Multiple Household Water Sources and Their Use in Remote Communities With Evidence From Pacific Island Countries

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Abstract Global water research and monitoring typically focus on the household’s “main source of drinking-water.” Use of multiple water sources to meet daily household needs has been noted in many developing countries but rarely quantified or reported in detail. We gathered self-reported data using a cross-sectional survey of 405 households in eight communities of the Republic of the Marshall Islands (RMI) and five Solomon Islands (SI) communities. Over 90% of households used multiple sources, with differences in sources and uses between wet and dry seasons. Most RMI households had large rainwater tanks and rationed stored rainwater for drinking throughout the dry season, whereas most SI households collected rainwater in small pots, precluding storage across seasons. Use of a source for cooking was strongly positively correlated with use for drinking, whereas use for cooking was negatively correlated or uncorrelated with nonconsumptive uses (e.g., bathing). Dry season water uses implied greater risk of water-borne disease, with fewer (frequently zero) handwashing sources reported and more unimproved sources consumed. Use of multiple sources is fundamental to household water management and feasible to monitor using electronic survey tools. We contend that recognizing multiple water sources can greatly improve understanding of household-level and community-level climate change resilience, that use of multiple sources confounds health impact studies of water interventions, and that incorporating multiple sources into water supply interventions can yield heretofore-unrealized benefits. We propose that failure to consider multiple water sources undermines the design and effectiveness of global water monitoring, data interpretation, implementation, policy, and research.

1. Introduction

Global water research, surveys, and data sets neglect the use of more than one water source to meet daily household needs, a common and important practice in many developing country settings. There is a small body of economics literature on modeling household demand for multiple water sources in developing countries (e.g., Coulibaly et al., 2014; Devoto et al., 2012; Madanat & Humphlick, 1993; Mu et al., 1990; Nauges & Whittington, 2010; Pattanayak et al., 2005). However, we could identify only a few journal articles (Adekalu et al., 2002; Almedom & Odhiambo, 1994; Howard et al., 2002; Ozdemir et al., 2011; Tucker et al., 2014; Vedachalam et al., 2017) and one conference proceedings paper (Smith et al., 2015) that describe in detail and/or quantify multiple household water sources. Nearly all of these articles concern Sub-Saharan Africa. Despite the paucity of published studies and their relatively narrow geographic focus, there is growing recognition of the importance of multiple household water sources and a growing body of literature acknowledges the practice around the world and/or calls for further research (Ahmed & Hossain, 1997; Brown et al., 2013; Dos Santos et al., 2015; Evans et al., 2013; Foster & Hope, 2017; Henry, 1981; Jeuland et al., 2016; MacDonald et al., 2016a; Overbo et al., 2016; Shaheed et al., 2014; Thompson et al., 2000; Wang et al., 1989). This dispersed literature lacks consistent vocabulary and methodologies; published studies can be difficult to find; and most articles cite few or no prior studies. Hence, there are considerable gaps in our knowledge of household water management practices and how they vary over space and time.
The lack of understanding around usage of multiple water sources by households is reflected in, and partially attributable to, the almost exclusive focus on the main household drinking water source in major global surveys. These include the Demographic and Health Survey, the Multiple Indicator Cluster Survey, the World Health Survey, and the Living Standards Measurement Survey as well as associated consolidated data sources (e.g., Joint Monitoring Programme [JMP]) used to track progress toward the Millennium Development Goal (MDG) and Sustainable Development Goal (SDG) targets. These surveys gather nationally representative household water data and are founded on core questions that were consolidated in the early 2000s (Bartram et al., 2014; WHO/Unicef, 2006):

Q1: What is the main source of drinking water for members of your household?
Q1a: What is the main source of water used by your household for other purposes, such as cooking and hand washing?

While Q1a could be useful in filling knowledge gaps on multiple water sources, embedded skip patterns in these surveys dictate that it is typically asked only when the response to Q1 is “bottled water.”

