Water and Food Security in the Pacific

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1 Future security in the Pacific: Water and food linkages

This briefing paper discusses the resilience of water systems in the context of future water and food demands for four Pacific food commodities. It introduces a simple approach to frame the initial discussion of the water–food nexus and to illustrate future impacts on the water required to produce traditional and staple foods. The initial approach is to link water and food with projected population and climatic changes in the Pacific region.

The briefing paper offers a cross-sectoral knowledge base for designing future interventions that supports traditional knowledge and considers water and food to be a single integrated system in Pacific countries. With this knowledge, we are providing regional agencies working in food and water, such as the SPC and FAO, with a starting point for planning future activities targeting rural water and food in selected Pacific countries.

Water and food are fundamental to human prosperity and sustainable development. The regions of Micronesia, Melanesia and Polynesia in the Pacific Ocean will see an increase of almost 60% from 11 million to 17 million people by 2050 (Firth, 2018). Parallel to this population growth, the Pacific Ocean and its people will face increasing changes to their natural resource base (World Meteorological Organization, 2021). Agriculture and water resources are very diverse throughout the region and continue to play pivotal roles in rural and urban livelihoods and wellbeing.

Water and food are inextricably linked. The sectors impact each other, and increasing evidence on climate futures in the Pacific indicates that future climate and environmental changes will result in greater variability and uncertainty in both the availability of freshwater and the optimal conditions for food production (IPCC, 2021). Understanding how these interactions operate under a nexus security context, where water, food and energy are secured for nation-states, can help determine how human and natural resource security may change in an increasingly disrupted future socio-ecological world.

The projected impacts associated with a warmer atmosphere and rising ocean temperatures in the Pacific include increased storm surge and sea level rise, which will adversely affect freshwater supplies and soil productivity in low-lying areas. Contrastingly, some areas in the Southern and Eastern Pacific will experience drier conditions, which will create long-term risks to livelihoods. More intense but less frequent rainfall events will reduce water availability for agriculture, while increased atmospheric temperatures will increase crop evapotranspiration water demand. The huge biophysical diversity of Pacific countries means that any water–food interaction needs to be understood within very specific, island-level contexts. Overall, the Pacific will become wetter with the impacts of climate change; however, freshwater availability will decline, which will be largely attributed to saltwater intrusion from sea level rise (IPCC, 2021. Coupled with a 1 in 2 chance of drought conditions increasing the rate of evaporation, water stress on food production systems is likely to accelerate. Understanding the interactions between existing and future freshwater conditions and food crops is needed to develop interventions targeting water management in the Pacific region.

Water resources management and agriculture are essential to Pacific countries, given their important economic and environmental benefits. A nexus approach focuses on identifying integrated and sustainable interventions through understanding the interactions between different sectors. Further context for the nexus concept is found in the policy review (*Report 1*) that accompanies this briefing paper. Nexus thinking and practice help to better understand and systematically analyse the interactions between the natural environment and human activities, and to work towards a more coordinated management and use of natural resources across sectors and scales. The Pacific region has existing national policy windows that illustrate how the water–food nexus is embedded in both explicit and implicit ways in different national policies and strategies. While each country has different framings, the six major policy windows identified in the policy review provide clear public policy prioritisation for sustainable water and land management practices to support the region.

This briefing paper provides an overview of 1) the nexus concept and its relevance to water and agricultural security in the Pacific, 2) a summary of water and agricultural contexts and 3) a synthesis of separate water and agriculture data on selected subsistence commodities. The aim of the briefing paper is to complement *Report 1* and provide examples of the implications of future water and food links for Pacific development.

2 Water and food security: Grounding concepts for nexus analysis

Before undertaking a nexus analysis, we define two important concepts that make the nexus an important driver of regional prosperity: water security and food security. The global literature on the nexus focuses on water, food and energy; this is largely due to the fact that much of this work has focused on systems where large hydropower developments have affected freshwater systems (Allouche et al., 2019; Orr et al., 2012). Another focus of the water–food-energy nexus has been where energy demand has been large for pumped groundwater, which results in uneconomic and subsidised systems. Neither of these is the case for most Pacific countries, and while energy will be a future security challenge, the focus here is on water–food interactions given the immediate pressures both sectors face and their biophysical connections.

2.1 Water security

Water security is an increasing priority for development policy, notably as it changes due to climate change and human conflict (Bakker, 2012; HLPE, 2015). The Global Water Partnership (GWP) catalysed initial integrative guidance for developing a water security focus, which emphasised links between i) access and affordability, ii) human needs and iii) ecological health. This GWP definition acknowledges the physical hydrological interconnections and notes that water, on a given special and temporal scale, is a finite resource. This aligns with the broadly accepted principles of Integrated Water Resource Management (IWRM). IWRM places primacy on good governance of water, land and other resources to ensure maximum utility of a finite resource with equitable outcomes for both economic and social stakeholders while maintaining the health of ecosystems and the environment. Cook and Bakker (2012) suggest that IWRM brings governance to the forefront of a system that considers the economic utility, social and cultural values and ecosystem dependency in the definition of water security.

One way of understanding water security risk is through National Water Security (NWS) scores. In 2007, the Asian Development Bank launched the Asian Water Development Outlook (AWDO), which was the first attempt to bring an integrated approach to water stewardship in the Asia-Pacific region. The AWDO proposes a general water security score based on five weighted dimensions, including i) rural household water security, ii) economic water security, iii) urban water security, iv) environmental water security and v) water-related disaster security. Based on the 2020 NWS scores weighted for population in the smaller PICTs (excluding Papua New Guinea [PNG]), water security has not changed since 2013 at 54.7 (out of 100). The inclusion of PNG (pop. 8.79M) reduces the average NWS score weighted for population for all PICTs by 9 points to 45.7. Table 1 summarises the NWS score for 14 PICs.

