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Survey of Rainwater Catchment Use and Practices on Hawaii Island

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Abstract: The harvesting of rainwater for domestic use on Hawaii Island is widespread, particularly in areas not served by municipal water. Rainwater catchment is currently unregulated in Hawaii with the responsibility of installing and maintaining appropriate systems on owners and users. Well-designed and maintained rainwater catchment systems are more likely to provide water free of pathogens than poorly designed or maintained systems. We conducted outreach to rural Hawaii Island communities on rainwater catchment best practices and explored household uses and practices associated with these systems via survey of 110 individuals. Nearly 90% (N=96) of all survey respondents used harvested rainwater as a potable water source or for bathing, and we estimate only 66% of those systems may reasonably be expected to produce safe drinking water. Reported testing frequency of captured rainwater falls below recommended levels and varies significantly with rainwater use and system adequacy. Outreach was effective in changing perceptions on rainwater catchment as evidenced by individuals' reported beliefs before and after engagement. The majority (N=75) of all survey respondents reported they will change how they maintain their catchment systems, and over 50% (N=61) reported they will change their catchment system elements, as a result of outreach. We conclude there is a demonstrated need for ongoing, professional, evidence-based outreach programs to serve rainwater catchment system users in Hawaii.

Keywords: *Zika virus, dengue virus, rat lungworm disease, rainwater harvesting, Sea Grant*

The Island of Hawaii, the largest and most southerly island in the Hawaiian archipelago, is characterized by diverse communities including rural and remote communities not served by municipal water. These communities rely on private or shared wells, water trucked to cisterns, or rainwater catchment for their water needs. Rainwater catchment is the harvest of falling rain, often shed from rooftops, which can be stored in barrels, tanks, cisterns, ponds, or other repositories for household, agricultural, or commercial use. An ancient practice (Pandey et al. 2003), particularly in arid regions (AbdelKhaleq and Alhaj 2007), rainwater harvesting is used worldwide in rural areas without centralized water systems (Pacey and Cullis 1986), including islands, to augment domestic water supply (Han and Ki 2010; Quigley et al. 2016). Rainwater harvesting has also been identified as a technology that communities across the globe may increasingly rely upon to adapt to climate change (Pandey et al. 2003). With proper design, maintenance, and water treatment, a rainwater catchment system can provide water that is free of contamination, soft, clear, odorless, and suitable for drinking and other daily needs (Cunliffe 1998; Macomber 2010). However, improperly designed or maintained rainwater catchment systems may pose a health risk, for example via the introduction of waterborne illness that can be exacerbated in persons with compromised immunity (Pathak and Heijnen 2005; Ahmed et al. 2011).

Up to 60,000 people in the state of Hawaii were estimated to be dependent on rainwater catchment as their primary domestic water source in 2010, with the majority of obligate rainwater catchment users residing on the Island of Hawaii (Macomber 2010). Hawaii Island's population increased

25% between 2000 and 2010, with the greatest increases in districts heavily dependent upon private rainwater catchment systems to supply their daily water needs (Western Rural Development Center 2010; Department of Business, Economic Development and Tourism 2012). The availability of municipal water service has not increased commensurately with the increase in population size over this period (Department of Water Supply, County of Hawaii 2010).

Waterborne and vector-borne illness may be transmitted to users from rainwater catchment systems that lack appropriate system elements and maintenance or from insufficient treatment of stored water (Koplan et al. 1978; Lye 1987; Yaziz et al. 1989; Crabtree et al. 1996; Pathak and Heijnen 2005; Ahmed et al. 2011). For example, rainwater catchment tanks lacking covers or with damaged or poorly sealed covers can provide breeding opportunities for mosquitos known to be disease vectors. During the 2015-2016 dengue virus outbreak on Hawaii Island, which sickened hundreds, The Hawaii State Department of Health identified "uncovered catchment systems…" as a potential source for dengue virus infected mosquitos (Hawaii State Department of Health 2016) and suggested "…essential actions to control mosquito breeding in rainwater catchment systems" (Hawaii State Department of Health 2015). Other vector-borne diseases transmitted by mosquitos, such as the globally emerging Zika virus, are of concern in areas where mosquitos may breed, including mosquito-accessible rainwater catchment systems. Microbial contamination of roof-harvested rainwater that is insufficiently disinfected may also pose a health risk due to bacterial or protozoal pathogens, the latter including *Giardia spp.* and *Cryptosporidium spp*. (Crabtree et al. 1996; Fewtrell and Kay 2007; Ahmed et al. 2010). Additionally, an invasive semi-slug found in Hawaii, *Parmarion cf. martensi*, which has a propensity to climb up and into water tanks, is a host of the parasitic nematode responsible for infecting humans with rat lungworm disease (Hollingsworth et al. 2007).