These major international surveys, like most research studies, yield cross-sectional data from a single time point. However, many factors are reported to influence the availability and choice of water sources. These include perceived quality, reliability, volume required, distance, price, and other factors (Howard & Bartram, 2003; Mu et al., 1990). While some vary randomly, others vary systematically and somewhat predictably. For example, water source quality is known to vary seasonally in many settings (e.g., Carlton et al., 2014; Kostyla et al., 2015; MacDonald et al., 2016b); thus, survey findings are dependent on the season of implementation which is influenced by logistical factors (e.g., ease of travel).

Temporal changes in water source quality and availability are likely to influence community health outcomes. Indeed, to derive the health benefits associated with improved water quality, high-quality water must be consumed exclusively throughout the year; even occasionally drinking contaminated water undermines nearly all health gains (Brown & Clasen, 2012; Enger et al., 2013; Hunter, 2009). A consistent water supply has also been associated with increased handwashing and other hygiene practices (Devoto et al., 2012; Evans et al., 2013) and decreased diarrhea (Dos Santos et al., 2015; Overbo et al., 2016). These studies highlight how temporal changes in water quality and availability challenge development goals and affect health.

Addressing knowledge gaps around multiple source usage is essential to understanding and modeling the impacts of water on health, hygiene, and climate change resilience and adaptation options (Hadwen et al., 2015). Climate change will influence both the quality and quantity of water resources (Cisneros et al., 2014), and will threaten water security in many regions, including Small Island Developing States (SIDS) (Belmar et al., 2016; White et al., 2007). We contend that there is a major opportunity to strengthen understanding of household-level and community-level resilience to climate change through robust assessments of household water sources and uses. This opportunity coincides with the recent emergence of electronic survey platforms which make such data acquisition practical and affordable (Fisher et al., 2016; MacDonald et al., 2016a).

This study was set in Pacific Island Countries (PICs) due to their place at the forefront of global development and climate. The Pacific region made the least progress toward global drinking water and sanitation targets (MacDonald et al., 2017; WHO & UNICEF, 2015); SIDS are a focus of the SDGs (United Nations, 2016); and many PICs are highly vulnerable to water-related climate change threats, such that an understanding of source diversity and usage are essential for adaptation (Hadwen et al., 2015).

In this paper, we report on multiple household water source usage in two PICs, the Republic of the Marshall Islands (RMI) and the Solomon Islands (SI). We discuss the implications of our findings for PICs, SIDS and for developing countries around the world. This is the first published study of multiple household water sources encompassing multiple countries and the first concerning SIDS.

The main objectives of this paper are to describe: (1) the number and type of household water sources and their uses; (2) changes in the use of these sources between wet and dry seasons; and (3) the implications of these findings for climate resilience, implementation of water supply projects, development goals and other topics.
1.1. Study Area

RMI is an independent nation in a Compact of Free Association with the United States. The population of 53,000 people is spread across 29 coral atolls and over 1,000 islands in the equatorial Pacific. The two parallel island chains, Ratak (meaning Sunrise) and Ralik (meaning Sunset), are part of the island cluster of Micronesia, and are spread across $2 \times 10^6$ km$^2$ of ocean. The Inner Islands of RMI are Majuro, the capital, with a population of 28,000 and Ebeye, a very densely populated urban island home to more than 15,000 people. The remaining population is scattered throughout the more remote Outer Islands in small rural communities, many with traditional lifestyles and very few modern technologies. We studied eight RMI communities (two from inner islands and six from outer islands).

Unlike the low-lying sandy atolls of RMI, SI consists of six major islands with groundwater and river-fed forests and over 900 smaller islands that together form part of the island cluster known as Melanesia. The capital city of Honiara, on the island of Guadalcanal, is home to one tenth of the country’s population with more than 64,000 residents. We studied five SI communities, two on Guadalcanal, and three on Malaita. All were rural; however, those on Malaita are more self-sufficient and have less access to the large markets and shopping centers of Honiara than those on Guadalcanal.

The SI and RMI are vastly different countries presenting contrasting challenges to drinking water provision; SI with plentiful freshwater resources, but high risk of contamination and elevated risk of flooding; and RMI with very limited freshwater resources and very high risk of drought.