Table 1. National water security of Pacific countries (ADB, 2020)

Pacific Island Country	Population (000s)	NWS, 2013	NWS, 2016	NWS, 2020
The Cook Islands	19	66.3	70.4	72.5
Fiji	886	57.1	59.8	59.5
Kiribati	113	45.8	45.8	48.2
Marshall Islands	55	42.9	40.9	48.9
Micronesia	103	39.5	37.7	42.0
Nauru	11	55.9	62.0	58.6
Niue	1.7	55.5	59.9	61.0
Palau	18	62.8	69.4	73.0
PNG	901	41.1	42.8	42.8
Samoa	198	57.2	62.9	62.4
The Solomon Islands	667	51.9	49.6	49.3
Tonga	100	61.4	61.4	61.5
Tuvalu	12	47.1	48.3	53.0
Vanuatu	285	51.1	49.7	49.9
Average, population weighted		44.1	45.5	45.4
Average without PNG		55.3	55.3	54.7

Note. NWS = National Water Security, PNG = Papua New Guinea.

2.2 Food security

Food security is a situation when all people, at all times, have physical and economic access to sufficient, safe and nutritious food that meets their dietary needs and food preferences for an active and healthy life (FAO, 2021b). It is a widely used concept to support national policies and programs targeted at different population groups. In Pacific countries, food security is an ever-present risk. Non-communicable diseases related to poor diets are the leading cause of mortality and morbidity in the region, which creates major risks to health systems with limited infrastructure and human capacity across a geographically vast region (Guell et al., 2021; SPC, 2016). A major driver of these health risks is diet due to a shift from relying on traditional crops and foods towards more convenient and increasingly available imported foods (Charlton et al., 2016; Sievert, Lawrence et al., 2019). In 2019, diabetes prevalence rates for persons aged 20 to 79 years old ranged from 7.5% in Samoa to 33.8% in the Marshall Islands (Chan et al., 2014). PICs account for 7 of the top 10 countries projected to have the highest prevalence rates of diabetes by 2035.

Pacific agriculture contributes to food security in two ways: providing food for subsistence diets and providing income from produce sold to markets. Two agricultural activities contribute to subsistence and income: crops and livestock. Crops include starchy vegetables, fruit and non-starchy vegetables and nuts. Cash crop production declined by 38% between 1995 and 2013, although the production of fruit and non-starchy vegetables increased by 50%, nuts by 25% and starchy vegetables by 37%. However, this increase is not reflected in increases above the WHO's recommended consumption of 400 g or 5 portions of fruits and vegetables per capita per day (FAO, 2020, 2021b).

3 Regional context of water resources and agriculture

3.1 Water resources

The three main forms of naturally occurring fresh water in the Pacific are surface water, groundwater and rainwater; their relative importance is determined by island type and season (Dixon-Jain et al., 2014). Surface water in the PICTs is comprised of four categories: surface and subterranean streams, springs, lakes/swamps/wetlands and dams on some of the larger islands (Falkland & White, 2020). Perennial streams only occur on the larger, higher rainfall islands such as PNG, Fiji and the Solomon Islands. Ephemeral streams occur more typically in small, steeper catchments, where flows occur for days or hours following rainfall. Groundwater makes up the majority of naturally occurring freshwater on most Pacific islands (Holding et al., 2016), and it occurs on both large volcanic islands and on many small coral and limestone islands as fresh groundwater lenses (Alberti et al., 2017; see also *Report 4, Atolls briefing paper*). Geographical features play a major role in determining the hierarchy of importance, or in some cases absence, of naturally occurring water sources; island area, shape, topography, soils and lithology influence both the occurrence and distribution of natural freshwater sources (Falkland & White, 2020).

Groundwater lenses vary greatly in size, which results in variable water reliability across the region. The sustainable use of groundwater requires balancing extraction and recharge rates. Individual households rely on shallow bores, while deeper bores supply larger municipal systems. Demand increases during periods of greater evapotranspiration and less rainfall. Conversely, recharge increases during wetter and more humid periods. As a result, thinner groundwater lenses are more vulnerable to over-extraction during drier periods. In addition, seawater located beneath a freshwater lens limits the amount of groundwater that can be extracted due to the potential for depletion of the freshwater lens and salinisation of the bore site (Werner et al., 2017). Such salinisation is escalated in the event of poor groundwater management, as found in the Bonriki aquifer in Kiribati (Lal & Datta, 2019). Consequently, groundwater reliability will vary with function, location, time of year, rainfall, air temperature, evapotranspiration and interaction with ocean water (White & Falkland, 2010).

The tropical climate of the Pacific makes rainwater harvesting a valuable component of water supply for the Pacific's small island nations, and the necessary decentralised infrastructure is highly suited to the large rural portion of the population. Houses and community buildings already have a catchment surface from which rainwater run-off can be collected. Some highly water-scarce countries, notably atolls (such as Kiribati and Tuvalu), rely on community and public infrastructure, such as paved sporting areas and airport runways, to collect and then store rainwater in underground tanks. A variety of factors, from climate change and El Niño and La Niña oscillations to shifts in rainfall belts due to volcanic eruptions, affect rainfall distribution in the Pacific (Higgins et al., 2020). Adequate size, maintenance and space for water storage infrastructure is a challenge for the reliability of supply. Storage is important to make use of potentially abundant rainwater, and on high-rainfall, low-lying islands, water storage can prove to be a useful buffer for drought periods. Some large storage infrastructure exists, such as the Afulilo Dam in Samoa, which was designed and constructed to provide water and energy security and take into account future climate projections. While these large storage systems exist, the majority of rainwater capture remains at the household or village level.

Given the diverse water contexts within countries, place-based understanding of how the resource intersects with food production systems is essential for managing future climate impacts. For example, in both the Fongafale islet in Tuvalu and the island Nauru, there are no confirmed freshwater resources (Duncan, 2011), which means that drought projections for both countries pose serious risks to people and to agricultural productivity. In low-lying atolls, there is no surface water, and citizens must rely on limited groundwater and rainfall catchment. Approaching the water–food nexus in low-lying atolls requires understanding how water is captured, saved and used by different atolls. Contrastingly, PNG has an annual water availability of 120,000 m^3 of water per person (Duncan, 2011). Approaching the water–food nexus in PNG would, thus, require substantial re-framing of the 'water security' problem as one of possible water abundance, conflict and water sharing between cultural groups for different agricultural purposes. In volcanic islands, localised thermo-topographic forces that produce rainfall from passing moisture-laden air play a significant role in rainfall patterns. For example, the mountains of Viti Levu and Vanua Levu in Fiji create wetter localised climates on their windward sides and dryer climatic zones on their leeward sides.

