Journal of Contemporary

Water Research & Education

Issue 182
April 2025

Sponsored Research of the National Institutes for Water Resources

UCOWR
UNIVERSITIES COUNCIL ON WATER RESOURCES

A publication of the Universities Council on Water Resources with support from Southern Illinois University Carbondale

JOURNAL OF CONTEMPORARY WATER RESEARCH & EDUCATION

Universities Council on Water Resources
1231 Lincoln Drive, Mail Code 4526
Southern Illinois University
Carbondale, IL 62901
Telephone: (618) 536-7571
www.ucowr.org

ISSN 1936-7031

Cover photos: Left: *Sarah Nelson (WVU) sampling Robinson Run, Monongalia County, WV* Credit: S.Rabemanjakasoa **Top Right:** *Landing of a replica batteau boat at Percival's Island in Lynchburg, Virginia, during the annual James River Batteau Festival, June 15, 2013.* Credit:Alan Raflo **Bottom Right:** *High School students conduct field research and stream monitoring as a part of an educational program led by NYSDEC and NYSWRI staff*. Credit: Chris Bowser

Journal of Contemporary Water Research & Education

Issue No. 182 April 2025

Universities Council on Water Resources
Journal of Contemporary Water Research & Education
Issue 182, Page 1, April 2025

Introduction to the Special Issue: Celebrating 60 Years of the Water Resources Research Act

The Water Resources Research Act (WRRA) of 1964 created the network of water research centers and institutes now known as the National Institutes for Water Resources (NIWR). Through its unique model of shared federal, state, and local investment water in NIWR centers and institutes at public universities across the nation, the WRRA ushered in six decades of locally-tailored research, education, and outreach on water resource challenges as they continued to evolve. This special issue highlights the rich history and wide-ranging impacts of the work of NIWR centers and institutes.

Appropriate to the 60-year anniversary, several articles in this issue reflect on the past, present, and future of the NIWR community. Gerald Kauffman traces the legislative history and legacy of the WRRA, describing the evolution of NIWR centers and institutes through changing environmental and policy issues. Erik Porse presents a deep dive into the history of one NIWR institute, applying natural language processing models to analyze a database of funded research projects over the history of the California Institute of Water Resources. Jonathan Yoder assesses the recent accomplishments of NIWR centers and institutes with a quantitative analysis of their 2016-20 comprehensive reports submitted to the U.S. Geological Survey. All of these articles reveal the ways that NIWR centers and institutes have successfully leveraged a modest federal investment in their work, attracting additional funding to address locally and regionally relevant topics.

Another set of articles showcase the long-term impacts of this leveraging process, in which initial research supported by a center or institute grew into a lasting program with multiple sources of support. Ralph Wurbs describes how a project supported by the Texas Water Research Institute in the 1980s began the development of the Water Rights Analysis Package (WRAP), a software tool that models water availability in river basins under alternative management scenarios. WRAP has been continually used by state agencies and regional authorities in Texas and has been improved and updated through investments from multiple sponsors. Steven Shulz presents the results of research on flood risk that was initiated by a 2008 grant from the Nebraska Water Center. Using detailed data on specific structures and state-of-the art modeling of flood potential in, Schulz provides new insights on the risks of flood damages in Omaha, Nebraska. Sitraka Rabemanjakasoa et al. present long-term water quality trends in the Monongahela River basin using data from the Three Rivers QUEST (3RQ) program. Launched by a water monitoring study at the West Virginia Water Resources Research Center in 2009, 3RQ has grown to provide water monitoring data on streams and tributaries in three major river basins with support from multiple partners.

A third group of articles exemplify the research that NIWR centers and institutes support on complex emerging topics, connecting biophysical water issues with social science and policy research methods. David Lampert et al. review the limitations and challenges of the regulatory landscape for per- and polyfluoroalkyl substances (PFAS), including insights an analysis of semi-structured interviews with PFAS experts. Grace Winningham addresses the role of water resources in nature-based tourism, using literature reviews and oral histories to examine the significance of natural souvenirs such as water samples from destination water bodies in managing sustainable tourism.

Finally, the issue includes several contributions highlighting the important education and public outreach functions of NIWR centers and institutes. Alan Raflo shares the experience of Virginia Water Radio, which evolved from a radio program to a podcast series distributed by the Virginia Water Resources Research Center over a 14-year period (2010-2024). Rewa Phansalkar et al. describe the efforts of the New York State Water Resources Institute to prepare future generations of water professionals, which integrates K-12 programs, university-level internships and coursework, and hands-on professional development opportunities.

Together, these papers offer a rich tapestry of insights and reflections on the past, present, and future of water resources research, education, and management. As we celebrate the 60th anniversary of the WRRA, this special issue serves as a testament to the enduring legacy of the Act and the ongoing efforts to ensure sustainable water management for future generations.

Sincerely,

Yu-Feng Forrest Lin
Director, Illinois Water Resources Center
University of Illinois Urbana-Champaign

Jeffery Peterson
Director, Minnesota Water Resources Center
University of Minnesota

Universities Council on Water Resources
Journal of Contemporary Water Research & Education
Issue 182, Pages 35-54, April 2025

Long-term Water Quality Trends in the Monongahela River Basin

*Sitraka Rabemanjakasoa[1], Sarah Nelson[1], Leslie Hopkinson[1], Rachel Spirnak[2], and Melissa O'Neal[2]

[1]Civil and Environmental Engineering, West Virginia University; [2]West Virginia Water Research Institute
**Corresponding author*

Abstract: The West Virginia Water Research Institute (WVWRI) has been monitoring water quality in the Monongahela River basin since 2009 through its Three Rivers QUEST (3RQ) initiative. This study examined 3RQ data for trends in the water quality of the Monongahela River basin. Water quality was monitored at 18 sampling locations in the Monongahela River basin with six locations on the main stem and 12 locations on main tributaries. Temperature, pH, electrical conductivity (EC), dissolved alkalinity, dissolved sulfate (SO_4), and dissolved analyte concentrations (aluminum (Al), calcium (Ca), chlorine (Cl), iron (Fe), magnesium (Mg), manganese (Mn), and sodium (Na)) were measured during 2009 to February 2023. Total dissolved solids (TDS) and acidity were also estimated. Mean daily discharge at the time of water quality sampling was recorded from a United States Geological Survey (USGS) gage when available and calculated when needed. Four nonparametric statistical tests were performed to determine if there were significant monotonic trends over time: i) Mann-Kendall trend test, ii) Mann-Kendall trend test adjusted for discharge, iii) Seasonal Kendall test, and iv) Seasonal Kendall test adjusted for discharge. Slopes of significant relationships ($\alpha = 0.1$) were estimated by the Theil-Sen estimator. Of the six mainstem sampling locations, widespread decreasing trends in TDS, SO_4, Cl, and Na were observed, regardless of adjusting for discharge or season; similarly, increasing trends or no trends in pH were observed at all sampling sites. Many of water quality gains are likely related to the voluntary management plan that was implemented by the coal industry. This independent monitoring through 3RQ is important to communicate the impacts as well as plan for future water management.

Keywords: *trend analysis, long-term monitoring, water quality, acid mine drainage, surface water*

The Monongahela River basin, located in north central West Virginia, western Maryland, and southwestern Pennsylvania, USA, is highly industrialized and includes West Virginia and Pennsylvania coal fields. Historically, acid mine drainage (AMD) is the main water quality concern. AMD originates from deep-mine openings or surface mine seeps at abandoned mine sites and is characterized by low pH and high concentrations of iron (Fe), manganese (Mn), aluminum (Al), and sulfate (SO_4). Traditional gas drilling, industrial and municipal pollution, land use, and Marcellus Shale gas development also contribute to water quality concerns in the watershed (USACE 2012).

In 2008, concentrations of SO_4 and total dissolved solids (TDS) that exceeded the drinking water secondary maximum contaminant levels (500 mg/L for TDS, 250 mg/L for SO_4) (USEPA 2024) were observed in the Monongahela River. Historically, TDS concentrations only exceeded 500 mg/L at low flows when discharge was less than 2,000 cfs (Ziemkiewicz 2010). During this time, there was increased gas development in the region (Ziemkiewicz 2010), and levels of brominated disinfection by-products (DBPs) suggested that elevated levels of bromide also occurred (Handke 2008). The relative contributions to TDS from the coal and gas industries were unknown (Ziemkiewicz 2010).

Research Implications

- Long-term water quality trends (2009-2023) were documented in the Monongahela River basin, an important resource for the population in northern West Virginia and southwestern Pennsylvania.
- Overall, trends in acid mine drainage (AMD) signals in the mainstem were either improving or showed no trend.
- Evidence presented through this study supports the continuation and support of long-term water quality monitoring programs like Three Rivers QUEST (3RQ).