2. Materials and Methods

Data for this cross-sectional household survey were collected through in-person interviews (Table 1). All data are self-reported and include respondent recall across seasons. Islands and communities were selected based on: (1) discussions with local stakeholders (government employees, NGO staff and community leaders) who suggested communities that had either been exposed to flood, drought, or cyclone in recent years or, in SI, that had received recent visits from the rural WaSH agency; and (2) the safety and feasibility of reaching the community (e.g., travel to some RMI outer islands required sea voyages of more than 24 h). Surveys were conducted at different times of year based on travel logistics (Table 1). One adult resident of each household was asked to participate in the survey.

For communities of <50 households, we attempted to achieve 100% survey coverage. For larger communities, we used a preset skip pattern, conducting an interview at every x houses, in which x was the total number of households in the community divided by the target number of households in the survey of that community. If no one responded at a home, we proceeded to the next home.
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), the Historic Preservation Office of the Republic of the Marshall Islands (2014-01), and the National Health Research and Ethics Committee of the Solomon Islands (HRC 2014/29).

The survey instrument was based on a questionnaire designed to investigate multiple water sources and uses within households (Whittington, 2000), expanded to include questions relevant to households in remote communities in climate-vulnerable PICs. Due to the complexity of the survey, with 70 skip patterns and seven nested loops of questions for each household water source, the survey was administered using computer assisted personal interviewing (CAPI) with the SurveyCTO app and a Samsung Galaxy Note Tab 3 Lite. The complete survey instrument, its development and the benefits of the CAPI format are described by MacDonald et al. (MacDonald et al., 2016a). The water use option “Share with Neighbors” was added after piloting for the first RMI community; piloting in SI did not indicate a need for this use option. “Share with neighbors” was not included for the first two SI communities and is therefore not included in the country-level data for SI (Table 2).

Survey data were recorded for up to 10 specified household water sources and 8 specified uses for each source; options for “Other” water source and “Other” use were also available. Drinking and cooking were defined as “consumptive” uses and all other uses as “nonconsumptive.” For access and use questions, respondents were asked (1) if their household could access each water source, (2) whether and for which purposes they used that source during the wet season, (3) whether their use of that source differed from wet to dry season, and, if yes to the third question, (4) for which purposes they used the source during the dry season. For each source/use, respondents were asked whether use occurred at home, at the source, or both. Data on reported use of water sources are based on binary use/nonuse. No measure of the extent of use (e.g., volume of water used, handwashing frequency) was included; such data are not amenable to self-reported recall.

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 nonconsumptive uses was analyzed by the Phi Coefficient of Correlation and the chi-square score.

3. Results

In smaller communities (<50 households), household participation was 94–100%. For communities with 60 or more households, we secured survey responses from 20 to 40 households per community (Table 1). Of the more than 400 households approached in this study, less than 10 households had an adult at home but refused to participate.

Water sources were listed in the survey according to the categories in supporting information Table S1 (also see MacDonald et al., 2016a). Supporting information Table S1 also includes descriptions of the water source types in the communities surveyed, how common they were, and whether they would be considered “improved” based on the definition used for monitoring progress toward the MDGs (which corresponds to at least “basic” coverage under the SDGs). Differences in private rainwater storage volume between RMI (typically 800–3,000 L per home) and SI (small pots and pans) noted in supporting information Table S1 have implications for dry season water use (section 4).

3.1. Access Versus Use of Water Sources

Of the 1,026 water sources reported by households as accessible, in 1,014 (98.8%) at least one use was reported by the household. Twelve households (3%) reported having access to a water source that was unused in both the wet and dry season. However, households likely responded “yes” only on sources they used, so this is almost certainly an underestimate. The 12 accessible but unused sources were eliminated from the data set and subsequent analyses.
### Republic of the Marshall Islands

**Table 2**  
Percentage of Households Reporting Use of Water Sources and the Purposes for Which They Use Those Sources, by Season in (a) Republic of the Marshall Islands and (b) the Solomon Islands

