*Title Page

Mitigating drought impacts in remote island atolls with traditional water usage behaviors and modern technology

Morgan C. MacDonald[1]*, *Mark Elliott*[2], *Dustin Langidrik*[3], *Terry Chan*[4], *Angela Saunders*[5], *Ben Stewart-Koster*[1], *Irene J. Taafaki*[3], *Jamie Bartram*[6] and *Wade L. Hadwen*[1,7]

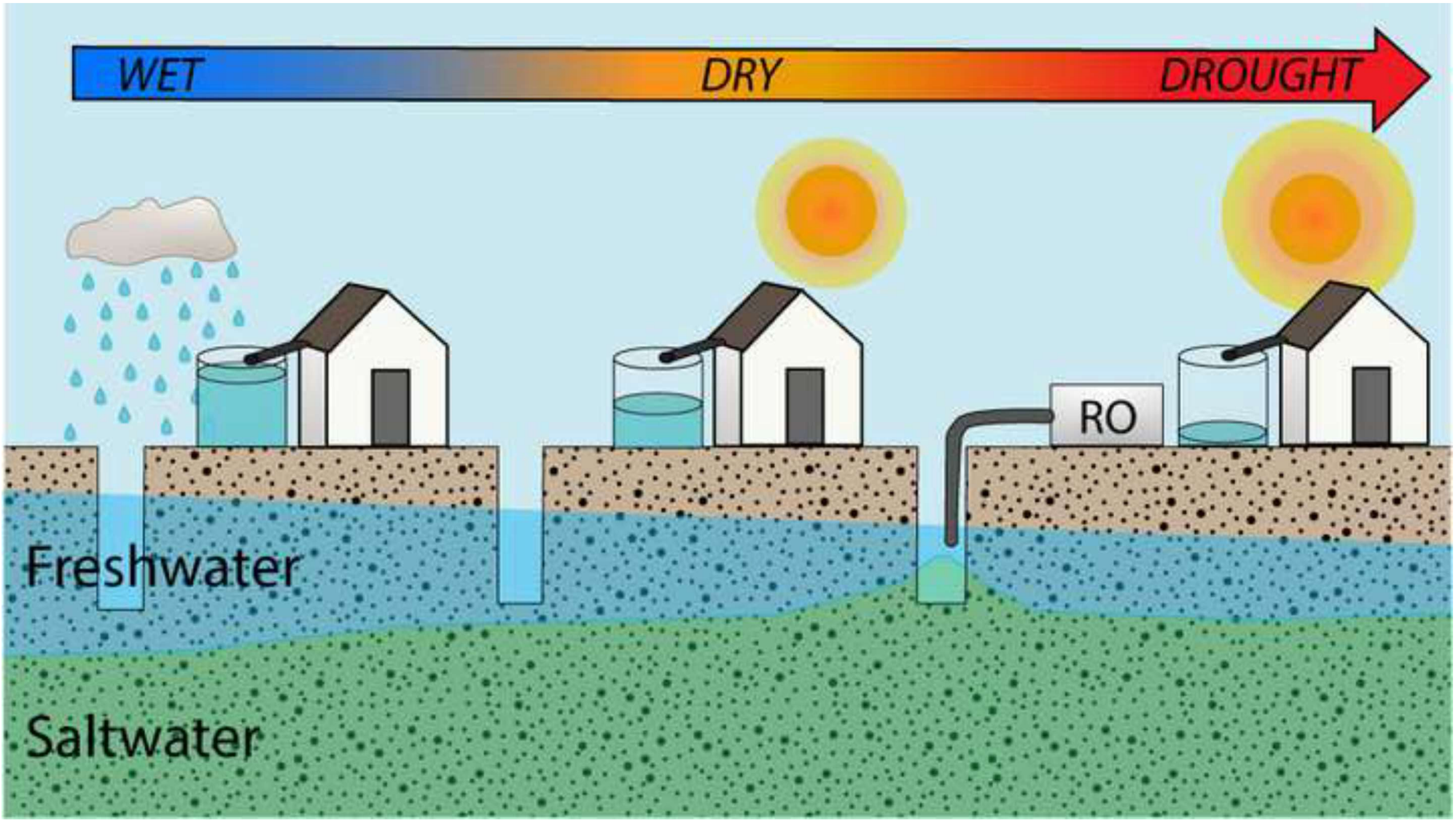
[1]Australian Rivers Institute, Griffith University, Nathan, Queensland 4111, Australia; [2]Department of Civil, Construction and Environmental Engineering, University of Alabama, Box 870205, Tuscaloosa, AL 35407, USA; [3]University of the South Pacific, Marshall Islands Campus, P. O. Box 3537, Majuro, MH 96960, Marshall Islands; [4]Monash Sustainability Institute, Monash University, Clayton, Victoria 3800, Australia; [5]International Organization for Migration, Majuro, MH 96960, Marshall Islands; [6]The Water Institute, Department of Environmental Sciences and Engineering, University of North Carolina, CB#7431, Chapel Hill, NC 27599, USA; [7]Griffith Climate Change Response Group, Griffith University, Nathan, Queensland 4111, Australia.

Corresponding author*: Morgan C. MacDonald (morgan.macdonald82@gmail.com)

Highlights:

- Small island states are among the most vulnerable to drought and climate change.
- Cycling of multiple household water sources increases resilience to drought.
- Austere usage behaviors conserve rainwater for drinking during drought.
- Emergency water created using reverse osmosis presents a hazard to groundwater.

*Graphical Abstract



*Highlights (for review : 3 to 5 bullet points (maximum 85 characters including spaces per bullet point)

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Abstract

Adaptation to drought is particularly challenging in the Republic of the Marshall Islands (RMI), a nation of 55,000 populating 29 low-lying coral atolls spread over >2 million km^2. Household surveys (n=298) and focus group discussions in eight RMI communities revealed that 86% of households have experienced drought and 88% reported using multiple water sources to meet regular household needs. With no surface water and a thin freshwater lens (FWL), rainwater collected from rooftops is the most common household water source. The traditional use of carved hollows in the base of coconut trees to collect rainwater ("Mammaks") appears to have been displaced by large rainwater tanks. However, rationing of rainwater for consumption only during drought was widely reported, with private wells supporting non-consumptive uses. Reverse osmosis (RO) desalination units have provided relief during drought emergencies but concerns have been raised around dependency, maintenance challenges, and loss of traditional water practices. Most notably, RO use has the potential to adversely affect the FWL; 86% of RO units were installed at central island locations where excessive pumping can cause upconing, making the FWL brackish. Balancing the introduction of desalination technology to mitigate drought with maintenance of traditional water conservation practices requires further investigation.

Keywords: Adaptation, Marshall Islands, multiple water source use (MWSU), Pacific Island Countries (PICs), reverse osmosis.

1 Introduction

Small-island developing states (SIDS) are particularly vulnerable to many of the hazards associated with water and climate change, including drought, sea-level rise and interannual variability in precipitation (UN-OHRLLS, 2011). Low-lying coral atolls are particularly susceptible to these hazards as there is typically no surface water and only a thin freshwater lens (Werner, Sharp, Galvis, Post, & Sinclair, 2017). The Republic of the Marshall Islands (RMI) is one of many SIDS with a substantial fraction of the population living on low-lying atolls. Many of these RMI atolls have also suffered from a number of extended droughts in the last 40 years, including the devastating El Niño driven drought of 1982-83 in the Western Pacific (van der Burg, 1986) and more recent droughts in 1998, 2013 and 2015 (Barkey & Bailey, 2017; Presley, 2005).