Motivated by these elevated levels of TDS, biweekly water quality monitoring of the Monongahela River and its major tributaries began in July 2009 by the West Virginia Water Research Institute (WVWRI) (Ziemkiewicz 2015; Ziemkiewicz et al. 2022). Four sites on the Monongahela River and the mouth of 12 major tributaries were monitored, focusing on TDS and its major constituents (Ziemkiewicz et al. 2022). This sampling continues today as the long-term Three Rivers QUEST (3RQ) monitoring and reporting program.

In August and September of 2009, a massive fishkill and complete mussel kill occurred in Dunkard Creek, a tributary to the Monongahela River. This event was triggered by a toxin from a substantial bloom of golden algae (*Prymnesium parvum*), resulting from high TDS levels that provided favorable conditions for the golden algae to grow (Reynolds 2009). In December 2010, the Monongahela River was listed as "impaired" for SO_4 by the West Virginia Department of Environmental Protection (WVDEP) in its 2010 water quality assessment report (Hopey 2014).

Results from the initial water quality monitoring suggested that treated mine drainage characterized by high levels of calcium (Ca), sodium (Na), and SO_4 were the controlling factors of the TDS load. Using monitoring data, WVWRI developed a non-mandated total maximum daily load management plan to reduce TDS to levels less than 500 mg/L (Ziemkiewicz 2010). The management plan accounted for the pumping capacities at 14 major mine pumping and treatment plants and connected the salt output to flowrate. The model sets a maximum TDS level of 500 mg/L with a factor of safety of 2. Industry plant operators can coordinate outflows by reviewing the gage readings and setting pumps to the suggested rate (Ziemkiewicz et al. 2022). This approach was applied in January 2010 by the coal industry on a voluntary basis (Ziemkiewicz 2015; Ziemkiewicz et al. 2022). In addition, Pennsylvania passed TDS regulations to address new or increased TDS resulting from natural gas production in 2010 (25 Pa. Code § 95.1) (Chase 2014). Pennsylvania restricted flowback from hydraulic fracturing publicly owned treatment works in May 2011 (Rassenfoss 2011), and in May 2013, a reverse osmosis plant began operations in Mannington, WV to treat wastewater from the coal industry (Ziemkiewicz et al. 2022). SO_4 and TDS levels have met Environmental Protection Agency (EPA) standards in the Monongahela River since the application of these management strategies (Ziemkiewicz 2015; Kingsbury et al. 2023), and the Monongahela River was removed as "impaired" for SO_4 in December 2014 (Hopey 2014; PADEP 2014).

The 3RQ project has expanded to monitor the Monongahela, Allegheny, and Ohio watersheds. Rivers, tributaries, and headwater streams draining more than 64,750 km^2 are monitored. Academic researchers, citizen scientists, and conservation groups collect, analyze, and monitor water quality and the results are published for the public (WVWRI 2024a). Since 2015, the 3RQ program has engaged local volunteer-based organizations to enhance the dataset. Over 25 volunteer groups have contributed field data (i.e., conductivity (EC), pH, and temperature) from over 1,000 tributary sites (Ziemkiewicz et al. 2022). As a result of these efforts, a long-term water quality record for the Monongahela River basin exists. This dataset has been explored to address specific questions related to changes in TDS (i.e., Merriam et al. 2020; Kingsbury et al. 2023). Merriam et al. (2020) used a mixed modeling approach to characterize TDS variability in the Monongahela River basin and identified spatial (e.g., land-use) and temporal (e.g., flow variability) factors that impact source water TDS. Kingsbury et al. (2023) assessed trends and changepoints in bromide, chloride, SO_4, and TDS in the Monongahela River basin using locally weighted polynomial regression with a segmented regression. Results indicated that all remediation actions (i.e., voluntary discharge management plan, prohibition of wastewater in publicly owned treatment facilities, and the construction of a reverse osmosis treatment facility) contributed to maintaining SO_4 and TDS levels below secondary drinking water standards. There is potential to add to this previous research to better understand overall water quality trends in the Monongahela River basin by utilizing the 3RQ database.

The overall objective of this study was to evaluate long-term trends in water quality in the Monongahela River basin. The null hypothesis, H_0, was that there was no monotonic trend in central tendency of the water quality variables monitored. Utilizing the publicly available 3RQ dataset, a trend analysis approach was used to determine if there were trends in water quality parameters of the Monongahela River and its major tributaries.

Methods

Monongahela River Basin

Water quality data were collected as part of the 3RQ water quality monitoring initiative (WVWRI 2024a), focusing on the Monongahela River basin. The Monongahela River flows north from north central West Virginia, USA into southwestern Pennsylvania, USA where it ends at the confluence of the Allegheny River (watershed area = 19,010 km^2) (WVWRI 2024b). The watershed is located within the Western Allegheny Plateau Appalachian Plateau ecoregion (Level III) (USEPA 2015). The watershed is highly industrialized and includes West Virginia and Pennsylvania coal fields. AMD, traditional gas drilling, industrial and municipal pollution, land use, and Marcellus Shale gas development contribute to water quality concerns in the watershed (USACE 2012).

Three Rivers QUEST (3RQ) Water Quality Monitoring

Water quality was monitored at 18 sampling locations in the Monongahela River basin with six locations on the main stem and 12 locations on main tributaries (Figure 1; Table 1). Sample locations were originally selected to determine the effects of AMD treatment plants (n = 25), major coal fired power plants (n = 5), and a brine treatment facility (Figure 2) on water quality. AMD treatment facilities raise the pH level of impacted waters and remove metals. Some AMD treatment facilities are considered active treatment, utilizing chemicals through a mechanical process for water treatment; this method is often used in areas where there are high volume discharges. Passive treatment systems often treat low volume discharges through a series of chemical treatments and a series of ponds and wetlands.

Water samples were collected, and *in situ* measurements were completed at two-week intervals during July 2009 to April 2015 by the WVWRI. Then, the frequency was reduced to monthly with the sampling date occurring between the 10^{th} and 20^{th} day of each month. No data collected by watershed groups were included in this analysis.

At each site, a 500-mL unfiltered grab sample was collected under the water surface of the moving channel. In addition, approximately 250-mL of water was filtered through a 0.45-micron filter. This filtered sample was poured into a pre-acidified bottle (nitric acid). Samples were then placed in a sample cooler with ice. Additional details regarding field methods were reported by Ziemkiewicz et al. (2022) and Kingsbury et al. (2023).

Water grab samples were analyzed for alkalinity (SM2320B); SO_4 and chloride (EPA 300.0); and dissolved Al, Ca, Fe, magnesium (Mg), Mn, and Na (EPA 200.7). Values less than the detection limit were recorded as half of the detection limit (USEPA 2000). TDS was calculated as the sum of the concentrations of all measured dissolved constituents and represents total dissolved major ions (referred to as TDS_{sdc} where the subscript refers to sum of dissolved constituents) (Ziemkiewicz et al. 2022). Acidity was estimated considering the molecular weight of each acid-soluble metal in solution, the number of protons to be generated per mole as those metals precipitate, and the solution pH. In addition, a YSI Pro-Plus Multiparameter Instrument or YSI 556 Handheld Multiparameter Instrument (Yellow Springs, Ohio) measured EC, pH, and temperature directly in the field.

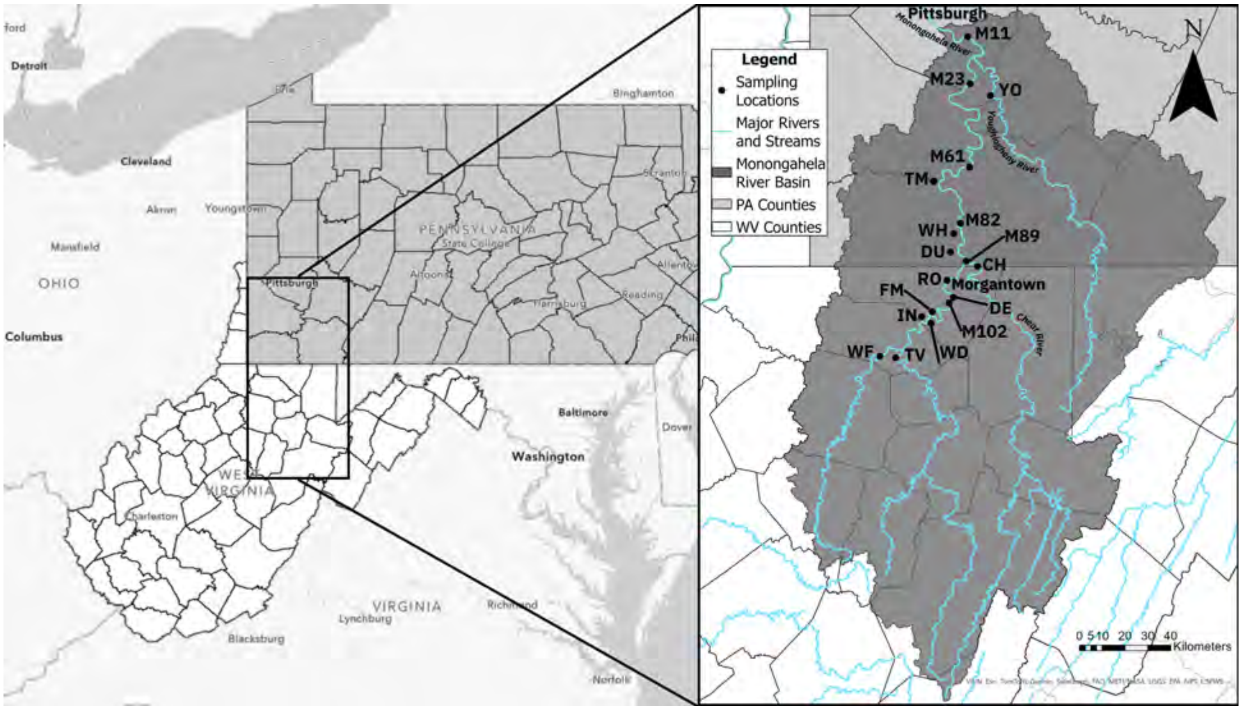


Figure 1. Locations of sampling sites along the Monongahela River and major tributaries.