#### (a) Republic of the Marshall Islands

<table>
<thead>
<tr>
<th>Water source</th>
<th>Wet season (% of households)</th>
<th>Change from wet to dry season (percentage point change)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>% HHs that use (any time)</td>
<td>Any use</td>
</tr>
<tr>
<td>Rainwater (private)</td>
<td>90.3</td>
<td>90.3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Any</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Cook</td>
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<tr>
<td></td>
<td></td>
<td>Bathe</td>
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<td></td>
<td></td>
<td>Wash</td>
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<td></td>
<td></td>
<td>Clothes</td>
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<tr>
<td></td>
<td></td>
<td>Animals</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Garden</td>
</tr>
<tr>
<td>Public well</td>
<td>67.8</td>
<td>67.8</td>
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<tr>
<td></td>
<td></td>
<td>Any</td>
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<td></td>
<td></td>
<td>Cook</td>
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<td></td>
<td></td>
<td>Bathe</td>
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<td></td>
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<td>Wash</td>
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<td></td>
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<td>Clothes</td>
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<td></td>
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<td>Animals</td>
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<tr>
<td></td>
<td></td>
<td>Garden</td>
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<tr>
<td>Private well</td>
<td>3.4</td>
<td>3.4</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Any</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Cook</td>
</tr>
<tr>
<td>Public standpipe</td>
<td>0.3</td>
<td>0.3</td>
</tr>
<tr>
<td>Bottled water</td>
<td>3.0</td>
<td>3.0</td>
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<tr>
<td></td>
<td></td>
<td>Any</td>
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<td></td>
<td></td>
<td>Cook</td>
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<td></td>
<td></td>
<td>Bathe</td>
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<td></td>
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<td>Wash</td>
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<td></td>
<td></td>
<td>Clothes</td>
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<td></td>
<td></td>
<td>Animals</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Garden</td>
</tr>
<tr>
<td>Piped to home</td>
<td>6.4</td>
<td>6.4</td>
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<tr>
<td></td>
<td></td>
<td>Any</td>
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<td></td>
<td></td>
<td>Cook</td>
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<td></td>
<td></td>
<td>Bathe</td>
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<td>Wash</td>
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<td></td>
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<td>Clothes</td>
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<td></td>
<td></td>
<td>Animals</td>
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<tr>
<td></td>
<td></td>
<td>Garden</td>
</tr>
<tr>
<td>Seawater</td>
<td>35.9</td>
<td>35.9</td>
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<tr>
<td></td>
<td></td>
<td>Any</td>
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<td></td>
<td></td>
<td>Cook</td>
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<td>Animals</td>
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<tr>
<td></td>
<td></td>
<td>Garden</td>
</tr>
</tbody>
</table>

**Note.** Change from wet to dry season is shown as a percentage point change, with negative reflecting a reduction in source use and positive changes reflecting an increase. "Share with Neighbors" was not a response option for two of the five Solomon Islands communities and thus country-level data are not included.  

* \( p < 0.05 \), ** \( p < 0.01 \), *** \( p < 0.001 \).
3.2. Use of Multiple Water Sources

Use of more than one type of water source in one or both seasons was reported by 368 (91%) of households (Figure 1; supporting information Table S1). The mean number of water sources used by each household was 2.3 (SD 0.73) in RMI and 3.1 (SD 0.89) in SI. Only 37 households (9%) reported using only a single water source, all in the RMI (36 reported private rainwater and 1 a private well). The maximum number of sources used was five, reported by nine households, all in the SI. Households using two-to-three sources were most common in both countries, constituting 81% of households surveyed (Figure 1).

The percentages of households using each type of water source at any time during the year are reported in Table 2. The typical RMI household relied on both private rainwater collection and private wells throughout the year, with over one third also using seawater (Table 2, a). In SI, source use was more diverse with nearly all households using local rivers/streams, a majority using public taps and many using natural springs and private and/or shared rainwater collection (Table 2, b).

3.3. Mapping Sources to Uses

There was a clear distinction between sources used for consumptive (drinking and cooking) and those used for nonconsumptive (e.g., bathing, handwashing) purposes; this contrasts with the typical distinction in global monitoring between water sources for drinking and those for other uses (see section 4). Use of a source for cooking was strongly positively correlated with use of that source for drinking (Phi Coefficient = 0.543; p < 0.0001). In contrast, use of a source for cooking was not correlated with nonconsumptive use for animals, bathing, handwashing and gardening (Phi Coefficients −0.012 to −0.058; p > 0.05); it was weakly negatively correlated with use for washing clothes (Phi Coefficient = −0.081; p < 0.05). One notable exception is culturally specific: many outer islands households in the RMI reported cooking with seawater, a traditional practice that adds salty flavor to boiled fish.