An additional source of freshwater water in the Pacific is desalination. The high energy requirement in production precludes its use for agriculture due to cost and is not considered further in this nexus analysis.

While noting the core water resource focus of the nexus analysis, water, sanitation and hygiene (WASH) are major issues in the Pacific region and receive substantial funding attention. Prioritising investments into WASH over water resources is understandable, given the limited use of water for agriculture and the substantial use of water for human hygiene needs. The availability of safe water for drinking varies considerably across the Pacific. In Melanesia, the most populous region, 78% of the population has access to an improved drinking water source, but county-to-country variation is large and ranges from 40% in PNG to 98% in Fiji (FAO, 2021a). In the Pacific region, only one-third of people have access to basic sanitation facilities, and half to safe drinking water, with large differences between countries. Low-quality septic tank pollution and shallow groundwater can severely degrade the quality of the water resource, and poor access to WASH services has a multitude of consequences for human health, nutrition, infectious disease, infrastructure and gender and social inclusion issues. While this background brief focuses on water as a resource (and its link to food production), useful resources on WASH in the Pacific include Redman-MacLaren et al. (2018), Mactaggart et al. (2021), Clarke et al. (2014) and Willetts et al. (2009).

3.2 Agriculture and food

Pacific diets vary greatly depending on the geography of the country. In the Solomon Islands, for example, over 50% of diets are based on roots, tubers and plantains. Imports, such as cereals, are increasingly dominant in diets: in Kiribati, cereals contribute to over 40% of total energy intake (FAO, 2021a). In rural areas, 50–90% of animal-sourced protein consumed comes from fish (SPC, 2015). Cash crops account for more than 75% of production, followed by starchy vegetables (15%), fruit and non-starchy vegetable (7%) and nuts (less than 1%). Excluding PNG, a total of 3,952,000 tonnes of crops were produced in the region in 2018.

Agriculture is predominantly found on the volcanic islands with larger surface and groundwater water resources; atoll nations are more reliant on local seafood and food imports (Campbell, 2020; Charlton et al., 2016). The IPCC (2021) indicates that there is now a 1 in 2 chance of drought conditions increasing, and freshwater availability from groundwater is very likely to decline. While rainfall events will be more frequent, they will also intensify by 7% per degree of warming. In some parts of the world, agriculturally viable lands will reduce, and people may migrate in response to changing rainfall and temperature patterns. The small geographical extent of island nations means that PICTs have no such option.

Most studies researching the effects of climate change on agriculture are global studies on the main global food crops of rice, wheat and corn, with limited data for crops grown in PICTs (Savage et al., 2020). Changes in climate will impact Pacific agriculture through 1) average and extreme temperature increases that will reduce crop yields, 2) a higher frequency of and more intense extreme weather events such as droughts and tropical cyclones, which cause damage to crops and infrastructure, 3) sea level rise resulting in coastal erosion, flooding, saltwater intrusion, arable land loss, groundwater contamination and degraded soil fertility, 4) changed weather patterns encouraging the spread of new pests, plant diseases and weeds, 5) variations in rainfall patterns disrupting regular crop seasons and rain-fed farming systems and 6) increasing carbon dioxide levels altering crop productivity (Taylor et al., 2016).

There are substantial aid investments in the agriculture sector (see *Report 1: Policy review*). Very large investments from the Green Climate Fund are actively targeting sustainable agricultural practices in light of climate change, such as the project on climate resilience in the Federated States of Micronesia (2021)[1]. Population growth, urbanisation and climate uncertainty are affecting agroecosystems. Historically, the traditional crops and farming practices in the Pacific provided resilience against climate shocks and helped to maintain food security throughout periods of intense wet or dry conditions (McGregor et al., 2009). However, many traditional farming practices have declined in recent years, often in response to commercial production needs, which heightens the vulnerability of food security to climate change in the Pacific today (Taylor et al., 2016. Climate change is projected to increase the vulnerability of agriculture both within the region and beyond. PICTs are sensitive to future fluctuations in imports due to the high transport and logistics costs in such a geographically remote region.

An overview of key local crops, their role in calorific contribution to Pacific societies and the importance of their import and export is provided in Table 2.

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[1] See full proposal here: https://www.greenclimate.fund/sites/default/files/document/funding-proposal-sap020.pdf

Table 2. Staple food crops of the Pacific

Food crop	Calorific contribution to diet (kcal/capita/day)	Key nutritional contribution to diet	Countries (ranked by national production)	Agricultural practice (e.g., low-lying fields, hillside plantations, rain-fed/irrigation)
Taro	62	Manganese 30% DV and Potassium 18% DV per 132 g serving	PNG	Taro is grown in all the lowland parts of PNG and performs best in these conditions. Taro thrives where soil moisture is high and can be grown successfully under flooded conditions. It requires flowing water in the lowlands but can grow well in stagnant water in the highlands, such as on the edge of flooded limestone dolines.
	133		Fiji	Taro is grown mainly in the wet areas where rainfall exceeds 2500 mm. Cultivation occurs on fertile hillside slopes as well as alluvial flat land.
	147		The Solomon Islands	Taro is usually the first crop to be planted after bush fallow in a shifting cultivation system.
	209		Samoa	Most of the taro crop is grown by itself on newly cleared land that has been fallowed for 2–3 years.
Banana	233	Potassium 8% DV from 100 g	PNG	Banana is a flexible crop in terms of water requirements and grows in a range of soil moisture conditions. Banana is a staple food in lowland locations where rainfall is continuously heavy such as inland Gulf and Western provinces. It can also thrive in locations that experience several months of water stress each year, such as Markham Valley in Morobe Province and the coastal Central Province.
	86		Vanuatu	Banana crops are able to tolerate volcanic ash and acid rain. Issues with growth occur in the dry season with shallow soil. It can grow in clay soil (Hoffman, 2013).