While there is widespread interest in the effects of climate change and adaptation options for low-lying and remote atolls, adaptations to date have been largely reactive and short-term (McCubbin, Smit, & Peace, 2015). Independent global climate change models agree that El Niño and La Niña events are expected to continue, but the frequency and severity of corresponding droughts and floods is still unclear (Hoegh-Guldberg et al., 2018; PACCSAP, 2014). There is also a shortage of household water management research in SIDS because field work is often cost-prohibitive, time-consuming and logistically challenging. Therefore, the conclusions drawn from the data reported in this paper for eight RMI communities are not only relevant to drought management for the rest of the island-nation, but also contain lessons generalizable to other SIDS, and capable of addressing knowledge gaps that are otherwise likely to remain.

The physical geography of RMI greatly complicates the logistics of preparing for and responding to drought. The island nation population of 53,000 is spread across 29 coral atolls and more than 1,000 islands of the North Pacific. The atolls form two parallel island chains: Ratak (meaning Sunrise) to the east, and Ralik (meaning Sunset) to the west, and form part of the Micronesian island cluster. The greatest concentration of people live in the inner islands, namely

Majuro, the capital with 28,000 people, and Ebeye, a densely populated urban island home to 15,000 people. However, it is the small rural communities of the outer islands scattered throughout the two million square kilometers of equatorial Pacific Ocean of RMI territory that present the greatest challenge to a centralized drought response. Nearly all of these communities practice traditional lifestyles and have very few modern technologies. The distances between islands, the high cost of travelling between them and the challenges associated with inter-island communication places these communities in charge of their own drought response until external help arrives. Freshwater from abundant and predictable rainfall is key to survival on these low-lying coral atolls.

Household use of multiple water sources is widespread in many low and middle income country settings where affordable access to a single convenient and reliable source of high-quality water is unavailable (Almedom & Odhiambo, 1994; Coulibaly, Jakus, & Keith, 2014; Elliott et al., 2019; Foster & Willetts, 2018; Howard, Teuton, Luyima, & Odongo, 2002). In RMI, a country where drought is extremely common, two sources of rainwater sustain the vast majority of communities throughout the year: deliberate harvesting and storage of rainwater in tanks receiving roof runoff; and the natural storage of rainwater in a freshwater lens (FWL). Rainwater harvesting occurs both at individual household or private scale and also at a more organised, shared and public scale (Elliott et al., 2017). The FWL retains rainwater in the islands' semi-permeable substrate of coral sands and gravel, overlaying a denser layer of seawater and a platform of reef-limestone (Chui & Terry, 2013; White & Falkland, 2009). Both sources depend on rainfall for recharge and can be depleted if use is not prudently managed, if extended dry periods or more extreme drought conditions occur, or if both poor use and dry conditions overlap.

The largest source of freshwater on RMI atolls is stored in the FWL. Rainfall is critical to its recharge, while island size, shape and topography determine the maximum volume of water that can be stored (White & Falkland, 2009). Islands to the northwest have the lowest recharge rates and average annual rainfall decreases across the region from the southeast to the northwest (Barkey & Bailey, 2017). For the two locations where long-term precipitation data are available, Enewetak in the northwest receives around 150 cm per year which is less than half that received by Majuro in the southeast. Smaller atolls are disproportionately limited in their ability to store water, because the relationship between island area and freshwater lens capacity is non-linear, such that an island half the size of another will have less than 50% the volume of freshwater (Chui & Terry, 2013). As 70% of rainfall occurs during the wet season from May to November, proper management of abstraction from the FWL can be important for the water stored to last through the dry season (Gingerich, Voss, & Johnson, 2017). With climate change leading to greater uncertainty in the future frequency and severity of drought in the Pacific, improved understanding of water management options during drought and their implications for the sustainability of FWLs is essential.

It has been estimated that the FWLs of more than half of all populated RMI islands were completely depleted during the El Niño driven drought of 1998, conditions that were repeated in the drought of 2015 (Barkey & Bailey, 2017). The quantity and quality of water stored within the freshwater lens depends on a delicate balance between consumptive uses, climatic, and hydrogeological factors. Under normal circumstances, water loss through evapotranspiration is more than half of annual rainfall (White & Falkland, 2009). In response, management of aquifer recharge on some islands includes the removal of natural vegetation to reduce loss by plant transpiration and increase freshwater supply in the FWL (Hejazian, Gurdak, Swarzenski, Odigie, & Storlazzi, 2017).

Over-extraction poses a threat to the FWL when excessive pumping from boreholes or dug wells increases the salinity of the FWL through up-coning, drawing brackish water towards the surface from the transition zone (White & Falkland, 2009). Three decades of hydrogeological data on Bonriki atoll in Kiribati revealed that it can take a FWL more than two decades to recover from prolonged over extraction (Post, Bosserelle, Galvis, Sinclair, & Werner, 2018). Infiltration galleries, sometimes called "skimming wells", are a technological adaptation to dug wells where a horizontal system of slotted plastic pipe is laid in a trench below the water table. They are designed to reduce up-coning and the ingress of seawater into the FWL by distributing the pumping over a wider area (Falkland, 1992).

The majority of RMI communities rely heavily on stored rainwater throughout the year; and during the dry season use of stored rainwater is restricted to consumptive uses (Elliott et al., 2017). Such conservation of rainwater has been documented in other SIDS to sustain communities through the dry season or drought (Bailey, Barnes, & Wallace, 2016), likely due to a lack of alternative water sources. However, increasingly unpredictable rainfall during the wet season makes rainwater harvesting less reliable as a drought mitigation strategy. The Intergovernmental Panel on Climate Change (IPCC) predicts with high confidence that global warming will amplify the frequency of extreme El Niño and La Niña events with corresponding increases in the number of severe floods and droughts in SIDS (Hoegh-Guldberg et al., 2018). Despite the large volumes of storage tanks in RMI, between 800 and 3000 litres per household (Elliott et al., 2017), these are likely to be insufficient to sustain communities through severe droughts that are documented to last up to 44 months (White & Falkland, 2009).

Rising sea levels independently increase the vulnerability to RMI communities experiencing drought with the risk of king tides and wave-driven coastal flooding. Seawater flooding from tropical storms and wave inundation can damage rainwater storage infrastructure and contaminate the FWL. The combined risk of drought and coastal flooding is extremely hazardous to remote communities. It takes 22 to 26 months for a freshwater lens to return to equilibrium after an overwash event under normal rainfall conditions (Gingerich et al., 2017; Terry & Falkland, 2010); and 3 to 6 months for groundwater to return to acceptable salt concentrations (Bailey & Jenson, 2014). The IPCC predicts with high confidence that the long-term risks of coastal flooding and its impacts on infrastructure and populations in SIDS will increase as a result of rising sea levels and reef degradation caused by higher temperatures (Hoegh-Guldberg et al., 2018).