There were considerable differences between RMI and SI when mapping household water sources to uses (Table 2). In RMI, 95% of households reported drinking rainwater in the wet season, with less than 10% reporting any other source of wet season drinking water. Rainwater was also the most common source used for cooking, although seawater (34%) and private wells (23%) were also commonly used for cooking in the wet season (Table 2, a). Private rainwater and private well water were used by a majority of households for nonconsumptive uses such as bathing, washing hands, and washing clothes (Table 2, a). Sharing of private water sources was commonly reported in RMI, with 51% sharing their private rainwater and 43% sharing private well water with neighbors at some time during the year.

In SI, the most common wet season drinking water sources included shared rainwater (41%), public standpipes (34%), and private rainwater (22%); these were also the sources used by the most households for cooking (39%, 37%, and 29%, respectively) (Table 2, b). However, a distinction is apparent between consumptive and nonconsumptive usage, with rivers and streams supporting the majority of nonconsumptive uses, along with some water sourced from public standpipes and private rainwater sources.

3.4 Seasonal changes in water sources and uses

Although households in both RMI and SI reported seasonal changes in water use, the nature of these changes varied substantially between countries. In RMI, there was no significant change in the overall water sources used in the wet and dry seasons (Table 2, a, columns “Any Use”). However, there was substantial seasonal change in the purposes for which private rainwater was used (Table 2, a). The number of households using private rainwater for drinking did not change, but those using it for cooking decreased by 20 percentage points (p < 0.001) from wet season to dry season (Table 2, a). For nonconsumptive purposes, there were substantial declines (over 40% points) in households using private rainwater for bathing, handwashing, and washing clothes (p < 0.001 for all) but without a concomitant increase in the reported frequency of use of other sources. Sharing private rainwater was also significantly less common during the dry season (p < 0.001). Overall use of private well water did not increase significantly from wet to dry season.
but use did increase in the dry season for drinking (5.7% points; \( p < 0.001 \)) and cooking (9% points; \( p < 0.001 \)).

In contrast to RMI, SI households reported substantial seasonal changes in both the water sources used and in uses of those sources (Table 2, b). The use of rainwater for any purpose declined substantially from wet to dry season for both private (36% points; \( p < 0.001 \)) and shared (29% points; \( p < 0.001 \)) rainwater, and there was a corresponding increase of 26% points (\( p < 0.001 \)) in households reporting use of river water. Use of private rainwater for any purpose declined from more than 40% to less than 5% of households (\( p < 0.001 \)). The use of small pots and pans to collect private rainwater in SI precludes its storage and use in the dry season (supporting information Table S1). Increases in drinking from public standpipes (\( p < 0.05 \)), private wells (\( p < 0.05 \)) and springs (\( p < 0.01 \)) during the dry season may, therefore, be attributable to the inability to store sufficient volumes of rainwater (Table 2, b). Use of river/stream increased in the dry season for all purposes (\( p < 0.001 \)); for handwashing, bathing and washing clothes the increase in the number of households using river/stream (\( p < 0.001 \) for all) mirrors the decline in the use of private rainwater for those purposes (\( p < 0.001 \) for all).

3.4. Seasonal Changes in Handwashing

Water sources used for handwashing varied substantially between RMI and SI during the wet season (Table 2). In RMI, the most commonly reported sources for handwashing in the wet season were private rainwater (69% of households) and private wells (60%). In SI, river/stream (58%), private rainwater (39%), and public taps (38%) were the most commonly reported sources for handwashing during the wet season. In both countries, there were substantial changes by season (Table 2).

In RMI, the percentage of households using private rainwater for handwashing declined by over 45% points (\( p < 0.001 \)) from wet to dry seasons. At the same time, handwashing using private well water increased only slightly (from 60% to 64%; \( p < 0.05 \)). Furthermore, 50 households (17%) did not report use of any water source for handwashing in the dry season, compared to just 12 (4%) in the wet season (\( p < 0.001 \)).