Food crop	Calorific contribution to diet (kcal/capita/day)	Key nutritional contribution to diet	Countries (ranked by national production)	Agricultural practice (e.g., low-lying fields, hillside plantations, rain-fed/irrigation)
	132		Samoa	A variety of banana species are grown in Samoa, from coastal strands to volcanic ridge-lines on sloping terrain (Sardos et al., 2019).
	97		Kiribati	Very common on wetter islands in North Kiribati, such as Makin and Butaritari and in Southern Tuvalu (Taylor et al., 2016.
Coconut	124	Manganese 75% DV Copper 22% DV Selenium 14% DV From 100 g raw coconut meat	PNG	PNG has one of the lowest yields per hectare among countries in the Asia-Pacific. Almost 106,000 ha were planted between 1910 and 1940, amounting to around 40% of the current plantings. Due to old age, up to 100,000 ha can be expected to disappear in the next 20 years without sustained replanting efforts. Coconut is grown in most of the coastal regions of the mainland and islands. The major producing regions are located on the northern coast of the country’s mainland (Ollivier et al., 2001).
	453		Vanuatu	Mainly located in coastal zones but had spread to more fertile soil to compete with other crops. Plantations are recommended to occur in low-fertility zones such as coral coastal terraces (FAO, 2013).
	363		Samoa	Present in tropical, coastal climates (Hoff, 2008).
	618		Kiribati	The islands of Kiribati have porous sandy, rubbly coral soils. The soil layer is very thin and supports little vegetation unless higher rainfall is received, in which case, the vegetation becomes lush (Bourdeix, 2019).
Cassava	43	Vitamin C 35% DV	PNG	

Food crop	Calorific contribution to diet (kcal/capita/day)	Key nutritional contribution to diet	Countries (ranked by national production)	Agricultural practice (e.g., low-lying fields, hillside plantations, rain-fed/irrigation)
	89	Manganese 20% DV Potassium 8%DV From 100 g raw cassava	Fiji	Cassava grows best in warm-moist climates with temperatures ranging from 25–29˚C. A well-distributed rainfall of 1000–2000 mm per year is optimum and increases yield; however, cassava can be grown in areas with less rainfall, as long as rain occurs at time of planting. Soil with a light sandy loam of medium fertility gives the best yield. Cassava is a short-day plant and is most productive when grown between latitudes 30˚N and 30˚S (University of Queensland, 2021).
	7		Timor-Leste	
	-		Tonga	
Yam	108	Vitamin C 28.5% DV Pyridoxine 23% DV Copper 20% DV From 100 g raw yams	PNG	The two main yam species are staples in lowland areas, where rainfall is strongly seasonal or has a high coefficient of variation. Yams grow well if planted in the dry season followed by a wet season with at least 1150 mm of rain. A deep, well-drained sandy loam is required to allow good soil drainage. Most yams can be grown well at low or medium elevations but cannot grow above 900 m elevation due to cold temperatures and frost. Long day length of 12 hours favour vine growth, whereas short day length favours tuber development (Taylor et al., 2016).
	187		The Solomon Islands	
	60		Samoa	
	-		Tonga	
Sweet Potato	204	Vitamin A 122% DV Vitamin C 38% Vitamin B6 26% From 114 g raw sweet potato	PNG	There are ecological conditions where sweet potato will not grow, which includes the Sago dominant marshy parts of West and East Sepik and swampy parts of Western Province. It is most prolific in highland provinces such as Marobe and smaller parts of Madang and Gulf provinces (Iese et al., 2018).
	459		The Solomon Islands	Sweet potato is intolerant of wet conditions. It thrives on well-drained soils in lowland terrain with seasonal rain or
	25		Fiji	

Food crop	Calorific contribution to diet (kcal/capita/day)	Key nutritional contribution to diet	Countries (ranked by national production)	Agricultural practice (e.g., low-lying fields, hillside plantations, rain-fed/irrigation)
	-		Tonga	highlands with significant slope, which generates enough run-off to not oversaturate the soil.
Rice	-	Vitamin B6 5% DV Magnesium 3% DV Iron 1% DV From 100 g cooked rice	Fiji	Rice is typically grown in warm climates with significant rainfall. In Fiji, there are two seasons. The wet season from November to April has temperatures up to 32ºC and rainfall between 3000–6000 mm in mountainous areas. In the dry season, from May to October, temperatures are much cooler at 22ºC and rainfall lower at 2000 mm (Bong, 2017).
	-			
	-		The Solomon Islands	
	-		PNG	
Sugarcane	-	-	Fiji	Sugarcane production requires significant rainfall and sunlight followed by a dry, sunny and cool ripening period and, thus, thrives in tropical climates. The optimum temperature for sprouting is 32–38°C. Although not requiring specific soils, sugarcane flourishes in well-aerated soil with a depth between 1 to 5 m.
	-		PNG	
	8		French Polynesia	
	-		Samoa	

Note. All data presented in the table was accessed from http://www.fao.org/faostat/en/#data unless otherwise referenced.
DV = Daily value, PNG = Papua New Guinea.

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3.3 Drivers of change: Climate change and population growth

The two largest threats to water resources security in the Pacific are climate change and increased human demand. As explained in earlier sections, the main water resource challenges in the Pacific relate to the following:

1. small areas of catchment;
2. limited storage in groundwater and especially in surface water (which is limited largely to rivers in Melanesia);
3. rapid run-off from rainfall (especially after storms and cyclones); and
4. the fragility of groundwater (especially lenses in atolls and small islands).

Climate change will impact these challenges across different regions of the Pacific; the Western and Equatorial Pacific are likely to experience more rainfall, while the subtropical Southern and Eastern Pacific are forecast to face drier conditions (IPCC, 2021). Weather conditions are forecast to become more severe across the region, and higher temperatures foreshadow a 50% chance of drought conditions increasing in all Pacific countries (IPCC, 2021). Higher temperatures increase evapotranspiration from plants and evaporation from surface waters and shallow groundwater, which places additional stresses on both water and food systems. Where wetter conditions are forecast (e.g., Fiji, PNG), this is due to the increased intensity of rainfall events, which means that destructive flooding is more likely, and they will not necessarily match the timing of water availability for both seasonal and perennial crop needs. Both increasingly intense rainfall events and cyclonic storms that bring destructive winds, flooding and coastal overtopping are predicted to become more frequent (IPCC, 2021). Sea level rise will see a reduction in groundwater availability in the majority of Pacific nations, with the low-lying islands and nations at the most immediate risk (IPCC, 2021).