Mean daily discharge values (Q) were obtained from nearby United States Geological Survey (USGS) gage stations at the time of sample collection for M82 (USGS 03072655), M23 (USGS 03075070), WF (USGS 03061000), TV (USGS 03056250 + USGS 03056250), YO (USGS 03083500), DE (USGS 03062500), TM (USGS 03073000), and DU (USGS 03072000). Mean daily discharge for M102, M89, and WH were estimated by the following relationships as reported by Kingsbury et al. (2023):

$$Q_{M102} = Q_{M89} - Q_{DE};$$
$$Q_{M89} = Q_{M82} - Q_{WH} - Q_{DU} - Q_{CH};$$
and $Q_{WH} = 0.5Q_{DU}$.

Mean daily discharge were estimated by the following relationships for M61 and M11:

$$Q_{M61} = 0.5(Q_{M82} + Q_{M23});$$
and $Q_{M11} = Q_{YO} + Q_{M23}$.

For streams without gages (IN, FM, RO, and WD), Q was estimated by the Watershed Modeling and Characterization System (Strager et al. 2010).

Statistical Analyses

Four nonparametric statistical tests were performed to determine if there were significant monotonic trends over time: i) Mann-Kendall trend test, ii) Mann-Kendall trend test adjusted for discharge, iii) Seasonal Kendall test, and iv)

Table 1. Description of monitoring sites.

Code	Description	Location	Drainage Area (km^2)	Sampling Dates
Mainstem				
M11	Monongahela River (river mile 11)	Homestead, PA 40°24'52" N; 9°53'53" W	19,010	May 2013-February 2023
M23	Monongahela River (river mile 23)	Elizabeth, PA 40°16'23" N; 79°53'17" W	13,831	July 2009-February 2023
M61	Monongahela River (river mile 61)	Brownsville, PA 40°1'18" N; 79°53'25.6" W	12,898	March 2012-February 2023
M82	Monongahela River (river mile 82)	Masontown, PA 39°51'7" N; 79°55'34" W	11,707	July 2009-February 2023
M89	Monongahela River (river mile 89)	Point Marion, PA 39°44'13" N; 79° 54' 14" W	7,030	July 2009-February 2023
M102	Monongahela River (river mile 102)	Morgantown, WV 39°36'40" N; 79°58'16" W	6,660	July 2009-February 2023
Tributaries				
YO	Youghiogheny River	40° 14' 13" N; 79°48'25" W	4,429	July 2009-February 2023
TM	Ten Mile Creek	39°58'52" N; 80°2'2" W	865	July 2009-February 2023
WH	Whiteley Creek	39°49'16" N; 79°57'7" W	136	September 2009-February 2023
DU	Dunkard Creek	39°45'54" N; 79°57'54" W	596	July 2009-February 2023
CH	Cheat River	39°43'16" N; 79°51'29" W	3,652	July 2009-February 2023
DE	Deckers Creek	39°37'41" N; 79°57'14" W	163	July 2009-February 2023
FM	Flaggy Meadows Run	39°35'2" N; 80°2' 17" W	4	May 2010-February 2023
IN	Indian Creek	39°34'8" N; 80°4'44" W	51	May 2010-February 2023
TV	Tygart Valley River	39°26'38" N; 80°10'52" W	3,550	July 2009-February 2023
WF	West Fork River	39°26'56" N; 80°14'38.4" W	2,140	July 2009-February 2023
Tributaries with Incomplete Datasets				
WD	White Day	39°32'56" N; 80°2'31" W	83	July 2010-December 2013, October 2019-February 2023
RO	Robinson Run	39°40' 44" N; 79°58'44" W	20	May 2010-December 2013, October 2019-February 2023

Seasonal Kendall test adjusted for discharge (Helsel et al. 2020). Slopes of significant relationships ($\alpha = 0.1$) were estimated by the Theil-Sen estimator (Helsel et al. 2020). All statistical analyses were performed using R version 4.3.2 with the rkt (Marchetto 2021) and the lubridate packages (Grolemund and Wickam 2011).

The statistical tests were performed for all measured water quality parameters at all locations with at least 12 years of interrupted sampling data ($n = 16$; Table 1). To account for the change in sampling frequency, data were reduced to one measurement per month for consistency in data and comparisons between the Mann-Kendall trend tests and Seasonal Kendall tests. For months with two measurements, the value measured closest to the middle of the month was used. The Mann-Kendall trend test was completed for each water quality parameter. The Mann-Kendall trend test adjusted for discharge was completed on residuals of each water quality parameter from loess (Local Polynomial Regression Fitting) of the parameters on daily discharge. The Seasonal Kendall test defined season as monthly. The Seasonal Kendall

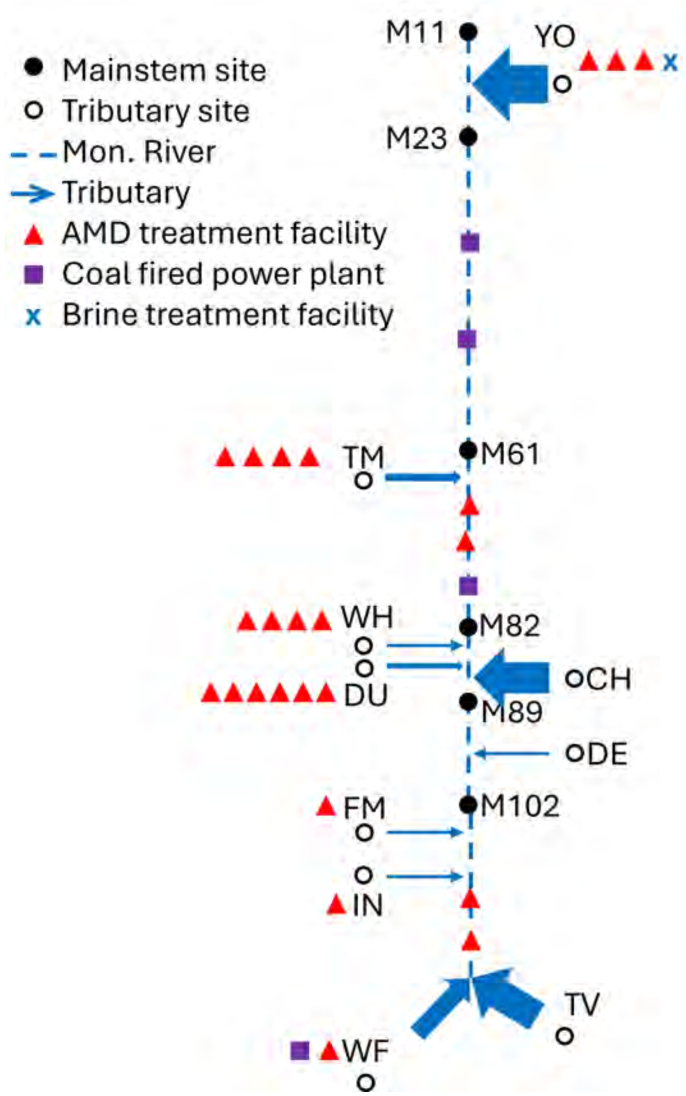


Figure 2. Figure of sampling locations along the Monongahela River relative to known acid mine drainage (AMD) treatment facilities, coal fired power plants, and a brine treatment facility; arrows represent tributaries with the width scaled to contributing watershed area of the sampling site.

trend test adjusted for discharge was completed on residuals of each water quality parameter from loess of the parameters on daily discharge with season defined as monthly (Helsel et al. 2020).

