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Arizona rooftop harvested rainwater: How clean is it?

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1. Why does rooftop harvested rainwater matter?

1.1. Rooftop harvested rainwater can help address water scarcity

The United Nations Sustainable Development progress report states that 2.3 billion people live in water-stressed countries and that water scarcity could force migration for more than 700 million people by 2030 (United Nations, 2021). As climate change worsens water scarcity (Schewe et al., 2014), the U.S. and even Arizonans will become more reliant on alternative sources of water (Pearson et al., 2015; Tamaddun et al., 2018), such as rooftop harvested rainwater (RHRW). In Arizona (AZ), the average resident uses 120 gallons (454.2 L) of water per day; this municipal use contributes to 20% of the state's water budget. In comparison, 78% is allocated for agricultural and 1% for industrial uses (Arizona Department of Water Resources, n.d.). Up to 70% of residential water is used for outdoor activities such as gardening and filling swimming pools, with that number increasing during the warmer months (Arizona Department of Water Resources, n.d.). Furthermore, to address the urban heat island effect, which disproportionately affects environmental justice communities, low-cost interventions and climate change adaptations are being developed, including active rainwater harvesting to support the increase of tree canopy in these areas (Sandhaus et al., 2018). Rainwater harvesting has become very important in many AZ communities, to the point that municipalities like in Tucson, have begun. offering tax incentives and rebate programs (City of Tucson, n.d.) for homeowners andbusinesses installing harvesting systems (Radonic, 2019). RHRW systems improve wateravailability for various uses, including gardening, watering of green spaces and shade plants,irrigating crops, refilling swimming pools, and livestock production (Mbilinyi et al., 2005). Figure 1 shows several rainwater harvesting systems in Tucson, AZ.

1.2. Trying to do the right thing for water conservation and climate justice, but what about environmental pollution?

The risks of using rooftop harvested rainwater systems is unclear; environmental pollution might negatively affect the quality and safety of RHRW. Environmental pollution was responsible for an estimated nine million premature deaths globally in 2015 (Landrigan et al., 2018). The U.S. Environmental Protection Agency's (EPA) Toxic Release Inventory (TRI) Program requires industry to report the storage, use, and release of regulated, hazardous substances (US EPA, 2024). In 2018 (around the inception

Figure 1. Select images of community scientists' rooftop harvested rainwater systems. Image Credits: Flor Sandoval and Ann Marie Wolf, Sonora Environmental Research Institute, Inc.

of Project Harvest, see details in section 2.2), AZ had 263 reported TRI sites, which are typically large-scale facilities that handle hazardous chemicalsknown to have adverse human or environmental health effects (US EPA, 2023, 2024). Of thesesites, the five facilities with the largest releases are mining and smelting sites (US EPA, 2023, 2024). In 2022, the total TRI on- and off-site disposal or other releases added up to over 30,000 tons in AZ, with copper, lead, and zinc as the top chemicals (US EPA, 2023, 2024). There are also unregulated contaminants that could affect harvested rainwater quality.

In 2020, AZ had 401 active mines (Richardson et al., 2020), contributing pollutants like arsenic and lead into the environment. Mining has been connected to climate change, increased industrialization, and ecosystem destruction (Csavina et al., 2012). As of 2023, there are 13 federally designated cleanup sites in AZ governed and funded by the federal Comprehensive Environmental Response, Compensation and Liability Act of 1980 (CERCLA), commonly known as Superfund (ADEQ, n.d.-b). These sites are on the National Priorities List because they are sources of uncontrolled hazardous waste, and based on the U.S. EPA's hazard ranking system, they pose the greatest potential threat to public health and the environment. AZ also has 38 state funded cleanup sites and 12 Department of Defense sites (ADEQ, n.d.-b, n.d.-a) in addition to state-regulated emergency sites, biohazardous medical waste facilities, and brownfield sites (ADEQ, n.d.-a, n.d.-b; US EPA, 2023, 2024).

Despite potential negative health outcomes (Ahmed et al., 2016; Csavina et al., 2012; Entwistle et al., 2019; Patra et al., 2016; Phillips, 2016; Urkidi & Walter, 2011; Velicu, 2020; White, 2013), industrial facilities continue to release toxic chemicals into and near AZ communities (US EPA, 2023, 2024).

2. Is my rooftop harvested rainwater safe?

2.1. Rooftop harvested rainwater monitoring programs and regulations do not exist to ensure water safety in AZ

Use of harvested rainwater is encouraged in AZ, but in 2024, information regarding the quality of harvested rainwater is largely lacking. Regulations for the domestic use of rainwater collected from the roofs of residential and commercial buildings exist in Australia, Taiwan, Jordan, and Brazil (Aziz et al., 2020). With the exception of the U.S. EPA non-enforceable *E.coli* and Total Coliform guidelines for the use of harvested rainwater indoors, national recommendations or regulations for the use of RHRW from residential and commercial buildings in the United States have not been established.

2.2. Project Harvest - co-created community science to understand rainwater quality

The University of Arizona's (UArizona) Project Harvest (PH) (Figure 2) was created in collaboration with the Sonora Environmental Research Institute, Inc. (SERI) and worked with three rural communities near active and legacy mining: Dewey-Humboldt, Globe/Miami, Hayden/Winkelman; and one urban community: Tucson (Figure 3) (Project Harvest, n.d.). Using a peer education model, promotoras (community health workers) trained community scientists on how to properly collect environmental monitoring samples, which were then analyzed for contaminants and pathogens at UArizona. See Table 1 for a description of organic, inorganic, and

Figure 2. Project Harvest logo.

