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Water Resources and Reuse for Remote Arctic Communities

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Water Resources and Reuse for Remote Arctic Communities

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Water Resources and Reuse for Remote Arctic Communities

written by Kaitlin Jean Mattos

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Dr. Karl Linden

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Date_____

The final copy of this thesis has been examined by the signatories, and we

find that both the content and the form meet acceptable presentation standards

of scholarly work in the above-mentioned discipline.

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Abstract

Mattos, Kaitlin Jean (M.S., Environmental Engineering)

Water Resources and Reuse for Remote Arctic Communities

Thesis directed by Professor Karl G. Linden

Access to safe water and effective sanitation is an issue of major concern in developing communities. While most of the international focus on water, sanitation and hygiene is on improving water *quality* in communities that don't have access to clean water resources, the challenge in rural cold climate communities is making sure a sufficient *quantity* of water is available to households for drinking and washing. Traditional piped utilities and pump-and-haul systems are expensive and difficult to build, operate and maintain in rural cold climate communities. Instead, unserved communities self-haul water to their homes and drastically reduce the volume of water that they use each day for drinking, washing and cleaning. The decreased quantity of water used in unserved communities has been linked to increased rates of skin, respiratory and gastrointestinal infections.

This research evaluates two alternative water resources that could increase the quantity of water available for hygiene purposes in rural Alaska: rainwater catchment systems and a household greywater reuse system. Rainwater samples were collected and analyzed from 48 catchment tanks in nine villages. Overall, rainwater quality was very high and met US EPA drinking water standards in >80% of cases without any treatment required. Depending on the weather patterns in the village, rainwater use could be increased to account for 13-40% of annual household water use if proper infrastructure is used and best management practices are followed.

A pilot household greywater reuse system was built and operated daily for nine months in Alaska to determine whether water can be produced onsite that is safe for human contact. Sixty gallons of water were produced per day under normal and stress conditions, meeting state and federal water quality standards. Wash water had low TOC (total organic carbon), turbidity and conductivity, normal pH, and high UV transmittance. The treatment process provided at least 18-$\log_{10}$ reduction of viruses and >8-$\log_{10}$ bacteria. While the treatment system produced sufficient wash water to protect health, the concentrated wastes produced by the system could pose a threat to the household if proper waste disposal methods are not facilitated along with installation of the reuse systems.

Dedication

To everyone who helped put a roof over my head during this process. Moving is hard, but you all made it much easier. If I can't ever pay you back, I hope I can pay it forward.

Acknowledgements

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Chapter 1: Water, sanitation and hygiene in rural Alaska

Water and sanitation in rural and developing areas

The lack of water and sanitation in developing communities around the world is well documented by local, national and international groups that have been working for decades to improve the situation. The Joint Monitoring Program of the World Health Organization estimates that approximately 2.5 billion people don't have access to improved sanitation and about 800 million lack access to improved drinking water worldwide (World Health Organization 2015), but these numbers increase when examining communities that lack either access to basic services or access to safely managed services.

While water and sanitation access has been expanding rapidly in recent decades with international commitment to the Millennium Development Goals in 2000 (United Nations 2015) and the Sustainable Development Goals in 2015 (World Health Organization 2015), rural and remote areas are still far behind in making progress on providing these services (World Health Organization and UNICEF 2004; Ford et al. 2017). Rural areas are a particular challenge for the provision of safe drinking water and properly managed sanitation services because they often lack economies of scale, access to supplies and materials, nearby municipally-managed utilities to support their operations, and technical design, operation and maintenance expertise (Pitzer and Sudman 2008; Haddaway 2017). Funding does not go as far in rural areas, and often the limited funding for water projects that provide new coverage to previously unserved rural areas has to be shared with recurrent investments that are needed by urban areas (Hutton and Bartram 2008). Additionally, some rural communities are so inaccessible for travel or communications that they are nearly forgotten by the larger jurisdictions of which they are a part, such as in the US where

many small communities are without access to improved water and sanitation even though the country is considered to have 100% coverage (World Health Organization 2017). Further, many rural residents are part of low-income, minority, or indigenous groups and are historically underserved, making them vulnerable to adverse health impacts that often come alongside lack of access to safe water and sanitation services (for examples in rural Alaska, see T. K. Thomas et al. 2016). To intensify the situation, rural areas often provide challenging engineering conditions because of remoteness, lack of infrastructure, difficult terrain, and extreme weather or climatic conditions (for examples in rural Alaska see Hickel et al. 2017; US Arctic Research Commission 2015). In spite of and because of all of these challenges, improving water and sanitation services in underserved rural communities around the world needs to become a specific and prioritized undertaking for researchers, engineers and social scientists in the immediate future.

Situation in rural Alaska

The state of Alaska is home to a population of approximately 740,000 people dispersed across 570,640 square miles of land (US Census Bureau 2017). With an average population density of just over one person per square mile, the state can be divided into two regions: the remote rural areas that contain less than 10% of the population spread out in 150 communities over 395,000 square miles, and the urban economy-base of the state which contains 90% of the population in 200 communities over 175,000 square miles (see Figure 1). The remote rural areas are mostly in the north and west of the state, and the community members there are 78% Alaska Natives whose households subsist on a mixture of cash, subsistence fishing and hunting, sharing and non-cash trading, based on a 2008 report (Goldsmith). These areas are rarely served by road and railways, and therefore are only accessible by air services year-round, coastal/river boat or

barge and all-terrain vehicles in the warmer months, and snow machine in the colder months

(Figure 2). Because jobs and other economic opportunities are scarce in the remote rural areas,

poverty is widespread and reliance on government jobs and public assistance programs is very

common (Goldsmith 2008).
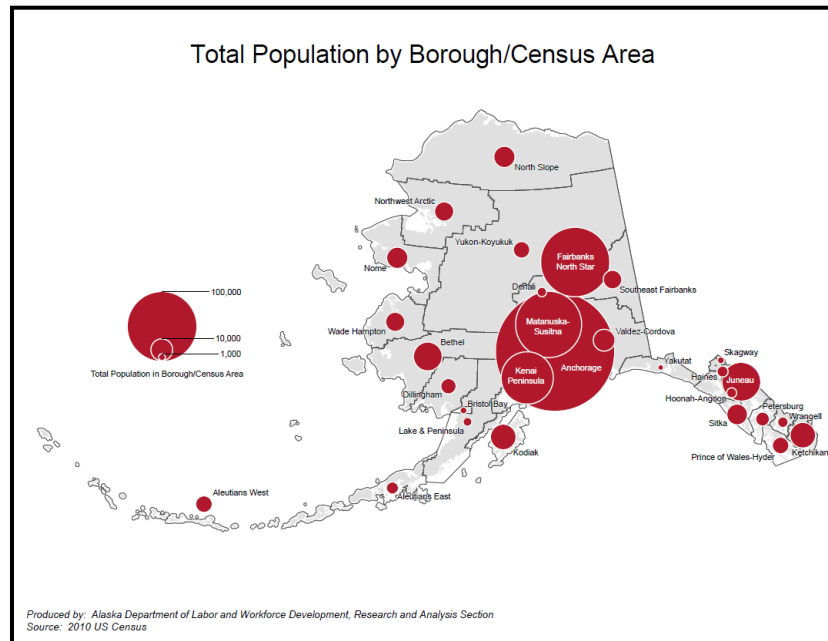
Figure 1: The population density map of Alaska shows that the majority of boroughs/census areas have fewer than 10,000 residents who are spread out across large tracts of land. The urban centers of Anchorage, Fairbanks and Juneau are not easily accessible to many of these communities (Alaska Department of Labor and Workforce Development 2010).

Figure 2: The road system and fuel distribution areas of the state of Alaska. Only region 2 (in green) has road and rail access. Region 1 (blue) is served primarily by the Alaska Marine Highway and air services. Region 3 (yellow) is exclusively accessible by coastal or river boat or barge, air services, and off-road trail or snow vehicles (Alaska Department of Environmental Conservation 2017a).

The lack of improved water and sanitation services in over 3,300 rural Alaska homes (Alaska Department of Environmental Conservation 2017b) is related to the remoteness and difficulty of living in rural Alaska. Communities in rural Alaska are classified into three categories based on their level of water and sewer access: "served", where most homes have piped water and sewer; "underserved", where piped utilities are not available but a closed-haul system provides water and sanitation services; and "unserved" where less than 55% of homes have water or sanitation services. Most unserved communities have access to a "washeteria" that has potable water, laundry and shower available for varying fees, but residents must self-haul water to their homes, usually in 5-gallon buckets. These communities often use outhouses (pit latrines) or honey buckets (5-gallon buckets) for human waste (Hickel et al. 2017). The lack of in-home piped water has been linked to higher hospitalization for pneumonia, influenza and respiratory syncytial viruses (Hennessy et al. 2008) and to higher incidences of respiratory, skin

and gastrointestinal infections (T. K. Thomas et al. 2016). The high prevalence of water-washed diseases, as opposed to waterborne diseases, in rural Alaska is probably related to observed in-home water reuse practices that many households observe, such as reusing the same wash basin for multiple hand-washings or using hand-wash water for household cleaning. While these extreme water conservation techniques demonstrate a concern for hygiene and cleanliness, they may also increase health risks to families (Hickel et al. 2017) that don't have sufficient quantity of water or suitable water treatment and disinfection techniques available. Meanwhile, unimproved sanitation in the villages has been hypothesized to contribute to increased risk for fecal-oral transmitted diseases (Chambers et al. 2009), since residents in unserved or underserved villages are more likely to come into contact with human waste.

Water and sanitation has been an ongoing priority for public and private organizations in Alaska for over 50 years with varying progress and success (US Arctic Research Commission 2015), but Alaska lags behind the rest of the United States in percent of the population with access to modern water and sanitation services (Hennessy et al. 2008), in part because of the unique challenges that face engineering projects in cold climate regions. Infrastructure projects in cold climate regions must be completed during certain times of the year (usually late spring, summer or early fall) when materials can be delivered and worksites are accessible, specific (often expensive) materials must be used that can hold up to temperatures reaching -40 degrees Fahrenheit and intense snow and icefall events, and special consideration must be taken into insulation for utilities to protect the infrastructure and fragile permafrost. Thus, typical water and sanitation solutions for other rural areas must be specifically adapted or rewritten for remote Alaska communities.

Water quantity – demand

An initial step for providing in-home water and sanitation services to unserved villages in Alaska is determining how much water is desired and required for health and hygiene purposes. The World Health Organization (2017) recommends 2 gallons/capita/day (g/c/d, equivalent to 7.5 liters/capita/day, L/c/d) for consumption for highly vulnerable members of the population (breast-feeding mothers with average levels of activity in higher-than-average temperatures) and 5 g/c/d (20 L/c/d) for personal and food hygiene purposes. Thomas et al. (2016) observed that houses in rural Alaska used a mean of 1.5 g/c/d (6 L/c/d) before they had piped water services and 25 g/c/d (97 L/c/d) after receiving reliable piped water services in the home. These volumes varied between homes based on the household characteristics and cultural and social traditions of the community. For example, women living alone with children used less than 0.25 g/c/d (<1 L/c/d), while other households would use up to 1.8 g/c/d (6.8 L/c/d) before getting piped water (T. K. Thomas et al. 2016), likely because of the effort and cost of self-hauling water. Cultural and social traditions are likely to affect the types of water sources used and the use of water for hygiene purposes. For example, villages that make use of rainwater collection systems make use of more water in months when the resource is available. Some Alaska Native populations do not take traditional western baths, but use steam baths as their primary way to clean themselves.

The state of Alaska prescribed a goal of providing 15 g/c/d (57 L/c/d) of "wash water" for hygiene purposes and 0.5 g/c/d of drinking water to unserved villages (Alaska Department of Environmental Conservation 2017b). For an average household of four people, this meant 60 gallons per household (hh) per day (230 L/hh/d) of wash water and 2 gallons per household per day (8 L/hh/d) of drinking water. These targets are in between the WHO recommendations and the volumes observed by Thomas et al. to be correlated with decreases in many common

illnesses, and are therefore used in this study to examine possible alternative water resources that could be employed in rural Alaska.

Water quality – fit for purpose

Two significant parts of the challenge of providing sufficient quantities of in-home water and sanitation to rural villages in Alaska are 1) getting large quantities of water of appropriate quality to the home without introducing contamination and 2) removing wastes from the home without unmanaged human exposure. A relatively innovative way to manage this problem is by segmenting storage vessels, fixtures, piping and treatment into different systems based on expected uses and the associated required quality of water – that is, providing "water fit for purpose" (Muller 2010; Schimmoller and Kealy 2014). This framework for water treatment and management allows for water, energy, and money to be saved by using lower levels of treatment for water with lower level uses through substitution or regeneration (Grant et al. 2012).

In rural Alaska, water fit for purpose and water reuse is already practiced. Many homes choose and change their water sources based on seasonal changes in their water resources and the intended uses within their household. For example, rainwater is widely used in some villages during the rainy season, but when temperatures get low, water is hauled from a watering hole drilled through the ice on a mostly frozen river. The river resource is abandoned during spring break-up when sediment levels get too high and begin to impact color and taste. Rainwater is considered to be a high-quality resource in some villages and is reserved for drinking and cooking, while chlorine-disinfected water from local washeteria will be used for non-consumptive purposes. Similarly, people will reuse wash basin water to clean their floors, which they perceive to require a lower quality of water.

While employing a fit for purpose model can save energy and financial costs and can conserve scarce water resources, it can also introduce new risks. Oesterholt et al. (2007) found that when waters of different qualities were provided through separate plumbing systems to several homes in the Netherlands, instances of cross-connections, high bio-film growth, and incidental contact cause microbiologically unsafe conditions for members of the household. This example demonstrates that matching water quality to use within a household requires extra care and caution in order for health benefits to be realized.

Untapped resources

Because the worldwide demand for clean drinking water is increasing and the increasing burden of disposing of contaminated wastewaters is challenging existing water resources, the application of innovative technologies, management strategies and financing is required (Corcoran et al. 2010) to solve water and sanitation problems. Innovation will have to be applied to a variety of situations experiencing water issues, including remote military bases, refugee camps, desert communities, and areas struck by disasters. Compared to these other situations, rural Alaska has abundant, high quality water resources owing to the small numbers of people on large areas of land. However, in order for individuals to realize the health benefits of this water abundance, there must be new innovations for how to produce or transport this water directly to households with minimal effort and appropriate treatment. Expanding the use of rainwater catchment systems and developing and introducing onsite greywater treatment and reuse systems have the potential to help solve these problems.

Rainwater catchment systems

The development of alternative decentralized water resources is highly recommended for addressing water scarcity problems (Mankad and Tapsuwan 2011; Massoud, Tarhini, and Nasr 2009). While alternative resources, such as rainwater or surface water, are commonly used by communities that don't have consistent access to water supply, they are often correlated with low water quantity and low quality (Majuru, Suhrcke, and Hunter 2016). Rainwater, however is often considered to be a high quality source where it is readily available, can be inexpensive to catch and store (Rahman et al. 2014), and can be immediately ready for use on-site without transport. However, water managers and government regulators are often reluctant to promote rainwater because of concerns about safe implementation, operation and management of catchment systems (Domènech, Heijnen, and Saurí 2012; Lye 1992).