Two sampling locations, White Day (WD) and Robinson Run (RO), had incomplete datasets due to changes in funding availability (Table 1). White Day was initially considered a “control” site because there were no energy extraction activities within the watershed at the time sampling began. Robinson Run was visibly impacted by AMD. Due to the multi-year gap in data, a two-sided Mann-Whitney U test was completed to determine if there were differences in the water quality parameters, comparing the data from 2010-2013 to 2019-2023 ($\alpha = 0.1$) (Ott and Longnecker 2001).

Results

Median levels of pH, SO_4, Fe, Al, and TDS_{sdc} generally met the drinking water secondary maximum contaminant levels in the mainstem (6.5-8.5 for pH, 250 mg/L for SO_4, 0.3 mg/L for Fe, 0.05-0.2 mg/L for Al, and 500 mg/L for TDS) (USEPA 2024). Generally, median concentrations of Mn were above secondary maximum contaminant levels (0.05 mg/L for Mn) (USEPA

2024) (Table 2). The median values represent the central value from 2009 to 2023, and the secondary drinking water standards are provided as a frame of reference for overall water quality.

Trends in the Mainstem

In the mainstem, decreasing trends over time were observed for levels of chlorine (Cl), Na, TDS_{sdc} (river mile 23 to river mile 102), Mg (river mile 23 to river mile 89), and SO_4 (river mile 23 to river mile 102). Decreasing trends were also observed for portions of the mainstem for EC (river mile 23, and river mile 82 to river mile 102) and Mn (river mile 89). Levels of pH and alkalinity increased over time for a large portion of the mainstem (pH: river mile 11, 23, 82, and 102; alkalinity: river mile 23, 82, 89, and 102). Increasing trends were also observed for portions of the mainstem for acidity (river mile 61), Fe (river mile 61), and Al (river mile 82). Few significant trends were observed for temperature, acidity, Fe, Mn, Al, and Ca (Tables 3-7).

Four nonparametric tests were completed to determine the presence of monotonic trends. Generally, all tests resulted in the same result for each parameter in the mainstem. An exception is temperature. The seasonal Mann-Kendall tests adjusted for discharge resulted in increasing trends at four locations, while no trends were observed for all other tests (Table 7).

Trends in the Major Tributaries

Among the major tributaries, decreasing trends were observed for SO_4, Mg, Cl, Na, and TDS_{sdc} in several locations. Increasing trends were observed for pH, alkalinity, and Al for several locations. The fewest significant trends were observed at TM and TV (Tables 3-7).

Data monitored in two tributaries, WD and RO, did not meet the assumptions of the trend tests due to a disruption in data collection during 2013-2019. Whiteday Creek was considered a "control" study site because the watershed has fewer impacts due to mining and hydraulic fracturing than most watersheds in the region. The only significant difference was found when comparing the SO_4 before and after the data gap (p = 0.009). Significant differences for the AMD-impacted Robinson Run were found for acidity (p = <0.001) and concentrations of Fe (p = <0.001), Mn (p = <0.001), Ca (p = 0.001), Cl (p = <0.001), and Na (p = <0.002) (Table 8).

Discussion

Long-term Trends in the Monongahela River Basin

The Monongahela River was listed as "impaired" for SO_4 in 2010 and was removed as "impaired" in 2014 after EPA standards were met (PADEP 2014). Remediation actions including the implementation of a voluntary discharge management plan of treated AMD, prohibiting the disposal of wastewater in publicly owned treatment facilities, and adding a reverse osmosis treatment facility contributed to reducing levels of SO_4 and TDS (Ziemkiewicz 2015; Kingsbury et al. 2023). We identified decreasing trends in SO_4 and TDS_{sdc} among 83% of the mainstem 3RQ monitoring locations regardless of statistical test, supporting this change in "impaired" status. Similarly, TDS_{sdc} and SO_4 decreased at 63% of all monitored locations (Table 7).

Previous research suggested that TDS, chloride, and SO_4 levels in the Monongahela River are seasonal and related to flowrate (Wilson and Van Briesen 2013; Ziemkiewicz 2015). For example, Wilson and Van Briesen (2013) conducted a three-year study evaluating if constituent concentrations were related to shale gas extraction. The highest concentrations in TDS, chloride, and SO_4 were reported during the summer months of 2010-2012, following the seasonal pattern of flowrate. Most of the trends that we observed in the main stem were the same for TDS_{sdc}, chloride, and SO_4 regardless of adjusting for discharge or seasonal effects (Table 7). The only exception was site M11 where decreasing trends were only observed when adjusting for discharge. This location is down stream of the Youghiogheny River (YO), a major tributary with the greatest contributing watershed area of any of the monitored tributaries (Table 1). Decreasing trends were also only observed at YO when adjusting for discharge, potentially impacting trends in M11.

Kingsbury et al. (2023) assessed trends and changepoints in bromide, chloride, SO_4, and TDS at 12 sites in the Monongahela River basin using

Table 2. Summary of water quality data for all sampling sites during the monitoring period (July 2009-February 2023), reporting median and the interquartile range (in *italics*).

Code	Temp (ºC)	pH	EC (µS/cm)	Alkalinity (mg/L as $CaCO_3$)	Acidity (mg/L as $CaCO_3$)	SO_4 (mg/L)	Fe (mg/L)	Mn (mg/L)	Al (mg/L)	Ca (mg/L)	Mg (mg/L)	Cl (mg/L)	Na (mg/L)	TDS_{sdc} (mg/L)
Mainstem														
M11	13.9	7.6	286	50	0.61	65.4	0.076	0.056	0.060	29.7	7.31	21.6	21.2	170
	5.9, 22.9	*7.4,7.9*	*214, 396*	*42, 56*	*0.35, 0.86*	*51.9, 85.7*	*0.0, 0.1*	*0.037,0.079*	*0.025, 0.084*	*24.9, 33.7*	*6.10, 8.83*	*15.8, 27.9*	*16.1, 29.4*	*140, 210*
M23	13.5	7.5	280	48	0.55	69.8	0.078	0.050	0.050	28.3	7.39	14.6	19.5	170
	6.1, 23.3	*7.2, 7.8*	*203, 410*	*40, 58*	*0.36, 0.94*	*53.1, 100.0*	*0.0, 0.1*	*0.029, 0.071*	*0.025, 0.078*	*23.4, 34.5*	*5.74, 9.12*	*10.5, 21.2*	*13.5, 31.6*	*128, 221*
M61	14.7	7.6	250	46	0.68	66.7	0.095	0.066	0.058	26.6	6.70	12.1	17.9	153
	6.7, 23.2	*7.5, 7.9*	*196, 369*	*38, 54*	*0.41, 0.97*	*48.7, 93.4*	*0.0, 0.1*	*0.045, 0.098*	*0.025, 0.091*	*21.6, 31.5*	*5.34, 8.23*	*9.1, 16.1*	*12.40, 28.88*	*117, 207*
M82	13.9	7.7	230	36	0.72	68.5	0.083	0.084	0.064	24.9	6.30	9.3	14.9	144
	6.1, 23.3	*7.5, 7.9*	*160, 360*	*28, 44*	*0.51, 1.01*	*47.1, 99.3*	*0.0, 0.1*	*0.051, 0.109*	*0.036, 0.090*	*19.9, 30.2*	*4.80, 8.23*	*6.7, 12.7*	*8.97, 25.93*	*107, 203*
M89	14.5	7.7	255	44	0.55	75.3	0.069	0.063	0.042	28.4	7.49	9.5	14.6	156
	6.8, 23.2	*7.5, 7.9*	*194, 401*	*34, 54*	*0.36, 0.84*	*50.8, 106.5*	*0.0, 0.1*	*0.044, 0.091*	*0.025, 0.075*	*23.2, 37.2*	*5.49, 10.13*	*6.5, 13.5*	*9.69, 24.34*	*119, 218*
M102	14.2	7.4	247	44	0.54	70.9	0.073	0.050	0.049	28.2	6.71	7.7	14.5	152
	6.9, 22.7	*7.0, 7.7*	*182, 385*	*36, 56*	*0.34, 0.90*	*46.4, 101.2*	*0.0, 0.1*	*0.031, 0.077*	*0.025, 0.077*	*22.3, 34.7*	*4.89, 8.47*	*5.6, 11.1*	*10.05, 23.57*	*110, 208*
Tributaries														
YO	12.3	7.6	470	72	0.73	85.7	0.075	0.110	0.058	42.0	11.25	48.3	41.9	272
	15.1	*5.6, 20.7*	*317, 574*	*60, 82*	*0.56, 0.95*	*63.0, 112.0*	*0.0, 0.1*	*0.083, 0.149*	*0.025, 0.083*	*32.8, 47.9*	*8.87, 13.28*	*39.2, 59.6*	*31.4, 49.6*	*209, 318*
TM	13.0	7.9	586	140	0.57	106.0	0.035	0.055	0.060	56.1	11.30	39.4	53.4	339
	5.3, 20.9	*7.8, 8.2*	*378, 879*	*118, 159*	*0.39, 0.83*	*72.3, 182.3*	*0.0, 0.1*	*0.036, 0.073*	*0.028, 0.098*	*49.8, 65.3*	*8.98, 14.75*	*28.5, 62.0*	*35.83, 95.95*	*262, 486*
WH	13.3	8.2	1,117	189	0.30	336.5	0.035	0.034	0.025	76.2	28.30	47.6	126.5	690
	6.5, 18.9	*7.9, 8.4*	*614, 2003*	*152, 234*	*0.19, 0.50*	*195.5, 195.5*	*0.0, 0.0*	*0.021, 0.049*	*0.006, 0.053*	*65.5, 92.5*	*21.57, 36.20*	*20.4, 130.8*	*53.50, 326.80*	*456, 1353*

Table 2 (cont.).