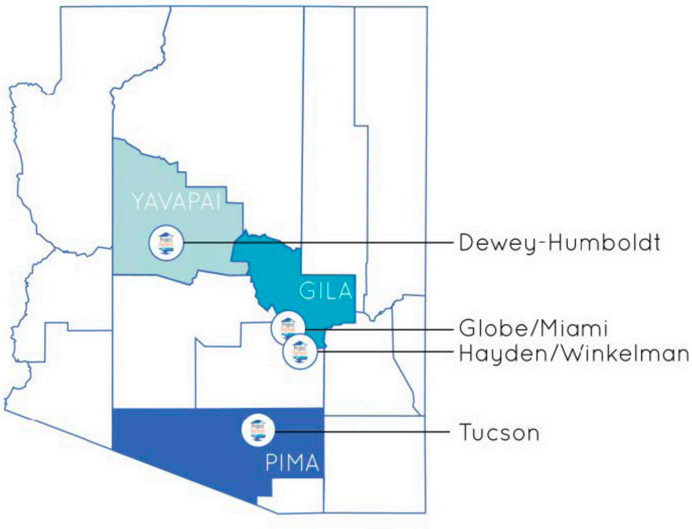


Figure 3. Map of Project Harvest Arizona partnering communities.

Table 1. Description of contaminants of concern and related health effects.

Chemical	What is it?	Reason to study	Cardiovascular (Heart & Blood Vessels)	Dermal (Skin)	Developmental (periods when organs are developing)	Endocrine (Glands and Hormones)	Gastrointestinal (Digestive)	Hematological (Blood Forming)	Hepatic (Liver)	Immunological (Immune System)	Musculoskeletal (Muscles & Skeleton)	Neurological (Nervous System)	Ocular (Eyes)	Possible carcinogenic (cancer causing)	Proven Carcinogenic	Renal (Urinary System or Kidneys)	Reproductive (Producing Children)	Respiratory (From Nose to Lungs)
ORGANIC COMPOUNDS																		
2,4-D	pesticide	Runoff from herbicide used on row crops; multiple health effects				X		X								X		
Atrazine	pesticide	Runoff from herbicide used on row crops	X		X				X					X			X	X
Carbaryl	pesticide	The most common pesticides are insecticides in urban water (U.S. Geological Survey)			X				X			X						
Chlorpyrifos	pesticide	Was widely used in home and garden settings (top 5 used in USA); NHEXAS Gordon 1999										X						
Pentachlorophenol	industrial compound	Pima Storm water consistent detection			X	X		X	X					X			X	
Perfluorobutanesulfonic acid (PFBS)	industrial compound, Fluorosurfactant	CCL, toxicity, global persistence			X			X	X								X	
Perfluorononanoic acid (PFNA)	industrial compound, Fluorosurfactant	CCL, toxicity, global persistence	X		X	X			X								X	X
Perfluorooctanoic acid (PFOA)	industrial compound, Fluorosurfactant	CCL, toxicity, global persistence	X		X	X			X	X					X		X	
Perfluorooctanesulfonic acid (PFOS)	industrial compound, Fluorosurfactant	CCL, toxicity, global persistence	X		X	X			X	X					X		X	
INORGANICS																		
Aluminum	metal	Living in areas where the air is dusty, where aluminum is mined or processed into aluminum metal, near certain hazardous waste sites, or where aluminum is naturally high									X	X						X
Arsenic, inorganic	metalloid	#1 contaminant of concern due to: frequency at which it is found, toxicity, and potential for human exposure at hazardous waste sites (Agency for Toxic Substance and Disease Registry)		X			X		X			X			X			X
Barium	metal	Barium gets into the air during the mining, refining, and production of barium compounds, and from the burning of coal and oil. The length of time that barium will last in air, land, water, or sediments depends on the form of barium released. Barium compounds, such as barium sulfate and barium carbonate, which do not dissolve well in water, can last a long time in the environment. Fish and aquatic organisms can accumulate barium	X				X										X	
Beryllium	metal	Beryllium dust enters the air from burning coal and oil					X			X					X			X
Cadmium	heavy metal	#7 contaminant of concern due to: frequency at which it is found, toxicity, and potential for human exposure at hazardous waste sites (Agency for Toxic Substance and Disease Registry); Cadmium is emitted to soil, water, and air by non-ferrous metal mining and refining, manufacture and application of phosphate fertilizers, fossil fuel combustion, and waste incineration and disposal.	X		X	X	X					X			X	X	X	X
Chromium	heavy metal	industries using or manufacturing chromium, living near a hazardous waste facility that contains chromium, and cigarette smoke. Rural or suburban air generally contains lower concentrations of chromium than urban air								X					X*	X		X
Copper	heavy metal	Copper is released into the environment by mining, farming, and manufacturing operations and through waste water releases into rivers and lakes. Copper is also released from natural sources, like volcanoes, windblown dusts, decaying vegetation, and forest fires. Copper released into the environment usually attaches to particles made of organic matter, clay, soil, or sand.					X		X									
Lead	heavy metal	#2 contaminant of concern due to: Frequency at which it is found,	X		X		X	X			X	X	X	X		X	X	
Manganese	heavy metal	Manganese is a naturally occurring metal that is found in many	X						X			X						X
Nickel	heavy metal	Nickel is released into the atmosphere by industries that make or	X	X						X				X	X			X
Zinc	heavy metal	Some zinc is released into the environment by natural processes,					X	X		X								X
MICROORGANISMS																		
E. Coli	indicator bacteria	Naturally occur in the intestines of living organisms and their					X											
Fecal coliforms	A group of bacteria	Generally originates in the intestines of warm-blooded animals.					X											

*Only the hexavalent chromium species (Cr VI) is considered a carcinogen

REFERENCES:

ATSDR Toxic Substances Portal: https://www.atsdr.cdc.gov/substances/index.asp

ATSDR's Substance Priority List: https://www.atsdr.cdc.gov/spl/index.html

https://www.epa.gov/sites/production/files/2016-06/documents/drinkingwaterhealthadvisories_pfoa_pfos_updated_5.31.16.pdf microbial contaminants of concern and their health effects for humans. Together, the community-academic team evaluated pollution in nearly 600 harvested rainwater samples, as well as in irrigated soil and grown plants, from 184 participants; building capacity and individual and community-wide environmental health and data literacy. See Davis et al., 2018, 2020; Kaufmann et al., 2023; Moses et al., 2022, 2023; Palawat et al., 2023b, 2023a; Project Harvest, n.d.; Ramírez-Andreotta et al., 2019, 2023; Villagómez-Márquez et al., 2023 for more information. Community members wanted to know the quality of their RHRW and if it was safe to use. After 2.5 years and almost 600 Arizona RHRW samples analyzed for contamination, UArizona PH has some answers.