In SI, households reporting use of rainwater for handwashing (Table 2, b) declined steeply from 39% in the wet season to 4% in the dry season for private rainwater and from 24% to 4% for shared rainwater (both \( p < 0.001 \)). Use of rivers and streams for handwashing purposes increased from 58% (wet season) to 88% (dry season) (\( P < 0.001 \)). Over 62% of households using river/stream water for handwashing in the dry season reported that washing took place exclusively at the source (with 4.7% reporting exclusive use at home and 33% a mix of at source and at home).

4. Discussion

The use of multiple water sources to meet daily household needs is practiced in diverse developing country settings that vary in precipitation patterns, water resources, piped water availability, etc. For example, it has been observed in Southeast Asia (Brown et al., 2013; Evans et al., 2013; Özdemir et al., 2011; Shaheed et al., 2014), Sub-Saharan Africa (Adekalu et al., 2002; Almedom & Odhiambo, 1994; Dos Santos et al., 2015; Evans et al., 2013; Foster & Hope, 2017; Howard et al., 2002; Thompson et al., 2000; Tucker et al., 2014; Vedachalam et al., 2017), North Africa (Devoto et al., 2012), Western Asia (Coulibaly et al., 2014), East Asia (Wang et al., 1989), South Asia (Ahmed & Hossain, 1997; Madanat & Humphlick, 1993), and central America (Smith et al., 2015). This study is the first on multiple sources in SIDS or PICs, the first contrasting practices between countries, one of three to report cross-seasonal differences, and one of the few to provide detailed description or quantification of the practices.

In our RMI and SI study communities, multiple sources of water were available and used for both consumptive and nonconsumptive purposes by over 90% of households (section 3.2). Most RMI households relied on stored rainwater and private wells, with many in the outer islands also engaging in the traditional use of seawater to cook fish. In SI, a greater diversity of water source types was used, with greater than 30% of households reporting use of each of the following: public taps, both private and shared rainwater, natural springs and rivers/streams (Table 2). In both countries, households collected rainwater in private containers. However, storage volume was on average much greater in RMI (typically 800–3,000 L tanks) compared to SI (small pots and pans); this difference in household water infrastructure had substantial implications for water use, as discussed below.
Our data reveal a strong positive correlation between the use of a source for cooking and its use for drinking. Furthermore, use for cooking was either not correlated or negatively correlated with use for nonconsumptive purposes, indicating that the most coherent division in household water use in our study was between consumptive (drinking/cooking) and nonconsumptive use. In contrast, the core global survey questions separate drinking from all other uses and state “hand washing and cooking are a proxy for all other water uses” (WHO/Unicef, 2006). While the emphasis on drinking water is understandable, having sufficient high-quality water for both consumptive and nonconsumptive uses has important implications for health and development outcomes (Howard & Bartram, 2003; WHO, 2011). We propose that further investigation is needed, including mining of existing survey data, to determine whether the consumptive/nonconsumptive correlations in our study area are true in other settings. If so, reconsideration of survey questions and household water management frameworks may be necessary to avoid conflating uncorrelated uses.

Reported water sources and their uses changed substantially between the wet and dry seasons (Table 2), though the nature of these changes was different in the two countries studied. In RMI, there was little change in the types of water sources used in wet and dry seasons, but substantial change in the way the most common water source, private rainwater, was used; drinking, and to a lesser extent cooking, were prioritized in the dry season. This demonstrates important water management practices in RMI: many households ration stored private rainwater in the dry season, saving it for consumption, and switching to another source for nonconsumptive purposes. In contrast, in the SI, overall use shifted strongly from rainwater in the wet season to rivers/streams in the dry season. These differences between countries likely reflect household adaptation to current and anticipated water availability and quality. Storing rainwater to ensure availability for drinking through the dry season is an adaptation that requires large private rainwater tanks, like those common in RMI; this has also been reported in Vietnam, where rainwater storage volume is similar (Özdemir et al., 2011). The potential efficacy of rationing to ensure availability of stored rainwater during not only the dry season but also through severe drought has previously been reported for PIC atolls (Wallace & Bailey, 2015). In contrast, private rainwater collection in SI typically used pots and pans, precluding storage of large volumes to last through the dry season. These differences in the culture of rainwater storage have probably developed based on the reliability of rainfall and lower likelihood of drought in SI, and the presence of other natural sources (springs, rivers, and wells) nearby. There is a corresponding lack of alternatives on RMI atolls, where there is no surface water and fresh groundwater is limited to a thin lens (White & Falkland, 2010). Achieving water security and sustainability is particularly challenging in many SIDS (Belmar et al., 2016); local multiple water source usage appears to have evolved in response to the specific water sustainability challenges faced by these remote communities.