Rainwater harvesting is not regulated by the federal government in the United States; it is up to individual states to regulate the collection and use of rainwater (Loper 2015). Rainwater catchment systems on individual homes serving less than 20 individuals are not regulated by the Hawaii State Department of Health. Consequently, it is important for owners and end-users of these systems to understand how to use rainwater catchment systems in a safe and appropriate manner. It is therefore critical that stakeholders who harvest rainwater in Hawaii understand the associated potential negative impacts on human health and employ best practices to mitigate these impacts. Development and delivery of effective outreach on rainwater catchment, in Hawaii and worldwide, will be increasingly needed as reliance on these systems increases due to climate change (Pandey et al. 2003). Here, we share information on a professional outreach project that aimed to: educate and empower rural Hawaii Island communities reliant on rainwater catchment to make informed decisions related to their catchment practices; and better understand rainwater catchment use and practices on Hawaii Island to inform future outreach needs.

Methods

In March and August 2015, we conducted 11 rainwater catchment workshops on Hawaii Island. Workshops were conducted in six of the nine island county council districts in the following census designated places: Ocean View, Naalehu, Volcano, Pahoa, Keeau, Hilo, Honokaa, Kealakekua, and Kona, encompassing a wide geographic area. Workshops were scheduled for 2.5 hours in length in the early evening weekdays or Saturday mornings to facilitate public attendance. Workshops were conducted in venues selected to be of convenience to community members such as community centers, civic centers, public schools, and county government buildings. Workshop components were developed to provide and deliver evidence-based outreach on rainwater catchment in multiple modalities and included an oral presentation accompanied by projected visual content. Written material was also made available to participants at no charge in the form of seven unique thematic "Rainwater Catchment Solutions" brochures (College of Tropical Agriculture & Human Resources, CTAHR 2009) and the 51-page publication, "Guidelines on Rainwater

Catchment Systems for Hawai'i" (Macomber 2010). Workshop participation was free of charge and complimentary PathoScreen™ using the WhirlPak® Fecal Bacteria Water Test Kits were distributed at the end of workshops to increase awareness of and facilitate testing of rainwater catchment system water. Learning outcomes were also identified to evaluate outreach effectiveness as follows. Upon completion of a workshop, participants are able to: indicate the need for testing water in a catchment system; identify what to test for, and how and when, to test water in a catchment system; and recall what rat lungworm disease is and how it is transmitted.

We invited participants to complete a one-page, voluntary paper survey at the conclusion of the workshops addressing rainwater catchment systems, maintenance practices, and water use. Workshop participation and provision of published outreach materials were not tied to survey participation. Participants were instructed that they could elect not to participate in the survey and were free to decline to answer one or more survey questions. No individually identifying information was collected or maintained with survey responses and selected survey data presented here are in aggregate. Participants were informed that the survey was intended to gain insight on future outreach that might benefit communities in the state of Hawaii. A survey response rate was calculated by dividing the total number of completed surveys by the total number of workshop attendees and multiplied by 100. As survey participants were allowed to skip questions, we considered a survey complete if it was actively handed in at the completion of a workshop with one or more questions answered. To further explore nonresponse bias, item nonresponse rate at the question level was also calculated. Item nonresponse rate was calculated by dividing the total number of blank responses per question by the total number of surveys handed in and multiplied by 100.

The survey included specific questions on the uses of captured rainwater, rainwater catchment system components and treatments, and the frequency of testing of captured rainwater. The survey was not developed to explore specific water tests employed by workshop participants, but to gain insight on the perceptions of rainwater catchment system owners and users regarding water testing in general. While more detailed information on water testing is desirable, survey length and content were crafted to optimize participation and response rate. The survey also included a retrospective pretest section that specifically addressed the learning outcomes described above.

The survey retrospective pretest section, also known as a "post then pre" design (Rockwell and Kohn 1989; Davis 2003), allowed us to investigate participants' perceptions of their rainwater catchment knowledge after (post) and before (pre) workshops using a single survey per participant at the end the workshop. Post then pre survey design asks participants to reflect upon their pre workshop knowledge after they have reported their post workshop knowledge. A post then pre design is appropriate when seeking to reduce the burden on participants of taking two surveys, when time with participants is limited, and to reduce response shift bias (Rockwell and Kohn 1989; Davis 2003; Hill and Betz 2005). The post then pre section documented the change in participants' beliefs after participation in the workshop regarding the specific learning outcomes described above. This section also included two questions aimed at detecting future changes in behavior as result of workshop participation for which a pre response was not requested. This section of the survey is included in Table 4.