Code	Temp (ºC)	pH	EC (µS/cm)	Alkalinity. (mg/L as $CaCO_3$)	Acidity (mg/L as $CaCO_3$)	SO_4 (mg/L)	Fe (mg/L)	Mn (mg/L)	Al (mg/L)	Ca (mg/L)	Mg (mg/L)	Cl (mg/L)	Na (mg/L)	TDS_{sdc} (mg/L)
Tributaries (cont.)														
DU	14.0	8.0	643	104	1.19	242.0	0.072	0.089	0.134	57.3	16.85	28.9	87.7	482
	5.6, 22.2	*7.8, 8.2*	*436, 1545*	*86, 117*	*0.92, 1.77*	*106.8, 577.8*	*0.0, 0.2*	*0.055, 0.149*	*0.088, 0.232*	*44.2, 44.2*	*10.93, 27.95*	*11.8, 63.4*	*33.52, 219.00*	*259, 1030*
CH	13.3	7.5	90	15	0.70	22.0	0.073	0.059	0.065	11.4	2.42	3.0	2.7	51
	5.6, 21.6	*7.3, 7.9*	*69, 113*	*12, 20*	*0.48, 0.93*	*18.7, 27.9*	*0.0, 0.1*	*0.043, 0.085*	*0.033, 0.089*	*9.9, 14.0*	*2.10, 2.90*	*2.4, 4.0*	*2.24, 3.31*	*44, 60*
DE	12.3	7.4	247	34	1.21	68.1	0.125	0.099	0.079	32.5	6.31	12.4	9.4	148
	5.6, 18.9	*6.9, 7.8*	*184, 393*	*26, 49*	*0.74, 2.03*	*51.5, 107.8*	*0.0, 0.4*	*0.069, 0.140*	*0.025, 0.150*	*25.1, 47.5*	*5.09, 8.91*	*9.8, 16.5*	*7.29, 14.48*	*117, 227*
FM	14.5	7.8	5,153	116	1.43	3,370	0.035	0.160	0.118	361.0	140.50	91.2	1,040.0	5,150
	8.9, 21.1	*7.6, 7.9*	*3190, 6745*	*91, 136*	*0.78, 2.01*	*2102, 4100*	*0.0, 0.1*	*0.100, 0.346*	*0.072, 0.200*	*290.2, 400.0*	*96.15, 165.75*	*36.4, 119.8*	*410.50, 1357.50*	*3071, 6160*
IN	12.0	8.1	1,660	179	0.38	840.5	0.035	0.050	0.025	124.5	40.50	29.8	262.5	1,370
	5.7, 19.4	*7.9, 8.4*	*1093, 2976*	*140, 226*	*0.29, 0.57*	*544.8, 1380.0*	*0.0, 0.1*	*0.037, 0.076*	*0.006, 0.058*	*93.9, 170.3*	*29.52, 59.27*	*19.0, 52.7*	*152.60, 486.20*	*933, 2279*
TV	12.7	7.8	119	26	0.49	25.3	0.080	0.039	0.027	14.1	3.00	4.4	6.4	68
	6.7, 21.6	*7.4, 8.1*	*89, 152*	*19, 30*	*0.29, 0.78*	*20.8, 31.0*	*0.0, 0.1*	*0.027, 0.058*	*0.025, 0.062*	*11.8, 16.9*	*2.56, 3.50*	*3.4, 5.5*	*4.99, 7.93*	*56, 79*
WF	13.1	7.8	509	90	0.55	172.0	0.049	0.057	0.047	65.1	17.20	12.8	27.2	351
	6.7, 21.3	*7.5, 8.0*	*375, 718*	*75, 106*	*0.32, 0.87*	*119.0, 234.2*	*0.0, 0.1*	*0.039, 0.086*	*0.025, 0.079*	*49.1, 77.7*	*12.68, 21.02*	*8.8, 16.5*	*18.30, 39.27*	*246, 443*
Tributaries with Incomplete Datasets														
WD	10.9	7.8	97	23	0.38	12.0	0.072	0.011	0.025	10.9	2.29	5.7	4.1	46
	4.8, 20.4	*7.4, 8.0*	*75, 131*	*16, 40*	*0.24, 0.52*	*10.6, 13.2*	*0.0, 0.1*	*0.009, 0.024*	*0.006, 0.050*	*8.7, 15.3*	*1.99, 2.85*	*4.5, 7.3*	*3.06, 5.67*	*40, 66*
RO	12.9	7.1	1,959	50	4.24	1,125.0	0.639	0.598	0.092	282.0	76.10	28.2	91.0	1,661
	6.1, 19.8	*6.4, 7.5*	*1439, 2603*	*7, 78*	*1.89, 25.02*	*888.0, 1530.0*	*0.2, 6.9*	*0.460, 1.040*	*0.050, 1.000*	*235.0, 364.3*	*63.20, 91.40*	*10.9, 73.3*	*64.50, 150.00*	*1351, 2241*

Table 3. Results of Mann-Kendall trend test of each parameter, reporting *p*-value and Theil-Sen's slope for significant trends (in *italics*, $\alpha = 0.1$).

Code	Temp (ºC)	pH	EC (µS/cm)	Alkalinity (mg/L as $CaCO_3$)	Acidity (mg/L as $CaCO_3$)	SO_4 (mg/L)	Fe (mg/L)	Mn (mg/L)	Al (mg/L)	Ca (mg/L)	Mg (mg/L)	Cl (mg/L)	Na (mg/L)	TDS_{sdc} (mg/L)
Mainstem														
M11	0.866	<0.001	0.238	0.241	0.977	0.386	0.210	0.162	0.647	0.977	0.402	0.004	0.058	0.260
		0.048										*-0.869*	*-0.518*	
M23	0.560	0.003	0.046	0.057	0.244	<0.001	0.100	0.202	0.076	0.129	0.010	0.015	<0.001	0.003
		0.028	*-5.92*	*0.466*		*-2.27*	*0.002*		*0.001*		*-0.129*	*-0.329*	*-0.730*	*-3.727*
M61	0.687	0.231	0.421	0.253	0.054	0.023	0.042	0.723	0.179	0.700	0.155	0.013	0.018	0.062
					0.023	*-1.832*	*0.004*					*-0.349*	*-0.582*	*-2.892*
M82	0.988	0.094	0.035	0.424	0.139	<0.001	0.201	0.234	0.012	0.102	0.071	0.002	<0.001	<0.001
		0.011	*-5.282*			*-2.86*			*0.002*		*-0.093*	*-0.281*	*-0.944*	*-4.536*
M89	0.894	0.824	0.034	0.092	0.510	<0.001	0.758	0.045	0.427	0.133	0.077	<0.001	<0.001	0.002
			-5.77	*0.439*		*-2.42*		*-0.002*			*-0.100*	*-0.325*	*-0.720*	*-3.753*
M102	0.913	<0.001	0.029	0.165	0.773	<0.001	0.936	0.344	0.176	0.347	0.174	<0.001	<0.001	0.004
		0.045	*-5.28*			*-2.50*						*-0.287*	*-0.725*	*-3.895*
Tributaries														
YO	0.891	<0.001	0.127	0.231	0.530	0.914	0.536	0.027	0.447	0.677	0.567	<0.001	0.204	0.444
		0.035						*-0.004*				*-1.717*		
TM	0.915	0.506	0.989	<0.001	0.422	0.141	0.009	<0.001	0.370	0.095	0.344	0.688	0.460	0.689
				2.68			*-0.001*	*0.003*		*0.391*				
WH	0.450	0.976	<0.001	0.118	0.063	<0.001	<0.001	0.349	0.715	0.949	0.104	<0.001	<0.001	<0.001
			-69.6		*-0.008*	*-18.9*	*-0.002*					*-8.16*	*-13.7*	*-43.3*
DU	0.971	<0.001	<0.001	0.081	0.087	<0.001	<0.001	<0.001	0.008	<0.001	<0.001	<0.001	<0.001	<0.001
		0.020	*-100*	*0.895*	*-0.021*	*-44.9*	*-0.006*	*-0.006*	*0.005*	*-3.34*	*-1.40*	*-4.75*	*-17.9*	*-73.8*
CH	0.783	0.499	0.344	0.084	0.101	<0.001	0.094	0.957	0.015	0.436	0.193	0.288	0.998	0.016
				0.136		*-0.525*	*0.001*		*0.002*					*-0.559*
DE	0.967	<0.001	0.507	0.024	0.958	0.076	0.195	<0.001	0.006	0.306	0.485	0.434	0.627	0.252
		0.045		*0.622*		*-1.16*		*-0.003*	*0.004*					
FM	0.205	0.121	<0.001	0.067	<0.001	<0.001	<0.001	<0.001	0.061	<0.001	<0.001	<0.001	<0.001	<0.001
			-336	*-1.67*	*0.077*	*-240*	*-0.003*	*0.019*	*0.004*	*-10.2*	*-8.93*	*-6.04*	*-97.5*	*-366*
IN	0.359	0.038	0.082	0.576	0.002	0.026	<0.001	<0.001	0.826	0.074	0.028	0.014	0.018	0.031
		0.017	*-44.6*		*-0.018*	*-23.6*	*-0.004*	*-0.003*		*-1.98*	*-0.922*	*-0.989*	*-9.80*	*-37.9*
TV	0.827	0.006	0.721	0.004	0.922	0.244	0.422	0.708	0.409	0.904	0.384	<0.001	0.651	0.606
		0.031		*0.462*								*-0.143*		
WF	0.614	0.004	0.019	0.240	0.085	0.006	0.017	0.051	0.499	0.045	0.033	<0.001	0.005	0.006
		0.026	*-11.43*		*-0.014*	*-4.43*	*-0.001*	*-0.002*		*-0.752*	*-0.259*	*-0.378*	*-0.820*	*-7.21*