Some of the reported seasonal changes in water source use indicate potential for increased risk of illness in the dry season. Some households appear more willing to consume water from unimproved sources (supporting information Table S1) during the dry season; for example, drinking from unprotected wells was reported to be much more common in both countries during the dry season than in the wet season (Table 2). A recent study documented for the first time that households that report drinking from an improved water source when presented with the standard core drinking water survey question (WHO/Unicef, 2006) will, if asked specifically, concede that they also regularly drink water from an unimproved source in at least one season (Vedachalam et al., 2017). Multiple sources and seasonal changes in usage are potential causes of the lack of reported health impacts in blinded drinking water treatment studies (Clasen et al., 2007). Additionally, there were substantial declines in the number of households using private rainwater for handwashing in both RMI and SI in the dry season and many household reported no handwashing source in the dry season. In RMI, our data suggest that handwashing frequency could decline as availability of stored rainwater declines. The lack of water for handwashing is often cited as a health risk. Tucker and colleagues (Tucker et al., 2014) highlighted how water use for handwashing was reported to “decline perilously” during the dry season in rural Ethiopia. Changes that make handwashing less convenient would almost certainly decreased handwashing (Luby et al., 2009; Drebelbis et al., 2013).

In international development, most “drinking water” projects or programs are undertaken with the implicit, if unstated, goal to provide communities with a single water system (e.g., piped to home) or source (e.g., a central borehole or standpipe) for all household purposes. However, the premise that a new water source must replace all traditional sources may be unrealistic, may exclude affordable and appropriate options, and can increase vulnerability to changing precipitation patterns and climate-related hazards. We contend
that if implementers understand the use of multiple sources in a community, including the relationship between consumptive and nonconsumptive uses, they may be supportive of projects that supplement rather than replace existing water sources. For example, a community with adequate water quantity but poor water quality could benefit from household rainwater storage containers. Ultimately, the combination of water sources and their uses by households also depends on the functionality and service-level provided (Fisher et al., 2015).

In our study communities, the use of multiple household water sources appears to reflect adaptation to local water resources and precipitation patterns. For example, the lack of surface water and limited supply of fresh groundwater in RMI has made rainwater storage essential. RMI communities have a culture of harvesting and conserving rainwater for drinking, and of sharing that water with neighbors for the same purpose. In contrast, our SI communities have historically had ready access to fresh water sources (albeit often of poor quality); this may have reduced the perceived need for longer-term rainwater storage. Research is required to determine whether the introduction of privately owned water storage containers can enable provision of high-quality drinking water throughout the year, including whether seasonal water rationing will emerge in settings where the cultural norm is not already established. Implementers should attempt to identify and prevent adverse unintended consequences of water storage interventions (e.g., rainwater containers left uncovered can increase mosquito-borne disease). Rationing and sharing of private rainwater in RMI illustrate how household-level infrastructure could contribute to community-level resilience to climate change. However, the relative efficacy and equity of private versus public/community water storage infrastructure for contributing to climate resilience is unknown. We propose that implementation of household rainwater tanks should be explored as an option for projects with a primary or supplementary goal of improving resilience to climate change, while acknowledging that outcomes are uncertain and will vary based on local factors. Major questions that require investigation relate to whether (and how) implementers can “import” multiple source usage to new communities and if those communities can accrue the same benefits experienced by communities where multiple source usage developed indigenously.