To quantify changes in perception before and after workshop outreach, responses to the post then pre survey section were scored numerically: a negative one (-1) for each *Disagree* answer, a zero (0) for each *Don't Know* answer, and a positive one (+1) for each *Agree* answer. For each participant response, the change in score was calculated (Δ score = post score - pre score). The possible range of change in score values per question was -2 to +2; the larger the number, the greater perceived knowledge gain. For example, if a respondent checked *Disagree* (-1) for a statement pre workshop and *Agree* (+1) for the same statement post workshop, the change in score is +2, the greatest possible gain in perceived knowledge. The average change in score for each question for all respondents pooled was calculated to provide a quantitative measure of perceived knowledge change for the learning outcome addressed by each question. The change in score values also provided an indirect measure of outreach effectiveness.

To qualitatively estimate the potential adequacy of rainwater catchment systems currently in use by survey participants, we evaluated the system components and treatments reported by each participant. We defined potential adequacy as any combination of system elements and treatments in place that might reasonably be expected to provide safe potable water, inclusive of the removal of disease causing organisms, as described by Macomber (2010). For a system to be deemed potentially adequate we required, at minimum, either 1) an ultraviolet (UV) light disinfectant component coupled with fine physical filtration or 2) the use of chlorine as a disinfectant coupled with fine physical filtration. Estimates of potential adequacy did not include parameters of system maintenance that can affect water quality, such as frequency or level of chlorine treatment or routine cleaning of UV bulbs, nor did it factor in the presence or absence of a water tank cover. Thus, potential adequacy *is not* an estimate of active systems that have been confirmed to be producing a safe water supply; rather it reflects an estimation of systems that have the potential to do so with appropriate maintenance, assuming respondents' systems were representative of existing systems on Hawaii Island.

Statistical analysis was conducted where noted in the text when sample sizes and assumptions allowed using Fisher's exact test.

Results

Rainwater Catchment Water Uses

Of a total of one hundred thirty-eight (N=138) workshop participants, 110 participants completed surveys for a survey response rate of 80%. One hundred eight (N=108) of the 110 respondents provided information on their uses of rainwater catchment water in response to the survey question: "What do you use your rainwater catchment system water for?" (Table 1). The nonresponse rate for this question was 1.8%; two survey participants declined to answer this question. Nearly one-half (48%; N=52) of those providing information on uses of their rainwater catchment system used harvested water as a potable source. Eighty-nine percent (N=96) of survey respondents answering this question reported using rainwater catchment for drinking water *or* bathing water. Other uses of rainwater catchment that were identified by a majority of participants were agriculture and gardening, and other household uses. Just over 40% of those answering this question used harvested rainwater for pets or livestock. All survey responses identifying uses of rainwater catchment are presented in Table 1.

Table 1. Reported uses of rainwater catchment water on Hawaii Island in 2015. The number of survey responses and percent of survey respondents by use in response to the rainwater catchment survey question, "What do you use your rainwater catchment system water for?"

Reported use of rainwater catchment water	# Survey responses	% Survey respondents
Drinking water	52	48
Bathing water	92	85
Other household supply	92	85
Irrigation/gardening	81	75
Pets or livestock	45	42
Other	10	9
I do not have a catchment system	11	10

Please note individual respondents (N=108) could identify multiple uses. Percent of survey respondents' values do not include those who declined to respond to this question.

Rainwater Catchment System Components or Treatments

Of persons participating in the survey that owned or used a rainwater catchment system and provided a response to the survey question: "Do you have and/or use any of the following with your rainwater catchment system?" (N=89), the most common components or treatments used were: fine filtration (61%), chlorine bleach (52%), tank covers (52%), and UV light "filter" (49%) (Table 2). Rainwater catchment tank covers were not reported to be in widespread use, with just over one-half of those surveyed (52%) indicating they used a cover on their water tanks. Of those reporting use of a tank cover, most used a soft rather than hard cover (38 of 46). The nonresponse rate for this question was 19% inclusive of 11 survey participants who indicated they did not have a rainwater catchment system; if these 11 records are excluded, the nonresponse rate for this question was 9%. All survey responses identifying rainwater catchment system components and treatments are provided in Table 2.

Of all respondents who owned or used a rainwater catchment system (N=99), we estimate 66% (N=65) had rainwater catchment systems in place and used treatments that were potentially adequate, i.e. could reasonably be expected to result in safe potable water with appropriate maintenance. The 66% estimate of potentially adequate systems includes ten systems reported in use for which no data on components or treatments were provided; these ten systems were not considered potentially adequate in calculations.

Rainwater Catchment System Water Testing

Overall, 56% (54 of 96) of those providing information on their rainwater catchment testing

Table 2. Reported rainwater catchment system components and treatments on Hawaii Island in 2015. The number of survey responses and percent of survey respondents by component or treatment in response to the rainwater catchment survey question, "Do you have and/or use any of the following with your rainwater catchment system?"