2.3. Adapting existing regulatory standards, recommendations, guidelines and/or advisories based on usage

For someone who wishes to use harvested rainwater, a good rule of thumb would be to match one's water needs to existing guidelines (FDA, 2023; Nappier & Bone, 2012; US EPA, 2015). Table 2 shows a summary of the exceedances of existing standards/recommendations/guidelines/advisories documented in AZ RHRW, by use for 12 organic contaminants, 11 inorganic contaminants, and 2 microbial contaminants. The number of samples analyzed and percentage of those samples that exceed a given standards/recommendations/guidelines/advisories are displayed in the table, further split by community where relevant.

From 577 UArizona PH RHRW samples analyzed for metal(loid)s, only 2 exceeded the U.S. Department of Agriculture's (USDA) recommended maximum irrigation concentration for continuous use on all soils for aluminum, 1 for arsenic, 4 for cadmium, 1 for chromium, 35 for copper, 17 for manganese, 2 for nickel, 25 for zinc, and 0 for beryllium and lead (Table 2). Each of these values represent less than 7% of the total number samples.

Across all AZ communities sampled for three years, only 2.9% of RHRW samples exceeded the U.S. Food and Drug Administration's (US FDA) agricultural irrigation criteria for *E. coli* at a geometric mean of 126 CFU/100 mL (Table 2) (Moses et al., 2023). This irrigation criteria technically applies to the geometric mean of 5 samples collected from one location; however, here for comparative purposes, we apply it to each sample individually. If we were to calculate the geometric mean of all samples submitted across the entire project from each home, only one would exceed 126 CFU/100 mL. But only one rooftop harvested rainwater sample was collected from that location, not five.

At the time of writing this bulletin, there were no available irrigation standards/recommendations/limits for organic contaminants.

3. Where is the contamination coming from?: Major findings from Project Harvest

Figures 4 - 7 visualize results from the study showing detection frequencies of various contaminants (Figure 4) and summary graphs of inorganic arsenic and lead (Figure 5), microbial (Figure 6), and organic (Figure 7) contaminants. The main takeaway from Figure 4 is that RHRW is not "pure" and contains detectable levels of contaminants, but the detections alone do not tell us about safety. Figure 5 shows that arsenic and lead are highest in Hayden/Winkelman, a community with an active copper smelter at the time of the study; but it further shows that there is not a clear divide in contamination between rural and urban spaces. Figure 6 shows that there were higher concentrations of total coliforms in the RHRW than E. coli. And rural communities had higher levels of total coliforms than Tucson, but Tucson had higher concentrations of E. coli than the rural communities. Figure 7 shows that across all four communities, there were higher concentrations of industrial organic contaminants found in the RHRW compared to pesticides.

3.1. Overall considerations for contamination

RHRW contamination can occur when rainwater assimilates chemicals and pathogens from the atmosphere, from roofs and collection systems, or during storage. RHRW quality can be affected by factors beyond a resident/owner's control such as weather conditions and proximity to potential sources of chemical contaminants like industrial activities (e.g., resource extraction/mining and toxic release inventory sites). Other contamination sources like automobile traffic (Huston et al., 2009) and agricultural activities need to be considered. Our data shows that contaminants associated with both industrial and agricultural activity were found in the RHRW (Figures 5 and 7).

3.2. How the seasons impact contamination in AZ

In general, the observed contamination in AZ was higher during the summer monsoon season compared to the winter season. The relationship was significant for arsenic, lead, total coliforms, *E. coli*, prometon, simazine, and pentachlorophenol concentrations (Moses et al., 2023; Palawat et al., 2023b, Villagómez-Márquez et al., 2023). This could be due to increased dust activity during the spring and summer (Huang et al., 2015) leading to build up of dust on roofs, which is then washed into cisterns during the monsoon rains.