The simplistic characterization of RMI communities as inherently vulnerable to drought and climate change overlooks the survival of these communities under dry and periodic drought conditions for millennia, such as the Medieval Warming Period between 750 and 1250 AD. For example, Nunn et al. (2017) postulate that exchange networks and production surpluses developed during this period in Micronesia out of necessity, as did the production of storm-proof foods, broadening diets and strategies that allowed damaged/overutilized production systems to recover. In the past, RMI households sometimes limited themselves to two-child families to control village populations and ensure that they did not exceed what was believed to be sustainable (Spennemann, 2009). The Marshallese culture of boiling fish in seawater which conserves freshwater is still common (Elliott et al., 2017). Traditional knowledge – the skills, philosophies and understandings of a society developed through a long history of interacting with their environment (de Coninck et al., 2018) – is essential for any climate adaptation policy or drought impact mitigation strategy (Berkes, Colding, & Folke, 2000; McNamara, 2013; McNamara & Prasad, 2014). However, many communities express demand for modern technologies (e.g., reverse osmosis for desalination) to assist in adaptation to adverse climatic conditions.

In this paper, we utilize in-depth survey and focus group data to report on the diverse approaches employed to mitigate drought impacts in RMI, including the strategic use of multiple household water sources, other traditional practices, and desalination using reverse osmosis. Research in remote SIDS is inherently challenging due to their remoteness, the vast distances between islands and the expense associated with travel to these isolated communities. Therefore, our dataset comprised of eight RMI communities spanning nearly 8,500 nautical miles, with between 35% and 100% of community households surveyed represents an unusually rich sample size for the context. We employ both quantitative an qualitative data and discuss the implications of our findings for SIDS and other drought-prone developing countries around the world. Our objectives were to describe and provide novel insights into: (1) changes in the number and type of household water sources and their uses between drought and regular seasonal usage; (2) the roles of rainwater and groundwater in household water management during drought; and (3) the use of modern and traditional drought mitigation strategies in RMI.

2 Materials and Methods

The household survey was adapted from a questionnaire used to investigate multiple water sources and uses within households (Whittington, 2000). We expanded the survey to incorporate location of use, and the impact of drought on household water management. The augmented survey was long and complex, employing multiple skip patterns and grid pattern response recording, so the survey process was streamlined by developing a digital version using SurveyCTO (MacDonald et al., 2016).

Three local enumerators in RMI attended three full days of training and practical exercises, covering diverse topics including informed consent, operational definitions, question understanding, survey structure and use of the digital survey tool. After training the survey was field tested and improvements made to increase question clarity and facilitate delivery.

Eight RMI communities were selected for study following recommendations from the Marshall Islands Water, Sanitation and Hygiene (WaSH) committee, a group of stakeholders composed of senior officials from government, public works, local NGOs, the International Organization of Migration (IOM), and the United Nations where access to acceptable drinking water sources had been challenged by recent droughts (either through perceived contamination or loss of access); and that were from different parts of RMI to best represent variability within the country (Supplemental information Figure S1).

Household (HH) surveys and focus groups (n = 16) were conducted in the selected communities (n = 298 HH) between August 2014 and November 2015. In addition to focus groups and surveys, informant interviews explored water availability, distribution and management as well as the impact of extreme weather events with key stakeholders from the RMI government, local NGOs and public works.

Quantitative data from the household surveys were coupled with qualitative social, cultural and environmental knowledge gathered through focus group discussions. Male and female participants were consulted through separate focus group discussions in which a participatory exercise elicited responses on where, why and how water was used, and how these 'day-to-day' behaviors changed according to the seasonal shifts in water availability and extreme weather events such as drought.

Survey data were exported from SurveyCTO (Dobility, Inc.; Cambridge, MA) to Microsoft Excel using the integrated data exporting function. Statistical analysis was conducted in R version 3.3.2 (R Core Team, 2013). Seasonal changes in water source use were tested by paired analysis using McNemar's Test. Correlation within and between consumptive and non-consumptive uses was analyzed by the Phi Coefficient of Correlation and the chi-square score. A principle component analysis (PCA) was performed to explore the similarities (and differences) in how communities use different water sources under different climatic conditions. As part of the analysis, water uses were organized into two groups. Consumptive uses described drinking and cooking, while all other household uses, such as bathing, handwashing, gardening, providing for animals, sharing with neighbours and washing clothes were described as non-consumptive uses.

The study was approved by the human research ethics committees of Griffith University (ENV/47/13/HREC) and the University of Alabama (14-OR-425), and the Historic Preservation Office of the Republic of the Marshall Islands (2014-01). Approval was received from local chiefs and the RMI government to conduct research in the selected communities.

3 Results and Discussion

Of the eight communities selected, two were located on Majuro (Jenrok, Laura) and considered central island communities by local people. Of the remaining six communities from the outer islands, four were of the Ratak island ch ain (Arno, Likiep, Ailuk, Wotje), and two were of the Ralik island chain (Lae, Ujae). A summary of household numbers, the coverage relative to total community size and the reported number of household water sources used for each community is presented in the Supplemental Information Table 1.

3.1 Using multiple water resources to mitigate drought impacts

Of the 685 water sources reported by surveyed households as accessible, at least one use was reported for each source. There were 14 water sources (2%) that were reportedly normally unused during the wet season, but were used during the dry season when preferred water sources were exhausted; eight (57%) of these were private wells.

Most (84%) households used two-to-three sources at some point during the year. Of the 37 households (12%) that reporting using a single water source throughout the year, 36 reported private rainwater and one a private well. The maximum number of sources used was four, reported by eleven households.

Over 95% of households reported drinking rainwater in the wet season, with 90% not using any other source for drinking. Rainwater was also the most common source used for cooking, however, during the wet season seawater (34%) and private wells (23%) were also commonly used (Table Ia). During the wet season, most households also used private rainwater and private well water for non-consumptive uses such as bathing, washing hands, and washing clothes (Table Ia). Water was often shared within communities, with 51% sharing their private rainwater and 43% sharing private well water with neighbors at some time during the year.

Of the 298 RMI households surveyed, 256 reported having lived through drought at that location. For the purpose of the survey, drought was defined for the respondents as "an exceptionally long dry period (a minimum of 3 months) with little to no rain, during which time many of the island's plants turned brown and died and the leaves fell off the trees."

During drought, the average number of water sources used per household fell to 2.0 (SD 0.8) from 2.3 (SD 0.73) during the wet season. Of the 602 sources reported by households that self-identified as having experienced drought, 73 (12%) were either depleted or contaminated and considered unusable during drought. A total of 69 (27%) households reported losing access to at least one water source during drought, with four reporting the loss of two sources. Private rainwater accounted for over 80% of lost sources.

For many households on the atolls of RMI the loss of access to stored rainwater presents a major challenge. This is most true for the 36 households that reported private rainwater as their only water source. Of these, eight (22%) experienced the loss of their sole water source, forcing them to turn to an emergency source or to rely on their neighbours. More than half of these households were from Ailuk. They substituted the loss of their single water source, rainwater, with water treated using reverse osmosis (RO). Ailuk, like many of the outer islands of RMI, had been issued a temporary emergency water management solution in the form of a small and portable RO unit, the Spectra Aquifer 360 Watermaker (Katadyn, Lindau, Switzerland), with a maximum capacity of 1,350 liters per day.