In rural Alaska, many communities trust and prefer rainwater to other water sources, but no large-scale studies have previously been done that examine the quality and quantity of rainwater that can be captured in the villages. Additionally, the extreme cold temperatures in much of Alaska during half of the year means that a lot of the precipitation falls as snow and not rain (Domènech, Heijnen, and Saurí 2012), and that outdoor catchment and storage materials can be compromised when cold weather hits. The potential opportunities and problems with rainwater quality and quantity are evaluated in Chapter 2 of this document.

Onsite greywater treatment and reuse

Compared to rainwater, household greywater is a much more reliable and consistent resource of much lower quality. Greywater reuse systems have traditionally been employed to address water scarcity concerns in dry areas or places with insufficient water for large populations (e.g. Al-Jayyousi 2003; Jeppesen 1996; A. Hurlimann 2011). However, greywater reuse is beginning to be employed in areas where other water resources are unreliable or

insufficient (e.g. Najm et al. 2017), but mostly for non-potable uses such as toilet flushing (e.g.

Oesterholt et al. 2007; Campisano and Modica 2010; Christova-Boal, Eden, and McFarlane

1996; Diaper et al. 2001) or agricultural purposes (Jhansi and Mishra 2013).

Despite the slow uptake of this technology in more urbanized areas, small-scale onsite

greywater reuse for potable or semi-potable (used here to mean safe for human contact but not

approved for human consumption) purposes could be promising for rural Alaska because it

would improve the quantity of water available within a household with minimal hauling

requirements, and it would reduce the quantity of wastewater needing to be hauled from the

home. The results of a demonstration household greywater reuse system project are presented in

Chapter 3 of this document along with an analysis of the feasibility of this system for rural

Alaska.

Chapter 2: Rainwater catchment systems

Introduction

Rural Alaskan communities often draw water for household use from multiple sources including piped water from treatment plants (where available), treated hauled water from washeterias, and untreated water from melting snow, rain water, rivers, lakes and streams. The majority of these water sources require labor intensive or expensive hauling practices that can also result in the contamination of good quality water. Making use of rainwater catchment systems that allow collection of water onsite is a promising alternative to hauling in communities without piped water, if the rainwater is of sufficient quality. Having a readily available water source onsite, such as a rainwater catchment tank, can also allow homes to increase the quantity of water they use for hygiene purposes, which has been linked to improved health in rural Alaska (Hennessy et al. 2008; T. K. Thomas et al. 2016).

Rainwater is often assumed to be of high quality, but pathogenic microbes, metals and VOCs are often contaminants of concern in roof catchment systems (Lye 2002; Gould 2017; Lye 1992). Pathogenic microbes such as coliforms, fecal coliforms, enteroviruses, Enterococci, *Escherichia coli*, *Salmonella spp., Legionella* spp., *Clostridium perfringens, Campylobacter* spp., *Cryptosporidium* spp., *Giardia* spp., and *Pseudomonas aeruginosa* have been detected in rainwater samples (Gould 2017; Lye 2002). Microbes in rainwater tanks have been attributed to a variety of illnesses including bacterial diarrhea, bacterial pneumonia, bacterial toxin, tissue helminth, and protozoal diarrhea (as summarized in Lye 2002). Some studies suggest that bacteria can be introduced to rain catchment systems by birds (Chidamba and Korsten 2015; Fewtrell and Kay 2007), small mammals, and dust particles, (Lye 2002) but direct causes and effects of microbial contamination in rain systems used for human consumption are poorly

understood. At least one study found that presence of a household rainwater cistern was associated with lower incidences of diarrhea among members of the household, possibly because use of rainwater was safer than use of other more contaminated water sources (Marcynuk et al. 2013).

Some heavy metals, such as magnesium and zinc (Gould 2017) are commonly detected in rain catchment systems but are not of major health concern. Lead, however, is a common metal constituent of rain systems that can be dangerous even at low levels (action level = 15 ug/L, micrograms per liter, US Environmental Protection Agency 2017) that could leach from roof construction materials or deposit from nearby industrial sources. Metals can be detected at higher concentrations when rainwater is more acidic, either due to atmospheric conditions or to higher quantities of organic matter decaying in the tank. Acidity itself is not a major concern for human consumption of rainwater (T. Thomas 1998).

Some of the hesitation to accept and promote widespread use of rain catchment systems by regulatory bodies is related to the large number of small, individual systems that would need to be inspected and maintained. Proper construction and maintenance has been shown to be connected to functionality and water quality (Domènech, Heijnen, and Saurí 2012) and it therefore an important concern for rural areas where construction and maintenance of such system is likely to be haphazard using any available materials, and systems are unlikely to be cleaned, monitored or tested with any regularity.

Although the concerns about illnesses related to rainwater catchment are troubling for the villages in rural Alaska that are currently making use of this resource in their homes, the reality is that there are few other options for many of these remote places. Many communities prefer rainwater to other government-endorsed water sources. The difficult of accessing and

transporting other water to the home, the dislike of the taste of heavily chlorinated water, and the resulting low quantities of water used in the home in rural Alaska could be as problematic as the uncontrolled and unmonitored use of rainwater. The risks and rewards of different water resources needs to be evaluated.

Research objectives

Rainwater catchment samples in rural Alaskan villages were collected and analyzed to assess overall water quality, identify primary contaminants and to correlate any health-related contaminants to collection system characteristics, where available. Additionally, this study examined the microbial contamination of outdoor rain catchment containers compared to indoor point-of-use storage containers and compared general rainwater quality characteristics from rural villages to the quality of rainwater and tap water in Anchorage. Community meetings were used to understand how rainwater catchment contributes to total household water use, how much rainwater is collected compared to how much is available, and what concerns community members have about rainwater quality. Qualitative data from the community forum and village visits was evaluated to understand how the two different communities use rainwater. Rainwater usage information from the community was compared to data collected on catchment sizes and rainfall data from nearby weather stations to understand how much of the potential rainwater available to the community is being utilized in households.

Even though rainwater is widely used, most published studies focus on warm weather regions (T. Thomas 1998; Lye 2002; Marcynuk et al. 2013; Rahman et al. 2014; Imteaz et al. 2011; Jordan et al. 2008). There is a single published study on rainwater in rural Alaska that examines lead, copper and zinc, but overall water quality is not discussed (Hart and White 2006). The current study examines water quality and estimates community acceptance and quantity of

rainwater available for household use in rural Alaska. Further, because environmental data collection is difficult and expensive to collect in hard-to-reach places like the rural Arctic, this study took advantage of an earlier citizen science initiative that looked at rainwater samples in rural Alaska villages and incorporates citizen science data from 2015 into datasets collected by researchers in 2016. The data presented here provides a starting point for future evaluations of rainwater as a significant household water resource in rural Alaska.

Methods
Water quality samples and catchment observations

Rainwater catchment samples were collected from households in two un-piped villages in rural Alaska to quantify water quality parameters from household catchments, to determine how rainwater quality compares to other source water qualities, and to evaluate microbiological contamination of indoor water quality compared to outdoor catchment water quality.

At homes chosen for rainwater samples, observations were recorded of the roof material, collection system, collection vessel, water quantity and cleanliness, and presence of nearby wood burning (e.g. chimney smoke, wood pile, steam bath). The approximate number and size of collection vessels was determined and one vessel was arbitrarily chosen for sample collection. In less than 10% of homes, a resident gave instructions on which vessel to sample from based on the age of the water or the vessel being actively drawn from for use in the home. Water samples were taken wearing fresh nitrile gloves by dipping a 250mL (milliliter) sample bottle into the surface of the collection vessel and pouring the water into each container in the sampling kit. If there was a scoop or pitcher already in or connected to the catchment vessel or provided by the homeowner, it was used to fill the sampling kit bottles to simulate the collection of water the

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exact way that the household would collect the water. In homes where the vessel had a spigot, the spigot was allowed to free-flow for three seconds before the collection bottles were filled. If the surface of the water in the storage vessel was frozen, this was recorded and the ice was broken with a piece of wood. Care was taken to not let the wood contact the liquid water. At each home, residents were asked if they currently had rainwater in use in a storage vessel inside the home, and if they would consent to a water quality sample for bacterial analysis. Where consented, these samples were taken by filling a sample bottle directly from a pitcher or vessel that the residents use on a regular basis.

Two field blank samples were taken in each village using deionized water transported in sterile bottles from the University of Alaska Anchorage civil engineering laboratory. Two rainwater samples from each village were taken in duplicate from a single vessel by taking two samples, thoroughly mixing them and splitting them between two sets of sample bottles at a single site. In Kipnuk, turbidity measurements were taken onsite and in Koyukuk measurements were taken at the field laboratory within an hour of sampling with a portable field turbidimeter (HACH 2100Q). The turbidity sample bottle was rinsed at least twice with sample water before being filled and wiped down with delicate task wipes and the turbidity read. All other samples were transported back to Anchorage in coolers with ice packs at approximately 4 degrees Celsius and analyzed within 48 hours of collection. Conductivity (analytical method SM21 2510B), pH (analytical method SM21 4500-H B), total organic carbon (TOC, analytical method SM 5310B) and metals (analytical method SW6020A) samples were submitted to a certified laboratory in Anchorage for analysis. Metals assessed by the certified laboratory included aluminum, antimony, arsenic, barium, beryllium, cadmium, calcium, boron, chromium, cobalt, copper, iron, lead, magnesium, manganese, mercury, molybdenum, nickel, potassium, selenium, silver,

sodium, thallium, vanadium and zinc. Ultraviolet absorbance (UVA) at 254nm wavelength was measured on a Cary 60 UV Vis spectrophotometer.

Most probable number (MPN) of *E. coli* was measured using the Aquagenx Compartment Bag Test (CBT). Samples were collected and transported in the 100mL plastic bottles provided with the CBT test kits. Prior to analysis, samples were allowed to warm to room temperature and the chromogenic *E. coli* media were added and allowed to dissolve for 25-60 minutes until the ampule containing the media turned white. Samples were incubated at 37 degrees Celsius for 20-22 hours and enumerated according to the provided CBT MPN table (Sobsey 2017). Enterococci (total colony forming units per 100mL) were enumerated by filtering 100mL of sample through a 0.45-micron membrane on a vacuum manifold, rinsing with 20-40mL of sterile water, placing the membrane on a pre-poured membrane-Enterococcus Indoxyl-B-D-Glucoside (mEI) agar plate and incubating the plates at 41 degrees Celsius for 24 hours (US Environmental Protection Agency, n.d.). Colonies were enumerated using a light and magnifying glass.

Rainwater sample data from Kipnuk and Koyukuk in 2016 was compared to 19 samples from 8 villages taken from September to December 2015 through a citizen science initiative coordinated by Masters of Public Health student Elizabeth King at the University of Alaska Anchorage (King 2016). King recruited volunteers with existing travel plans in remote rural villages to carry a sampling kit and obtain a convenience sample of one or more rainwater catchment tanks and accompanying observational data about the catchment system during the course of their planned trip. Rainwater sample collection protocols matched those used in Kipnuk and Koyukuk (described above), and volunteers were asked to self-rate the accuracy with which the protocol was followed after collecting the samples. Samples were stored in coolers

with snap-activated ice packs and gel ice packs for up to several days before being transported to Anchorage. *E. coli* samples were analyzed as described above by King at a University of Alaska Anchorage laboratory and pH, conductivity, TOC and metals were analyzed as described above by the same certified laboratory.

Community meetings

A community meeting was held in Kipnuk and Koyukuk in 2016 during the period of rainwater catchment sample collection. The meeting was coordinated by the University of Alaska Anchorage Alaska Water and Sewer Challenge team, but the use of rainwater as a household water source was discussed as well. Broad discussions were led by visiting scientists about water resources used in the home. Five questions addressing the use of rainwater were written on poster paper and hung on the walls for community members to respond to by posting sticky notes on the poster and adding their notes and ideas: 1) About what percent of water that you use in your home is rainwater in spring, summer and fall? 2) Do you have any concerns about the use of rainwater in your home? 3) How much rainwater (in gallons) do you collect each season? 4) If you could collect more rainwater, would you? And 5) What supplies would you need to build or expand your collection? Responses were recorded along with discussion notes and stories shared by community members during the meetings.

Rainwater catchment potential estimation

To evaluate the future possible contributions of rainwater to household water use in rural Alaska, theoretical rainwater catchment volumes were calculated for the villages of Kipnuk and Koyukuk. Estimates of total roof catchment area were made by measuring and averaging the square footage of at least 10 houses in each village using the measurement tool and a zoomed in image of the homes on Google Earth. Monthly rainfall and average temperature normals from 1981-2010 were obtained from the Alaska Climate Research Center (2017) for Bethel and

Galena, which were the closest villages to Kipnuk and Koyukuk respectively for which data was available. Low estimates of annual rainfall were obtained by adding up the monthly rainfall values for all months where the average temperature was above 32 degree Fahrenheit (assuming that in months with an average temperature below 32 degrees F the precipitation fell as snow, not rain). High estimates of annual rainfall were obtained by taking the total rainfall indicated directly on the Alaska Climate Research Center website for each location. Total annual rain catchment estimates were calculated by multiplying the annual rainfall by the measured average square footage in each village. Individual rain catchment estimates for months with an average temperature above 32 degrees F were also calculated.

Results
Rainwater quality

Forty-eight samples from nine villages (Figure 3) were analyzed between 2015 and 2016 sampling periods and the water quality results are summarized in Table 1.

In 2016, 21 rainwater samples were collected from Kipnuk on October 1, 2016 between 10:30am and 5:30pm while it was overcast and actively raining. Over 80% of residential homes had rain catchment tanks (approximately 140 households). Samples were taken from every 5th house after homeowner permission was obtained. If permission was not given at the designated sampling house, the next closest house was sampled instead. Rain samples from Kipnuk had a turbidity of 1.05 ± 0.44 NTU (Nephelometric Turbidity Units, min=0.31, max=2.17) and an average UVT of 97%.

Eight rainwater samples were collected in Koyukuk on October 15-16, 2016 between 2pm and 7pm each day. Although many households in Koyukuk had gutters and containers set

up for rainwater collection, most houses had dumped their rainwater buckets the previous week because the rainwater was starting to freeze. Many residents said they were no longer using their rainwater but still had it stored outdoors and allowed samples to be taken if the water wasn't frozen. Because so few homes still had rainwater available for sampling, samples were taken from every available home where permission was given. Rain samples from Koyukuk had a turbidity of 4.48 ± 5.8 NTU (min=0.31; max=18.4) and an average UVT of 87%.
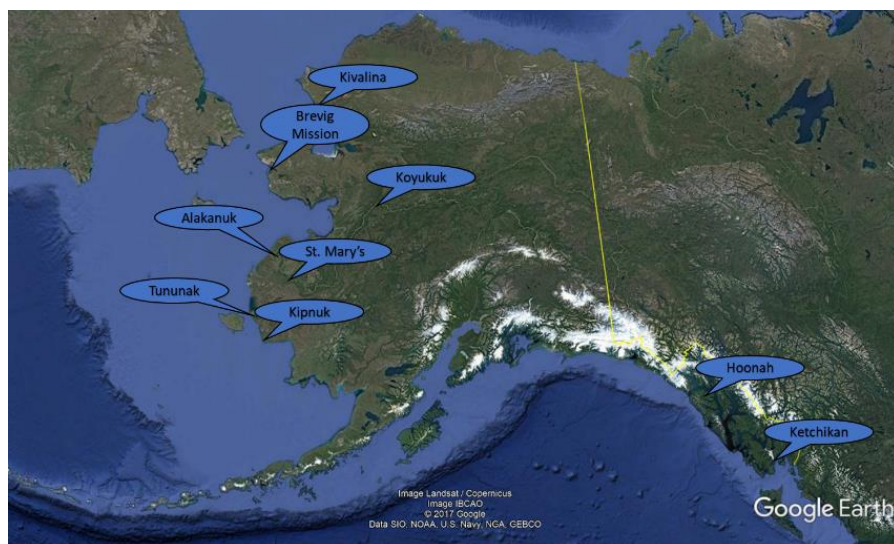
Figure 3: Locations of 2015 and 2016 rainwater catchment samples

The 2015 citizen science study produced 19 samples from eight villages that were analyzed for TOC, conductivity, pH and metals. *E. coli* was tested via the Compartment Bag Test method, but all samples were several days outside of the holding time when the test was performed. The bacteria data (all 0 MPN/100mL) is not necessarily valid and is therefore not presented here. No rain catchment characteristic data was available from the 2015 study.