3.3. How rainwater harvested infrastructure impacts contamination in AZ

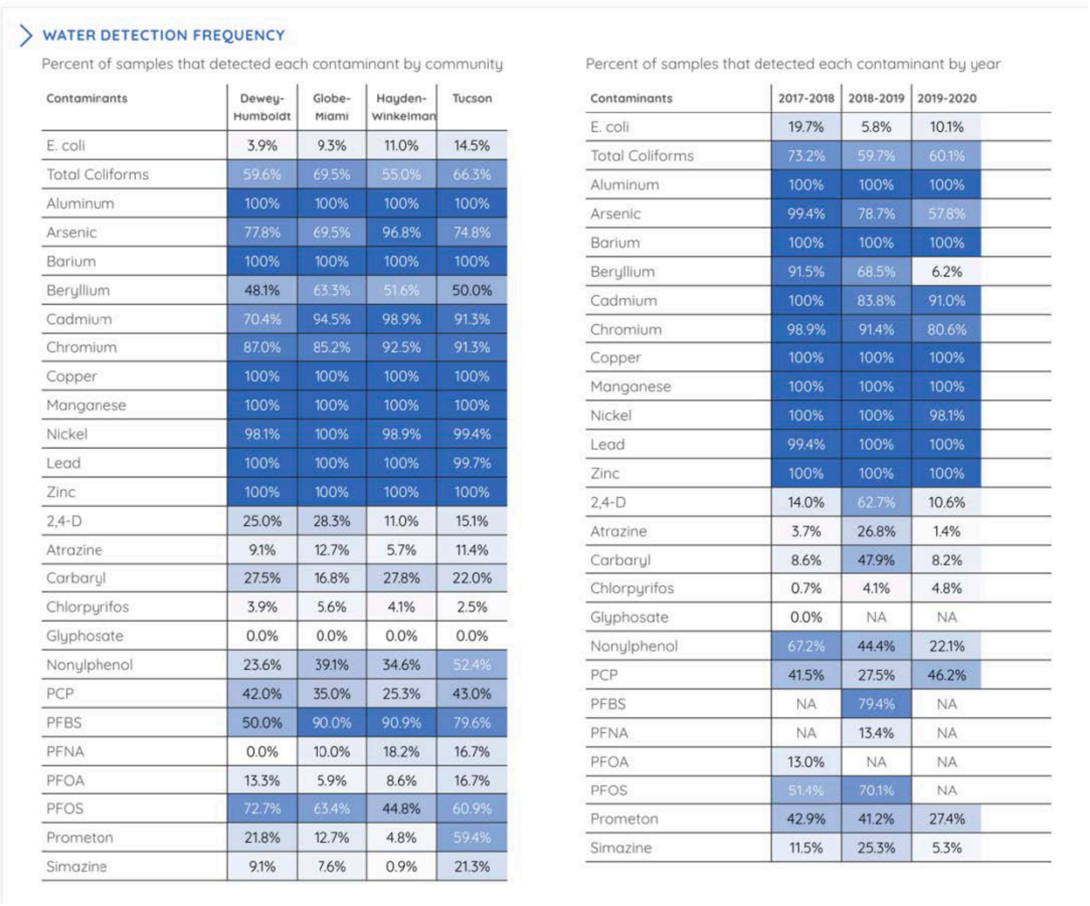
Infrastructure such as roof material, presence of a cistern screen, and first-flush systems were not significant with

Table 2. Harvested rainwater sample exceedances of nine water quality standards, recommendations, and maximum levels