Note: Units of Theil-Sen's slope are the units of the parameter (see Table 2) per year.

Table 4. Results of Seasonal Mann-Kendall trend test of each parameter, reporting *p*-value and Theil-Sen's slope for significant trends (in *italics*, α = 0.1).

Code	Temp (ºC)	pH	EC (µS/cm)	Alkalinity (mg/L as $CaCO_3$)	Acidity (mg/L as $CaCO_3$)	SO_4 (mg/L)	Fe (mg/L)	Mn (mg/L)	Al (mg/L)	Ca (mg/L)	Mg (mg/L)	Cl (mg/L)	Na (mg/L)	TDS_{sdc} (mg/L)
							Mainstem							
M11	0.219	0.009	0.025	0.295	0.764	0.172	0.220	0.785	0.803	1.000	0.311	0.005	0.056	0.199
		0.037	*5.83*									*-0.893*	*-0.520*	
M23	0.011	0.003	0.080	0.033	0.106	<0.001	0.080	0.318	0.061	0.027	0.005	0.010	<0.001	<0.001
	0.111	*0.030*	*-3.65*	*0.434*		*-2.54*	*0.002*		*0.001*	*-0.305*	*-0.125*	*-0.334*	*-0.807*	*-4.08*
M61	0.357	0.289	0.225	0.287	0.041	0.008	0.103	0.822	0.097	0.822	0.088	0.015	0.008	0.023
					0.023	*-2.03*			*0.002*		*-0.100*	*-0.369*	*-0.559*	*-3.14*
M82	0.186	0.044	0.026	0.081	0.175	<0.001	0.576	0.132	0.020	0.155	0.022	0.004	<0.001	<0.001
		0.013	*-4.43*	*0.311*		*-2.73*			*0.002*		*-0.098*	*-0.259*	*-0.860*	*-4.66*
M89	0.794	0.806	0.046	0.064	0.524	<0.001	0.657	0.003	0.242	0.137	0.043	<0.001	<0.001	<0.001
			-4.35	*0.457*		*-2.51*		*-0.002*			*-0.097*	*-0.300*	*-0.689*	*-3.73*
M102	0.482	<0.001	0.078	0.079	0.731	<0.001	0.974	0.295	0.157	0.503	0.360	<0.001	<0.001	0.005
		0.043	*-3.53*	*0.464*		*-2.50*						*-0.289*	*-0.602*	*-3.90*
							Tributaries							
YO	0.466	0.025	0.042	0.095	0.436	1.000	0.557	0.086	0.243	0.668	0.597	0.001	0.378	0.744
		0.031	*10.5*	*1.00*				*-0.003*				*-1.39*		
TM	0.052	0.492	0.922	<0.001	0.352	0.124	0.015	<0.001	0.368	0.303	0.360	0.590	0.462	0.731
	0.076			*2.50*			*-0.001*	*0.003*						
WH	0.013	0.689	<0.001	0.041	0.065	<0.001	<0.001	0.495	0.644	0.790	0.062	<0.001	<0.001	<0.001
	0.110		*-68.3*	*-1.73*	*-0.008*	*-20.1*	*-0.002*				*-0.300*	*-8.24*	*-14.7*	*-48.4*
DU	0.070	0.003	<0.001	0.116	0.086	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
	0.071	*0.018*	*-102*		*-0.016*	*-45.0*	*-0.007*	*-0.006*	*0.005*	*-3.60*	*-1.44*	*-4.82*	*-19.0*	*-77.0*
CH	0.987	0.266	0.492	0.004	0.165	<0.001	0.084	0.671	0.057	0.534	0.266	0.150	0.719	0.006
				0.176		*-0.500*	*0.002*		*0.002*					*-0.497*
DE	0.227	<0.001	0.635	<0.001	0.961	0.165	0.016	<0.001	<0.001	0.442	0.647	0.395	0.857	0.423
		0.042		*0.667*			*-0.004*	*-0.004*	*0.003*					
FM	0.333	0.419	<0.001	0.059	<0.001	<0.001	<0.001	<0.001	0.082	<0.001	<0.001	<0.001	<0.001	<0.001
			-371	*-1.92*	*0.069*	*-257*	*-0.004*	*0.016*	*0.003*	*-9.63*	*-9.53*	*-6.19*	*-98.1*	*-393*
IN	0.351	0.055	0.033	0.298	0.002	0.006	<0.001	<0.001	0.942	0.018	0.013	0.003	0.007	0.007
		0.015	*-39.5*		*-0.019*	*-23.4*	*-0.004*	*-0.003*		*-2.03*	*-0.853*	*-0.932*	*-9.26*	*-37.63*
TV	0.445	0.013	0.816	<0.001	0.947	0.195	0.462	0.868	0.143	0.973	0.351	<0.001	0.319	0.690
		0.033		*0.500*								*-0.150*		
WF	0.567	0.005	0.006	0.102	0.070	0.004	0.036	0.039	0.288	0.025	0.011	0.001	0.002	0.001
		0.026	*-11.3*		*-0.012*	*-4.45*	*-0.001*	*-0.002*		*-0.796*	*-0.257*	*-0.359*	*-0.818*	*-6.83*

Note: Units of Theil-Sen's slope are the units of the parameter (see Table 2) per year.

Table 5. Results of Mann-Kendall trend test adjusted for discharge of each parameter, reporting *p*-value and Theil-Sen's slope for significant trends (in *italics*, $\alpha = 0.1$).