Table I. Percentage of households reporting use of water sources and the purposes for which they use those sources, by season in (a) and drought in (b). Change is shown as a percentage point change, with negative (bold) reflecting a reduction in source use and positive (non-bold) changes reflecting an increase. Significant seasonal differences indicated by superscript symbols * (P<0.05), † (P<0.01) and ‡ (P<0.001).

a) Wet season usage (left) and change to dry season (right).

Water source	% HHs that use (any time)	Wet season (% of households)									Change from Wet to Dry Season (percentage point change)								
		Any use	Drink	Cook	Bathe	Wash Hands	Wash Clothes	Ani-mals	Garden	Share w/ Neigh-bours	Any use	Drink	Cook	Bathe	Wash Hands	Wash Clothes	Ani-mals	Garden	Share w/ Neigh-bours
Rainwater (private)	90.3	90.3	84.9	87.0	69.9	69.2	63.5	20.7	18.1	43.1	-	**-0.6**	**-19.7**‡	**-45.8**‡	**-45.2**‡	**-43.5**‡	**-9.4**‡	**-6.7**‡	**-14.4**‡
Rainwater (public)	10.4	10.4	10.4	9.0	3.0	2.0	1.7	0.3	-	-	+0.3	+0.3	**-0.3**	**-2.3***	**-1.7**	**-1.3**	**-0.3**	+0.3	+3.7
Private well	67.8	67.8	2.7	22.7	59.5	60.2	60.2	39.1	31.1	25.4	+2.0	+5.7‡	+9.0‡	+4.0‡	+3.3*	+3.7†	+7.7‡	+8.0‡	+3.7*
Public well	3.4	3.4	0.3	1.0	3.3	3.3	3.3	1.7	1.3	2.0	-	+0.4	+0.3	-	-	-	-	-	-
Public standpipe	0.3	0.3	-	-	0.3	0.3	0.3	-	-	-	-	-	-	-	-	-	-	-	-
Bottled water	3.0	3.0	2.3	0.7	0.3	0.3	0.3	-	-	-	-	-	-	-	-	**-0.3**	-	-	-
Piped to home	6.4	6.4	0.3	1.0	5.4	5.4	5.0	1.0	2.3	2.0	-	-	+0.7	-	**-0.3**	**-0.3**	-	-	**-0.3**
Seawater	35.9	35.9	-	33.8	0.3	0.3	0.3	-	-	-	+1.0	+0.3	+1.0	+0.3	+0.3	+0.3	+0.3	+0.3	+0.3

Adapted from Elliott et al. 2017

b) Change of usage from wet season to drought (left) and dry season to drought (right).

Water source	Change from Wet to Drought (percentage point change)									Change from Dry to Drought (percentage point change)								
	Any use	Drink	Cook	Bathe	Wash Hands	Wash Clothes	Animals	Garden	Share w/ Neigh-bours	Any use	Drin k	Cook	Bathe	Wash Hands	Wash Clothes	Ani-mals	Garden	Share w/ Neigh-bours
Rainwater (private)	+0.7‡	**-21.2**‡	**-51.4**‡	**-61.3**‡	**-60.6**‡	**-57.7**‡	**-16.4**‡	**-14.2**‡	**-24.8**‡	+0.7‡	**-20.6**‡	**-31.7**‡	**-15.5**‡	**-15.5**‡	**-14.2**‡	**-7.1**‡	**-7.5**‡	**-10.4**‡
Rainwater (public)	**-0.6**	**-2.2**	**-4.3**†	**-3.0**	**-2.0**	**-1.7**	**-0.3**	-	+2.0	**-1.0**	**-2.5**	**-4.0**†	**-0.7**	**-0.3**	**-0.3**	**-**	**-0.3**	**-1.7**
Private well	+5.7	+19.6‡	+24.1‡	+8.4*	+7.8	+7.8	+14.0‡	+15.4‡	+9.0†	+3.6	+13.9‡	+15.1‡	+4.4	+4.4	+4.1	+6.3	+7.4	+5.3
Public well	-0.6	+1.3	+0.6	**-0.6**	**-0.6**	**-0.6**	**-0.1**	+0.2	**-0.1**	**-0.6**	+0.9	+0.2	**-0.6**	**-0.6**	**-0.6**	**-0.1**	+0.2	**-0.1**
Public standpipe	+0.1	-	+1.0	+2.0	+3.0	+4.0	+5.0	+6.0	+7.0	+0.1	-	+0.4	+0.1	+0.1	+0.1	-	-	-
Bottled water	**-0.7**	**-0.7**	+0.1	**-0.3**	**-0.3**	**-0.3**	-	-	-	**-0.7**	**-0.7**	**+0.1**	**-0.3**	**-0.3**	-	-	-	-
Piped to home	**-0.1**	+0.1	+1.7	+0.5	+0.5	+0.8	+0.2	**-0.8**	**-0.4**	**-0.1**	+0.1	+1.1	+0.5	+0.8	+1.2	+0.2	**-0.8**	**-0.1**
Seawater	+3.5	+0.4	+2.9	+0.4	+0.4	+0.4	+0.4	+0.4	+0.8	+2.5	+0.1	+1.9	+0.1	+0.1	+0.1	+0.1	+0.1	+0.4

3.2 The roles of rainwater and well water in household water management during drought

The behaviors around water sources and how people use them during times of drought are noticeably different from the mapping of sources to uses during the annual wet and dry season cycle (Table I). During drought, there was a significant decrease (-21 percentage points) in the drinking of private rainwater ($p < 0.001$), with only 72% of households reporting sufficient stored rainwater to last the duration of the drought. In contrast, the number of households using private rainwater for drinking did not change between the wet and dry seasons, but those using it for cooking decreased by 20 percentage points ($p < 0.001$) from wet season to dry season (Table Ia). In drought, the consumptive needs of households were supplemented with private well water, which increased above levels reported for the dry season for both drinking (+14 percentage points) and cooking (+15 percentage points).

During drought, water for cooking came primarily from private wells (47%). The greatest reported change in household water use between the dry season and drought was demonstrated with respect to cooking, with a 32 percentage point reduction in the number of households using private rainwater ($p < 0.001$); this reduction is on top of a 20 percentage point decrease ($p < 0.001$) reported from wet to dry seasons. This reduction in rainwater use is somewhat balanced by the greatest increase in use of a water source from dry season to drought, with a 15 percentage point increase in the use of private well water for cooking ($p < 0.001$); this was reported in addition to a nine percentage point increase ($p < 0.001$) from wet to dry season (Table I).

For non-consumptive purposes, there were substantial declines (-55 percentage points) in households using private rainwater for bathing, handwashing, and washing clothes ($p < 0.001$ for all) between the wet season and drought conditions; however, there was no concomitant increase in the reported frequency of use of other sources. The same was true of the difference between the dry season and drought ($p < 0.001$ for all) with a decrease of over 14 percentage points for all non-consumptive uses.

Water sharing is common between water-insecure households and is often used to increase each households' overall resilience to drought and water scarcity (Stoler et al., 2019). Sharing of private water sources was commonly reported, with 51% sharing their private rainwater and 43% sharing private well water with neighbours at some time during the year. When asked about sharing rainwater during times of drought one man said: "*When I run out of drinking water, I would go and ask my neighbour if I could fill up my 1 gallon drinking container. In my house, we have 7 family members living in it and that 1 gallon water is only for drinking, for one day supply*" (Men's Focus Group Discussion, 2015). The source type most commonly shared during drought was private well water (34%) followed by private rainwater (18%). Sharing private rainwater was significantly less common during drought than the dry season ($p < 0.001$), with no significant change in private well water sharing.