Six of the 48 total samples from both years were above the MCL (maximum contaminant level) of 2.0 mg/L for TOC. Four of the six high samples were from Koyukuk in 2016 when

water catchments had already begun to freeze. The maximum TOC value observed was 5.7 mg/L. Conductivity was 38.13 ± 34.74 and ranged from 3.30-217.00 mS/cm (micro-Siemens per centimeter) across all samples. Thirty samples were outside of the acceptable range of 6.5-8.5 and on average the pH was 6.1. At least one sample with low pH (<6.5) was collected at each village except for Brevig Mission and Tununak (which only had one sample collected).

None of the 48 samples were above the detection limit for arsenic, beryllium, boron, mercury, molybdenum, selenium, silver, thallium or vanadium. For several other metals, multiple samples read above the detection limit but were still below the national MCL, or no MCL was specified: barium (n=11 samples above detection limit but below MCL), calcium (n=12), chromium (n=1), cobalt (n=1), copper (n=6), magnesium (n=18), manganese (n=33), nickel (n=7), potassium (n=1), and sodium (n=34).

Only eight samples were positive and above the National Primary (US Environmental Protection Agency 2017) or Secondary Drinking Water Regulations (US Environmental Protection Agency 2015) for one of the metal parameters tested. In Kipnuk, three homes had zinc levels >5000 ug/L (5140, 5910, and 5780 ug/L). In Koyukuk, one home had high levels of aluminum (259 ug/L), one home had high levels of iron (1530 ug/L) and lead (21.2 ug/L), and one home had high levels of aluminum (700 ug/L), antimony (6.51 ug/L), iron (1380 ug/L) and zinc (9890 ug/L). Two samples from Kipnuk that had cadmium levels over 10 times higher than the MCL of 2 ug/L were from a single house that was sampled both in 2015 (50.3 ug/L) and 2016 (29.8 ug/L).

Table 1: Overall rainwater catchment water quality characteristics. N=48, units of ug/L unless otherwise specified. (Drinking water MCLs from US Environmental Protection Agency, 2015)

Water Quality Parameter	Detection limit (DL)	Number of samples below DL	Number of samples above DL	Mean ± St. Dev. of samples above DL	National Primary or Secondary Drinking Water MCL
TOC (mg/L)	0.5 mg/L	26	22	1.84 ± 1.67	2.0
Conductivity (mS/cm)	1.0 mS/cm	n/a	n/a	38.13 ± 34.74	Not specified
pH	n/a	n/a	n/a	6.1 ± 0.7	6.5-8.5
Aluminum	200	46	2	479 ± 221	50-200
Antimony	3	47	1	6.5	6
Barium	3	37	11	14.0 ± 12.8	2000
Cadmium	2	45	3	27.7 ± 19.4	5
Calcium	500	36	12	1652 ± 1318	Not specified
Chromium	4	47	1	8.1	100
Cobalt	1	47	1	1.1	Not specified
Copper	6	42	6	165 ± 221	1000
Iron	500	46	2	1455 ± 75	300
Lead	1	37	11	5.77 ± 5.63	Action Level = 15 ug/L
Magnesium	500	30	18	1152 ± 629	Not specified
Manganese	2	15	33	9.11 ± 9.01	50
Nickel	2	41	7	2.76 ± 0.46	Not specified
Potassium	1000	47	1	2040	Not specified
Sodium	1000	14	34	5685 ± 5030	Not specified
Zinc	25	5	43	1851 ± 2259	5000

Table 2 summarizes select rainwater quality parameters for each village versus the average across all samples, but most village sample sizes were too small for statistical analysis.

Kipnuk data from 2015 (n=8) was compared to 2016 (n=20) to look at the consistency in select parameters over time. Both sets of samples were taken between September 29 and October 1 each year, although seasonal variation in temperature, precipitation and wind are likely to affect this temporal comparison. TOC was very low in both years, with only 25% of samples

having detectable levels. pH was not significantly different between the two years (2015 mean = 5.3, 2016 mean = 6.0, p = 0.12). Conductivity was significantly higher in 2016 (20.56 mS/cm) than in 2015 (47.96 mS/cm, p<0.0001). Magnesium was detected in over half of the samples in 2016 but none of the samples in 2015. Nickel was detected in 75% of the samples collected in 2015 but none of the samples in 2016. Sodium and zinc were detected in almost every sample in both years, while barium, cadmium, calcium, copper and lead were present in a fewer than 25% of samples in each year. Manganese was detected in approximately 50% of samples in each year.

Table 2: Averages of selected rain catchment water quality parameters by village (non-detect samples were calculated to be at the detection limit for this analysis)

Village	No. of samples	TOC (mg/L)	Conductivity (mS/cm)	pH	Metals detected
Alakanuk	2	3.70	16.35	5.9	Ba, Mn, Na, Zn
Brevig Mission	3	0.64	19.17	6.8	Ca, Pb, Mg, Mn, Na, Zn
Hoonah	1	0.72	3.30	6.0	Ni
Ketchikan	2	2.35	113.60	6.3	Ba, Ca, Cu, Pb, Mg, Mn, K, Na, Zn
Kipnuk	28	0.54	41.11	5.8	Ba, Cd, Ca, Cu, Pb, Mg, Mn, Ni, Na, Zn
Kivalina	2	<0.50	88.45	6.2	Ba, Ca, Pb, Mg, Mn, Na, Zn
Koyukuk	8	2.45	17.58	6.6	Al, Sb, Ba, Cd, Ca, Cr, Co, Fe, Pb, Mg, Mn, Ni, Zn
St. Mary's	1	<0.50	9.2	5.4	Mn, Zn
Tununak	1	0.54	31.6	6.7	Cu, Pb, Mn, Na, Zn
OVERALL	**48**	**1.11**	**38.13**	**6.1**	**n/a**

Bacteria analyses

Fourteen out of 21 Kipnuk samples (Figure 4) and four out of eight Koyukuk samples (Figure 5) from 2016 tested positive for bacteria. Twenty out of 21 Kipnuk homes sampled and four out of eight Koyukuk homes sampled consented to collection of an indoor sample of stored rainwater in addition to the outdoor sample. Nine samples from outside rain catchments in

Kipnuk and three from Koyukuk were positive for *E. coli*, but only two of these homes in

Kipnuk and one of these homes in Koyukuk also tested positive for *E. coli* in the indoor sample.

One home in each village that tested positive in the indoor sample was negative in the outdoor

sample. Seven homes in Kipnuk tested positive for Enterococci, but only three of these also had

E. coli in the outdoor catchment. In Koyukuk, one sample was positive for Enterococci and that

home also had *E. coli* in the outdoor sample.
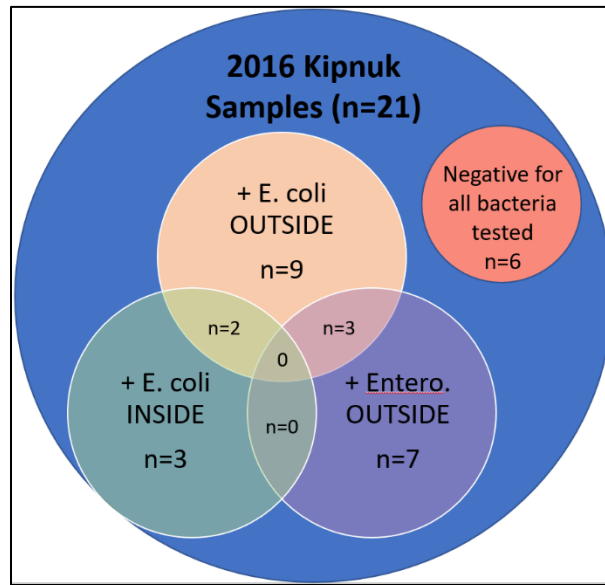
*Figure 4: Bacteria results from Kipnuk rainwater catchments that were sampled for E. coli in
indoor and outdoor containers and for Enterococci in outdoor containers. Out of 21 total
samples, 6 were negative on all three bacteria tests. Nine homes tested positive for E. coli in the
outside sample, two of which were also positive for E. coli inside and three of which were also
positive for Enterococci outside. One additional sample only tested positive for E. coli inside the
home and four additional samples only tested positive for Enterococci in the outside sample. No
homes tested positive on all three bacteria tests.*
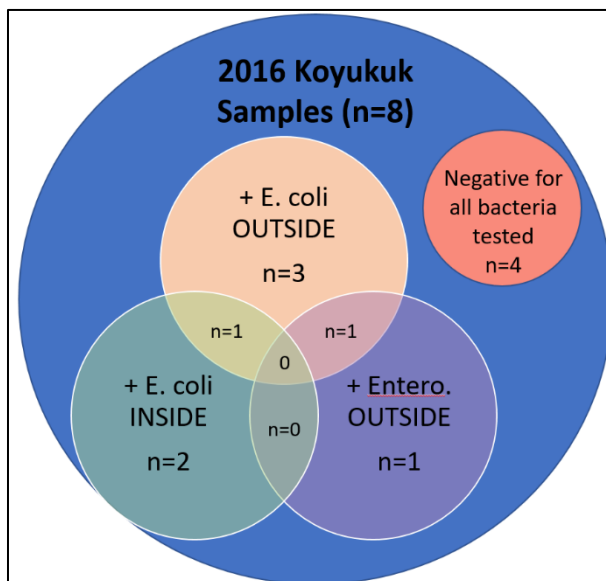
Figure 5: Bacteria results from Koyukuk rainwater catchments that were sampled for E. coli in indoor and outdoor containers and for Enterococci in outdoor containers. Eight homes were sampled and four were negative for all three bacteria tests. Three households were positive for E. coli in the outside sample taken, one of which was also positive for E. coli inside and one of which was also positive for Enterococci in the outside sample. One additional sample tested positive for E. coli indoors only. No homes tested positive on all three bacteria tests.

Table 3: Compartment Bag Test (E. coli) microbial health risk (Sobsey 2017)

E. coli (CFU or MPN/100mL)	Health Risk Category
<1	Low risk/Safe
1 – 10	Intermediate risk/Probably safe
10 – 100	High risk/Probably unsafe
>100	Very high risk/Unsafe

Of the thirteen total samples that tested positive for *E. coli*, eight had <5 MPN/100mL, representing an intermediate risk and suggesting that the water is probably safe according to the Aquagenx sampling literature (Table 3). One Kipnuk sample had 32.6 MPN/100mL *E. coli* in the

outside sample and tested positive for Enterococci, and one Koyukuk sample had >100

MPN/100mL *E. coli* (outside) and tested positive for Enterococci, suggesting high risk for *E. coli*

and that the water was unsafe. One Kipnuk sample was at high risk for both the inside and

outside sample taken, while one Kipnuk sample was at high risk for the inside sample and not the

outside sample, and one Koyukuk sample was at high risk for the outside sample but not the

inside sample. Of the eight samples that tested positive for Enterococci, only one had >2

CFU/100mL (colony-forming units per 100mL of sample).

      E. coli samples from 2015 data collection were outside of holding time, and Enterococci

was not analyzed in 2015. Therefore, all 2015 samples were non-detect for bacteria.

Anchorage rain and tap water samples

      Average values of water quality parameters from the village rainwater samples were

compared to the 2012 Anchorage Water and Wastewater Utility's (AWWU) water quality report

(Anchorage Water and Wastewater Utility 2012) for tap water in the municipal service area.

Village rainwater samples had higher average TOC, chromium and lead levels than AWWU

water (0.38 mg/L, 3 ug/L, 2.44 ug/L respectively), but lower levels of barium, copper, and nickel

(AWWU average: 16.18 ug/L, 180 ug/L, 6.1 ug/L respectively). Village rainwater sample

averages were slightly higher in TOC and pH than a single sample of rainwater measured at the

University of Alaska Anchorage (0.85 mg/L TOC and pH 5.8).

Catchment observations

      Catchment characteristic data was only available from the 2016 samples in Kipnuk and

Koyukuk. All catchment systems in both villages collected water off of roofs made of metal

siding. All systems collected rain off of a house, except one system that caught rain from a shed.

Most homes used standards open gutters made of metal or plastic with a downspout. One home

had no gutter system and instead caught runoff where it collected into a drip on the corner of the roof. Four homes didn't have downspouts, but some had tied strings to guide the water down from the gutter into the collection vessel. No standard first flushes apparatuses were observed, but several homes had clothing (e.g. socks) or cloth covering the end of their downspout or the top of the catchment vessel to serve as a filter for debris. All but two homes used metal (20%) or plastic (80%) barrels, garbage cans or tubs that were less than 100 gallons in volume. Many homes had multiple collection vessels either actively catching water from multiple locations or storing water for later use. The exceptions to this were one home that had a ~500-gallon plastic cistern and one home that collected water in a 15-foot long skiff that sat upright next to the home.

Most homes left their catchment vessels uncovered, but ~15% used hard plastic or wooden covers and ~10% used mesh cloths as a cover. The lack of covers in Kipnuk may have been due to active rain collection happening while observations were being recorded. One third of the collection vessels in Kipnuk and over half of the vessels in Koyukuk had visible leaves, insects, and debris inside the containers. In Kipnuk, most homes indicated that rainwater is a preferred source of drinking and washing water in the home. In Koyukuk, homeowners in over half of the homes samples indicated that they do not use the water for drinking (only for cleaning/washing) or that they had stopped using it once it started to freeze a few weeks earlier.

Community meetings

The Kipnuk community meeting was held on September 30, 2016 with approximately 20 community members in attendance representing at least 10 homes. Most participants said that they used rainwater as a key water source in their homes. Responses to the poster questions suggest that residents exclusively rainwater in the spring and summer and that 50% of the water

used in their home is rainwater in the fall. Community members were reluctant to estimate the quantity of rainwater that they collect, but two people recorded over 500 gallons collected each season. All respondents (n=6) indicated that they would like to collect more rainwater. Good roofing material, sturdy gutters and more storage containers were listed as needs to expand their systems. Concerns about the use of rainwater in the home included rust, dust from the road, bird poop, and smoke from nearby steam baths.