The increasing demand for food is a result of both the growth of the human population itself and the increased urbanisation of the population. The increasing demand for food associated with a growing population (see Table 10, p. 18) needs to be matched by either intensifying existing agricultural output or continuing to rely on international imports, which make up a substantial amount of the total food available to Pacific populations (Andrew et al., 2022). Increasing internal trade between Pacific countries will increase pressure on those Pacific countries exporting food (which remain small in total food exports at this stage). Hypothetically, if taro demand grows regionally, which will cause increased production in taro-exporting Fiji and Samoa, these exporting countries would bear disproportionate pressures on their landscapes and ecosystems associated with intensified or expanded production.

Increased urbanisation and economic growth, fuelled by both population demand for resources and foreign investment in infrastructure projects, is increasing the demand for raw materials required for road building materials, cement production and major infrastructure projects, such as ports. In the land-poor and dispersed countries of the Pacific, local extraction sites for gravel and sand are often fluvial deposits in perennial riverbeds that are pumped dry but otherwise connected to the hydrological system. Both activities result in major contamination of waterways by sediments and severe downstream degradation of aquatic systems, both in the rivers themselves and coastal reef habitats. These combined effects of human population and demand place multifaceted pressures on these environmental systems. These systems are essential to maintaining all ecological services, including usable water resources and sustainable food systems.

4 An approach to the water–food nexus in the Pacific

Sections 2 and 3 provided an initial interdisciplinary overview of water–food–climate interactions in the Pacific region. Comprehensive reporting has been carried out on water resource systems (Falkland, 2002; White et al., 2007) and agricultural production in a changing climate (Taylor et al., 2016). However, the increasing scientific evidence of climate futures (IPCC, 2021) and the emphasis on continuing to support agriculture as a driver of sustainable food systems in the Pacific calls for an examination of how climate, water and food intersect. In this section, we propose a simple approach to provide initial insight into the water–food nexus within a changing population and climate context.

4.1 Water–food approach

This section consists of two parts. The first is to assess the applicability of existing models and see how they can be adapted to help inform discussions about food security, water and climate risks in the Pacific. We examine existing models and adapt them to the uniqueness of the Pacific presented above to emphasise that existing global calculations and models are not necessarily directly transferable to the Pacific context.

4.1.1 An existing approach

The PODIUMSim model[2] is an example of an existing tool used to generate scenarios of water and food supply and demand in relation to various policy options. This global model was developed for large, transboundary applications using FAOStat data and provides an established approach to examine the ability of future water to meet future food needs. The model is, however, unsuitable for investigating the Pacific for a number of reasons. These are the lack of FAOStat parameters behind the model for the Pacific region, the unique needs of staple and traditional crops of focus in this briefing paper, the need to embed a climate change risk, and the lack of a nexus approach in the development in PODIUMSim, which focuses on policy change cause and effect. As such, an application of the established PODIUMSim model is unsuitable for the Pacific. An initial approach to calculating future water requirements for staple food crops provides an example of the types of integrative work that can support water–food integrated decision-making.

4.1.2 A nexus approach for the Pacific based on population growth and crop contribution to national caloric intake

In light of the limitations identified, a semi-quantitative approach to discuss the water–food nexus was conducted to assess the water required to grow critical food crops expressed in terms of crops' contribution to the national caloric intake. The per cent water budget per crop demand normalised for population in 2050 (GL/ep for each crop) is proposed as an approach that incorporates two important pressures on liveability and sustainability in PICTs: 1) population growth and dietary trends and 2) the effects of climate change via the inclusion of evapotranspiration that responds to variations in temperature and humidity (see Box 1). These two macro-drivers are crucial conditions for the future of Pacific countries' resilience, as they are major drivers, including land and water resource use in the region. The output of this calculation is a normalised crop water demand, which may be expressed as a percentage of the national water budget for agriculture that considers precipitation, run-off and groundwater estimates (see Appendix 2).

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[2] PODIUMSim was developed by the Integrated Water Management Institute (IWMI), https://www.iwmi.cgiar.org/resources/data-and-tools/models-and-software/podiumsim/

Box 1. Water demand from food production

A simple food production–water demand calculation can be used to identify if the continued production of a staple food crop can be sustained after the consideration of population and climate pressures (see Table **10**). We assume that the basic key commodities will continue to be produced in the region, given their cultural and economic importance. This water–food approach can be applied to a particular crop in a specific country. For example, the analysis could be transferred to understand the water demand of swamp taro in Tuvalu (discussed in *Report 4: Atolls briefing paper*). The normalised crop water demand considers the FAO variables for crop evapotranspiration per unit of production (mm/kg), the calorific yield of the crop (kJ/kg), the contribution of the crop to the daily caloric intake of the population (kJ/ep/day) and the projected population growth from 2020 to 2050.

Our approach calculates the annual crop water demand required to meet the contribution to the calorific needs of a growing Pacific country–level population in 2050 and expresses this as a percentage of the estimated water availability. The approach helps identify the water dependencies of each crop as a function of population change and to assess its vulnerabilities to the impacts of climate change. These include but are not limited to sea level rise, cyclonic activity and rainfall distributions.

The amount of water required to grow enough kilograms of crops to meet population forecasts in 2050 was calculated for the four selected staples in selected countries as follows: taro in Fiji, sweet potato in PNG, coconuts in Vanuatu and bananas in Samoa (see also Table 4, p. 18). The calculations were made using existing data on water requirements for crop type and considers basic pluvial, fluvial and groundwater interactions. The full equations are provided in Appendix 2 and were made by considering the crop production area as a percentage of the total country land area, current rainfall data, ground evaporative losses, crop evapotranspiration and a basic ratio estimate of precipitation to groundwater flow. Calorific content allowed the proportion of the crop to be calculated as part of the national diet (see Table 9) and then adjusted to the forecasted population size in 2050. Using the crop demand (L/kg), the total water availability, or the amount of water to produce enough kilograms of the staple crop to satisfy demand, was then calculated in gigalitres (GL, a measure of 1 billion litres) as part of the national water resource.