Reported rainwater catchment system components and treatments	# Survey responses	% Survey respondents
Ceramic filter	2	2
Ultraviolet (UV) light filter	44	49
Chlorine bleach	46	52
Activated carbon	32	36
Reverse osmosis	5	6
Distillation	0	0
Boiling water	7	8
Solar disinfection	0	0
Hard tank cover	8	9
Soft tank cover	38	43
Sediment (coarse) filters	33	37
Ozonation	1	1
Fine filters	54	61
Other	4	4

Please note individual respondents (N=89) could identify multiple components or treatments. Percent of survey respondents' values do not include those who declined to respond to this question.

frequency in response to the survey question "Please indicate if and/or when you last tested the water in your rainwater catchment system" reported never testing the water in their rainwater catchment system (N=43) or did not know or remember when they had last tested the water in their catchment system (N=11). Forty-four percent (42 of 96) reported some history of testing the water in their catchment system. One-third of those responding to this question reported they had tested their captured rainwater within the last year and an additional 10% reported testing harvested rainwater over one year ago. The nonresponse rate for this question was 13% inclusive of 11 survey participants who indicated they did not have a rainwater catchment system; if these 11 records are excluded, the nonresponse rate for this question was 3%. All survey responses on rainwater catchment system water testing frequency are provided in Table 3.

Of the subset of survey respondents that used rainwater catchment for drinking water or bathing water (N=96), over one-half (53%, N=51) had never tested the water in their system or did not know/remember if or when they had last tested their catchment water and 44% had some testing history (N=42) (Figure 1A). However, those who drank their rainwater catchment water were significantly more likely to have tested their water within six months as compared to non-drinkers and this was also significant for testing within the last year ($p < 0.005$ for both, Fisher's exact test). Those who drank or bathed in their rainwater catchment water were also significantly more likely to have tested their water within six months as compared to non-drinkers or bathers and this was also significant for testing within the last year ($p < 0.05$ for both, Fisher's exact test).

Those with rainwater catchment systems qualitatively characterized as potentially adequate, i.e. systems reasonably expected to result in safe potable water as a result of appropriate components and treatments, were also significantly more likely to have tested their water within six months as compared to those with potentially inadequate systems (this was also significant for testing within the last year, $p < 0.05$ for both, Fisher's exact test) (Figure 1B).

Insufficient sample sizes prevented statistical analysis of variation in rainwater catchment parameters with geographic (workshop community) location.

Learning Outcomes and Outreach Efficacy

Survey participants' perceptions on rainwater catchment and associated learning outcomes after (post) as well as before (pre) workshop participation are summarized in Table 4. Across all learning outcomes there is a trend toward agreement with the survey question statements from pre to post workshop. The greatest area of

Table 3. Reported rainwater catchment water testing frequency on Hawaii Island in 2015. The number of survey responses and percent of survey respondents by frequency in response to the rainwater catchment survey question, "Please indicate if and/or when you last tested the water in your rainwater catchment system."

Reported rainwater catchment system water testing frequency	# Survey responses	% Survey respondents
Never	43	45
Last 6 months	24	25
6 months to 1 year ago	8	8
Over 1 year ago	10	10
Don't know/remember	11	11
Total	96	99

Please note that the number of individuals responding to this question was ninety-six (N=96). Percent of survey respondents' values do not include those who declined to respond to this question and are rounded to the nearest integer.

perceived knowledge pre workshop related to the statement, “Water in a rainwater catchment system should be tested regularly” with 65% of those answering this survey question agreeing with this statement; post workshop agreement rose to 98%.

With regard to the survey statements, “I know *what* to test for in my catchment system;” “I know *how* to test the water in my catchment system;” and “I know *when* to test the water in my catchment system,” 73%, 75%, and 80%, respectively, of those responding to these statements pre workshop answered either *Disagree* or *Don’t Know.* Post workshop, the percentage of those responding *Disagree* or *Don’t Know* to these statements