The Koyukuk community meeting was held on October 15, 2016 with approximately 15 community members in attendance. All participants were women heads-of-household. Most participants in Koyukuk were reluctant to discuss rainwater in person or to admit that they use it for drinking. Conversations with some community members during this visit and on previous occasions suggest that rainwater is widely used during the warmer months, but that residents are concerned that visiting officials will not approve of the practice. Several responses to the poster questions indicate that people collect 50-120 gallons per month in the spring, summer and fall. All respondents (n=5) said they would like to collect more rainwater if they had more and better gutters and holding tanks. Community members in Koyukuk did not state any concerns about the quality of rainwater, only about the volume that they were able to collect. Notably, many houses in Koyukuk only had a gutter on a single side of their pitched roof.

Potential rainwater catchment volumes

Kipnuk houses were approximated to have 750 ft^2 and Koyukuk houses were approximated to have 625 ft^2 of roof catchment area. Kipnuk and Koyukuk low and high estimates for total theoretical rain catchment volume per year is shown in Table 4. The low estimates were 70% and 60% of the high estimate volumes for Kipnuk and Koyukuk respectively. These estimates suggest that 6000-8600 gallons of rainwater per year could be

captured per home in Kipnuk, supplying water for 27-40% of the year. In Koyukuk, 2900-4800

gallons/year/household could be captured, supplying 13-22% of the water for the home at a

usage rate of 60 gallons per household per day, an estimated 10x increase from current water use

for a household of four (T. K. Thomas et al. 2016).

    In order for this quantity of water to be harvested, homes would have to make use of all

available roof area by installing gutters and downspouts in appropriate locations. Monthly

variation in rainfall would require collection vessel volume totaling approximately 1500 gallons

for Kipnuk and 900 gallons for Koyukuk.

Table 4: Rainwater catchment potential in high and low rainfall scenarios.
*(*days of water supplied assumed 60 gallons used per household per day)*

	Rain (in.)	Roof area (ft^2)	Vol. of rain (gal/yr.)	Days of water supplied by rain*	% of year supplied by rain*
Kipnuk					
High	18.54	750	8670	144	40%
Low	12.87		6020	100	27%
Koyukuk					
High	12.37	625	4820	80	22%
Low	7.45		2902	48	13%

Discussion
Possible causes of contamination in individual samples

    Only ten of the 48 samples collected over both years had any water quality parameters

other than TOC or pH that exceeded the US EPA drinking water regulations. Two of these

samples (both with zinc levels >5000 ug/L) were from 2015 and no further data was available

that might help explain the results. Three samples were collected in 2016 in Koyukuk from

vessels that were at least partially frozen, and contained lots of debris. One of these contained

high aluminum (259 ug/L), high TOC (4.85 mg/L) and unsafe levels of *E. coli* in the outdoor

sample, although the indoor *E. coli* sample was probably safe. The homeowner said that the water was not used for drinking, only for washing. Another sample contained high iron (1530 ug/L), high lead (21.2 ug/L), and unsafe levels of *E. coli* in the outdoor sample. Cobalt (1.14 ug/L) and barium (3.1 ug/L) was also detected in this sample but not above the MCL. This homeowner said that they had stopped using the water source several weeks previously when they noticed it was dirty, but they did not indicate why it became dirty. The third sample had high aluminum (700 ug/L), antimony (6.51 ug/L), iron (1380 ug/L), zinc (9890 ug/L) and TOC (5.16 mg/L). Barium (8.37 ug/L) and chromium (8.13 ug/L) were also detected, but not above the MCL. These anomalies could be attributed to the freezing of the water, the method of breaking up the ice to collect a sample, or the debris in the sample.

Three samples from Kipnuk had concerning levels of *E. coli* in the sample but no other contaminants outside of the drinking water regulations. One home had unsafe *E. coli* levels in both the indoor and outdoor samples taken, which could be due to contaminated equipment used in the catchment system or to the spread of bacteria into the water from human or animal contact. Another home had unsafe levels in the outside sample but not the inside sample, suggesting that some, but not all, of the catchment containers could be contaminated or that the household practices point-of-use water treatment. The third home had unsafe levels in the inside sample but not the outside sample, suggesting that their source water may be safe but it is becoming contaminated on the way in or inside the home.

Another home in Kipnuk had high levels of zinc (5780 ug/L) and detectable lead (1.89 ug/L) that was under the action level. There were no atypical attributes of the catchment system that might explain these results, however the homeowner did express concern about insects that

were recently found in their rainwater catchment and inside some dead birds found in the area. It is unclear whether this anecdote is relevant to the quality of the rainwater in this home.

The most alarming sampling results from this study came from a single home in Kipnuk that was sampled both in 2015 and 2016 and had high levels of cadmium both years (15-25 times the MCL). This home also had low pH, low levels of *E. coli* in the outside sample in 2016, and detectable levels of barium both years, although barium was not above the MCL. When both samples were taken, a 55-gallon drum labeled "Dow Frost" was observed next to the rainwater barrels, but the homeowner said that this barrel didn't contain any chemicals and was not being used to store rainwater. No other catchment characteristics or sample collection anomalies were recorded that might explain these high contaminant levels. In each case, the homeowner was informed about the sample results and was contacted by public health officials connected to the University of Alaska who answered questions and encouraged the family to stop using their rainwater until further analysis could be done. The homeowner did not take any action based on these results.

Rainwater is a high-quality resource

Overall, rainwater has been shown to be a high-quality water source that is available in varying quantities in most rural Alaska villages. Almost 80% of the samples tested in nine villages were safe to drink based on EPA drinking water regulations. Additionally, rainwater was a culturally and socially acceptable and preferred water source in Kipnuk and Koyukuk, and has been shown to be widely used in other rural villages (King 2016). The use of rainwater collected onsite could greatly increase the quantity of water that households use for hygiene purposes without the additional cost, effort and risk of contamination that comes with hauling water in

from other sources. Even in relatively dry and cold areas like Koyukuk, rainwater potential could provide 60 gallons of water per household per day for over 20% of the year.

Best practices for rainwater use

Although rainwater can be very clean, the quality is localized and can vary based on the surrounding environment, climate, geography, and catchment system characteristics. To promote access to this high quality onsite water resource, government agencies, tribal authorities and community health practitioners should encourage the adoption of several best practices for rainwater catchment:

1. All parts of the catchment system should be cleaned and inspected regularly

2. Household waste and other contaminants should be kept far from catchment system components

3. Gutters, downspouts and storage containers should be screened or covered to reduce debris entering the water supply

4. Sanitary practices should be observed when drawing water from the storage tank and bringing it into the home

5. Point-of-use disinfection options should be considered to ensure that water doesn't contain microbial pathogens

6. Catchment containers should be protected from debris and freezing whenever possible

7. Rainwater should be periodically tested for bacteria, metals and other contaminants and action should be taken if any parameter readings fall outside of the EPA drinking water regulations

8. Gutters should be installed on all sturdy parts of the roof and sufficient catchment containers should be provided to maximize catchment volume.

Future research needs

This study represents a preliminary examination of the quality and quantity of rainwater available to rural Alaska villages, many of which do not have adequate alternative water resources for use in the home. A more comprehensive analysis of rainwater resources across the state is recommended to add robustness to this dataset and provide information on geographical, seasonal, temporal cultural and social trends in rainwater quality and use. The small number of samples collected in most of the villages in the present study made comparison between geographic locations difficult, however variation is highly likely based on factors such as nearby vegetation, bodies of water, wildlife, and industry. The possibility of using a citizen science approach and taking advantage of partnerships with other traveling professionals (such as nurses or pilots) to collect this data is promising and could help to overcome the hurdles of the cost and feasibility of travel to these remote locations (King 2016). However, citizen scientists must be carefully trained and observed and proper material and logistical support will need to be provided to ensure that accurate and useable data is collected. In the current study, microbiological parameters were drastically different in samples collected by trained scientists compared to those taken by citizen scientists. Citizen science programs should be carefully designed and executed if they are to be employed.

Alaska native tribes are culturally diverse and have different preferences and concerns about water resources, and this likely extends to the use of rainwater in the home. More information about individual communities' water source preferences and desires will be important for authorities to make decisions about how to improve and promote water quantity and access in rural villages. This need extends from outdoor infrastructure like rainwater catchment systems to indoor infrastructure such as indoor treatment and storage to see whether and how indoor behaviors can affect the ultimate water quality before it is used or consumed.

Chapter 3: Onsite water treatment and reuse

Introduction

Water reuse systems offer promising potential to address the water quantity problem in rural Alaska because they address the issues of producing clean water onsite and of treating wastewater and reducing wastewater removal needs. Traditionally, water reuse has been focused on large-scale systems (Jeppesen 1996) or on producing water for non-potable purposes (e.g. toilet flushing, Christova-Boal, Eden, and McFarlane 1996) and irrigation (Jhansi and Mishra 2013). In rural Alaska, the needs for water reuse technology are for small systems that serve individual or clustered households and that produce high quality water that is potable or at least suitable for human contact and incidental consumption.

Alaska Water Sewer Challenge

In 2013, the Alaska Department of Environmental Conservation (ADEC) initiated a new effort called the Alaska Water and Sewer Challenge (AWSC) to tackle the problems discussed above and examine the feasibility of building household water reuse systems in rural Alaska with funding from the US EPA. The Alaska Water and Sewer Challenge focuses on decentralized water and wastewater treatment, recycling and the efficient use of water (Alaska Department of Environmental Conservation 2017b) by funding new research and development of single household greywater reuse systems that would be appropriate for cold climate environmental and social conditions. The goal of the AWSC is "to significantly reduce the capital and operating costs of in-home running water and sewer in rural Alaska homes" (Alaska Department of Environmental Conservation 2017b). In the third phase of the Challenge in 2015, ADEC funded three teams to build and test pilot systems for 18 months and to work closely with two unserved rural Alaska communities to understand community water supplies, preferences and needs.

Much of the data and information presented here was generated as part of the University of Alaska Anchorage (UAA) AWSC team's work from January 2016 through July 2017. In addition to UAA, team partners included the University of Colorado Boulder, the Southern Nevada Water Authority, GV Jones and Associates, StreamlineAM, and the University of Southern California. Some of the data presented here is also included in the AWSC Phase 3 Final Report submitted to ADEC in July 2017. Additional project information, community input, pilot data, reports and photos can be found on the team website, reusewaterak.com.

Research objectives

The UAA AWSC system was designed in 2015 and a prototype pilot system was built in 2016 and tested from July 2016 through July 2017. With only 30 gallons of source water added and 30 gallons of concentrated waste removed from the greywater system each week, the prototype wash water system produced 420 gallons of clean water each week to typical household water fixtures (shower, sinks, laundry machine) – 58 gallons of wash water (for hygiene purposes) and at least 2 gallons of drinking water per day. During the testing period, influent and effluent water quality samples were taken from and analyzed at the university laboratory and at a certified offsite laboratory for an array of water quality and microbiological parameters. The three water systems and the produced water qualities are described below.

Toilet system

The toilet system for the UAA AWSC system was completely separate from the drinking water and wash water (greywater reuse) systems, and therefore is an individual module that can be modified independently of the other parts. Two different toilet configurations were used in the pilot system. Initially, a ceramic low-flow dual-flush toilet was installed that diverted flushwater,

urine and feces into a sealed 60-liter stainless steel haul container. The toilet used 0.3 liters (<.01 gal) of wash water to flush urine and 2.5 liters (0.7 gal) of wash water for a full flush for feces. The container therefore had to be replaced with an empty container 1-2 times per week depending on use, and approximately 60 liters (16 gal) of water had to be input into the wash water system to replace the loss of water from the toilet, since that water was not being recycled and reused like at other fixtures. Having a ceramic flush toilet was a specific request of the partner community members in Kipnuk and Koyukuk during initial end user feedback conversations, so this toilet configuration was piloted for several months to demonstrate that a flush toilet could be incorporated into the water reuse system.

The second toilet configuration was to use a Separette Villa urine-diverting dry toilet that would reduce hauling and water treatment costs by eliminating the use of wash water for toilet flushing. In this configuration, urine was diverted into a sealed tank or infiltrated directly into the ground on-site and solids were dried and hauled off-site or burned on-site. Many rural Alaskans are familiar with the Separette-style toilet because of the challenges of hauling large quantities of wastewater (including flushwater) from the home, but they are not preferred in many communities because they are considered unmodern. However, this toilet configuration puts no burden on the wash water/water reuse system and provides no additional haul effort, similar to continued use of honeybuckets or outhouse (pit latrines) in the villages.

Drinking water system

The drinking water system was designed to use the best quality source water and produce the highest quality water within the pilot system. Source water of the homeowner's choosing is poured into a 6-gallon drinking water tank for pre-treatment storage and then is pumped on demand at 1.1 gallons per minute (GPM) through a 1 micron cartridge
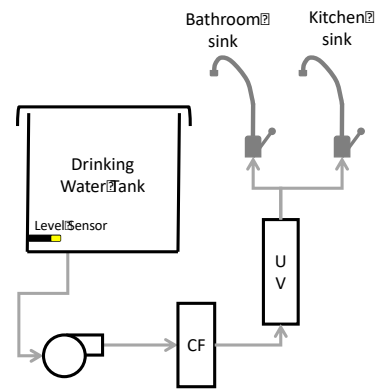
Figure 6: Drinking water treatment schematic

filter to remove debris. After filtration, the water is pushed through a low-pressure ultraviolet disinfection unit and dosed with at least 40 mJ/cm^2 (milli-Joules per centimeter squared) of UV light before being dispensed through a specified and separate drinking water faucet (Figure 6).

The drinking water tank and treatment system can be contained in a single cabinet within the home (e.g. underneath a kitchen counter) and drinking water faucet spigots can be located anywhere throughout the home (e.g. at the kitchen sink and bathroom sink). Treated washeteria water is the recommended source of drinking water since the system is designed to only provide microbial protection in waters with low turbidity (<1 NTU) and high ultraviolet transmittance (>95%). However, the system can provide additional drinking water quality enhancement to rainwater or surface water sources as well if they are preferred by the homeowner.

The drinking water system was tested three times during the pilot demonstration period. Water samples were sent to a certified laboratory in Anchorage where metals, mercury, fluoride, nitrate, nitrite, cyanide, VOCs, Total Coliforms and *E. coli* were measured (Table 5).

Table 5: Pre- and post-treatment drinking water quality compared to national standards (US Environmental Protection Agency 2017).

Measured Parameter (mean ± standard deviation)	Detection Limit (DL, laboratory)	Average Pre-treatment (n=2)	Average Post-treatment (n=3)	National Primary Drinking Water MCL
Metals scan: Barium (ug/L)	3.0	11.2 ± 0.3	12.5 ± 0.8	2000
Metals scan: Lead (ug/L)	0.200	0.834 ± .730	2.158 ± 1.17	Action Level = 15
Total coliform bacteria (CFU/100mL)	1	Not detected*	Not detected	0
***E. coli* (CFU/100mL)**	1	Not detected	Not detected	0
VOC: Bromodichloromethane (ug/L)	0.500	**	Not detected	0
VOC: Chloroform (ug/L)	0.500	5.41 ± 1.08	3.90 ± 3.47	70
VOC: Toluene (ug/L)	0.500	0.35 ± 0.49	0.18 ± 0.31	1000
VOC: Total Trihalomethanes (ug/L)	2.00	5.95 ± 1.17	4.03 ± 3.63	80
All other VOCs	Varies	Not detected	Not detected	Varies
Fluoride (mg/L)	0.200	0.513 ± 0.041	0.459 ± 0.087	4.0
Nitrate (mg/L)	0.100	0.341 ± 0.166	0.233 ± 0.114	10
Nitrite (mg/L)	0.100	Not detected	Not detected	1
Cyanide (mg/L)	0.0050	Not detected	Not detected	0.2
Mercury (ug/L)	0.200	Not detected	Not detected	2
*See team-identified challenge test information below. ***One of two samples contained 0.61 ug/L Bromodichloromethane, one was non-detect.*				

The treated drinking water was not significantly different from Anchorage tap water for any parameter and complied with USEPA drinking water standards (US Environmental Protection Agency 2017) for all three sample days.