Contaminant	Standard/recommendation/maximum level		Dewey-Humboldt (inorganic n = 53; microbial n = 52; organic specified in parentheses)	Globe/Miami (inorganic n = 124; microbial n = 118; organic specified in parentheses)	Hayden/Winkelman (inorganic n = 93; microbial n = 100; organic specified in parentheses)	Tucson (inorganic n = 307; microbial n = 317; organic specified in parentheses)	Overall (inorganic n = 577; microbial n = 587; organic specified in parentheses)
			Data shows % of samples exceeding the level				
Atrazine	U.S. EPA drinking water primary standard (maximum contaminant level)/action level/secondary standard	*3,000 (ng L-1)*	--	--	--	--	0.0% (594)
Simazine		*4,000 (ng L-1)*	--	--	--	--	0.0% (594)
PCP		*1,000 (ng L-1)*	--	--	--	--	0.0% (504)
2,4-D		*70,000 (ng L-1)*	--	--	--	--	0.0% (452)
PFNA[*]		*10 (ng L-1)*	--	--	--	--	0.0% (97)
PFNA + PFBS[*]		*Hazard Index of 1*[+]	--	--	--	--	0.0% (97)
PFOA[*]		*4 (ng L-1)*	46.7% (15)	38.7% (31)	54.3% (35)	60.2% (108)	54.5% (189)
PFOS[*]		*4 (ng L-1)*	68.2% (22)	61.0% (41)	41.4% (29)	54.5% (110)	55.4% (202)
Aluminum		*50 (µg L-1)*	23.0%	2.0%	34.0%	9.0%	4.0%
Arsenic		*10 (µg L-1)*	3.8%	0.0%	17.0%	0.7%	3.5%
Barium		*2000 (µg L-1)*	--	--	--	--	0.0%
Beryllium		*4 (µg L-1)*	0.0%	0.8%	0.0%	0.0%	0.2%
Cadmium		*5 (µg L-1)*	0.0%	8.1%	0.0%	0.0%	1.7%
Chromium		*100 (µg L-1)*	0.0%	0.0%	1.1%	0.0%	0.2%
Copper		*1300 (µg L-1)*	0.0%	1.6%	2.2%	0.0%	0.7%
Manganese		*50 (µg L-1)*	7.5%	4.0%	7.5%	0.0%	3.0%
Nickel		*140 (µg L-1)*	0.0%	1.6%	0.0%	0.0%	0.4%
Lead		*15 (µg L-1)*	0.0%	2.4%	5.4%	3.6%	3.3%
Zinc		*5000 (µg L-1)*	0.0%	0.0%	1.1%	3.3%	1.9%
Total coliforms		*0 CFU / 100 mL*	59.6%	9.5%	5.0%	5.3%	4.7%
E. coli		*0 CFU / 100 mL*	3.9%	9.3%	1.0%	4.5%	1.9%
Aluminum	USDA Livestock and Poultry Drinking Water Recommended Upper Limit	*5000 (µg L-1)*	0.0%	1.6%	0.0%	0.0%	0.4%
Arsenic		*10 (µg L-1)*	3.8%	0.0%	17.0%	0.7%	3.5%
Barium		*10000 (µg L-1)*	--	--	--	--	0.0%
Cadmium		*50 (µg L-1)*	--	--	--	--	0.0%
Chromium		*1000 (µg L-1)*	--	--	--	--	0.0%
Copper		*500 (µg L-1)*	0.0%	3.2%	6.5%	1.0%	2.3%
Manganese		*50 (µg L-1)*	7.5%	4.0%	7.5%	0.0%	3.0%
Lead		*100 (µg L-1)*	0.0%	0.0%	0.0%	0.7%	0.4%
Zinc		*25000 (µg L-1)*	--	--	--	--	0.0%
Atrazine	ADEQ Surface Water Full Body Contact Standard	*32,667,000 (ng L-1)*	--	--	--	--	0.0% (594)
Simazine		*4,667,000 (ng L-1)*	--	--	--	--	0.0% (594)
Chlorpyrifos		*2,800,000 (ng L-1)*	--	--	--	--	0.0% (543)
PCP		*12,000 (ng L-1)*	--	--	--	--	0.0% (504)
2,4-D		*9,333,000 (ng L-1)*	--	--	--	--	0.0% (452)
Arsenic		*30 (µg L-1)*	0.0%	0.0%	3.2%	0.0%	0.5%
Barium		*98000 (µg L-1)*	--	--	--	--	0.0%
Beryllium		*1867 (µg L-1)*	--	--	--	--	0.0%
Cadmium		*700 (µg L-1)*	--	--	--	--	0.0%
Chromium		*2800 (µg L-1)*	--	--	--	--	0.0%
Copper		*1300 (µg L-1)*	0.0%	1.6%	2.2%	0.0%	0.7%
Manganese		*130667 (µg L-1)*	--	--	--	--	0.0%
Nickel		*28000 (µg L-1)*	--	--	--	--	0.0%
Lead		*15 (µg L-1)*	0.0%	2.4%	5.4%	3.6%	3.3%
Zinc		*280000 (µg L-1)*	--	--	--	--	0.0%
E. coli		*235 CFU / 100 mL*	0.0%	2.5%	2.0%	1.9%	1.9%
Atrazine	ADEQ Surface Water Partial Body Contact Standard	*32,667,000 (ng L-1)*	--	--	--	--	0.0% (594)
Simazine		*4,667,000 (ng L-1)*	--	--	--	--	0.0% (594)
Chlorpyrifos		*2,800,000 (ng L-1)*	--	--	--	--	0.0% (543)
PCP		*4,667,000 (ng L-1)*	--	--	--	--	0.0% (504)
2,4-D		*9,333,000 (ng L-1)*	--	--	--	--	0.0% (452)
Arsenic		*280 (µg L-1)*	--	--	--	--	0.0%
Barium		*98000 (µg L-1)*	--	--	--	--	0.0%
Beryllium		*1867 (µg L-1)*	--	--	--	--	0.0%
Cadmium		*700 (µg L-1)*	--	--	--	--	0.0%
Chromium		*2800 (µg L-1)*	--	--	--	--	0.0%
Copper		*1300 (µg L-1)*	0.0%	1.6%	2.2%	0.0%	0.7%
Manganese		*130667 (µg L-1)*	--	--	--	--	0.0%
Nickel		*28000 (µg L-1)*	--	--	--	--	0.0%
Lead		*15 (µg L-1)*	0.0%	2.4%	5.4%	3.6%	3.3%
Zinc		*280000 (µg L-1)*	--	--	--	--	0.0%
E. coli		*575 CFU / 100 mL*	0.0%	1.7%	2.0%	1.3%	1.4%
Aluminum	USDA Recommended Maximum Irrigation Concentration For Continuous Use On All Soils	*5000 (µg L-1)*	0.0%	1.6%	0.0%	0.0%	0.4%
Arsenic		*100 (µg L-1)*	0.0%	0.0%	1.1%	0.0%	0.2%
Beryllium		*100 (µg L-1)*	--	--	--	--	0.0%
Cadmium		*10 (µg L-1)*	0.0%	3.2%	0.0%	0.0%	0.7%
Chromium		*100 (µg L-1)*	0.0%	0.0%	1.1%	0.0%	0.2%
Copper		*200 (µg L-1)*	0.0%	9.7%	17.0%	2.3%	6.1%
Manganese		*200 (µg L-1)*	1.9%	8.1%	2.2%	1.3%	2.9%
Nickel		*200 (µg L-1)*	0.0%	1.6%	0.0%	0.0%	0.4%
Lead		*5000 (µg L-1)*	--	--	--	--	0.0%
Zinc		*2000 (µg L-1)*	1.9%	4.0%	1.1%	5.9%	4.3%
E. coli	U.S. FDA Agricultural Irrigation Criteria	*126 CFU / 100 mL (geometric mean)*	0.0%	2.5%	4.0%	3.2%	2.9%
Total coliforms	U.S. EPA Non-Potable Indoor Use of Harvested Rainwater Standard	*500 CFU / 100 mL*	21.2%	4.6%	4.0%	2.7%	3.2%
E. coli		*100 CFU / 100 mL*	1.9%	2.5%	4.0%	3.2%	3.1%
Prometon	U.S. EPA Lifetime Health Advisory	*400,000 (ng L-1)*	--	--	--	--	0.0% (594)
Nonylphenol		*20,000 (ng L-1)*	--	--	--	--	0.0% (590)
Chlorpyrifos		*2,000 (ng L-1)*	--	--	--	--	0.0% (543)
PCP		*40,000 (ng L-1)*	--	--	--	--	0.0% (504)

[*] Enforceable for public water systems starting in 2029.

[+] This Hazard Index Maximum Contaminant Level applies to PFAS mixtures containing at least two or more of PFHxS, PFNA, HFPO-DA, and PFBS. The hazard index is calculated by dividing the concentration of a PFAS compound by the reported health-based value and then adding the ratios of the PFAS compounds together. See https://www.epa.gov/system/files/documents/2024-04/pfas-npdwr_fact-sheet_hazard-index_4.8.24.pdf for more details.