Figure 1 shows the results of a principle component analysis (PCA), a multivariate statistical approach used to summarize and illustrate the variation in the uses of all water sources across all seasons. Drinking and cooking are highly correlated because most households, across all communities, favoured private rainwater for both uses. There is very little correlation between consumptive and non-consumptive uses as indicated by the nearly perpendicular angles between the arrows for those kinds of uses in Figure 1. This suggests that rainwater is almost never used for non-consumptive purposes. However, there is strong correlation between all non-consumptive uses, because private well water is heavily favoured.

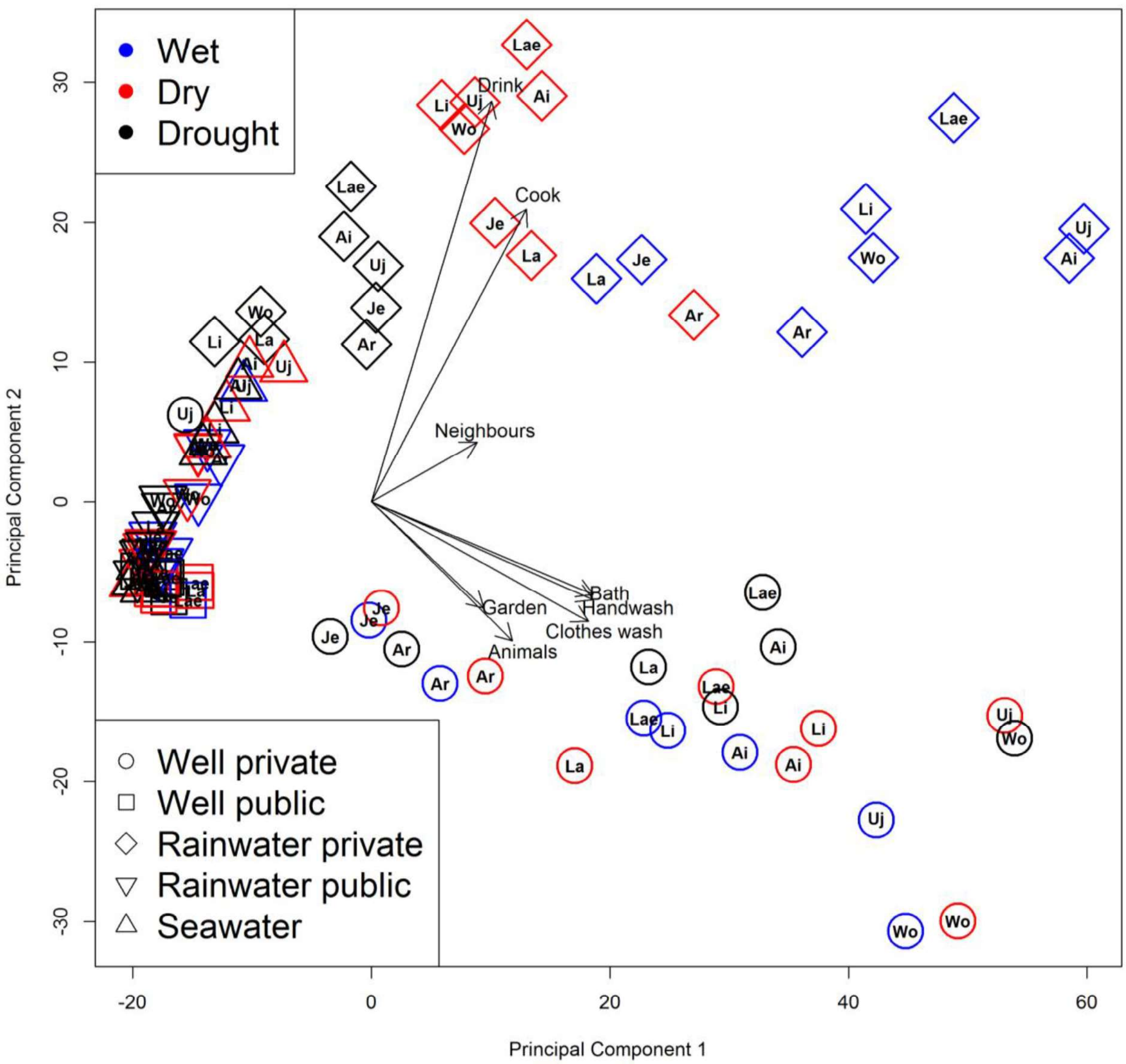

Figure 1. Principle component analysis (PCA) of water source usage behaviors for wet, dry and drought conditions. Seasons are represented by colour: blue for the wet season, red for the dry season, and black for drought. Water sources are represented by marker shape. Abbreviations for each community are inside each marker.

The upper half of Figure 1 reveals not only that private rainwater is used primarily for drinking and cooking, but also that the proportion of households consuming rainwater decreases from wet (right) to dry (middle) and drought (left) conditions. As private rainwater stores are depleted during the dry season and times of drought each household implements austere usage behaviors, reserving private rainwater only for consumptive uses that are necessary for survival. During one focus group, a woman explained the urgency of austere private rainwater usage behaviors during drought: "*We're just doing our best to conserve water. Some people ran out of water fast because they use it for everything*" (Women's Focus Group Discussion, 2015). Similarly, during a men's focus group a participant explains: "*First of all, we did not play with our water. We only use when it's absolutely needed*" (Men's Focus Group Discussion, 2015).

In Figure 1, the arrow for sharing water with neighbours is angled towards private rainwater as opposed to private well water, indicating it follows a similar use pattern to consumptive uses. This is likely because 43% of households reported sharing private rainwater with neighbours during the wet season; however, this number decreased by over 14 percentage points during the dry season, and by an additional 10 percentage points during drought (Table I). Despite reduction in the number of households that reported sharing private rainwater during times of water scarcity, it is a mainstay of drought resilience in some Marshallese communities. During a focus group, one man explained his dependence on shared water from his neighbours:

"*I usually ran out of drinking water because most people from the north end of the island always come to me for water. And when I run out of water, I started to look around just like my neighbours and this is how we survive.*" (Men's Focus Group Discussion, 2015)

In contrast to private rainwater, the pattern of private well water use (the bottom half of Figure 1), is driven by community variability with no seasonal trend and fewer commonalities across communities. This is evident by the clustering of individual community well water data points represented by circles of all colours, in Figure 1, as opposed to the seasonal effect on private rainwater, as indicated by the segregation of data points of different colours in the upper half of the plot. The lack of a seasonal trend in private well water use suggests that the availability of this resource is not substantially affected by changing weather patterns and that access to and use of groundwater varies across communities. However, this result does not preclude the possibility of water quality changes across season; because well water is not commonly used for consumption, a seasonal change in water quality could occur without affecting non-consumptive use. Additionally, the use of groundwater would be expected to vary across communities because the eight communities are spread across seven atolls and each community is accessing a different FWL.