In addition to evaluating normal operation of the drinking water system, two challenge tests were conducted on the drinking water system to simulate introduced contamination or use different than recommended. In one test, source tap water from the University of Alaska Anchorage was spiked with 1% secondary wastewater effluent from a nearby wastewater treatment plant to simulate contamination of drinking water during haul. Residual chlorine in the source water likely killed the bacteria before it was treated through the drinking water system,

because Total Coliforms and *E. coli* were not detected in pre- or post-treatment samples. In a second test, source tap water was stored in the pre-treatment storage vessel within the demonstration home for five months and had a biofilm growing within the vessel prior to treatment to simulate disuse of the drinking water system or not cleaning the storage vessel. Pre-treatment samples were not analyzed for this test, but post-treatment samples were normal for all parameters.

Wash water system

The wash water system is intended to produce water for human contact but not human consumption, and was designed to meet all US EPA drinking water regulations but to be used only for washing and hygiene purposes, including handwashing, bathing, showering, dishwashing, house cleaning and clothes washing. The system was required to reliably provide 60 gallons of water per day. Challenge tests were executed that altered the normal flow regimes, challenged the physical components of the system and added additional contaminants to the system, and the treatment system configuration was adjusted when problems were identified to reach the goal of producing sufficient quantity and quality of reused water. Several different configurations of the pilot treatment system were tested over the 10-month demonstration period. The final version was operated from February 27 through July 5, 2017.

Pilot system description

In the final pilot system, the wash water system was operated through simulated use of a kitchen sink, bathroom sink and shower in a small house on the University of Alaska Anchorage campus. The fixtures were plumbed to use wash water from a treated reuse water storage tank based on a daily schedule that simulates home hygiene activities for a household of four people.

When wash water is dispensed through a fixture, synthetic concentrates containing household and personal hygiene products, food, dust, and secondary effluent from a wastewater treatment plant are simultaneously dispensed down the fixture drains to simulate inputs from actual hygiene uses. The combined wash water and synthetic concentrates create synthetic greywater that meets ANSI – NSF350 water reuse requirements (NSF International 2011). A laundry machine was not included in the household operation during this period, but laundry greywater was simulated in the system by allocating additional flow to the shower and dispensing a concentrated laundry greywater recipe into the shower drain. Each fixture operating within the house had a 50-mesh screen connected to its drain inside the home for pre-treatment before the greywater flowed to a collection tank in the treatment unit.

The treatment unit sat on a skid and fit into a 10ft connex shipping container or in a vestibule inside or next to the home. The skid consisted of four 90-gallon tanks that contained water through different stages of treatment (Figure 7). Only two tanks were full at any given time and the others contained 5-15 gallons of water. Greywater flowing from the house fixture pre-treatment was collected in the greywater tank where soap was removed via an Skimz Monzter SM253 DC Internal protein skimmer that was constantly cycling the greywater. Greywater (GW) was held in this tank until there was enough to warrant a treatment cycle. At the beginning of the treatment cycle, the wash water (WW) tank and nanofiltration (NF) feed tank were nearly empty, and the reverse osmosis (RO) membrane feed tank was nearly full with partially treated water from a previous treatment cycle. At the beginning of the treatment cycle, the GW tank was pumped through three cartridge filters of decreasing pore size (1um, 0.45um, 0.2um nominal) into the NF feed tank. The NF feed tank remained full while the RO feed (ROF) tank contents were pumped across a DOW Filmtec LC LE4040 reverse osmosis membrane, the concentrate

was returned to the ROF tank and the permeate stream was sent through two Viqua VH200 UV disinfection units in series before being stored for future use in the wash water tank. Then the NF feed (NFF) tank contents were treated across a DOW Filmtec NF 270 nanofilter membrane, the concentrate was returned to the NFF tank and the permeate went to the RO feed tank to refill for the next treatment cycle. Membranes and plumbing were rinsed with wash water after each treatment cycle to avoid biological regrowth and contamination between water qualities which used the same pump and plumbing sections. The WW tank was periodically ozonated to stop pathogen regrowth and maintain freshness of the water. This process was repeated daily to provide up to 60 gallons (230 liters) of water for household use, or more frequently for a larger volume for daily use.

Because concentrates from the NF and RO membranes were sent back to their respective feed tanks for retreatment, the treatment cycle ended with 5-10 gallons of concentrated water in the NF and RO feed tanks. The NF feed tank concentrate was removed to an integrated waste haul container on the skid twice per week and the RO feed tank concentrate was removed once
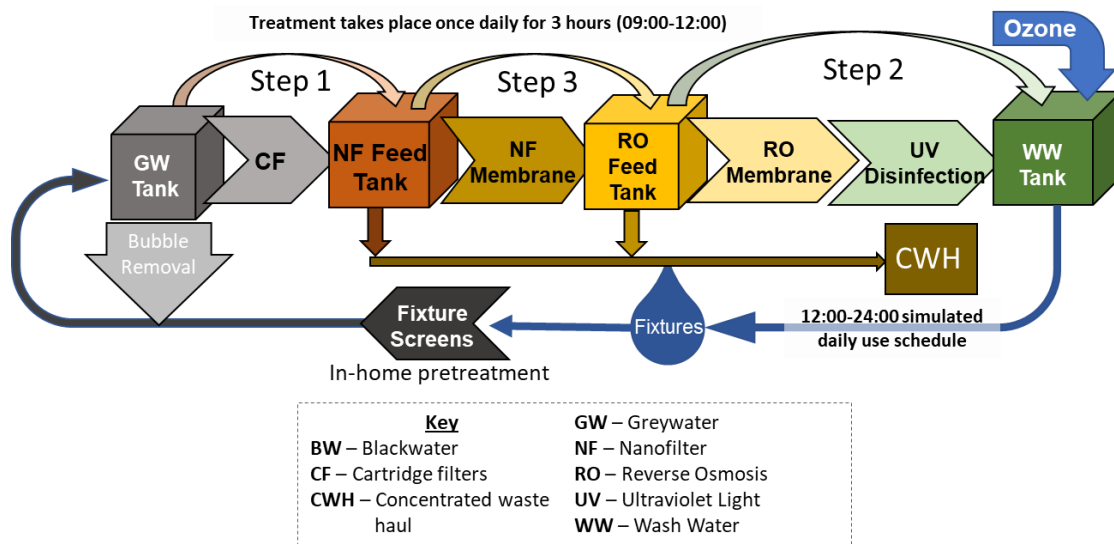
Figure 7: Wash water reuse/treatment system diagram showing the processes and chronology of the water treatment process.

per week. The waste haul tank was sealed and had a submersible pump in the bottom connected to a garden hose to allow for easy access and emptying. The waste haul container was emptied once per week, resulting in a total waste volume removed each week of approximately 30 gallons (120 liters). An equal volume of replacement water from tap, rainwater collection or surface water sources was then added once a week through the fixture drains inside the home.

Water quality analysis methods

To analyze the performance of the system and the quality of the produced wash water, samples were collected from each of the tanks at least three times per week during the pilot system operation through metal taps that drained from the bottom of the tanks. Sample taps were sterilized with 70% ethanol and wiped with a clean cloth before sampling. Bacteria samples were collected in sterile HDPE sample bottles and other water quality samples were collected in furnaced glass vials. Turbidity, pH, conductivity of each sample collected during the test period was analyzed within six hours of sample collection at the UAA water chemistry laboratory. Turbidity (NTU) was measured on a HACH 2100Q portable turbidimeter. pH was measured with a Thermo Scientific Orion Star A324 pH probe and conductivity (mS/cm) was measured with a Thermo Scientific Orion Star A222 conductivity probe. Samples were then refrigerated at 5 degrees Celsius for 5-15 days before Total Organic Carbon (TOC, mg/L) was analyzed on a Shimadzu TOC-L CSH analyzer and ultraviolet absorbance (UVA) at 254nm wavelength was measured on a Cary 60 UV Vis spectrophotometer. Wash water samples were analyzed for Total Coliform and *E. coli* once a week during operation and other tanks were analyzed infrequently. Total Coliforms (CFU/100mL) were enumerated by serially diluting the water samples, filtering 1 mL of sample through a 0.45-micron membrane on vacuum manifold, rinsing with 20-40 mL of sterile water and placing the membrane in a petri dish containing an absorbent cellulose pad soaked with 2mL of m-Endo broth (National Water Quality Monitoring Council 2017a). *E. coli*

(CFU/100mL) were enumerated through the same process but using HACH m-ColiBlue24 broth (National Water Quality Monitoring Council 2017b) on the cellulose pad. Greywater samples were only analyzed for conductivity and turbidity from this period, but greywater tank data was averaged with samples from previous prototype configurations because influent recipes did not change during the entire development and testing period.

Additional wash water samples were collected twice a month and sent to a certified laboratory to be analyzed for color (SM21 2120B), odor (SM21 2150B), and MBAS (SM 5540C).

Water quality throughout the treatment system
Feed tank water quality

The GW, NFF and ROF tanks showed large variation over time across all parameters measured (Table 6). This is likely attributed to the cycle of concentration of wastes over a week-long period of operation. pH of all tanks varied but was usually in the normal range of 6-8. Water quality did not improve during the first treatment step between the GW and NFF tanks because the contribution of the cartridge filters towards water treatment was obscured by the concentrating of waste from the nanofiltration membrane rejection line. Bacteria, TOC and turbidity were considerably lower and UVA was higher in the ROF tank as compared to the NFF tank.

Table 6: Water quality characteristic summaries for each tank in the wash water treatment system. In each cell, top line is average, middle line is range and bottom is number of samples.

	Greywater Tank	Nanofiltration Feed Tank	Reverse Osmosis Feed Tank	Wash Water Tank	AWSC WW contract requirements
Total Coliforms (CFU/100mL)	10^8 $10^6 - 10^9$ n=25	10^8 $10^7 - 10^8$ n=17	10^7 $10^5 - 10^7$ n=16	Not detected* Not detected n=19	Not detected
***E. coli* (CFU/100mL)**	10^6 $10^4 - 10^7$ n=8	10^6 $10^5 - 10^7$ n=9	10^4 $10^2 - 10^5$ n=10	Not detected Not detected n=17	Absent
Conductivity (mS/cm)	1.136 0.095 – 6.827 n=155	0.699 0.101 – 2.943 n=60	0.996 0.188 – 3.623 n=60	0.017 0.004 – 0.087 n=67	Not specified
pH	6.9 6.1 – 8.1 n=114	6.9 6.3 – 7.7 n=60	7.3 6.5 – 8.4 n=60	6.66 5.57 – 7.74 n=64	6.0-9.0
TOC (mg/L)	201.5 0.2 – 973.8 n=105	196.0 19.3 – 775 n=61	21.2 2.5 – 194.8 n=60	0.7 0.2 – 1.6** n=68	10 mg/L
Turbidity (NTUs)	50.0 1.2 – 203 n=141	109.9 3.5 – 493 n=60	8.9 0.8 – 81.4 n=60	0.13 0.07 – 0.23 n=67	Avg: 5 NTU Max: 10 NTU
UVA254 (cm^{-1})	No data	1.5 0.2 – 3.7 n=59	0.20 0.03 – 1.60 n=59	0.003 0 – 0.016 n=68	Not specified
Color	No data	No data	No data	Not detected	Not specified
Odor	No data	No data	No data	< 4.75 < 1.0 – 13.5 n=5***	"Not offensive"
Oil film and foam (MBAS)	No data	No data	No data	Not detected	Not detectable

*Two additional Total Coliform samples detected 1 and 10 CFU/100mL (June 4 and 8, 2017 respectively) when the ozone in the wash water tank was turned off to simulate a failure scenario during the household illness challenge test described below.

**TOC of 9.62 mg-C/L was measured once upon startup of Version 2 when a new RO membrane was loaded without any rinsing to clean out chemical preservatives.

***Three of the five samples were non-detect for odor. Odors of 13.5 and 7.27 were detected on 20 March and 18 April 2017 respectively. These are attributed to the end of a membrane life or new membrane installation. The ozone in the wash water tank was turned off in June 2017 for a household illness challenge test, resulting in odor detections of 30.6 (7 June 2017) and 19 T.O.N. (13 June 2017). These two samples are not included in the summary statistics in the table.

The wash water quality was very stable (Figure 8) and met all contract requirements established by ADEC as part of the Alaska Water and Sewer Challenge. Total coliforms and *E. coli* were absent (except for two samples at very low levels, discussed below). Conductivity was low and pH was in the required range in most samples. Turbidity and TOC were on average 10x lower than the contract requirements. Color and MBAS were not detected in any samples.

The changing of RO membranes was associated with abnormally high TOC (9.62 mg/L) in at least one instance. The ozone component of the system was added to ensure that bacteria regrowth did not affect stored wash water and to improve odor with higher water age if the

Figure 8: Wash water quality parameters from final pilot system configuration.
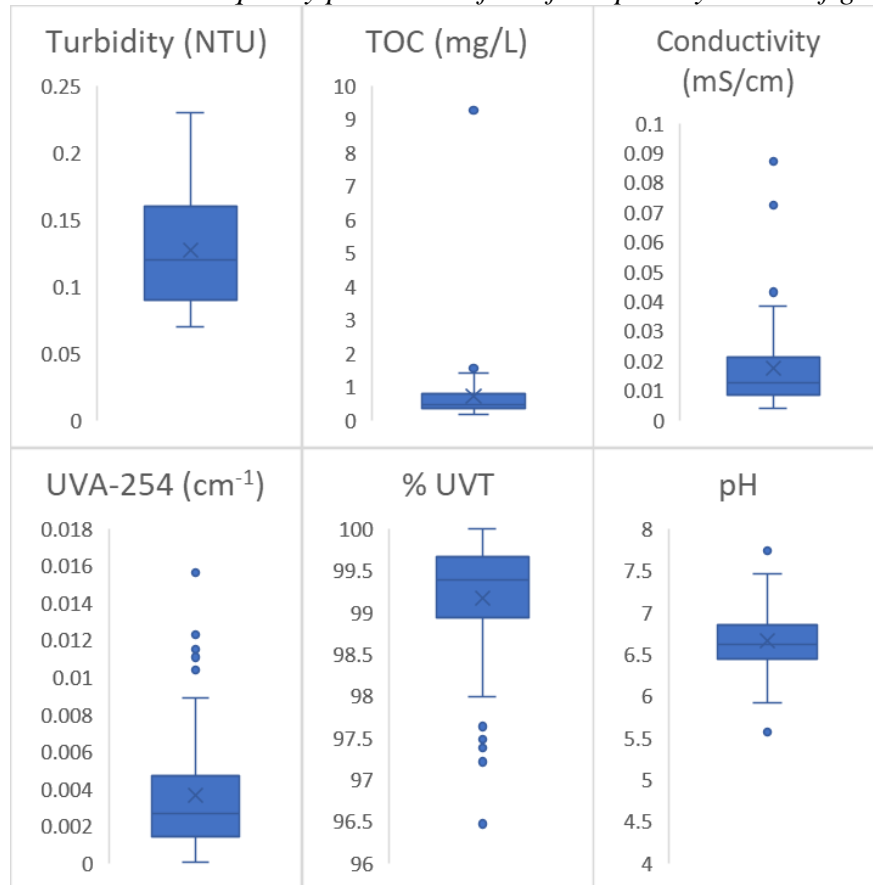
system was unused for several days. While the system operated at desired water quality specifications most days without ozone, two positive bacteria samples and two positive odor detections were seen when the ozone was turned off.