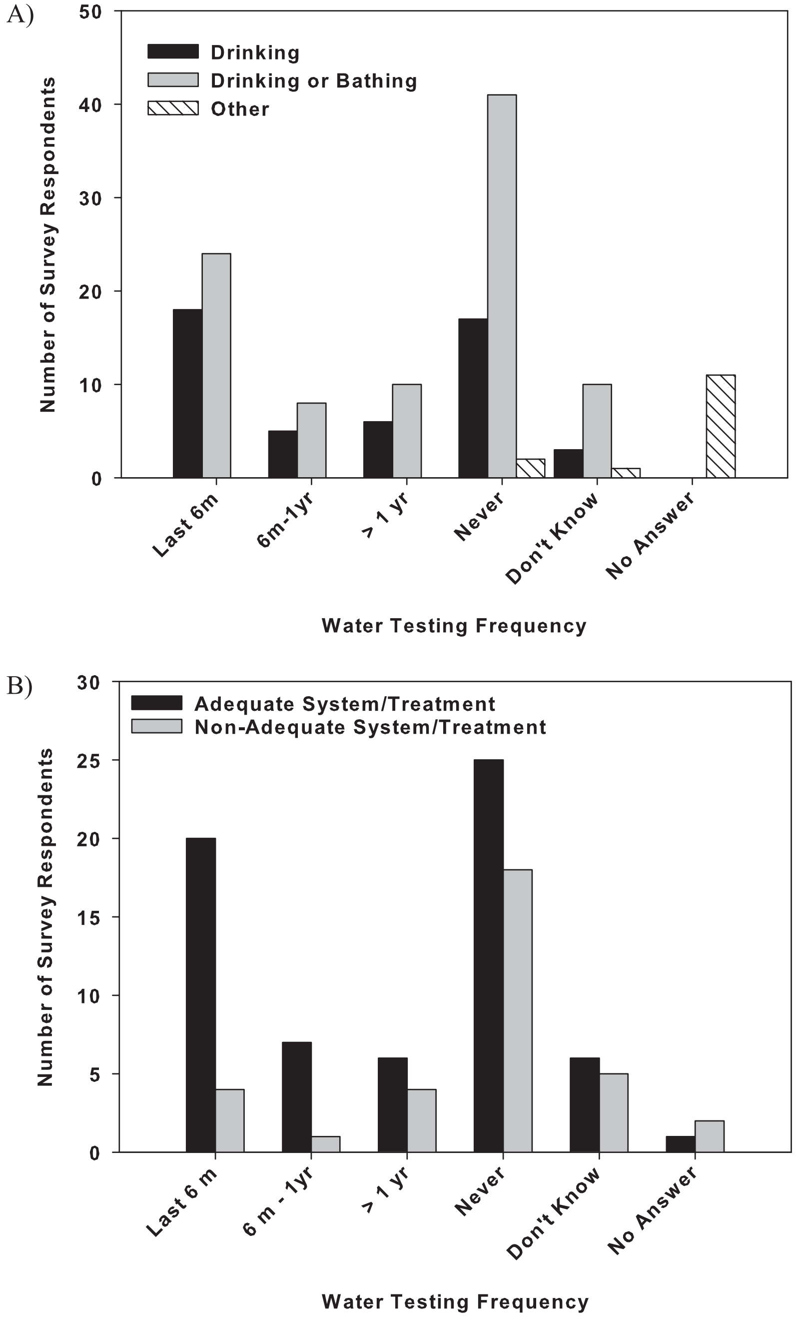

Figure 1. Rainwater catchment water testing frequency, Hawaii Island, 2015 by A) use of rainwater catchment water, and B) potential adequacy of rainwater catchment system components or treatments reasonably expected to result in safe potable water.

decreased to 8% (I know *what* to test for in my catchment system), 2% (I know *how* to test to test the water in my catchment system), and 12% (I know *when* to test the water in my catchment system). Before workshop participation, 46% of those answering the survey question statement, "I know what rat lungworm disease is and how it is transmitted" agreed with this statement; post workshop this value increased to 91%.

After workshop participation, 67% (N = 61) of the 91 participants who provided an answer to the survey question, "I will change my catchment system elements as a result of this workshop" *Agreed* with the foregoing statement. With regard to the statement, "I will change how I maintain my catchment system as a result of this workshop," 81% (N = 93) of participants who provided an answer to this survey question *Agreed* with this statement.

When perceived knowledge gains are quantified via numerical scoring of responses, the greatest perceived gains in knowledge were in understanding *when* to test the water in a rainwater catchment system, followed by *what* to test for in a catchment system, followed by *how* to test the water in a rainwater catchment system (Table 5). A positive

Table 4. Perceptions of participants before and after attending a public workshop on rainwater catchment best practices on Hawaii Island in 2015 from a retrospective pretest survey. This table provides survey questions in the retrospective pretest, associated learning outcomes, question sample size (N), question nonresponse rate, and number of responses by category (Disagree, Don't Know, or Agree).