In Figure 1, triangles representing seawater show a trend towards the cluster of consumptive uses. In many Marshallese communities seawater is used to boil fish, thereby preserving freshwater sources for drinking and other uses, and helping to maintain the salty flavor of the fish. This practice is independent of season.

3.3 Exploring the roles of modern and traditional drought mitigation strategies

3.3.1 Traditional Knowledge and Adaptation

In addition to cycling various water resources and prioritizing uses for each source, further traditional coping strategies for dealing with drought and water scarcity were revealed through focus groups and survey responses. Austere usage behaviors, to conserve as much freshwater as possible during periods without rain has been part of Marshallese culture for thousands of years. A woman explains, "*Our ancestors knew more about saving water, for example, my grandma used just a cup full [of water] to wash up*." (Women's Focus Group

Discussion, 2015) It was common practice to conserve high quality well water by using as little as possible. The same sentiment was echoed by another woman, who said "*Before, my grandma used one half of the coconut [shell of water] to clean herself but today we can use a bucketful*" (Women's Focus Group Discussion, 2015). Both statements reflect a culture of austere water usage, as well as a shift in contemporary usage that allows greater consumption of freshwater resources. Much of this change is attributable to the introduction of large rainwater storage tanks to RMI within the last half century. As discussed in the previous section, rainwater is now prioritized for consumptive uses, such as drinking and cooking, and well water is supplemented for non-consumptive uses.

Before the introduction of modern rainwater harvesting and storage technology, people in RMI harvested rainwater using the coconut tree. The "Mammak", as it is called in the Ratak island chain ("Emmak" in the Ralik chain), was a coconut tree hollowed out at the base to form a bowl for storing rainwater captured by the leaves of the tree and channeled to the base using a series of grooves carved into the trunk (Supplemental information Figure S2). To the authors' knowledge, this ancient technology has not been studied, but was acknowledged in the literature as a method of rainwater capture, early in the twentieth century (Kraemer & Nevermann, 1938). When other water sources are unavailable, some Marshallese still use the Mammak to get water, as one man described, "*We have quite a few that still working. When we have no choice then we will drink from these Emmak*" (Men's Focus Group Discussion, 2015). Another man discussed a different use for this water: "*In the past, the ancestors would go swimming in the lagoon or the ocean side and then used the Mammak to get rid of the salt from their bodies*" (Men's Focus Group Discussion, 2015). The same man continues by discussing the importance of passing this knowledge on to younger generations:

I used to live on the smaller islands nearby and when the children saw these [Mammak] *they would come and ask me and I would tell them who made them and why were they made. The Mammak is the most well known thing for saving people's lives in the past. It was made for one thing, to drink to survive* (Men's Focus Group Discussion, 2015).

However, in many other RMI communities this practice is being lost as people become more comfortable with and reliant on modern rainwater storage infrastructure. One man explains this, "*Now we still see Mammak but we don't see people drink from them but there are still Mammak. No one uses it today because there are water catchments [rainwater storage tanks]*" (Men's Focus Group Discussion, 2015).

Indigenous plants and vegetation also serve as emergency water sources in other ways during times of drought. When good quality drinking water is scarce, people in RMI drink coconut water, a practice reported in other SIDS as well (MacCracken, Jenson, Heitz, Rubinstein, & Mylroie, 2007). Similarly, the Pandana tree stores water that can be harvested when needed, as described by one man, "*You have to pound it [Pandana fruit] hard and put it in a underground oven to warm it up a little and then squeeze it and twist it hard and the water will come out*" (Men's Focus Group Discussion, 2015). Plant products, such as coconut husks, were also referred to in some community discussions as filter material that was historically employed to remove debris from water stored in Mammaks, while plant leaves were used to make straws from which to drink from Mammaks without contaminating the water source with unwashed hands (Men's Focus Group Discussion, 2015).

In the event of prolonged drought or overwash flooding, the complete depletion of rainwater stores and the degradation of FWL water quality, people have had to leave their communities in search of drinking water. Members of over half (n = 168) of households surveyed had to leave their home community to find drinking water at least once during a natural disaster, with over 60% of these households reporting leaving during multiple disasters. Only three households reported having to leave their home island in search of water; these same households also report having to leave their home island for more than one extreme weather event.

3.3.2 Modern Technology and Adaptation

While foreign aid was essential to RMI drought response during the 1998, 2013 and 2016 droughts, the use of portable RO units for drought response differed between the capital island of Majuro and the outer islands. Majuro is a town of 28,000 with a centralized water treatment and distribution network that is overseen by a utility, the Majuro Water and Sewer Company (MWSC). Outer island populations vary between 100 and 2000.

The first deployment of RO in drought response in RMI occurred in 1998, when the national government requested emergency disaster assistance from the United States (Freshwater & Talagi, 2010). In addition to three commercial RO units on Majuro that supplied the hotels, a brewery and a bottled water vendor, the Japanese government donated three RO units, each with a capacity of 22,700 L/d, and the RMI government with assistance from the US Federal Emergency Management Agency (FEMA) purchased five larger RO units capable of producing nearly 475,000 L/d in total. When the volume of RO-treated water is combined with water extracted from the FWL in the community of Laura, it is estimated that residents of Majuro could have received up to 37 L of fresh water per person per day during the 1998 drought (Presley, 2005). Much of this water had to be collected by bucket or container at RO stations and carried home by family members, which was a heavy load and difficult task to perform. One woman expressed concern about the quality of water received from the Laura lens, saying "*Sometimes the government water is dirty and unsafe*" (Women's Focus Group Discussion, 2015). Other women expressed difficulty in obtaining RO-treated water during the drought, such as having to wait in line for hours in the heat of mid-day, and avoid fighting that would sometimes erupt between frustrated people in line (Women's Focus Group Discussion, 2015).

The mandate of the MWSC is to provide water and sewer services to the residents of Majuro; however, they have also become central to drought response and all things water resources related across the entire country, including the distribution and management of RO units to the outer islands (Majuro Water and Sewer Company, 2015). At the time of this research, the MWSC had 17 small portable RO units, each capable of producing up to 1,350 L of freshwater per day, which they deployed to the outer islands in the event of drought or disaster. Additionally, the International Organization for Migration (IOM) had 20 similar units stored in a warehouse in Majuro reserved for drought response. Upon declaration of a state of emergency or disaster by the national government, these 1350 L/day RO units would be flown in or shipped to recipient communities, where they were typically powered by solar panels or diesel generators also provided by MWSC and IOM. Rapid response surveys conducted by inter-agency teams helped determine which community's water resources were critical and prioritize the most urgent cases to receive an RO unit (International Organization for Migration, 2015).