Code	Temp (ºC)	pH	EC (µS/cm)	Alkalinity. (mg/L as $CaCO_3$)	Acidity (mg/L as $CaCO_3$)	SO_4 (mg/L)	Fe (mg/L)	Mn (mg/L)	Al (mg/L)	Ca (mg/L)	Mg (mg/L)	Cl (mg/L)	Na (mg/L)	TDS_{sdc} (mg/L)
Mainstem														
M11	0.688	<0.001	0.063	0.133	0.184	0.114	0.761	0.111	0.070	1.000	0.200	<0.001	0.005	0.046
		0.047	*4.86*						*0.003*			*-0.956*	*-0.621*	*-2.58*
M23	0.128	<0.001	0.073	<0.001	0.616	<0.001	0.143	0.779	0.598	0.339	0.009	0.037	<0.001	0.001
		0.036	*-3.37*	*0.760*		*-1.98*					*-0.095*	*-0.233*	*-0.692*	*-4.08*
M61	0.821	0.182	0.311	0.048	0.029	<0.001	0.021	0.880	0.103	0.827	0.091	0.028	<0.001	0.004
				0.539	*0.027*	*-2.30*	*0.005*				*-0.082*	*-0.287*	*-0.724*	*-3.52*
M82	0.520	0.031	0.011	0.041	0.361	<0.001	0.347	0.263	0.109	0.191	0.069	0.003	<0.001	<0.001
		0.012	*-4.31*	*0.418*		*-2.54*					*-0.069*	*-0.229*	*-0.890*	*-3.83*
M89	0.616	0.584	0.033	0.014	0.249	<0.001	0.478	0.005	0.999	0.132	0.037	<0.001	<0.001	<0.001
			-4.54	*0.634*		*-2.19*		*-0.002*			*-0.089*	*-0.301*	*-0.713*	*-3.33*
M102	0.538	<0.001	0.070	0.027	0.841	<0.001	0.819	0.730	0.278	0.652	0.143	<0.001	<0.001	0.004
		0.050	*-3.89*	*0.556*		*-2.08*						*-0.268*	*-0.652*	*-3.02*
Tributaries														
YO	0.571	<0.001	0.044	0.196	0.877	0.544	0.856	0.032	0.350	0.190	0.082	0.001	0.054	0.037
		0.033	*6.35*					*-0.006*			*-0.084*	*-1.71*	*-0.654*	*-2.96*
TM	0.859	0.386	0.965	<0.001	0.992	0.020	0.057	0.582	0.820	0.254	0.572	0.194	0.066	0.241
				2.17		*-2.81*	*-0.002*						*-1.07*	
WH	0.761	0.952	<0.001	0.004	0.108	<0.001	<0.001	0.457	0.410	0.544	<0.001	<0.001	<0.001	<0.001
			-111	*-2.64*		*-34.3*	*-0.003*				*-0.650*	*-12.3*	*-24.2*	*-75.3*
DU	0.749	<0.001	<0.001	0.001	0.067	<0.001	<0.001	<0.001	0.024	<0.001	<0.001	<0.001	<0.001	<0.001
		0.021	*-125*	*0.978*	*-0.025*	*-56.7*	*-0.009*	*-0.007*	*0.004*	*-4.11*	*-1.69*	*-5.39*	*-22.8*	*-91.0*
CH	0.859	0.464	0.567	0.001	0.085	<0.001	0.081	0.877	0.037	0.626	0.252	0.231	0.742	0.006
				0.260	*0.011*	*-0.473*	*0.002*		*0.002*					*-0.450*
DE	0.981	<0.001	0.736	<0.001	0.967	0.031	0.439	<0.001	0.022	0.107	0.583	0.704	0.930	0.110
		0.043		*0.722*		*-0.820*		*-0.003*	*0.004*					
FM	0.071	0.297	<0.001	0.133	<0.001	<0.001	0.105	<0.001	0.453	<0.001	<0.001	<0.001	<0.001	<0.001
	-0.273		*-348*		*0.101*	*-239*		*0.029*		*-10.8*	*-8.77*	*-5.91*	*-96.2*	*-368*
IN	0.752	0.003	0.913	0.008	<0.001	0.662	<0.001	<0.001	0.026	0.875	0.899	0.572	0.439	0.664
		0.023		*2.60*	*-0.043*		*-0.008*	*-0.003*	*-0.003*					
TV	0.401	0.001	0.689	<0.001	0.689	0.984	0.444	0.692	0.881	0.354	0.904	<0.001	0.012	0.128
		0.035		*0.649*								*-0.120*	*0.106*	
WF	0.536	0.002	0.327	<0.001	0.009	0.082	0.013	0.007	0.198	0.602	0.213	0.001	0.024	0.074
		0.027		*1.16*	*-0.046*	*-1.86*	*-0.008*	*-0.002*				*-0.256*	*-0.370*	*-2.76*

Note: Units of Theil-Sen's slope are the units of the parameter (see Table 2) per year.

Table 6. Results of Seasonal Mann-Kendall trend test adjusted for discharge of each parameter, reporting *p*-value and Theil-Sen's slope for significant trends (in *italics*, $\alpha = 0.1$).

Code	Temp (°C)	pH	EC (µS/cm)	Alkalinity. (mg/L as $CaCO_3$)	Acidity (mg/L as $CaCO_3$)	SO_4 (mg/L)	Fe (mg/L)	Mn (mg/L)	Al (mg/L)	Ca (mg/L)	Mg (mg/L)	Cl (mg/L)	Na (mg/L)	TDS_{sdc} (mg/L)
Mainstem														
M11	0.428	0.004	0.031	0.133	0.096	0.199	0.978	0.199	0.085	0.723	0.312	<0.001	0.002	0.031
		0.037	*5.04*		*0.025*				*0.004*			*-0.980*	*-0.605*	*-2.39*
M23	<0.001	<0.001	0.442	<0.001	0.545	<0.001	0.155	0.707	0.683	0.197	0.015	0.027	<0.001	0.001
	0.288	*0.037*		*0.724*		*-1.66*					*-0.080*	*-0.203*	*-0.708*	*-2.98*
M61	0.111	0.185	0.062	0.101	0.037	0.002	0.076	0.805	0.144	0.875	0.111	0.026	<0.001	0.004
			4.32		*0.027*	*-2.03*	*0.005*					*-0.262*	*-0.628*	*-3.38*
M82	0.030	0.035	0.015	0.056	0.462	<0.001	0.731	0.233	0.070	0.129	0.019	<0.001	<0.001	<0.001
	0.168	*0.012*	*-3.49*	*0.439*		*-2.36*			*0.002*		*-0.096*	*-0.271*	*-0.803*	*-3.98*
M89	0.092	0.590	0.023	0.052	0.260	<0.001	0.423	0.005	0.883	0.080	0.023	<0.001	<0.001	<0.001
	0.113		*-5.23*	*0.531*		*-1.91*		*-0.002*		*-0.274*	*-0.098*	*-0.283*	*-0.683*	*-3.32*
M102	0.044	<0.001	0.146	0.015	0.806	<0.001	0.781	0.423	0.155	0.405	0.352	<0.001	<0.001	0.004
	0.123	*0.050*		*0.649*		*-2.12*						*-0.228*	*-0.593*	*-3.14*
Tributaries														
YO	0.563	0.019	0.008	0.182	0.821	0.597	0.633	0.083	0.237	0.138	0.113	<0.001	0.092	0.092
		0.030	*8.33*					*-0.004*				*-1.90*	*-0.664*	*-2.10*
TM	0.545	0.423	0.442	<0.001	0.659	0.035	0.075	0.246	0.909	0.405	0.482	0.220	0.186	0.442
				2.36		*-2.40*	*-0.002*							
WH	0.326	0.829	<0.001	0.004	0.087	<0.001	<0.001	0.702	0.295	0.777	<0.001	<0.001	<0.001	<0.001
			-85.6	*-1.77*	*-0.009*	*-23.9*	*-0.003*				*-0.498*	*-11.1*	*-18.3*	*-54.8*
DU	0.935	0.002	<0.001	0.005	0.065	<0.001	<0.001	<0.001	0.011	<0.001	<0.001	<0.001	<0.001	<0.001
		0.018	*-97.8*	*0.893*	*-0.025*	*-49.0*	*-0.009*	*-0.006*	*0.004*	*-3.445*	*-1.41*	*-5.13*	*-19.9*	*-79.5*
CH	0.186	0.274	0.319	<0.001	0.086	<0.001	0.056	0.482	0.032	0.781	0.319	0.086	0.832	0.008
				0.273	*0.012*	*-0.479*	*0.002*		*0.002*			*-0.036*		*-0.434*
DE	0.683	<0.001	0.524	0.001	0.612	0.016	0.220	<0.001	0.019	0.208	0.707	0.636	0.857	0.106
		0.047		*0.671*		*-0.747*		*-0.003*	*0.003*					
FM	0.070	0.628	<0.001	0.073	<0.001	<0.001	0.377	<0.001	0.399	<0.001	<0.001	<0.001	<0.001	<0.001
	-0.124		*-360*	*-1.50*	*0.097*	*-249*		*0.028*		*-10.6*	*-9.38*	*-6.29*	*-95.0*	*-378*
IN	0.028	0.005	0.957	0.013	<0.001	0.707	<0.001	<0.001	0.085	0.943	0.844	0.761	0.485	0.628
	0.183	*0.029*		*2.51*	*-0.040*		*-0.006*	*-0.003*	*-0.002*					
TV	0.163	0.005	0.273	<0.001	0.528	0.690	0.740	0.921	0.406	0.406	0.388	<0.001	0.013	0.144
		0.034		*0.605*								*-0.124*	*0.101*	
WF	0.070	0.003	0.659	<0.001	0.003	0.035	0.009	0.014	0.335	0.335	0.052	0.003	0.018	0.032
	0.105	*0.029*		*1.17*	*-0.035*	*-2.47*	*-0.007*	*-0.002*			*-0.112*	*-0.244*	*-0.462*	*-4.01*

Note: Units of Theil-Sen's slope are the units of the parameter (see Table 2) per year.

Table 7. Summary of significant monotonic trends; top left: Mann-Kendall test, top-right: Seasonal Mann-Kendall test, bottom-left: Mann-Kendall test adjusted for discharge, bottom-right: Seasonal Mann-Kendall test adjusted for discharge. (□ = no trend; ▲ = significant increasing trend; ▼ = significant decreasing trend).