WATER DETECTION FREQUENCY

Percent of samples that detected each contaminant by community

Contaminants	Dewey-Humboldt	Globe-Miami	Hayden-Winkelman	Tucson
E. coli	3.9%	9.3%	11.0%	14.5%
Total Coliforms	59.6%	69.5%	55.0%	66.3%
Aluminum	100%	100%	100%	100%
Arsenic	77.8%	69.5%	96.8%	74.8%
Barium	100%	100%	100%	100%
Beryllium	48.1%	63.3%	51.6%	50.0%
Cadmium	70.4%	94.5%	98.9%	91.3%
Chromium	87.0%	85.2%	92.5%	91.3%
Copper	100%	100%	100%	100%
Manganese	100%	100%	100%	100%
Nickel	98.1%	100%	98.9%	99.4%
Lead	100%	100%	100%	99.7%
Zinc	100%	100%	100%	100%
2,4-D	25.0%	28.3%	11.0%	15.1%
Atrazine	9.1%	12.7%	5.7%	11.4%
Carbaryl	27.5%	16.8%	27.8%	22.0%
Chlorpyrifos	3.9%	5.6%	4.1%	2.5%
Glyphosate	0.0%	0.0%	0.0%	0.0%
Nonylphenol	23.6%	39.1%	34.6%	52.4%
PCP	42.0%	35.0%	25.3%	43.0%
PFBS	50.0%	90.0%	90.9%	79.6%
PFNA	0.0%	10.0%	18.2%	16.7%
PFOA	13.3%	5.9%	8.6%	16.7%
PFOS	72.7%	63.4%	44.8%	60.9%
Prometon	21.8%	12.7%	4.8%	59.4%
Simazine	9.1%	7.6%	0.9%	21.3%

Percent of samples that detected each contaminant by year

Contaminants	2017-2018	2018-2019	2019-2020
E. coli	19.7%	5.8%	10.1%
Total Coliforms	73.2%	59.7%	60.1%
Aluminum	100%	100%	100%
Arsenic	99.4%	78.7%	57.8%
Barium	100%	100%	100%
Beryllium	91.5%	68.5%	6.2%
Cadmium	100%	83.8%	91.0%
Chromium	98.9%	91.4%	80.6%
Copper	100%	100%	100%
Manganese	100%	100%	100%
Nickel	100%	100%	98.1%
Lead	99.4%	100%	100%
Zinc	100%	100%	100%
2,4-D	14.0%	62.7%	10.6%
Atrazine	3.7%	26.8%	1.4%
Carbaryl	8.6%	47.9%	8.2%
Chlorpyrifos	0.7%	4.1%	4.8%
Glyphosate	0.0%	NA	NA
Nonylphenol	67.2%	44.4%	22.1%
PCP	41.5%	27.5%	46.2%
PFBS	NA	79.4%	NA
PFNA	NA	13.4%	NA
PFOA	13.0%	NA	NA
PFOS	51.4%	70.1%	NA
Prometon	42.9%	41.2%	27.4%
Simazine	11.5%	25.3%	5.3%

Figure 4. Frequency of contaminant detection by community and water year. Figure reproduced from https://projectharvest.arizona.edu/ (Project Harvest, n.d.).

Note: In 2019-2020 only the first and last winter samples are reported. We had to cancel the first and last monsoon sample seasons due to COVID-19. N/A = Not measured

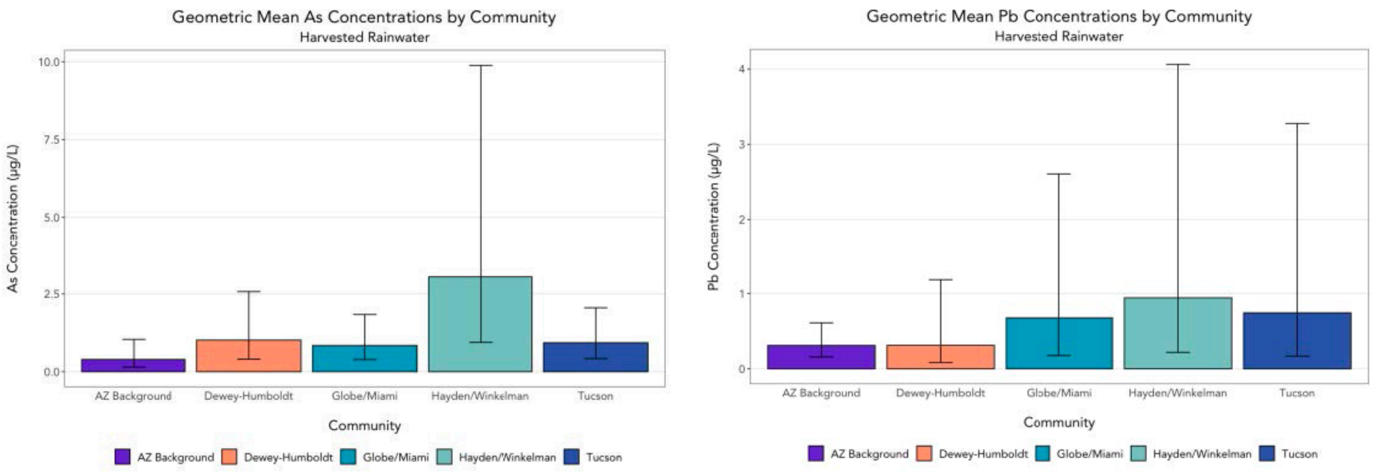


Figure 5. Geometric mean A) arsenic and (B) lead concentrations by community for all water years combined. Samples are compared to AZ background rainwater samples. For arsenic, all communities have significantly greater values than AZ background rainwater samples. All communities had significantly higher concentrations than AZ background and Hayden/Winkelman had the highest concentrations of any community for As. For Pb, Hayden/Winkelman and Tucson had significantly higher concentrations than Dewey-Humboldt. Error bars show the standard deviation. See https://projectharvest.arizona.edu/ for more visualizations (Project Harvest, n.d.)

