for atoll communities' identity and cultural practices. Historically, atoll communities have managed and adapted to global environmental changes and disruptions. A major disruption facing atolls is the relatively high availability of imported processed and low-nutrient foods, which are more convenient and affordable. This makes them more desirable. The limited markets for key commodities (e.g., cassava) also make it difficult to monetise crops. There is an opportunity to work with island communities in revitalising traditional seeds and crops that are tolerant to atoll soil and water contexts and may have potential value for tourist markets. Revitalising traditional varieties and water management practices requires a combination of technical assistance (e.g., for seed propagation and water quality/availability monitoring) and participatory processes that enable oral histories to capture how food and water systems have changed through time and how they can change in the future.

Stocktake island-level plans and support new island-level management plans that draw explicit links between the water and food security contexts of the community

This intervention is based on governance and policy opportunities across different countries. Island plans are often enabled financially by external partners, such as the SPC, SPREP, the Australian Department of Foreign Affairs and Trade, USAID and others. A stocktake of what plans exist and how they are implemented and monitored is an initial activity. A useful database establishment activity would help identify how current plans work with local knowledges and institutional processes to govern water and food resources.

Develop a specific overview of water and food security contexts of atolls in large, complex islands in Melanesia (piloting in the Solomon Islands and Vanuatu)

This briefing paper discussed the fact that large island countries with different island types, such as PNG and Vanuatu, have communities living on atolls and low-lying islands. The most comprehensive database of global atolls was prepared by Goldberg (2016). The work of Ian White and Tony Falkland has extensively documented the biophysical and institutional challenges of water management in atolls (Falkland, 2002; White, Falkland, Perez, et al., 2007). The level of granularity into atolls and their communities in Melanesian countries, however, is very difficult to determine. The seminal Pacific scholar Thaman (2008) stated that 'the status of many of the small islands included as possible atolls in the islands of Melanesia is uncertain due to the lack of detailed published information' (p. 36). An opportunity exists to enable a study, including case studies of current issues with data collected in-country, of how atoll communities are managing their water and food in Melanesia. Rather than a geological, hydrological and agronomic overview, the value-add of this Melanesian atoll study can contribute to knowledge on how gender, governance and climate change are all influencing water and food in atoll communities in Melanesia.

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