Survey Question (*Learning Outcome)	**N**	**Question Nonresponse Rate (%)**	**Before Workshop (Pre)**			**After Workshop (Post)**		
			Disagree	**Don't Know**	**Agree**	**Disagree**	**Don't Know**	**Agree**
Water in a rainwater catchment system should be tested regularly.*	99	10	4	31	64	0	2	97
I know *what* to test for in my catchment system.*	98	11	13	59	26	0	8	90
I know *how* to test the water in my catchment system.*	99	10	13	61	25	0	2	87
I know *when* to test the water in my catchment system.*	98	11	16	62	20	1	11	86
I understand what Rat Lungworm disease is and how it is transmitted.*	97	12	11	41	45	1	8	88
I will change my catchment system elements as a result of this workshop.	91	17	N/A†	N/A†	N/A†	8	22	61
I will change how I maintain my catchment system as a result of this workshop.	93	15	N/A†	N/A†	N/A†	6	12	75

†These two survey questions did not include a *Before Workshop (Pre)* component for respondents to answer.

perceived gain in knowledge was also achieved in an increased understanding of what rat lungworm disease is and how it is transmitted. Pre workshop, the majority of survey respondents (65%) already agreed with the statement, "Water in a rainwater catchment system should be tested regularly," and the smallest realized gain in perceived knowledge was in this area (Table 5).

Discussion

Rainwater Catchment Water Uses

Though residential rainwater catchment is assumed to be an important water source for those in areas not served by municipal water on Hawaii Island, to our knowledge this is the first published information on the private use of captured rainwater in Hawaii. Our results support the conclusion that a majority of rainwater catchment users on Hawaii Island rely on their harvested water for uses that may, absent appropriate rainwater catchment system components and practices, expose them to health concerns related to water quality. Not surprisingly, uses of particular concern are drinking and bathing. That nearly one-half of those providing information report using their harvested rainwater as a potable water source illustrates application of best practices in the capture and treatment of stored water cannot be over-emphasized. Of additional concern is the majority use of harvested rainwater as bathing water. Bathing is a potential route of exposure to waterborne pathogens, even absent intentional ingestion of bathing water. Incidental ingestion, for example via the mouth or nose during bathing, could result in exposure to insufficiently disinfected rainwater catchment water.

The question nonresponse rate for information on uses of rainwater catchment was the lowest in our survey at 1.8%, suggesting minimal item nonresponse bias on this topic. Our overall survey response rate of 80% is high, increasing confidence in our results. Our calculation of survey response rate did not factor number of questions answered in determining a completed survey (as respondents were allowed to skip questions), complicating comparisons to survey response rates that include such a factor. For comparison, if we define a completed survey as one on which 80% of questions are answered in our calculation of response rate, our survey response rate is 61%, potentially increasing survey nonresponse bias.

Worldwide, in areas that lack municipal water

Table 5. Quantified perceptions of participants before and after attending a public workshop on rainwater catchment best practices on Hawaii Island in 2015 from a retrospective pretest survey. Responses were assigned numerical scores: a negative one (-1) for each *Disagree* answer, a zero (0) for each *Don't Know* answer, and a positive one (+1) for each *Agree* answer. For each respondent who answered both before (pre) and after (post) for a given question, a change in score was calculated (Δ score = post score - pre score). The mean for all scores per question for all respondents pooled was calculated to provide quantitative insight on perceived knowledge gained and evaluate learning outcomes. This table provides survey questions in the retrospective pretest/learning outcomes, question sample size (N), mean score pre outreach, mean score post outreach, and mean Δ score.

Survey Question (Learning outcome)	N	Mean Score Before (pre)	Mean Score After (post)	Mean Score Δ
Water in a rainwater catchment system should be tested regularly.	99	0.61	0.98	+0.37
I know *what* to test for in my catchment system.	98	0.14	0.92	+0.78
I know *how* to test the water in my catchment system.	99	0.12	0.88	+0.76
I know *when* to test the water in my catchment system.	98	0.04	0.87	+0.83
I understand what Rat Lungworm disease is and how it is transmitted.	97	0.35	0.90	+0.55

but are developed for residential or agricultural use, reliance on rainwater harvesting is likely to increase. Climate change has also been proposed as a worldwide driver of increased use of rainwater harvesting (Pandey et al. 2003). In some areas, alternative sources of freshwater do not exist or are financially out of reach to individuals. For example, water well drilling is relatively expensive if wells must be drilled through rocky substrate, such as oceanic island volcanic rock. Even where municipal water is available, establishing a water line connection and meter may be prohibitively expensive, as may be trucking in fresh water. Thus, many households are financially or functionally obligate rainwater catchment system users. Given the documented uses of captured rainwater for diverse household needs, including potable water, rainwater catchment system elements, maintenance, and associated water treatment practices may directly impact human health in rural Hawaii Island communities and elsewhere.