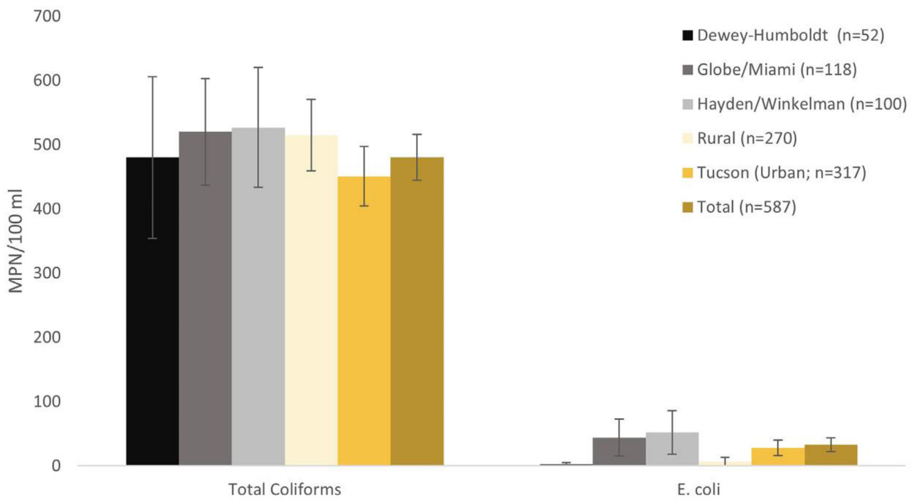


Figure 6. Harvested rainwater results by community. The average MPN of total coliforms (TC) and *E. coli* per 100 mL in harvested rainwater in each partner community. Limit of detection (LOD) and upper limit of quantification (ULOQ) were calculated at 0.5 and 2420, respectively. Error bars display standard error of the mean. Figure reproduced from Moses et al., 2023.

respect to arsenic and lead, but older cisterns (5+ years) were associated with higher lead concentrations and older homes were connected with higher levels of both arsenic and lead (Palawat et al., 2023b).

With regards to total coliforms and *E.coli*, PH analyses revealed that the quality of harvested rainwater has an association to animal presence (pets and livestock), cistern treatment or wash, cistern age, presence of cistern screen, first flush system (total coliforms only), and roof material type (*E.coli* only) (Moses et al., 2023).

3.4. How industry and built environment impacts contamination in AZ

In three out of four communities studied, arsenic and lead were greater from locations closer to industrial point sources of contamination (Globe/Miami, Hayden/Winkelman, Tucson – lead only). But there was no association between arsenic and lead concentrations and how close a home was to a road (Palawat et al., 2023b). There was an association between total coliforms and *E. coli* and proximity to a waste disposal facility or incineration facility (Moses et al., 2023). These results indicate that industrial activities like mining are influential drivers for environmental contamination, releasing contaminants into the environment, which are then assimilated into RHRW (Moses et al., 2023; Palawat et al., 2023b).

Arizonans harvesting rainwater can expect a small, but continual, exposure to pesticides due to common, non-industrial applications in homes, parks, golf courses, sports fields, and resorts. Both pesticides and industrial contaminants were found in the RHRW (Figure 7). But

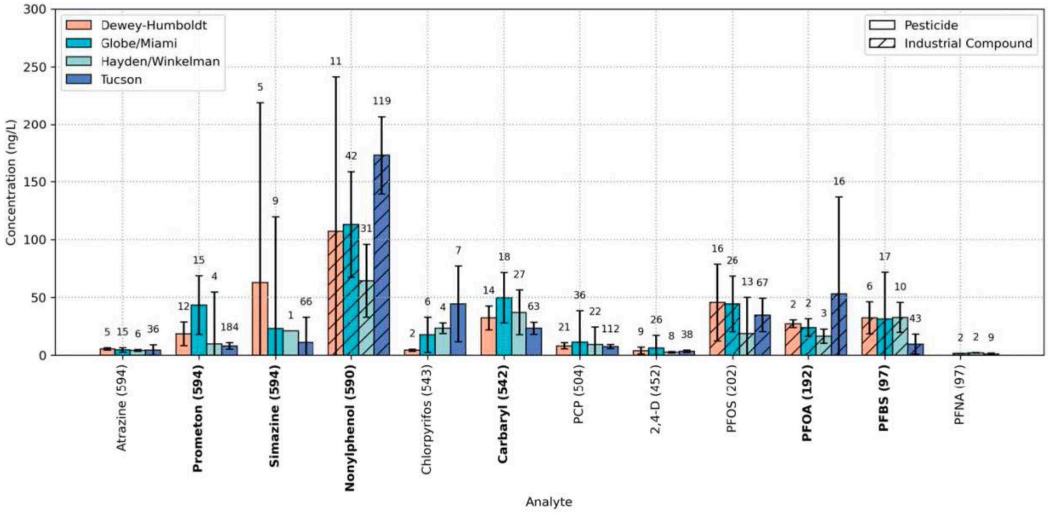


Figure 7. Median concentrations for organic contaminants over all water years, organized by community. The x-axis is reported as: analyte (number of measurements). Bold values indicate a statistical significance between communities' mean analyte concentration. The number above each bar indicates the positive detections. The error bars indicate standard deviation. Figure reproduced from Villagómez-Márquez et al., 2023.

pesticides measured in RHRW were not significantly correlated to low- or high-density population centers.

3.5. How living in rural AZ impacts contamination

In PH, rurality was not a consistent influence on contamination. In general, we observed higher concentrations of arsenic, lead, total coliforms, prometon, simazine, carbaryl, and PFBS in at least one rural community (Dewey-Humboldt, Globe/Miami, or Hayden-Winkelman) compared to the urban community, Tucson. But we also saw at least one rural community with lower contamination compared to Tucson (Figures 5 - 7). Pollution was typically higher in rural communities with active industrial activity like Globe/Miami and Hayden/Winkelman, though there were not consistent trends across all analytes and communities (Moses et al., 2023; Palawat et al., 2023b; Villagómez-Márquez et al., 2023). The research shows that pollution is complex and contaminant-specific analysis and comparisons should be done to best understand contamination.