Water quality during stress tests

The pilot system was challenged under a variety of different daily flow regimes and intermittent periods of disuse to ensure that consistent wash water quality was produced during abnormal use. These tests are described in NSF350 (wash efficiency stress, power/equipment failure, wash vacation stress, and wash surge stress) and no significant change in wash water quality was observed when these changes were made. To assess the durability of the system in winter conditions, the system was shut down and allowed to freeze for three weeks in December 2016. Upon restart, water of acceptable quality was produced with minimal repairs required.

In addition to the flow and equipment challenges, three contaminant challenge tests were performed on the system which are described below along with the water quality results. A Pine-sol challenge test was performed where Pine-sol cleaning solution was used to mop the floor of the house and the mop bucket was dumped down the drain. There was no noticeable change in any water quality parameter after the challenge test with most parameters at undetectable levels, pH=6.3 and conductivity=9.8 mS/cm.

A urine challenge test was performed where urine was added to the shower drain daily for four days to simulate someone urinating in the shower. Internal wash water quality samples indicated no noticeable changes in any water quality parameter after the challenge test. During this period, the wash water conductivity was 0.009 mS/cm, pH was 6.78, turbidity was 0.11 NTU, and TOC was 0.44 mg/L. Certified samples analyzed three days after the urine challenge

test showed no significant differences from normal weeks, with a pH of 6.5 and conductivity of 6.2 mS/cm.

Finally, a gas/oil challenge test where an oil/gas mixture was poured onto a rag and washed into the sinks in the house to simulate someone repairing four-wheelers and snow machines at home, as is common in rural Alaska. For 14 days after washing this mixture into the kitchen sink, benzene, ethylbenzene, toluene and xylene (BTEX) samples were taken daily to be analyzed at ARS Aleut Analytical, LLC. There was no noticeable change in any wash water quality parameter after the challenge test with most parameters at undetectable levels. The pH of the wash water was 6.5 and the conductivity was 6.7 mS/cm. Samples were taken and sent to an external laboratory from May 16-29, 2017 to sample for Benzene, Toluene, Ethylbenzene and Total Xylenes. None of these compounds were detected during this time period.

The completion of these challenge tests demonstrates that the pilot system can produce consistently high-quality wash water under normal and abnormal operation circumstances and can handle some misuse while still providing safe water.

Hauled waste hazards and risks

Because the household treatment system is likely to require that homeowners have a larger-than-normal role in operating and maintaining their system and that they may be responsible for disposing of concentrated waste, the concentrated waste haul container water quality was measured twice during the pilot system operation. The waste haul was found to have $10^{8.5}$ CFU/100mL of Total Coliforms and $10^{6.7}$ CFU/100mL of *E. coli*. The average turbidity was 230 NTU, conductivity was 3.23 mS/cm, pH was 7.0, and TOC was 193.7 mg/L. The high levels of bacteria are of concern, and a sanitary hauling process and best practices must be put in place to ensure that the person responsible for hauling the waste is protected.

Whole household illness simulation
Introduction

Onsite household water reuse is an innovative approach to decreasing the incidence of water-washed diseases in unserved rural Alaskan homes. However, recycling the water of a single home repeatedly could lead to an accumulation of hazardous chemicals and pathogens that are connected to household exposure or behaviors. Although some evidence points towards larger multi-user building reuse systems having higher risk of pathogen exposure due to longer pipes, more people, longer water residence times and more cross-connections, (Sharvelle et al. 2017) individual household systems with irregular water quality monitoring and high operation and maintenance requirements from homeowners present a different set of risks. For example, an entire family contributing greywater to a household reuse system is more likely to be exposed to pathogens and become sick at the same time than is an entire village contributing to a more centralized treatment system. Use of a single household reuse system could result in a higher pathogen concentration entering and lingering in the household wastewater system. The minimum infectious doses of viruses can vary from $<10^{-2}$ to >10 viruses/mL depending on the type of virus, method of exposure, and health of the individual (Yezli and Otter 2011; Schiff et al. 1983), therefore even small numbers of pathogens ending up in wash water could be harmful to a household (Gerba and Haas 1988).

To determine whether pathogens collect and ultimately break through treatment barriers (Hu et al. 2003) in a household-scale system, the AWSC wash water system was challenged with a virus and monitored daily for two weeks. The aim of this study was to determine how much virus removal occurs at each step of the treatment process, whether pathogens collect in the water reuse system and breakthrough treatment barriers, and whether pathogens could ultimately

get into finished hygiene water and re-expose family members to disease. Pathogens could collect in the water reuse system at very high concentrations and breakthrough treatment barriers. High stability (slow die-off) of enteric viruses in greywater over time (Rose et al. 1991) suggests that pathogens could linger in wastewater haul tanks and re-expose family members to disease when they haul waste.

Within the UAA AWSC pilot system, only the wash water system was tested for a whole home illness. The drinking water system does not recycle and uses high quality source water. The toilet system is sealed for hauling to prevent exposure during haul. Because the drinking water and toilet pose minimal risk for re-infection exposure, they were not included in the whole household illness grey water recycling system challenge test.

Methods
Whole household virus challenge and monitoring

A whole household illness challenge was performed June 3-22, 2017 by spiking the pilot system with the F^+-specific RNA coliphage MS2 (ATCC 15597-B1) and quantifying virus concentrations after each component of the treatment system. MS2 is an enteric virus surrogate and was chosen as a worst-case scenario to assess re-infection potential because of its greater resistance to disinfection versus bacterial pathogens, and its structural and physical similarity to pathogenic human viruses such as norovirus (Dawson et al. 2005) and adenovirus (Valegard et al. 1990).

Prior to the virus challenge, the stability of MS2 was examined in water from each of the four water treatment tanks (GW, NFF, ROF and WW) over a 24-hour period. During the virus challenge, 10^{11} PFU/mL (plaque-forming units per mL) MS2 was spiked daily into the fixture drains (185 mL into the shower, 55 mL into the kitchen sink, and 65 mL into the bathroom sink)

from day 0-6 (Figures 9-10). Each day, approximately 60 gallons (230 liters) of wash water and synthetic greywater concentrate also flowed into the fixture drains through 50-mesh stainless steel screens during normal operation of the pilot system (see above), accumulating in the greywater tank over a 12-hour period. The GW and ROF tanks ("ROFpre" samples) were sampled approximately 20 hours after the daily spike and before the daily batch treatment began. The nanofilter feed tank was sampled one hour later after the first treatment step was complete and the NFF tank was full. The pre-UV samples were collected during the second treatment step while water was being treated from the ROF tank across the RO membrane and through the UV unit from a plastic valve sterilized with 70% ethanol and wiped down with a clean cloth. While pre-UV samples were being collected, a valve connecting the RO membrane effluent line to the UV unit was closed to ensure that no UV-treated water back-flowed into the sample container. The ROF ("ROFpost" samples) and WW tanks were sampled immediately after treatment when they were full each day (Figure 9). All samples except pre-UV were collected via metal taps that drained from the bottom of the tanks and were sterilized with 70% ethanol and wiped with a clean cloth. Although the wash water system is designed to have two UV reactors in series and periodic ozone dosing of the WW tank during normal operation, only a single UV unit was turned on during the whole household virus challenge and the ozone was turned off. Microbiological samples were collected in sterile HDPE sample bottles and other water quality samples were collected in furnaced glass vials.
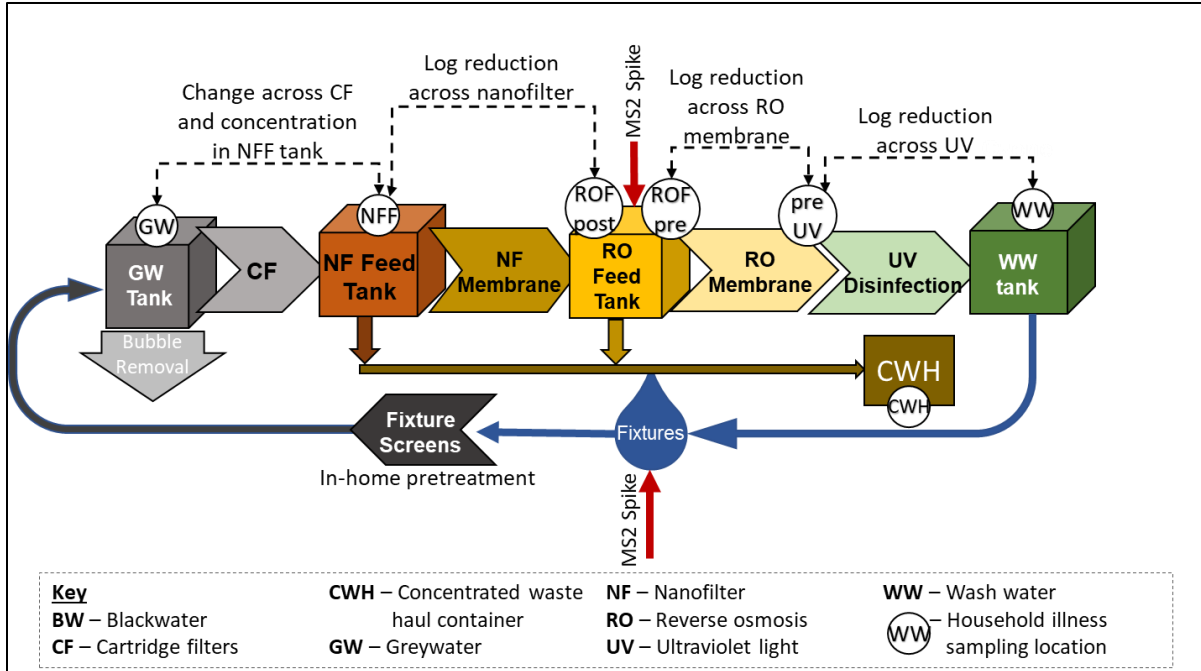
Figure 9: Household virus challenge spike and sampling schematic
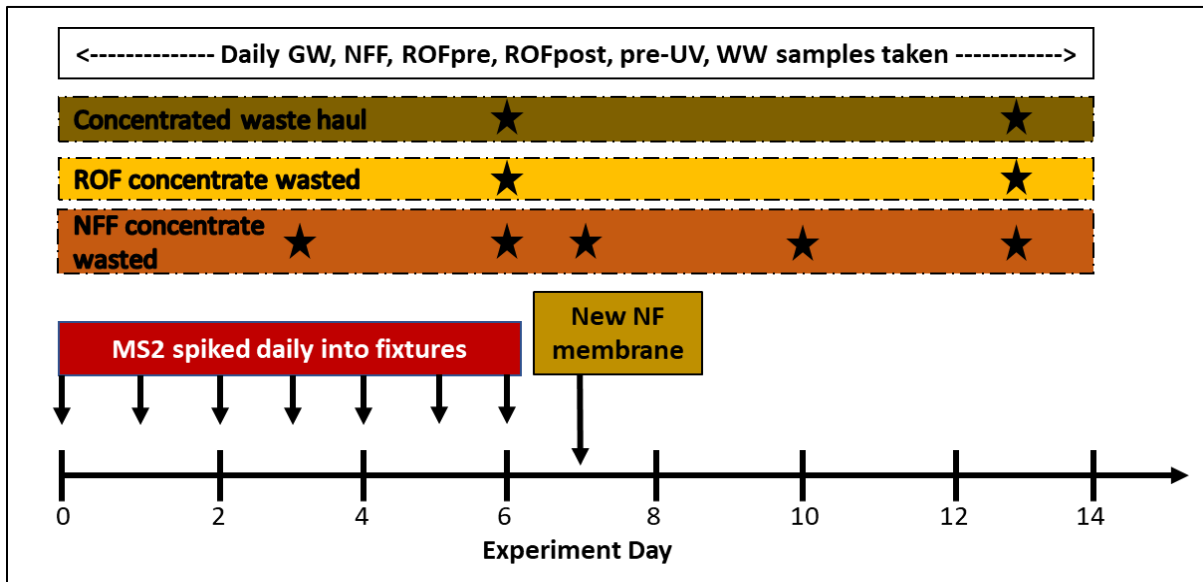
Figure 10: Household virus challenge timeline

After the seven-day spiking period, samples continued to be taken from all sample locations on the same schedule as described above daily from days 7-13 to monitor virus persistence within the reuse system after the loading period ended. The concentrated waste haul tank was sampled on the designated haul days during the testing period (day 6 and 13) to examine the virus concentration within the hauled waste.

Throughout the whole household virus challenge experiment, the system was operated normally (as described above). Concentrated waste from the NFF and ROF tanks was moved from the tanks to the concentrated waste haul container on regular semi-weekly and weekly schedules respectively. The concentrate waste haul tank was emptied weekly. On day 7 the NF membrane reached its minimum flux and was replaced, and the concentrated waste from the NFF tank was moved to the concentrated waste haul container during the replacement process.

System component virus challenge

Virus reduction across the reverse osmosis membrane was quantified individually on June 22, 2017 when 3000 mL of 10^{12} PFU/mL titer MS2 was spiked into approximately 300 liters (80 gal) of water in the reverse osmosis feed tank and allowed to mix turbulently as the batch of water was treated across the DOW Filmtec LE LC 4040 reverse osmosis membrane. Samples were collected immediately before treatment started from the reverse osmosis feed tank and twice during treatment from a sampling tap located after the reverse osmosis membrane and before the UV reactor.

Disinfection capability of the UV system was quantified individually with a bench-scale test because spiking virus into the pilot system immediately before the UV reactor was logistically infeasible. Instead, 30 liters of dechlorinated tap water were spiked with MS2 to achieve at least 10^6 PFU/mL and pumped through a single Viqua VH200 at 0.8, 1.0 and 1.2

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GPM to simulate flow through the pilot system UV system. Water samples were collected of the source water at the beginning and end of the experiment and of the UV effluent three times while the pump was running. The UV transmittance of the spiked water was modified using Lignon Sulfonic Acid (LSA) to quantify the range of virus reduction across influent water with 70%, 90% and 97% UV transmittance. The UV reactor was rinsed with at least 60 liters of clean dechlorinated tap water between each water quality and each water quality was run on a different day. Concurrent with each Viqua VH200 experiment, the same influent water was aliquoted into 4mL petri dishes and exposed in duplicate to 0, 20, 40, 60, 80, 100, and 120 mJ/cm^2 of collimated low-pressure ultra-violet light (Bolton and Linden 2003).