During the drought of 2013, portable RO units were deployed in the outer islands to provide emergency drinking water. An employee of MWSC described how communities usually decide on the location for installation based on ease of access and whether or not the well is owned by the government, which is preferred over private wells. Churches and schools were popular locations due to their communal nature and because they are generally located towards the centre of the island (Majuro Water and Sewer Company, 2015). However, research into the abstraction of water from the FWL on coral atolls is unanimous in concluding that excessive or continuous pumping of water from dug wells near the centre of an island is hazardous to the FWL (Barkey & Bailey, 2017; Kazuhisa Koda, 2015; White et al., 2007). With continuous pumping, which is common during drought in RMI and healthy for the RO membrane, each RO unit would be extracting over one thousand liters of water from the lens each day. Nearly all wells in the outer islands are vertical dug wells, which can be affected by upconing that allows the ingress and mixing of seawater and turns the well brackish. Additionally, the FWL is highly vulnerable to saltwater intrusion in the absence of rainwater, particularly during periods of drought (Chang & Clement, 2012). During a community discussion, two local women discussed the impact of RO pumping on their FWL:

[FACILITATOR] *When it first arrived, did the water taste salty?*

[Responder 1] *Not at all.*

[Responder 2] *After using it over and over, the water started to taste funny.*

[FACILITATOR] *Where is the water coming from before entering the RO unit and for how long did it take for the water to taste salty?*

[Responder 1] *The water is pumped out from the well into the RO unit and after about two months of processing* [running the RO] *the water started to taste different.*

[Responder 2] *No, I think the water started to taste bad because the water inside the well is almost empty.* (Women's Focus Group Discussion, 2015)

In addition to the selection of wells used for RO treatment from island interiors, some community members expressed a preference for drawing water from wells that already contained potable freshwater. It was believed that water from less saline wells would produce the best tasting and highest quality drinking water when treated with the RO unit. The recommendation from MWSC was to use high saline wells for RO treatment in order to preserve higher quality wells for other uses, with one representative suggesting "*the saltier, the better*" [for RO treatment] (Majuro Water and Sewer Company, 2015). Representatives from the MWSC revealed that communities typically did not want RO units setup on or near the beach because this is where many community members still practice open defecation. In our RMI communities, there appeared to be widespread preference for use of RO units with low-salinity wells located toward island interiors. A man who was responsible for operating the RO in his community said:

In the beginning we used the sea water. Later on we switched to well water. First, I put it [RO] *on the dock, using saltwater and it was kind of salty but better than some of the wells. When I noticed that the people were not really interested, then I took the unit to the well near the pastor's home and it was better that way.* (Men's Focus Group Discussion, 2015)

Of the surveyed households that had access to RO during drought, over 86% reported that the RO drew from either private or public wells. Of their reasons for treating water sourced from the FWL, 41% said the well water was "drinkable, but unsafe and RO water was better", 34% said that well water was, "drinkable but a little salty, and RO improved the taste", 10% said the, "RO water was closer to home and more convenient", and 7% said that, "RO water was more fashionable than well water". These findings suggest that by choosing the highest quality wells closest to the centre of the island for RO treatment, some communities may be unnecessarily degrading the quality of the FWL through up-coning.

The Spectra Aquifer 360 Watermaker, which is the MWSC RO unit deployed to the outer islands, can treat raw seawater with a 99.4% salt rejection rate, reducing sodium concentrations to a potable level and below taste-detection levels (Katadyn Group, 2019; WHO, 1997). Based on factory specifications, it is therefore, unnecessary to treat groundwater from the FWL with RO. In doing so, communities may increase their vulnerability to drought by depleting the FWL that could serve as a secondary emergency drinking water source in the event that the RO unit malfunctions, or at least provide a freshwater source for non-consumptive uses to preserve higher quality water for drinking.

In addition to upconing, brine disposal can also represent a threat to the FWL. If RO units in remote, low-density atolls are placed adjacent to saline wells near the ocean, disposing of brine onto the ground surface should not represent a substantial threat to the FWL. However, if RO units are drawing from centrally located, freshwater wells, disposing of high-concentration brine onto the ground surface could salinize the FWL by infiltration downward onto the top of the lens (Johnston, 2013). A 2013 report on the RMI water and sanitation sector included the non-specific claim that FWLs in some islands have been contaminated by brine (Johnston, 2013); this report requires further investigation.

Maintaining modern technologies is a major challenge in the outer islands due to a lack of replacement materials, limited availability of skilled technicians, and the high cost and time required to travel to these remote communities. During the drought of 2013, technicians from the MWSC accompanied the RO units to the outer islands to assist with installation and provide operational training to one or two local people. These local individuals did not receive technical skills training on maintenance and repair of the system, so in the event of a breakdown they were instructed to radio Majuro for help, which could take weeks to reach them (Majuro Water and

Sewer Company, 2015). The Japanese government donated 24 small capacity RO units to RMI for installation outside of schools in the outer islands. In the three communities we visited that had received one of these ROs, none were working. One island's unit had been damaged during a storm; help had been requested by the village but none had arrived as of six months later (Men's Focus Group Discussion, 2015). On the other two islands, the units had not worked properly since they were installed. One man who was trained in the RO unit's operation said:

When [I] *try to turn on the unit, it will not start and at the same time a warning light is blinking. The people I trained with instructed me that if the machine is having a problem, not to do anything. I have reported the problem. Nobody has come to fix the unit yet. It's been a year now since my reporting* (Men's Focus Group Discussion, 2015).

The portable ROs distributed by MWSC and IOM during the droughts of 2013 and 2015-16 provided critical emergency water to the outer islands. The surveyed communities reported neither malfunction nor breakdown of these units. The only criticism sometimes received was that they produced insufficient water for the community – this was especially true of ROs fitted with a single electric pump and ROs using solar power. Diesel driven units were preferred over solar powered ones for their ability to run 24 hours a day, and consequently their perceived ability to produce larger volumes of water.

After the drought of 2013, and the return of normal rainfall patterns that replenished water storage tanks, some communities were reluctant to return the portable RO units to Majuro. They were recalled to receive maintenance and undergo proper storage procedures at MWSC and IOM. When asked about reclaiming the ROs from the islands, a representative from MWSC said, "*They've* [MWSC staff] *had problems with the local people wanting those units* [RO] *to stay... They're not using it, but still they want it there*" (Majuro Water and Sewer Company, 2015). The

ROs likely provide the community with a sense of security against water scarcity. It has also been suggested that some of the components, such as solar panels and batteries, are co-opted to power phones and other electronic devices.

There is concern that communities will rely too heavily on RO units and become dependent on them throughout the seasonal cycle. A representative from IOM shared:

I think they're [RO] *just seen as an easy fix, now that people have had them, it's like "oh, it's getting drier let's just get our RO back out here"... I worry about the long term dependency that could be created with how expensive parts are and maintenance.* (International Organization for Migration, 2015)

The same concern around overdependence on RO was expressed by a member of the national government at the time, saying "*I get phone calls from Mayors who say* '*Okay – we're ready for our RO now', as if they were ordering a pizza*" (National Government of the Republic of the Marshall Islands, 2014). It was further explained that the strategy for RO deployment was in alignment with the El Niño Southern Oscillation cycle, approximately once every five years. However, the national government representative explained that requesting an RO unit "*has become the norm*" (National Government of the Republic of the Marshall Islands, 2014). A representative from MWSC suggested the reason for such frequent requests may be politically driven. It was postulated that Mayors for the outer islands try to improve their standing with the community by bringing in the RO units. Additionally, it was suggested that RO units may be requested prematurely in anticipation of upcoming dry periods or forecasted droughts in order to outcompete other islands for the limited number of RO units available (Majuro Water and Sewer Company, 2015).

4 Conclusions

Our findings have implications for climate change adaptation, drought preparedness and response in SIDS, the appropriate management and operation of RO on atoll aquifers, and research on the use of multiple water sources in disaster settings.