4.1.3 Limitations and invitation to expand the approach

This approach provides insight into the water availability for Pacific staple crops using existing data and is an initial starting point to assess and compare water demands in different PICTs for a range of crops under changing conditions. The approach presented here is based on average values that are inherently limited and ignore variations in water availability in different regions of a given PICT, for example, the enormous diversity of PNG. Further limitations include the use of 2050 population forecasts but not 2050 rainfall and other water availability projections that are subject to climate modelling that is beyond the scope of this work, but this could be expanded upon by future applications and expansions. The overall climate trends in the region are noted and used to inform the crop vulnerability ratings presented in this work. Further limitations are the simplification of rainfall calculated as a percentage of total rainfall based on total cropping area at a national level. This overlooks important sub-national rainfall patterns and wet versus dry areas of islands as influenced by topography and prevailing wind conditions. Lastly, the ratio of surface water and groundwater used is a broad indicator that overly simplifies the complex hydrological interactions and detailed assessments of groundwater resources required to make more informed calculations. We emphasise these limitations because, in this briefing paper, we are setting the context and initial foundations of this semi-quantitative approach. We would very much support others in this field to further develop and build on our work with in-country data and experts to advance the analysis.

4.2 Four crop case studies

To illustrate how climate change and population growth affect the water demand of key crops that are staples in the Pacific, we calculated estimates for normalised crop water demand and annual water budget for taro production in Fiji, sweet potato in PNG, coconut in Vanuatu and banana production in Samoa (see Table 10). These four crops were selected because they contribute to both livelihoods (e.g., market sales) and household diets. The four commodities are common horticulture commodities in the Melanesian and Polynesian countries selected. This approach can help guide conversations around the integrated nature of water and agriculture in Pacific countries.

Based on this analysis, there appears to be sufficient water in the annual budget to meet the calorific needs of the changing population; therefore, the risks do not lie in water availability but in other factors that can affect the annual harvest. These mostly include risk factors around a changing climate, as highlighted in each of the vignettes in Section 4.3.2 below for each of the selected crops.

The root vegetable staples (taro and sweet potato) contrast climate risks in Fiji and PNG based on the variation in NWS scores for agriculture under the second dimension (economic water security; Fiji 4.5 vs PNG 1.0, see Table 1, p. 7) and seasonal variations in drought based on the high crop coefficients in establishment phases. Contrasts between annual (banana) and perennial (coconut) crops highlight vulnerabilities to the increased frequency of extreme weather events that can adversely impact harvest and export income.

Table 3. Example calculations of annual crop water demand normalised for population

	Population in 2050[1]	Calories per EP[2]	Calorific Content[3] (cal/KG)	Total Production (Tonnes)[4]	Crop Demand (GL)[5]	Crop Demand (L/KG)[6]	Annual National Water Budget (GL)[7]	% Water Budget per Crop Demand (GL/ep per crop)
Taro (Fiji)	1,071,000	113	741	59,613	1.88	32	289	0.65
Sweet potato (PNG)	14,204,000	204	878	1,204,590	41.51	34	2,118	1.96
Coconut (Vanuatu)	557,000	148	161.3	186,541	1.12	6	41.4	2.71
Banana (Samoa)	54,000	132	950	2,739	0.32	118	54	0.6

Note: 1. Projected population growth, UN Statistics. 2. Contribution of crop to population calorific intake (based on Table 2). 3. Calorific content per kg (FAOSTAT). 4. National production (FAOSTAT). 5. Crop demand (GL) calculated by multiplying '% water budget per crop demand' and 'water budget'. 6. Crop demand presented in L/Kg for convenience. 7. Annual national water budget for agriculture (total).

4.3 Implications for food production and water management

4.3.1 Policy implications

The per cent of national water budget per crop demand, when combined with NWS scores (see Table 1, p. 7) and climate change projections, provides insight into the vulnerability of domestic or export crops to water availability in the future. In the calculation presented in Table 3, the use of FAO crop coefficients for establishment, growth and harvest stages can be qualitatively used to identify vulnerability to the timing of rainfall events. Taken with other climate considerations such as changes in sea level and the frequency and intensity of tropical storms, estimates for normalised annual crop water demand can underpin policy development that addresses resource allocation, the need to support alternative staple or export crops, land utilisation and investment in infrastructure to mitigate climate extremes. Based on the calculation, we provide a summary of the crop vulnerability to future climate risk. Our data in Table 4 provides an initial quantitative calculation to support similar crop projections made by previous studies (Bell et al., 2016; Taylor et al., 2016). Table 4 provides an overview of the crop vulnerability to climate change, taking into account the impact of climate change on water resources.

Table 4. Crop vulnerability and climate risk based on rainfall, sea level rise, temperature increase and extreme events

Crop	**Crop vulnerability**	**Climate risk**				**Policy implication**
		Rainfall Projections	Sea level Rise	Extreme Events	Increased Temperature	
Fiji **Taro**	M	Increase	M	M	L	Surplus water diverted to environment. Coastal protection where alluvial and coastal crops may see degradation due to salinisation by sea level rise and storm surge overtopping.
PNG **Sweet Potato**	M	Increased drought	L	H	L	Develop alternative food sources for eastern highlands to complement possible ‘hungry seasons’ in periods of drought.
Vanuatu Coconut	M	Increase	H	M	M	Invest in infrastructure to protect crops and increase yield.
Samoa **Banana**	M	Increase	L	H	H	Invest in capacity to maintain effective quarantine and inspection to prevent invasive pests and infection. Diversify plantation locations around island to mitigate losses due to storms.

Note. L = low, M = medium, H = high. PNG = Papua New Guinea.

4.3.2 Crop specific implications

To further contextualise this crop vulnerability, we explain how each of the crops will be affected by changes in water supply in light of climate and population pressures. Each of the vignettes below provides an example of these water–climate–population linkages.

Taro

Based on a projected population increase of 0.69% per annum, the projected demand for taro in Fiji is expected to reach 61,360 tonnes by 2050, with a projected water demand of 0.65% of the annual water budget. This indicates that sufficient water supplies are available for taro to provide a resilient food supply for Fiji. Taro is an important staple in Fijian diets. According to the FAO, the total area harvested for taro in 2018 was 2465 hectares or 6.8% of the total land area in Fiji (364 km^2). Taro currently contributes slightly less than 10% of the daily caloric intake (113 kCal/1500 kCal). Crop production expanded from 5000 tonnes per year in 1975 to a peak of 87,000 tonnes per year in 2015. However, while taro will remain a staple, changes in dietary preferences have resulted in the consumption of imported rice in place of taro, which has caused local production to decline to 50,000 tonnes per annum in 2020. Taro was rated to have a medium vulnerability at the water–food nexus. With sufficient water supplies available for taro, the implication is that more water could be allocated to other activities, including environmental flows and conservation. Given the relatively positive availability of water for taro, strategies focused on water allocation might not find taro to be the most efficient target crop.