Water quality analyses
Turbidity (NTU, HACH 2100Q portable turbidimeter), pH (Thermo Scientific Orion Star A324), and conductivity (mS/cm, Thermo Scientific Orion Star A222) of each sample collected during the test period was analyzed within six hours of sample collection at the University of Alaska Anchorage water chemistry laboratory. Samples were then refrigerated at 5 degrees Celsius for 5-15 days before TOC analysis (non-purgeable organic carbon on a Shimadzu TOC-L CSH analyzer) and ultraviolet absorbance (UVA) at 254nm measurement (Cary 60 UV Vis spectrophotometer). Total Coliforms (CFU/100mL) were enumerated by vacuum filtering 1 mL of serial dilutions (GW, NFF, ROFpre, ROFpost) or 100mL of sample (pre-UV, WW) through a 0.45-micron membrane, rinsing with 20-100 mL of sterile water and placing the membrane in a petri dish containing an absorbent cellulose pad soaked with 2mL of m-Endo broth (National Water Quality Monitoring Council 2017a). Bacteria plates were incubated at 36 degrees Celsius for 24 hours and enumerated using a light and handheld counter.

For the household illness simulation, MS2 samples were held on ice for up to 6 hours after sample collection and then frozen at -20 degrees Celsius for up to one month before being shipped to GAP EnviroMicrobial Services Ltd. for analysis. GAP analyzed MS2 samples by adding one mL of (pFamp)R *E. coli* (ATCC 700891), 20 mL of molten Trypton Yeast Extract Glucose agar with triphenyl tetrazolium chloride and 1-2 mL of serially-diluted sample to a culture tube, mixing by inversion, and pouring the agar into a sterile Petri dish. Plates were incubated at 35 degrees Celsius for 18-24 hours. Clear, round plaques were counted and results were reported as plaque-forming units per milliliter of sample (PFU/mL). Duplicates were run of each sample and an arithmetic mean was taken for final data analysis. For bench tests of the UV, samples were serially diluted within six hours of collection and 0.1mL of sample was added to 0.1mL of log-phase Famp *E. coli* and 10 mL of autoclaved double-strength tryptic soy agar with ampicillin and streptomycin in a sterile glass tube. Tubes were mixed by gently rolling them upright between the hands and poured into a sterile petri dish (US Environmental Protection Agency 2001). All samples were plated in duplicate. Plates were incubated at 35 degrees Celsius for 14-18 hours. Clear, round plaques were counted with a light and magnifier and results were reported as [Number of plaques counted on all plates containing a particular sample] ÷ [Total volume of original sample plated] PFU/mL. Sample replicates were averaged for final data analysis. If no plaques were observed at a 0 dilution, the concentration of MS2 was recorded as 1 ÷ [Total volume of sample plated], resulting in a method detection limit of 5 PFU/mL.

Data analysis

Daily water quality samples (conductivity, UVA-254, pH, turbidity and TOC) analyzed during the whole household virus challenge were averaged and compared to the same parameters from the wash water system before MS2 was introduced (where data was available) by two-

tailed t-tests with unequal variances. UVA-254 was converted to UV transmittance (UVT) using the formula $UVA = 2 - \log_{10}(UVT)$. Log_{10} reduction of viruses was quantified as $\text{LOG}_{10}(C_{before}/C_{after})$ for paired treatment steps (GW/NFF, NFF/ROFpost, ROFpre/pre-UV, pre-UV/WW) or for pre- and post-exposure for the bench Viqua and collimated beam tests, with C indicating the average concentration of MS2 (PFU/mL) across all replicates plated for a given day. The low-pressure UV light dose was plotted against the $\log_{10}$ reduction for the collimated beam experiment to obtain a quadratic equation relating the two variables for each UVT (Figure 15). This equation was used to determine a reduction-equivalent dose based on the $\log_{10}$ reductions calculated at each flow rate and UVT in the Viqua system.

Results
Water quality

The GW tank had significantly higher conductivity and turbidity during the MS2 spike than in samples prior to the virus challenge. The ROFpost samples were comparable to pre-spike data for conductivity and UVA-254, but pH and TOC were significantly lower and turbidity was significantly higher during the MS2 spike than previously. The WW tank samples were comparable to pre-spike levels on all parameters except TOC which was significantly lower during the MS2 spike than during the previous operation period (Table 7).

Table 7: Water quality summary for samples before and after MS2 fixture spike. ND = no data.

Tank Sample	Conductivity (mS/cm)		UVA-254 (cm^{-1})		pH		Turbidity (NTU)		TOC (mg/L)	
	pre-spike	MS2 spike	pre-spike	MS2 spike	pre-spike	MS2 spike	pre-spike	MS2 spike	pre-spike	MS2 spike
GW	0.173	0.230	ND	0.330	ND	6.34	13.8	21.0	ND	20.04
	p=0.05		ND		ND		p<0.001		ND	
NFF	ND	0.349	ND	0.641	ND	6.44	ND	34.9	ND	31.13
	No comparable data was available from the NFF tank prior to the MS2 spike.									
ROFpost	0.799	1.113	0.119	0.145	7.48	6.98	4.3	7.4	14.89	8.77
	p=0.23		p=0.29		p<0.001		p=0.04		p<0.01	
ROFpre	ND	1.033	ND	0.137	ND	6.88	ND	6.0	ND	7.67
	No comparable data was available from the ROF tank before treatment each day prior to the MS2 spike.									
pre-UV	ND	0.040	ND	0.002	ND	5.85	ND	0.11	ND	0.47
	No comparable data was available from the post-RO pre-UV line prior to the MS2 spike.									
WW	0.015	0.016	0.003	0.004	6.61	6.61	0.12	0.14	0.63	0.41
	p=0.77		p=0.06		p=0.99		p=0.07		p<0.01	

The GW tank, pre-UV, and WW tank water quality samples were consistent over time for all parameters except for a large day-to-day variation in the WW tank pH (Figure 11). The NFF tank parameters fluctuated predictably every 3-4 days coinciding with the NF concentrate wasting day (day 3, 6, 7, 10, 13): turbidity and TOC would decrease and UVT would increase immediately after the wasting day, while conductivity and pH stayed consistent throughout the wasting cycle. The ROFpre and ROFpost samples also showed weekly fluctuations with conductivity, turbidity, TOC and pH decreasing after the wasting day (day 6 and 13) and UVT increasing. The ROFpre tank showed these changes one day after the ROFpost tank due to the timing of the concentrate wasting versus sample collection times (Figure 7).

Figure 11: Conductivity, pH, TOC, turbidity, UVT and UVA in samples from six different points in the wash water treatment system during the whole household viral challenge with MS2.

Bacteria removal through the treatment process

Total Coliforms and *E. coli* were consistent in each tank throughout the experiment, with some small daily fluctuations (Figure 12). Total Coliforms occurred in the synthetic greywater on the order of 10^8 CFU/100mL and *E. coli* occurred at 10^6-10^7 CFU/100mL. No consistent and significant decrease in either indicator occurred between the GW tank and the NF feed tank because of regrowth and the concentrated waste that accumulates in the NF feed tank. Nearly 2-

log$_{10}$ reduction of both TC (total coliforms) and *E. coli* occurred across the nanofilter, and >4-log$_{10}$ reduction of both TC and *E. coli* occurred across the reverse osmosis membrane. Less than 10^2 CFU/100mL of Total Coliforms and no *E. coli* were detected in the pre-UV samples, so log$_{10}$ reduction could not be accurately measured across the UV unit.
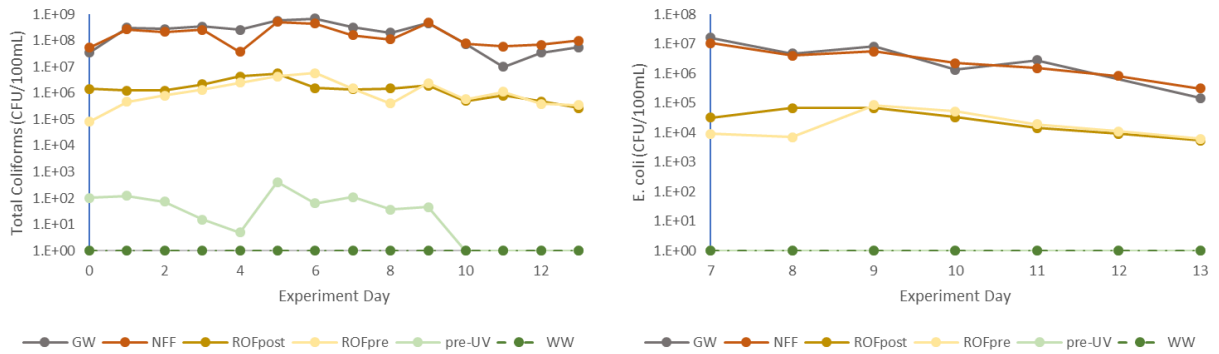
Figure 12: Total coliform (left) and E. coli (right) concentrations at six different sampling points in the wash water treatment system show relative stability in bacteria concentrations within each tank over time.

Virus removal through the treatment process

MS2 fluctuated less than one log and was therefore considered stable in water from each of the treatment tanks for at least 24 hours (Figure 13). The concentrations of MS2 at each sampling point over the entire experiment are shown in Figure 14. An initial concentration of > 10^7 PFU/mL of MS2 was achieved in the GW tank on each day of fixture spiking. During the seven-day spiking period, this concentration was maintained from the GW tank to the NFF tank. After the fixture spike period ended, the concentration of MS2 in the GW tank dropped to 10^4 PFU/mL over two days and slowly decreased on subsequent days. Because of the waste being concentrated in the NFF tank, after spiking, the NFF MS2 concentration dropped much more slowly to 10^5 PFU/mL after seven more days.
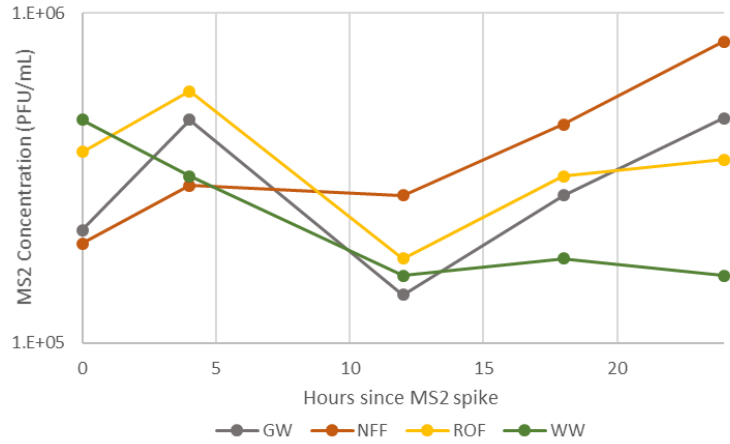
Figure 13: Concentration of MS2 in sample water from each tank in the treatment process over 24 hours during a bench-scale stability test.
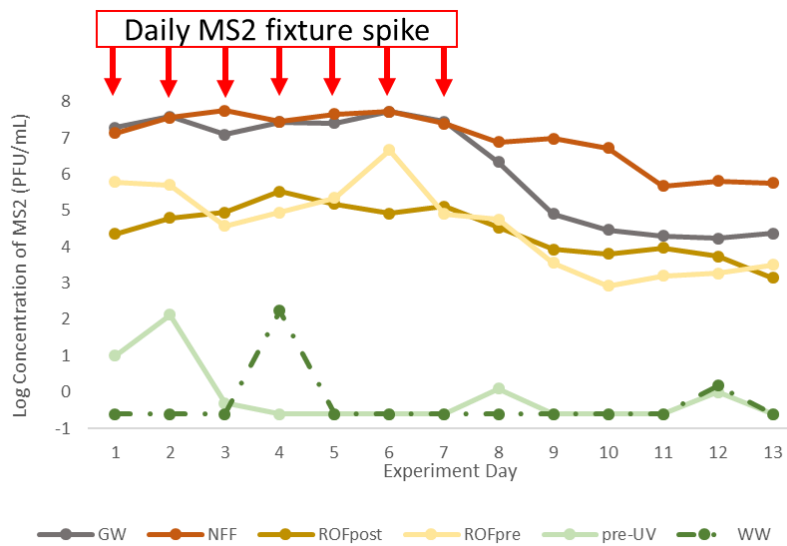
Figure 14: MS2 concentration within the treatment system during the seven-day fixture spike experiment and for seven days after daily MS2 spiking ended.

The nanofiltration membrane averaged 2.5-$\log_{10}$ reduction of MS2 over the 14-day test period. Average concentrations of MS2 in the ROF tank were $>10^5$ PFU/mL during the spike period, but dropped to slightly over 10^3 PFU/mL by the end of the experiment. Preliminary

experiments suggested $\log_{10}$ reduction across the RO membrane to be $>10^3$, so MS2 was spiked

directly into the ROF tank to quantify its treatment capacity. An initial MS2 concentration of

$10^{9.7}$ PFU/mL in the ROF tank was reduced to $10^{1.3}$ PFU/mL in the RO membrane effluent,

resulting in 8.4-$\log_{10}$ reduction of MS2.

MS2 concentrations in the GW, NFF and ROF tanks declined slowly after the seven-day

spiking period ended. MS2 was detected at low levels in four pre-UV sample during the entire

experiment, and only two WW samples were above the detection limit (Figure 14).
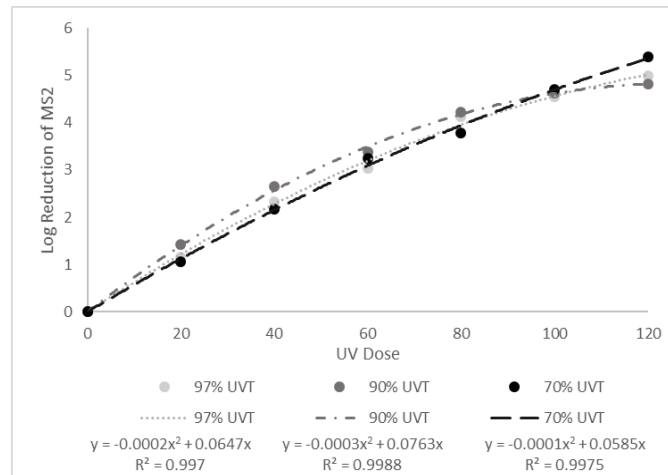
*Figure 15: Log$_{10}$ reduction curves of MS2 in a low-pressure UV
collimated beam reactor for waters with three different UVTs.*

The Viqua VH200 system demonstrated a 5.5 to 7-$\log_{10}$ reduction of MS2 at 97% UVT

and a flow rate of 0.8-1.2 GPM (Figure 16). $\log_{10}$ reduction decreased to 5-5.7 $\log_{10}$ of MS2 at

90% UVT and to 3-4.6 $\log_{10}$ of MS2 at 70% UVT (Figure 16). The average UVT of treated

water immediately before UV disinfection (pre-UV) in the pilot system is $>99\%$ (Table 7). At

this UVT and 1.0 GPM flow rate, a single Viqua VH200 system is expected to deliver

approximately 200 mJ/cm^2 (Figures 15-16) of low-pressure ultraviolet radiation to disinfect the

wash water before use. This dose decreases as UVT decreases or as flow rate increases. If the

UV disinfection were applied to water immediately after nanofiltration but without with RO treatment step, the UVT would be 71-76% and the reduction equivalent dose would be less than 100 mJ/cm^2 (Figures 15-16).
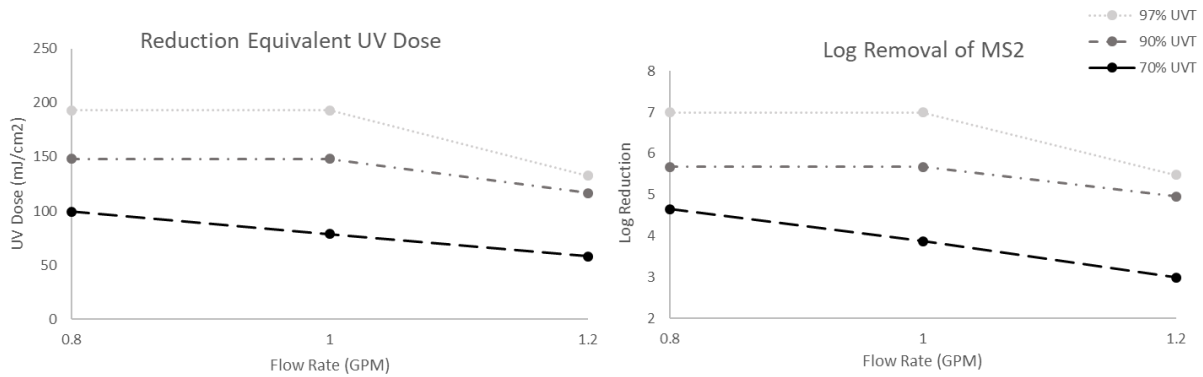
Figure 16: Reduction equivalent dose and log$_{10}$ reduction of MS2 for the Viqua VH200 UV component of the wash water treatment system.