In wealthy countries, approaches to increase resilience to precipitation variability and climate change comprise professionalization of centralized piped water supply and/or use of deep aquifers less vulnerable to variable precipitation. In the former, municipalities ideally plan for long-term demand and develop multiple reservoirs or connect to other piped systems. Whether centralized or at the household level, access to multiple sources increases resilience to climate change, as long as those sources do not originate from the same underlying resource (Howard et al., 2010). Many SIDS, PICs in particular, are highly vulnerable to climate change. The greatest benefits of multiple water sources for climate change adaptation may be in communities that have developed this approach to address historical precipitation variability. Climate change resilience projects should seek to build upon existing local adaptations to precipitation variability and seasonality.

Integration of multiple sources into country-level household surveys is a tempting solution to fill current knowledge gaps. However, this topic is just emerging as an area of research. Formulating broadly applicable survey questions that yield useful data may not yet be possible as many knowledge gaps remain. Likewise, establishing global indicators and targets and benchmarking success is a process requiring a nuanced understanding and may have unintended consequences, as reported with respect to the water and sanitation MDG and discussed in the buildup to the SDGs (Bair et al., 2014; Bartram et al., 2014; Cumming et al., 2014; Onda et al., 2012). Refining questions, integrating them into surveys and finally receiving data takes many years and data value is from sequential application. It is likely that use of multiple sources will decline over time as potable piped water expands, but that the practice will be of great importance in the populations where it remains. Therefore, broad integration into global surveys is inappropriate. However, as knowledge gaps continue to be addressed, we recommend targeted integration of multiple source questions in communities where the practice is common or may be beneficial.

Monitoring multiple source use could yield a more nuanced understanding of past and future progress in expanding coverage of higher service-level drinking water. While the population receiving piped water at home continues to expand rapidly around the world (WHO & UNICEF, 2015), the investment in and use of multiple sources may affect the eagerness to connect and shift use to piped water. For example, many rural residents of Vietnam were willing to pay for piped water during the dry season, but unwilling to pay the monthly fee during the wet season, when stored rainwater was abundant, possibly due to past investment...
in rainwater storage and preference for the taste of stored rainwater (Özdemir et al., 2011). Use of multiple sources could undermine willingness to pay for piped water, reducing global progress toward water sources that provide higher levels of service.

### 4.1. Limitations

While data on the volume and frequency of water use would be beneficial for determining the potential health implications of multiple source use, these variables are not amenable to self-reporting. All our data were self-reported and relied on recall across seasons. While many households did not report a dry season water source used for handwashing, or only distant source like a river, we can only infer the impact on handwashing frequency and timing. Likewise, though some households reported using private rainwater for nonconsumptive purposes during the dry season, we did not collect data on whether the volume used for these purposes declined over time as the dry season continued and/or as remaining storage volume decreased. Further research is needed to determine the impact of seasonal changes and multiple water sources on handwashing frequency and patterns of water source consumption, both of which affect incidence of diarrheal disease.

The cost and logistical challenges of travel to these remote sites limited us to thirteen communities. While there was potential bias in community selection, most study communities were selected based on factors (e.g., recent flooding; see section 2) that do not clearly correlate to the topic of this paper. Thus, while it would be preferable to include more communities from each country, there is likely no systematic bias with respect to household water practices.

### 5. Conclusions

Our findings have implications for research, monitoring, and projected global progress in drinking water. Water researchers should reflect on whether and how to integrate multiple water sources into data collection efforts, how to assist practitioners in collecting and using these data, and refining methods to generate data for specific parameters (e.g., access versus use, sources versus source types). Advances in CAPI have made this affordable and time-efficient for many surveys (MacDonald et al., 2016a). Research is needed to describe the use of multiple sources in more settings, determine the extent of possible seasonal bias in country-level survey data, and identify potential approaches to correcting survey data for seasonality.

Despite relatively little empirical data examining the practice, the use of multiple sources appears to be both fundamental to household water management in many settings and to have evolved independently in these settings. Furthermore, multiple sources, uses, and seasonal changes are typically ignored in WaSH monitoring, programming, and research. We propose that failure to consider a practice that is so widespread and fundamental could undermine the design and effectiveness of WaSH monitoring, data interpretation, implementation, policy, and research in developing countries.

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