Sweet potato

For PNG, the water demands for national sweet potato crops based on contribution to daily caloric intake and population growth are projected to reach almost 2% of the national water budget; however, the sweet potato crop has a high water demand during the establishment phase. Sweet potato is the main staple food of PNG, particularly for communities in the interior highlands, where the crop provides two-thirds of the caloric intake. PNG is dominated by mountainous terrain with high run-off, lower soil depth, fertility and moisture retention. Steeper land is preferred for sweet potato production as the crop is intolerant to excessive soil moisture. This poses a risk to food security for the projected increase in extreme rainfall events and wetter conditions for PNG. The total production area for sweet potato in PNG in 2018 was 142,516 ha or 1,425 km^2; the total land area of PNG is 462,840 km^2. The percentage of land used for sweet potato production is 0.31%. Based on our analysis, cropping activities in the eastern highlands, where climate change could extend periods of seasonally low to no rainfall, are particularly vulnerable. Sweet potato was rated as having a medium vulnerability at the water–food nexus. Therefore, a future-looking intervention could explore alternative food sources during dry periods for communities in the eastern highlands to avoid ‘hungry seasons’.

Coconut

By 2050, coconut crop water demands in Vanuatu are likely to account for 2.7% of the total water supply, and plantations in low-lying areas are susceptible to seawater ingress into groundwater due to sea level rise and reduced recharge due to changes in the frequency and intensity of rainwater events. Coconut is a critical crop for Vanuatu; it provides the second largest source of foreign income (behind tourism) and accounts for 45% of GDP. The crop occupies 42% of arable land (120x105 ha), with approximately 9.7x106 trees under cultivation at 120 trees per hectare. Coconut is processed for copra (precursor to coconut oil) and, increasingly, coconut water. Approximately 6000 nuts yield 1 tonne of dried copra with a value of US$450. Notwithstanding the economic importance of the coconut crop, only 45% of the annual yield is harvested for collection, with the remaining 55% lost on the tree due to storms or not being collected due to labour shortages. Coconut was rated with a medium vulnerability at the water–food nexus. The demand for all vegetable oils, including coconut oil, is projected to increase by a factor of three by 2050. Given the importance of the crop to the economy, policy development should encourage investment in increasing the yield of plantations with reliable groundwater supplies.

Bananas

The projected normalised crop water demand in 2050 (0.6% of available supply) indicates that sufficient water supplies are available for bananas to provide a resilient food supply for Samoa. Bananas are a major source of agricultural crop production in Samoa. The fruit has a high caloric density (average 950 cal/kg), and the local varieties of eating and cooking bananas are an important food staple. Bananas are grown in a wide range of microcosms, from coastal areas to volcanic ridge-lines and all but the most extreme sloping terrain. However, bananas are vulnerable to risks that may be exacerbated by climate change in the Pacific, including increased frequency of cyclones and disease. The fibrous trunks of the banana plant make banana plantations highly susceptible to destruction from cyclones; the Samoan crops were decimated in 2018 due to Cyclone Gita. As part of the recovery efforts, the Samoan Ministry of Agriculture and Fisheries imported 30,000 banana suckers. The suckers were a variant scientifically developed in Israel to be especially good for eating as well as having increased disease resistance (Mika, 2018). The new strain had led to the first export of Bananas to New Zealand in almost 50 years, which provided a source of revenue outside the local market. The predicted increase in cyclone intensity and associated wind strength due to climate change means that the risk of nationwide impacts on crop production will also increase. Similarly, the risk of disease is expected to increase with the wetter conditions forecast for Samoa. Modelling predictions (Yeeles, 2019) in other tropical regions show that wetter and warmer conditions provide favourable conditions for spores of fungal banana diseases responsible for significant crop yield reduction and even failure. Bananas were rated to have a medium vulnerability at the water–food nexus. The geographic isolation of the Pacific from other ecosystems means that not all diseases are found there, and the strict biosecurity laws in place will continue to play a significant role in maintaining food security in the region.

5 Recommendations and conclusions

A nexus approach to water and food issues in selected Pacific commodities helps identify some of the initial quantitative dimensions of water demand for key agriculture crops in Pacific countries. The use of standard water demand estimates for staple crop production, as calculated in this briefing paper, helps identify some opportunities and risks at the water–food nexus. Water budgets for selected commodities in selected Pacific countries at the national level are shown to be clearly adequate; however, climate change risks can result in spatial and temporal variations that will inevitably affect yield at the local scale. Furthermore, other risks associated with climate, including frequency and severity of storms, coastal inundation and sea level rise, amplify risks to a reliable annual harvest of staple crops, which shifts dependency on imported foods to meet national calorific needs.

Analysis of the vulnerabilities of key crops (taro, sweet potato, coconut and banana) across four Pacific countries (Fiji, PNG, Vanuatu and Samoa) through to 2050 suggest that overall water supply will be sufficient to partially support the caloric needs of populations that are growing at rates of 0.6% (Samoa) to 2.6% (Vanuatu) per annum. Moreover, in some cases, such as taro production in Fiji, it is expected that there may be opportunities to reallocate some of the water resources to other crops or other applications, such as environmental water or household use. This may also increase as diets transition away from taro with the increasing availability of imported foods.

This analysis has value for planning future scenarios concerning food supply and agribusiness planning, with the objective of providing resilience against climate change and satisfying forecast population size and demography. Local food crops have been traditionally managed by farmers though cyclical ENSO periods of increased rain or drought conditions. These staple food crops in the Pacific differ from those most focused on in climate projections and food security (e.g., wheat, maize and rice), and country-specific engagement to incorporate traditional knowledge and capacity should be engaged to build resilience against the effects of anthropogenic climate change.

To this end, some initial areas of interventions for policy systems for the AWP, FAO and SPC to develop projects in research, technical support or policy advocacy are as follows:

Capacity building and engagement: **Programs to facilitate bi-directional learning between transitional farming practices with regional and international funding agencies**. Awareness of the risks associated with climate change and food crop vulnerability can be collaboratively developed between funders and national agencies. Awareness and educational efforts can be deployed using a train-the-trainer model in-country.