Concentrated waste haul results

The concentrate waste haul container had an average conductivity of 2.79 mS/cm, pH of 6.9, turbidity of 164 NTU and TOC of 172 mg/L. Total coliforms were detected at $10^{8.6}$ CFU/100mL and *E. coli* at $10^{6.6}$ CFU/100mL. The waste haul container had an MS2 concentration of $10^{8.1}$ PFU/mL on day 6 of the spiking experiment and dropped to $10^{7.1}$ PFU/mL by day 13, six days after spiking ended.

Discussion

Bacteria and virus removal in wash water treatment system

The pilot water reuse system demonstrated high log$_{10}$ reduction of virus: 2.5-log$_{10}$ across the NF membrane, 8.4-log$_{10}$ across the RO membrane, and >7-log$_{10}$ from single UV unit. The total potential of this system is at least 18-log$_{10}$ reduction of virus and at least 8-log$_{10}$ bacteria based on naturally-occurring microbes. Use of a different endogenous bacteria performance surrogate such as *Staphylococcus* (Shoults and Ashbolt 2017) or evaluation of bacteria reduction

by a spike test would likely give higher and more accurate estimates of bacteria reduction in the treatment train.

During the seven days of spiking, MS2 concentration in each tank immediately hit a maximum and did not accumulate over that maximum during subsequent spiking, suggesting that break-through of the treatment and disinfection processes may not be a concern in this system. The system was tested with a single UV disinfection unit providing an estimated dose of 200 mJ/cm^2 of UV light to the finished wash water, however the pilot system is normally run with two UV units in series followed by periodic ozone dosing in the wash water tank to maintain the freshness of the water and prevent regrowth of pathogens. These added steps should result in a much higher total protection against microbial pathogens.

The water quality parameters measured fluctuated between tanks, over time, and from pre-MS2 spike levels to the levels observed during the household virus challenge. While finished (WW) water quality was always very high and free of viruses and bacteria, the fluctuations in the intermediate tanks may cause undesirable stress on the membranes or lead to operation issues in the long term. The NF membrane had to be replaced after only seven days during the MS2 fixture spike, which was 1-3 weeks earlier than the normal replacement schedule and could be related to the virus fouling the membrane and leading to shower operation of the treatment system. Additional data on how and why different water quality parameters change over time and whether they can be used as indicators for maintenance tasks or as alarms for changes in WW quality would be beneficial for future systems.

Water reuse infection risk

MS2 was highly stable in each tank over time, and the very slow ebb in MS2 concentrations of the GW, NFF and ROF tanks and the high concentration of MS2 in the

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concentrated waste haul container after 14 days suggests that viruses can linger in the treatment system for weeks or months after it is initially introduced. The concentrating process in the NFF and ROF tanks and the recycling of water within the system with minimal haul-in and haul-out requirements could represent a risk when high concentrations of a pathogen are introduced to the system. This risk is directly relevant to members of the household if homeowners are responsible for hauling concentrated waste out of the system. As with the toilet system described above, a sealed sanitary haul system must be developed to limit re-exposure to viruses during haul. In many Alaska villages, wastewater is disposed of in open sewage lagoons where the risk of community members being exposed to pathogens is high and dependent on community and environmental conditions. An equally or more important challenge than establishing a high-tech household water treatment system is ensuring that all wastewater streams are safely and properly disposed of in rural Alaska.

Even though the virus signature lingered at high concentrations for over a week after spiking ended and even though the concentrate haul container had high levels of the virus in the waste to be hauled, the pilot system produced high quality wash water for over two weeks. The small numbers of viruses detected in the WW on day 4 and 12 are more likely to indicate false positives or contaminated samples than they are to be indications of systematic virus breakthrough into the finished wash water. However, because many human enteric and respiratory viruses have very low minimum infectious doses and a high range of infectious doses, it is critical to ensure that wash water is completely free of pathogens. The use of both UV disinfection units and periodic ozone dosing (Shin and Sobsey 2003) in the wash water tank is likely to provide this extra protection.

Other pilot system performance targets

In addition to the requirement of the system providing 60 gallons of water per day of acceptable quality for drinking and hygiene purposes, the Alaska Department of Environmental Conservation outlined several other performance targets for the AWSC, described below.

Capital cost per system

ADEC defined that the capital costs for a single household system cannot exceed $160,000 including freight, equipment, materials, labor, installation, water heater and indoor plumbing. The UAA system total meets this requirement with a single system capital cost of approximately $136,300 which increases to $155,600 if 12-month operation costs and cooperative development costs are included (Table 8). Although this cost seems very high for a single household in a rural community, the state of Alaska is accustomed to having high investment costs in utilities for the rural villages and is willing to pay the cost.

Table 8: Capital and operational costs for a single household reuse system

Category	Cost
Capital costs	
• On-site reuse kit	$100,000
• Shipping by barge	$3,600
• Construction and installation	$32,700
Sub-total	
	$136,300
Monthly operation costs	
Water haul, waste haul, electrical, fuel, cooperative, consumables	$150
12-month Sub-total	$1,800
Cooperative development	
Building, parts, tools, water quality monitoring equipment contributions	$17,500
TOTAL	**$155,600**

Operation and maintenance costs and parts availability

Monthly operation and maintenance costs cannot exceed $135 (representing 5% of the Median Household Income of rural communities) per the AWSC requirements and a local cooperative is expected to be developed to be responsible for maintenance and repair of all the systems within a community for a membership fee of $40 per month. Replacement parts must also be available for purchase or shipping to the communities within a reasonable time period and cost. The UAA system has a monthly operation cost of $110 plus the $40 required cooperative fee, and therefore satisfies this requirement. Additional research into membrane optimization could decrease this cost even further, but lack of training and proper management of the system could greatly increase operation and maintenance costs. A complex, novel water reuse system could fail catastrophically, as other poorly operated and unmaintained water and sewer systems in rural Alaska have in the past, unless great lengths are taken to make operation of the system as simple as possible and provide for long- and short-term maintenance costs and expertise. Sustainable initiatives such as private-public partnerships or business initiatives related to the water reuse systems are highly recommended to ensure that operation and maintenance is feasible and perpetual for the life of the system.

Acceptance and use by end users

ADEC required that input from residents of rural communities be incorporated and the system be acceptable for use by residents, especially onsite water reuse components. The UAA team made every effort to work with two communities to get end-user feedback during the prototype development and testing process. However, because water and sanitation projects have been ongoing in rural Alaska for decades without universal success, many end users are getting tired of being probed for their input when they see little or no progress for their homes. Increased and directed education and outreach is needed to help residents understand why traditional piped

systems are unfeasible, how water reuse works, and how water reuse systems would provide desired health benefits. In some areas people don't want the added benefits of running water in their home if it will come at the expense of complex technology and high maintenance inputs.

Freeze/thaw recovery capability

One requirement of the AWSC was for systems to be able to be left unheated in a rural home for several weeks without damage and become operational with minimal effort. The UAA system was tested with a three-week outage during which the system was emptied and allowed to freeze to ambient temperatures (~10 degrees F). It was warmed and recovered with little effort and produced high quality water after this period, although critical to this success was proper preparation and maintenance before the freeze period.

Constructability, durability, modularity, feasibility

Finally, the AWSC specified that the reuse system require minimal floor space, withstand everyday use and occasional neglect and abuse, and be run with minimal expertise; that it be maximized for installation, maintenance, and to allow homeowner preference; and that it be appropriate for building and operating in rural Alaska, taking into consideration extreme temperatures, permafrost, remoteness, off-road villages, community acceptance and federal and state agencies who will participate in the funding and installation. The UAA system uses common parts readily available in Anchorage and Fairbanks and the costs summarized above include funds to stock the proposed village cooperative with these parts prior to widespread installation in a village. The system is highly modular, allowing a household to choose the specific fixtures they desire and to modify the volume of water available to those fixtures by increasing how often the treatment system is run. However, providing a system that is high-tech, low maintenance and allows for occasional neglect in extremely cold and remote areas is

incredibly difficult. Appropriate community engagement, training, and operation and

maintenance support must complement the technology provided to make this system successful.

Chapter 4: Conclusions and future steps

Potential of untapped water resources

The combined use of rainwater and greywater reuse could provide part of the solution to water, sanitation and hygiene problems in remote areas. Rainwater is naturally of high quality but not always predictable and only seasonally available. Greywater is predictably and consistently available but requires higher degrees of treatment. This has been suggested before (Dixon, Butler, and Fewkes 1999), but the research described above demonstrates that the resources and technology are available to provide adequate treatment and implement this approach in rural Alaska.

Implementation challenges

Importantly, the research described above was context-specific. Rainwater quality and quantity was evaluated in specific unserved Alaska villages, and an onsite greywater treatment system was constructed and challenged with inputs, flow regimes, and operation conditions that would likely be experienced in rural Alaska. The specificity of these solutions to the distinct communities where they will be employed is important. Although we recommend that rainwater catchment systems be expanded further into rural communities with state assistance for infrastructure and regular water quality monitoring, this approach should not be seen as one-size-fits-all for all underserved communities. Similarly, although greywater reuse has been shown to be possible on a household scale in cold climates, the solution may not be appropriate under some conditions.

Water quality and quantity problems are related to technological, social, cultural, economic and political issues (Elimelech 2006). Despite the technical feasibility of these two

alternative water resources to provide increased quantity of water in homes, the financing, operation and maintenance, and social and cultural acceptability factors still need to be worked out.

The financing requirement of rainwater catchment systems in unserved rural villages is minor, but the large-scale and long-term implementation of a government-supported rainwater program should also involve education and outreach, periodic water quality sampling, and possibly the distribution of point-of-use disinfection systems. While rainwater can improve the quantity of water available in the home, safe and sanitary methods for removing used greywater and wastewater from the home must be simultaneously implemented. Consideration of these factors may increase the cost of a rainwater approach.

The cost of single household greywater reuse system, at $155,000, is incredibly high for most decision makers in water short regions, but the US federal government and state of Alaska have demonstrated a willingness to fund this cost. The state should continue research on user willingness to pay (Cara Lucas, personal communication) and consider how much to subsidize these projects to ensure that they are appropriately valued and used by the beneficiaries. Substantial savings could be found if treatment systems are shared between households, however the costs of piping water to and from a treatment system that is not immediately within the home may outweigh the benefits of a reuse system over traditional piped services from centralized water and wastewater treatment plants. The sharing of treatment systems would also depend on household size, layout and village characteristics and should be tested further before implementation.

The operation and maintenance costs of a rainwater catchment system are quite low, but there is still a major concern about how to manage greywater and wastewater once water use is

increased with these systems. Additionally, storage requirements will increase and safe and clean storage containers must be managed. In villages where more rainfall can be captured than can be used during the rainy season, indoor storage or freeze prevention should also be considered.

The operation and maintenance of a household greywater reuse system should be a major cost and concern for regulators looking to implement this technology. Although the Alaska Department of Environmental Conservation described the development of a cooperative in each village that would be responsible for stocking parts and assisting homeowners with regular operation and maintenance, the realization of this vision will present many of the same problems that go along with traditional piped and pump-and-haul water services. The reuse system requires parts be available and easy to replace and identify, and that there be sufficient redundancy and an alert system so that the household isn't at risk of illness when the system isn't functioning properly. In the absence of parts, engaged and interested community members, and reliable outside technical support, the reuse system will likely fall out of use quickly. An operation and maintenance strategy must be developed and implemented before any technology installation moves forward.

Finally, rainwater is already highly socially and culturally acceptable in most communities in rural Alaska, although it is unclear how many people use it or would be willing to use it as a primary resource over other desired natural and treated water sources. However, greywater reuse for the types of household uses described in this study still have some social acceptance barriers to overcome. Public acceptance has been linked to positive perceptions and knowledge about the water source, awareness of water scarcity, and previous experience using alternative water resources (Dolnicar, Hurlimann, and Grün 2011), but also depends on the level of contact with the recycled water (Mankad 2012; A. C. Hurlimann and McKay 2006). The reuse

system described here requires high levels of contact with the water (e.g. showering) compared to current village reuse practices (e.g. reusing hand wash basin water for more handwashing) and compared to other household water reuse systems (e.g. toilet flushing and gardening, e.g. Oesterholt et al. 2007). Communities are more likely to accept this level of reuse if the early introduction of the systems comes along with optional use opportunities, social marketing campaigns, and raised awareness about the risk of illness that comes with low water use.

Alaska Water and Sewer Challenge lessons learned

The Alaska Water and Sewer Challenge was a noble initiative by the state to encourage the development of innovative solutions to rural Alaska's water quantity problems. While the technologies developed as part of the Challenge were interesting and may be viable, other aspects of the real challenge of providing water to rural Alaska were not sufficiently addressed. After over at least 50 years of attempting engineering solutions to water and wastewater issues in these communities, it is time to acknowledge that engineering alone will not cure WASH in rural Alaska. More research and funding must be applied to looking at social and cultural factors and specific behaviors that can be changed. Carefully designed education and outreach initiatives, behavior change campaigns and operation and maintenance programs are critical to the sustainability of any technological innovation introduced to improve water access in the villages.

The future of WASH in rural Alaska

It is hard to imagine the future discovery of a single solution that will solve all of the water, sanitation and hygiene problems in rural Alaska. More likely, future progress will be made through the careful collaboration of village councils, community members, WASH champions, government regulators and funders, and social and technical experts who will

evaluate the enabling environment of individual communities and choose hybrid solutions that fit

those circumstances. Rather than walking away after a project is built or a program selected,

these stakeholders will have to continue to reevaluate and ensure there is an environment that

supports long-term sustainability of their solutions.

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