Rainwater Catchment System Components or Treatments

A wide range of rainwater catchment system components and treatments are in use on Hawaii Island with varying expected efficacy with regard to providing a safe and reliable water supply. The frequency of use by survey respondents of fine filtration (61%), chlorine bleach (52%), and a UV light component (49%) in the treatment of stored rainwater is encouraging, as these components, when used in proper combination and maintained appropriately, can increase the likelihood of a safe and sustainable water supply. However, to maximize the probability of achieving a safe, reliable water supply, such components and treatments must be employed according to the best available science. For example, the concentration and frequency with which stored water is treated with chlorine affects the reliability of disinfection, but also alters the taste and odor of water complicating treatment (Flanagan et al. 2013). Further, chlorine alone is not adequate to produce safe drinking water due to its limited efficacy on *Giardia spp.* or *Cryptosporidium Spp.* cysts (Korich et al. 1990; McAnulty 1994). Ultraviolet light treatment and appropriate filtration, when combined, have been demonstrated to effectively remove pathogens from water when used and maintained correctly (National Sanitation Foundation 2016). However, UV light component users may be unaware that glass-like quartz UV bulb sleeves must be routinely cleaned to allow light to penetrate and effectively disinfect the passing water stream and that the turbidity of treated water can impact effectiveness (Macomber 2010 provides a summary of water treatment systems). Additionally, some UV light component users are unaware that a UV light filtration unit must run continuously, rather than intermittently with water demand, to ensure a safe water supply (Macomber, unpublished data). Professional outreach is needed to assist rainwater catchment system users in establishing and maintaining systems that increase the probability of generating a safe and sustainable water supply.

The lack of use of rainwater catchment water tank covers by about one-half of those surveyed identifies an area of opportunity with regard to improving the quality of stored rainwater, i.e. through increased tank cover use. The predominant use of soft rather than hard covers likely reflects economic drivers inclusive of the ability to fashion soft covers for standard as well as non-standard (e.g. above-ground swimming pool) water tanks. While soft tank covers are generally less expensive and can be adapted to fit a wide range of tank types, achieving a consistent seal between the tank rim and cover can be challenging. In addition to the utility of tank covers in reducing detritus entering stored water supplies, uncovered rainwater catchment tanks, or those with compromised or poorly fitting covers, may play a significant role in the establishment and propagation of mosquito-borne disease. Rainwater catchment tanks on Hawaii Island were directly implicated in a dengue virus outbreak in 2015-2016 and the control of mosquito breeding in such tanks identified as essential by the Hawaii State Department of Health (2015; 2016). While at press time, the U.S. Centers for Disease Control and Prevention (CDC) have reported no locally acquired cases of the Zika virus in the State of Hawaii (CDC 2016a), the mosquito species that transmit dengue fever, *Aedes aegypti* and *Aedes albopictus*, are the same as those that transmit the Zika virus (CDC 2016b). Local mosquito-borne Zika transmission has occurred in the U.S. Territories of Puerto Rico and the U.S.

Virgin Islands (CDC 2016a), areas where rainwater harvesting is common. Rainwater catchment tanks accessible to other animals may also pose a human health risk via microbial contamination of water via feces, urine, or when animals enter and die inside water tanks (Macomber 2010).

The parasitic nematode that causes angiostrongyliasis, commonly known as rat lungworm disease (Chen 1935), is also of concern to rainwater catchment system users. A species of invasive semi-slug now established in Hawaii is a known intermediate host of rat lungworm disease and has been proposed as a vector for rat lungworm transmission to humans (Hollingsworth et al. 2007). This species of semi-slug, *P. martensi,* has been observed in and near water tanks (Hollingsworth et al. 2007). Increasing the use of properly fitted tank covers on rainwater harvesting tanks is a straightforward action that has the potential to reduce community exposure to waterborne and vector-borne diseases in Hawaii and other areas where rainwater catchment is used.

Our evaluation of rainwater catchment systems indicates that while the majority of systems reported (66%) may potentially be expected to result in a safe water supply *assuming they are maintained according to recognized best practices,* over one-third (34%) of systems are of questionable efficacy and safety. Almost certainly, not all systems are maintained in an optimized fashion and thus our estimate of adequacy is liberal. Estimates of adequacy neither account for the use or non-use of rainwater catchment tank covers, nor the condition or application of tank covers in use, increasing the potential error of these estimates. The 9% question nonresponse rate for information on rainwater system components and treatments for those who have or use rainwater catchment suggests some sensitivity to this topic by respondents. Further, workshop attendance may reflect a non-random sample of rainwater catchment system owners and users. Attendance may favor those of sufficient socio-economic means to attend and those for whom cultural norms allow for broad gender and age-class participation in such forums. Additionally, attendance may be positively biased toward those who speak or understand the English language used to deliver workshops and on surveys. Nearly one in five (19%) Hawaii County residents speak a language other than English at home and of these 60% speak a Pacific Island language (Department of Business, Economic Development and Tourism 2015). Acknowledging the unknown quantification of identified and unidentified biases and associated ramifications, we present these outcomes as a “best case scenario” with the actual percentage of rainwater catchment systems that may pose a human health risk likely greater than the 34% estimated.