Modern technology plays an important role in mitigating drought impacts in RMI. The use of natural water resources, such as the FWL, is less expensive but climate sensitive. Joint systems that utilize a combination of water resources, including desalinated seawater with treatment from RO, are less vulnerable to changes in the environment and are adaptable to future climate uncertainties (Bhushan & Ling Ng, 2016). In settings such as RMI, with small and isolated populations that exhibit resilience through community cohesion and the application of traditional knowledge, it is important that modern technologies do not supersede or displace prevailing drought response strategies (Hiwasaki, Luna, & Shaw, 2014; Kelman, 2017). Similarly, local knowledge should not invalidate or disparage the integration of modern technologies with the capability to augment existing systems.

The balance of traditional water conservation practices and the implementation of modern technologies, such as large rainwater tanks and RO units for emergency response, will increase community resilience to drought in RMI. Longstanding practices of austere rainwater usage behaviors are effective at conserving high quality drinking water throughout the dry season and periods of drought. When possible, alerts should be issued to communities when droughts are forecasted, triggering the need for freshwater conservation. Furthermore, educating communities about the role of RO as a redundancy measure and the importance of selecting a brackish water source for desalination will help preserve the FWL as an additional emergency water source.

The most recent drought of 2015-2016 in the Republic of the Marshall Islands (RMI) caused five million US dollars, worth of damage to the sectors of water and sanitation, electricity and power supply, agriculture, health and education (Leenders, Holland & Taylor, 2017). This is proportionately larger than the economic fallout from the California drought of 2016, costing RMI approximately $100 per capita and disproportionately affecting the more vulnerable economies of the outer islands. It also had serious effects on the health and quality of life for people across the country, including the loss of livelihoods, food shortages causing malnutrition in children, and drinking water scarcity (Leenders et al., 2017). To facilitate a more robust response to drought stricken communities, the national government needs to exercise more oversight when distributing technology designed to increase water security in the outer islands. In addition to more technical training for local operators of modern devices, such as RO units, new technology must be implemented in a way that supports effective water management strategies and traditional knowledge that have existed in SIDS communities and protected against drought impacts for thousands of years.

Water researchers should consider how to incorporate multiple water sources into data collection efforts, and how to assist governments and practitioners with integrating these various sources into disaster risk reduction and disaster management plans. Advances in computer assisted personal interviewing tools have made this affordable and time-efficient for many surveys (MacDonald et al., 2016). Research is needed to describe the use of multiple water sources in other countries and more disaster scenarios, such as floods and tropical storms, to give insight on the optimization of each available source and increase community resilience to extreme weather events and the growing impacts of climate change. We believe that failure to consider a practice that is so widespread and inherent to global water culture in developing settings could undermine the effectiveness of disaster response and preparedness, climate change policy and research.

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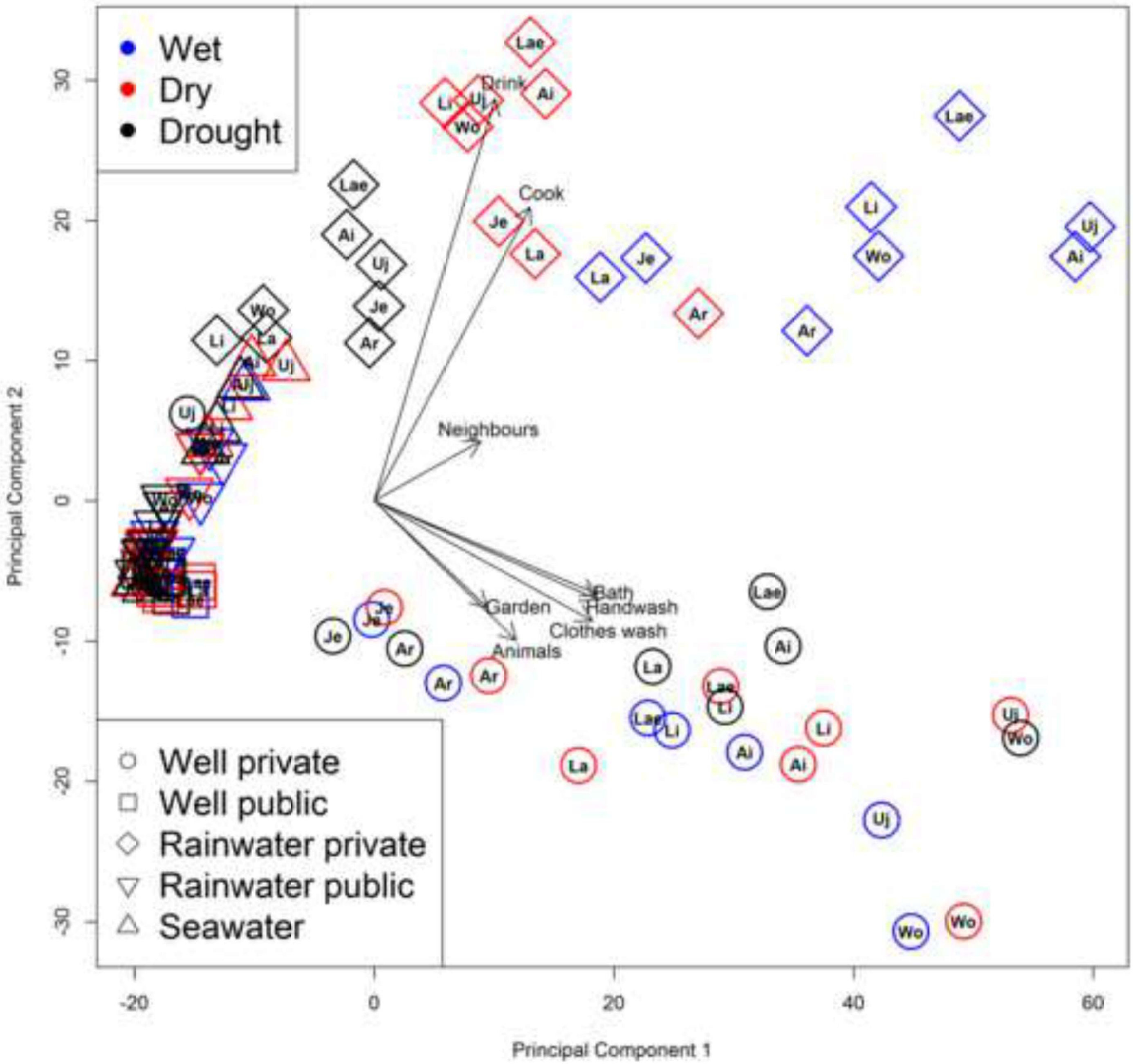

Conflicts of Interest Statement

Manuscript title: Mitigating drought impacts in remote island atolls with traditional water usage behaviors and modern technology

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Author names:

Morgan C. MacDonald,
Mark Elliott,
Dustin Langidrik,
Terry Chan,
Angela Saunders,
Ben Stewart-Koster,
Irene J. Taafaki,
Jamie Bartram
Wade L. Hadwen

The authors whose names are listed immediately below report the following details of affiliation or involvement in an organization or entity with a financial or non-financial interest in the subject matter or materials discussed in this manuscript. Please specify the nature of the conflict on a separate sheet of paper if the space below is inadequate.

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Morgan MacDonald		March 3, 2020