4. What can we do about this?

4.1. Site and local

For home and harvesting characteristics, some choices, such as roof/cistern materials and age are difficult to change. Contamination may also continue to build up in the harvesting system over time.

Therefore, we recommend focusing on smaller changes such as:

- cleaning one's cistern and roof
- adding a first flush system or diverter
- installing a screen/filter over the opening of the harvesting device
- keep pets and livestock animals out of the cistern area

Birds and small mammals are likely sources of *E. coli* on rooftops. While reducing the number of animals nearby will help specifically reduce the microbial contamination of rainwater, preventing contaminants from entering via first flush, diverters, or screens, will likely have a greater impact on RHRW quality. A first flush device can divert the first 10 gallons (40 liters) of a storm's precipitation away from the cistern, potentially reducing the amount of roof-deposited materials accumulated since the last storm. The article called, "Preparing Rainwater for Potable Use" describes many precautionary and treatment options in detail (Capehart et al., 2021).

However, substantial contamination may still come from non-infrastructure sources (e.g. industrial), which individual homeowners cannot immediately control.

4.2. Sociopolitical decision making can affect change at many scales

People in limited-income and marginalized communities largely do not cause contamination, yet often bear the brunt of it (Bullard, 2011; Lerner, 2010). In rural areas, the mining industry has been shown to significantly influence RHRW quality (Palawat et al., 2023b), but that does not mean individuals are powerless. There are many avenues for taking action.

Most change happens first with education and raising awareness. By supporting environmental justice and conservation education in one's local school district and community, one can help inform others about the environmental issues affecting them. With respect to rainwater harvesting, one could engage your local water utilities and urge them to support rainwater harvesting programs. One can also get involved with community advisory boards, local politics, and community-based research projects like PH, which aim to empower and build capacity among non-academic scientist community members to study and advocate for their environment.

There is also an important precedent of political action in Arizona in support of environmental and climate justice with examples like United Farm Workers, Defend Black Mesa, and Protect Quitobaquito Springs. Activists have successfully used practices such as marches, rallies, boycotts, blockades, strikes, public art, social media, mutual aid, fundraisers, electoral politics, writing books and op-eds, and more, to hold governments and corporations accountable to the health of the people and incite systemic change. For example, due to unfair labor practices, in October, 2019, the ASARCO Hayden strike shut down smelter operations (Kailey Broussard, 2019; *Nine-Month Strike Ends for Local 627 ASARCO workers*, 2020). This type of action could have positive impacts on environmental quality (Palawat et al., 2023b).

Environmentalism intersects with every social justice movement, so one could join an organization doing grassroots environmental work that one cares about like CHISPAAZ, Poder in Action, or one's local Black Lives Matter group such as BLM Phoenix Metro (Black Lives Matter Phoenix Metro, n.d.; CHISPA AZ, n.d.; Poder in Action, 2018). One can also gather their community and decide to form one's own change-making group.

In addition, Indigenous stewardship of land has been shown to cultivate a more resilient ecosystem compared to non-Indigenous stewardship (Garnett et al., 2018), and could lead to the reduction of RHRW pollution in the environment by shifting land use away from extractive industrial activity. One could support Indigenous land and water stewardship in AZ by returning care of the environment back to its original peoples through avenues such as donations, easements, land trusts, reparations, land exchanges, and/or land sales. This process is called Land Back and could benefit the interconnected health of the environment and humans by reducing RHRW pollution (Hill et al., 2024; Pieratos et al., 2021).

There are several recent examples of Land Back happening in AZ that could benefit the quality of RHRW such as the city of Tucson returning land at the base of Sentinel Peak to the Tohono O'odham Nation, the Pascua Yaqui tribe getting 30 acres back in Tucson, the federal government land buyback program, and the Yavapai-Apache Nation land exchange with the U.S. Forest Service (Alam, 2016; Silversmith et al., 2022; Tucson Is Giving a Stretch of Ancestral Land Back to the Tohono O'odham Nation, 2023; Yavapai-Apache Nation, 2024). Further reading on land return and water can be found in the article, "Water Back: a Review Centering Rematriation and Indigenous Water Research Sovereignty" (Leonard et al., 2023).

Finally, by building a culture of reciprocity in one's community, one can steward a culture shift to better protect human and ecosystem health, leading to higher quality rainwater.

5. Conclusions

As climate change exacerbates water scarcity around the world and in Arizona, we are becoming more reliant on alternative sources of water like rooftop harvested rainwater. Project Harvest showed that largely at the time of the study and based on the USDA definition, this rainwater is safe for irrigating crops (Moses et al., 2023; Palawat et al., 2023b, 2023a; Villagómez-Márquez et al., 2023), but it is important to match one's specific rooftop harvested rainwater usage to existing regulatory standards, recommendations, guidelines and/or advisories as one way to determine safety. Project Harvest also observed that for the most part, contaminant concentrations were higher during the monsoon season. Rainwater harvesting infrastructure was associated with concentrations of total coliforms and *E. coli*; proximity to industrial sources was associated with higher concentrations of arsenic, lead, total coliforms, and *E. coli* (Moses et al., 2023; Palawat et al., 2023b, 2023a). This indicates that individuals are not solely causing contamination, and therefore are not fully responsible for that contamination. While it can be helpful for individuals to change their rainwater harvesting infrastructure to match best practices, it is crucial that we also focus on institutional and policy level decision-making (i.e. industry, government). To instigate effective change for increased environmental public health, we must connect to community organizations, educational efforts, or scientific institutions. Contamination of rooftop harvested rainwater can come from many places; our solutions must also include many diverse strategies for changemaking.

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This information has been reviewed by University faculty.
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