Rainwater Catchment System Water Testing

The quality of harvested rainwater may vary considerably with capture circumstances and location, system components, physical or chemical water treatments, tank/cistern composition and condition, pathogen exposure, and other variables. Testing of captured and stored rainwater can provide information on water quality and potential risks to human health while informing appropriate treatments. Though water testing was reported by less than 50% of respondents, before outreach most (67%) agreed with the statement, “Water in a rainwater catchment system should be tested regularly.” Thus, workshop attendance was likely stimulated in part by a general knowledge that harvested rainwater should be tested coupled with a lack of specific knowledge on the “what,” “how,” and “when” of appropriate water testing.

Harvested rainwater testing frequency reported here falls well below recommended levels. Optimal water testing frequency is dependent on individual circumstances, such as storage tank condition, suspected contamination, increased water turbidity or changes in water color or taste, frequency of disinfection, presence of lead pipes, and on Hawaii Island, acid rain due to volcanic emissions, among other variables (Macomber 2010). On Hawaii Island periodic testing of harvested rainwater is recommended at six month intervals or whenever there is a change in a system or system’s water such as: a change in water odor or color; after installation of a new treatment system; or after decontamination or other treatments of an existing system (Macomber, personal communication). Specific water quality tests that may be appropriate for rainwater catchment systems are detailed in Macomber (2010); increased use of the appropriate water quality tests for individual concerns and circumstances would likely increase access to safe drinking water in rural Hawaii Island communities.

Though reported water testing frequency reported here does not meet recommended levels overall, our results suggest those who rely on harvested rainwater for potable or bathing needs have a higher frequency of water testing. Therefore, those who use their harvested rainwater in ways that may pose a relatively greater health risk may also have a greater awareness of these risks and increased commitment to water quality testing. That those with rainwater catchment systems characterized as potentially adequate had also tested their water more recently than those with potentially inadequate systems may reflect socioeconomic status. The low question nonresponse rate of 3% for information on water testing frequency supports these conclusions, though biases associated with workshop attendance remain undefined. Regardless, those in communities who may be most vulnerable or underserved may also be at greater health risk as a result of compromised water quality from inadequate rainwater catchment systems and insufficient water testing.

Learning Outcomes and Outreach Efficacy

Professional community outreach was effective in changing perceptions on rainwater catchment practices in rural Hawaii Island communities. Outreach efficacy is further supported by the majority of respondents reporting they would change their behavior related to rainwater catchment system practices, components, and treatments as a result of workshop outreach.

Achievement of learning outcomes is indirectly evidenced via the positive trend in mean numerical scores on the post then pre survey section (Table 5). The positive shift calculated for all responses indicates gains in perceived knowledge for all learning outcomes. Comparing changes in scores for the various learning outcomes reveals most respondents understood they should test the water in a rainwater catchment system, but did not have the knowledge base to do so prior to outreach engagement. Question nonresponse rates for the post then pre survey section were the highest in our survey, ranging from 10% to 17% (Table 4). Higher nonresponse rates may reflect sensitivity to question content, added complexity of the post then pre survey section, or other factors that may introduce bias. Nonetheless, community outreach on specific aspects of harvested rainwater testing is clearly a service area that could be fruitfully expanded on Hawaii Island and other rural areas that rely upon rainwater catchment.

A positive perceived gain in knowledge was also associated with the learning outcome associated with rat lungworm disease. Given the complex etiology of this disease, this positive gain is noteworthy and demonstrates outreach effectiveness. Similar outreach is likely to be critical in responding to emerging diseases in the state of Hawaii including those historically (e.g. dengue virus), and potentially (e.g. Zika virus) associated with rainwater catchment. Given that the design, maintenance, and water treatment of systems harvesting rainwater directly determine the quality of water available for use, the adoption of best practices by owners and users will increase access to safe and sustainable drinking water in Hawaii Island communities.

Conclusions/Findings

- Rainwater catchment is relied upon in rural Hawaii Island communities for potable or bathing water.
- Less than one-half of rainwater catchment system users reported testing captured rainwater regularly and about 66% are estimated to have rainwater catchment systems that may reasonably be expected to produce safe drinking water.
- Reported testing frequency of captured and stored rainwater falls below recommended levels and varies significantly with the use of captured rainwater and system adequacy.
- Community outreach was effective in changing perceptions regarding rainwater catchment practices in rural Hawaii Island communities.
- There is a demonstrated need for ongoing, professional, evidence-based outreach to serve rainwater catchment system users in Hawaii.
- Research aimed at identifying and understanding the barriers to achieving well-designed and maintained residential rainwater catchment systems on Hawaii Island is recommended.

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