Technology and infrastructure: **Programs to improve coastal protection**, particularly where alluvial and coastal crops may see degradation due to salinisation by sea level rise and storm surge overtopping. This includes specific investment for materials and training to support the diversification of cropping locations to mitigate the impact of storms on national crop production. **Mapping and monitoring of the groundwater resource** is needed, most urgently for coastal aquifers. The loss of income and livelihood due to the salinisation of groundwater from gradual groundwater depletion and sea level rise needs to be managed through education and awareness activities as well as reviewing crop diversification possibilities in coastal agricultural regions. Rapid salinisation of coastal groundwater aquifers due to overtopping in storm events needs to be prevented by nature-based or engineering coastal protection, with the costs of such measures readily calculatable against productive agricultural land protected.

Landscape view: **Environmental flow policy that supports both water and food system management**. Cohesive environmental considerations behind the water and food systems should be supported and encouraged to maintain and restore the ecological functions of the landscape. This underpinning ethos will provide a multitude of benefits across the broad biophysical spectrum and provide resilience against existing and forecast climate change pressures. This would build on investments to date in the ‘ridge to reef’ and ‘source to sea’ approach through the funding of restorative environmental systems and nature-based solutions. This is especially relevant in ensuring the water quality of the water resource, with an adequate quantity of water for environmental flows in place. The role of nature-based solutions and environmental services is equally important for coastal protection (e.g., mangroves, fringing reef systems) and at places of the interplay between freshwater and marine environments (e.g., river deltas, coastal lagoons, shore-based and near-shore reef systems, sea-grass meadows, coastal aquifers) that are readily degraded or destroyed due to land-based activities but provide ecological functions critical to non-terrestrial food systems that are essential for Pacific diets and livelihoods.

Governance support at different scales: **Socialise water–food demand analysis with relevant stakeholders in-country**. An activity building on the nexus approach applied in this briefing paper with in-country staff (at government, businesses and funding partners) working in specific commodities can help develop an understanding of future water demand. Build on the IWRM progress to date, both in national policy development and deployment, to **foster direct coordination between relevant land planning, agriculture and water agencies and staff**. National and regional forces should be supported to facilitate south-south knowledge exchange and can be developed in line with capacity building and engagement activities.

Farming systems and practices: **Map and create a risk index for staple food crops in the Pacific in light of the climate–population–water nexus**. This would provide the identification of over-reliance on specific crops in areas exposed to climate risk (e.g., taro supply in eastern PNG highlands) and the development of either alternative crop supply chains from areas with low climate risk or the development of alternative sources of nutrition that are less susceptible to prolonged drought or flood (such as the development of inland aquaculture). There is also an opportunity to understand how traditional and Indigenous varieties can adapt to future projected water availability contexts. **Investment in human and technical capacity** for the effective management of quarantine, inspection and plant breeding to prevent invasive pests and infection also requires continuing adaptation and improvement, as climate risks create more liveable environments for pests and disease.

Facilitate river basin and country-level water–food analysis: The semi-quantitative approach developed here is an initial step to thinking beyond traditional assumptions that the water–food nexus is driven solely by water resource availability and global food production systems. By looking at regionally important crops and adding variables of future climate and population growth, a more comprehensive and regionally tailored calculation is possible, one that factors in future Pacific water, population and climate scenarios. A next step in this analysis is to advance the approach by developing place-based river basin models cognisant of water cycle interactions, notably surface-groundwater interactions most relevant to Melanesia. This should be developed from the ground up with a water–food nexus approach and tailored to the context of high food production environments for Pacific staple crops of Melanesian countries, which would provide much-needed data and evidence on the water–food nexus.

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Appendix 1: Water availability estimates

Water Availability

Water availability for each country was calculated using net water storage estimates based on the various components of the hydrologic cycle. These components include:

$$\Delta S = P - E - ET \pm SRO \pm GF$$

Where,

$$\Delta S = Water\ Budget$$
$$P = Precipitation$$
$$E = Evaporation$$
$$ET = Evapotranspiration$$
$$SRO = Surface\ Runoff$$
$$GF = Groundwater\ flow$$

The following indicates how the estimate was developed for Fiji.

Comparing Fijian climate (in Taveuni), Latitude 16.9° South to Cairns, Australia, latitude 16.87°S helps determine the evaporation component. Cairns has an average rainfall of 2000 mm/year with mean daily sunshine hours ranging from 6.2 in February to 8.8 in October. Taveuni has more rainfall and less daily sunshine due to consistent cloud cover, 2200 mm/year and 5–8 hours, respectively (Bureau of Meteorology, 2021).

Evaporative losses were used to calculate the pan evaporative losses as described by Rohwer (1931). Based on an average evaporation of 2223 mm/year from 1970–2014, an evaporative rate of 1334 mm/year was calculated assuming a correcting factor of 0.6 to convert pan evaporation to actual evaporation.

The ratio of precipitation to groundwater was used to determine the average surface water available for crops. The reported precipitation in Fiji of 2592 mm/year equates to a volume of 933 million m^3. The taro production area is 6.77% of total land area, assuming a simplified uniform distribution of rain across the nation, 63.17 million m^3 of water is available for taro production. The volume of surface water produced from this precipitation is 559.8 million m^3, (approximately 60% of total volume). Therefore, the amount of surface water will be 1554 mm. (Fiji—Volume of groundwater produced, accessed from https://knoema.com/atlas/Fiji/Volume-of-groundwater-produced)

Total Water Estimate for Fiji:

$$P = 2592\ mm/year$$
$$E = 1334\ mm/year$$
$$ET = 5.5 * 365 = 2008\frac{mm}{year}$$
$$GF = 1554\frac{mm}{year}$$

$$\Delta S = P - E - ET + GF$$

$$\Delta S = 2600 - 1334 - 2008 + 1554$$

$$\Delta S = 812\ mm/year$$

$$P = \frac{2592mm}{year} = 933\ million\ m^3$$

$$1m^3 = 10^{-6}GL$$

$$933 \times 10^6 m^3 = 933GL$$

$$\frac{812mm/year}{2592mm/year} = 0.31$$

$$\Delta S = 0.31 \times 933\ GL$$

$$\Delta S = 289\ GL$$

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