Code	Temp	pH	EC	Alkalinity	Acidity	SO_4	Fe	Mn	Al	Ca	Mg	Cl	Na	TDS_{sdc}
Mainstem														
M11	□ □	▲ ▲	□ ▲	□ □	□ □	□ □	□ □	□ □	□ □	□ □	□ □	▼ ▼	▼ ▼	□ □
	□ □	▲ ▲	▲ ▲	□ □	□ ▲	□ □	□ □	□ □	▲ ▲	□ □	□ □	▼ ▼	▼ ▼	▼ ▼
M23	□ ▲	▲ ▲	▼ ▼	▲ ▲	□ □	▼ ▼	▲ ▲	□ □	▲ ▲	□ ▼	▼ ▼	▼ ▼	▼ ▼	▼ ▼
	□ ▲	▲ ▲	▼ □	▲ ▲	□ □	▼ ▼	□ □	□ □	□ □	□ □	▼ ▼	▼ ▼	▼ ▼	▼ ▼
M61	□ □	□ □	□ □	□ □	▲ ▲	▼ ▼	▲ □	□ □	□ ▲	□ □	□ ▼	▼ ▼	▼ ▼	▼ ▼
	□ □	□ □	□ ▲	▲ □	▲ ▲	▼ ▼	▲ ▲	□ □	□ □	□ □	▼ □	▼ ▼	▼ ▼	▼ ▼
M82	□ □	▲ ▲	▼ ▼	□ ▲	□ □	▼ ▼	□ □	□ □	▲ ▲	□ □	▼ ▼	▼ ▼	▼ ▼	▼ ▼
	□ ▲	▲ ▲	▼ ▼	▲ ▲	□ □	▼ ▼	□ □	□ □	□ ▲	□ □	▼ ▼	▼ ▼	▼ ▼	▼ ▼
M89	□ □	□ □	▼ ▼	▲ ▲	□ □	▼ ▼	□ □	▼ ▼	□ □	□ □	▼ ▼	▼ ▼	▼ ▼	▼ ▼
	□ ▲	□ □	▼ ▼	▲ ▲	□ □	▼ ▼	□ □	▼ ▼	□ □	□ ▼	▼ ▼	▼ ▼	▼ ▼	▼ ▼
M102	□ □	▲ ▲	▼ ▼	□ ▲	□ □	▼ ▼	□ □	□ □	□ □	□ □	□ □	▼ ▼	▼ ▼	▼ ▼
	□ ▲	▲ ▲	▼ □	▲ ▲	□ □	▼ ▼	□ □	□ □	□ □	□ □	□ □	▼ ▼	▼ ▼	▼ ▼
Tributaries														
YO	□ □	▲ ▲	□ ▲	□ ▲	□ □	□ □	□ □	▼ ▼	□ □	□ □	□ □	▼ ▼	□ □	□ □
	□ □	▲ ▲	▲ ▲	□ □	□ □	□ □	□ □	▼ ▼	□ □	□ □	▼ □	▼ ▼	▼ ▼	▼ ▼
TM	□ ▲	□ □	□ □	▲ ▲	□ □	□ □	▼ ▼	▲ ▲	□ □	▲ □	□ □	□ □	□ □	□ □
	□ □	□ □	□ □	▲ ▲	□ □	▼ ▼	▼ ▼	□ □	□ □	□ □	□ □	□ □	▼ □	□ □
WH	□ ▲	□ □	▼ ▼	□ ▼	▼ ▼	▼ ▼	▼ ▼	□ □	□ □	□ □	□ ▼	▼ ▼	▼ ▼	▼ ▼
	□ □	□ □	▼ ▼	▼ ▼	□ ▼	▼ ▼	▼ ▼	□ □	□ □	□ □	▼ ▼	▼ ▼	▼ ▼	▼ ▼
DU	□ ▲	▲ ▲	▼ ▼	▲ □	▼ ▼	▼ ▼	▼ ▼	▼ ▼	▲ ▲	▼ ▼	▼ ▼	▼ ▼	▼ ▼	▼ ▼
	□ □	▲ ▲	▼ ▼	▲ ▲	▼ ▼	▼ ▼	▼ ▼	▼ ▼	▲ ▲	▼ ▼	▼ ▼	▼ ▼	▼ ▼	▼ ▼
CH	□ □	□ □	□ □	▲ ▲	□ □	▼ ▼	▲ ▲	□ □	▲ ▲	□ □	□ □	□ □	□ □	▼ ▼
	□ □	□ □	□ □	▲ ▲	▲ ▲	▼ ▼	▲ ▲	□ □	▲ ▲	□ □	□ □	□ ▼	□ □	▼ ▼
DE	□ □	▲ ▲	□ □	▲ ▲	□ □	▼ □	□ ▼	▼ ▼	▲ ▲	□ □	□ □	□ □	□ □	□ □
	□ □	▲ ▲	□ □	▲ ▲	□ □	▼ ▼	□ □	▼ ▼	▲ ▲	□ □	□ □	□ □	□ □	□ □
FM	□ □	□ □	▼ ▼	▼ ▼	▲ ▲	▼ ▼	▼ ▼	▲ ▲	▲ ▲	▼ ▼	▼ ▼	▼ ▼	▼ ▼	▼ ▼
	▼ ▼	□ □	▼ ▼	□ ▼	▲ ▲	▼ ▼	□ □	▲ ▲	□ □	▼ ▼	▼ ▼	▼ ▼	▼ ▼	▼ ▼
IN	□ □	▲ ▲	▼ ▼	□ □	▼ ▼	▼ ▼	▼ ▼	▼ ▼	□ □	▼ ▼	▼ ▼	▼ ▼	▼ ▼	▼ ▼
	□ ▲	▲ ▲	□ □	▲ ▲	▼ ▼	□ □	▼ ▼	▼ ▼	▼ ▼	□ □	□ □	□ □	□ □	□ □
TV	□ □	▲ ▲	□ □	▲ ▲	□ □	□ □	□ □	□ □	□ □	□ □	□ □	▼ ▼	□ □	□ □
	□ □	▲ ▲	□ □	▲ ▲	□ □	□ □	□ □	□ □	□ □	□ □	□ □	▼ ▼	▲ ▲	□ □
WF	□ □	▲ ▲	▼ ▼	□ □	▼ ▼	▼ ▼	▼ ▼	▼ ▼	□ □	▼ ▼	▼ ▼	▼ ▼	▼ ▼	▼ ▼
	□ ▲	▲ ▲	□ □	▲ ▲	▼ ▼	▼ ▼	▼ ▼	▼ ▼	□ □	□ □	□ ▼	▼ ▼	▼ ▼	▼ ▼

Table 8. Results of Mann-Whitney U test comparing data from 2010-2013 to 2019-2023 for tributaries with incomplete datasets: Whiteday Creek (WD) and Robinson Run (RO); reporting median, interquartile range (in *italics*), and *p*-value.

	WD			RO		
	2010-2013	**2019-2023**	***p***	**2010-2013**	**2019-2023**	***p***
Temp, °C	13.8 *5.3 - 21.1*	10.1 *4.8 - 17.8*	0.242	15.7 *6.1 - 21.4*	11.5 *6.2 - 18.6*	0.408
pH	7.6 *7.1 - 8.1*	7.8 *7.5 – 8.0.*	0.600	7.3 *6.7 - 7.6*	6.9 *5.2 - 7.4*	0.015
EC, µS/cm	100 *57- 135*	97 *77 - 124*	0.497	2,066 *1554 - 2656*	1,917 *1410 - 2488*	0.652
Alkalinity, mg/L as $CaCO_3$	22 *17 - 41*	26 *17 - 40*	0.42	53 *23 - 74*	44 *0 - 94*	0.313
Acidity, mg/L as $CaCO_3$	0.38 *0.25 - 0.50*	0.35 *0.235 - 0.57*	0.896	2.35 *1.75 - 5.30*	23.05 *4.09 - 94.82*	<0.001
SO_4, mg/L	12.5 *11.4 - 13.7*	11.2 *10.2 - 12.7*	0.009	1,230 *1029 - 1682*	1,000 *735 - 1370*	0.013
Fe, mg/L	0.056 *0.049 - 0.088*	0.083 *0.055 - 0.124*	0.210	0.374 *0.126 - 0.647*	6.590 *0.708 - 15.600*	<0.001
Mn, mg/L	0.012 *0.009 - 0.028*	0.011 *0.009 - 0.020*	0.444	0.493 *0.390 - 0.560*	1.040 *0.754 - 1.770*	<0.001
Al, mg/L	0.025 *0.015 - 0.050*	0.021 *0.000 - 0.046*	0.190	0.085 *0.022 - 0.195*	0.110 *0.061 - 4.870*	0.015
Ca, mg/L	11.0 *8.3 - 14.6*	10.5 *8.8 - 15.4*	0.594	341.5 *263.0 - 397.2*	257.0 *195.0 - 294.0*	0.001
Mg, mg/L	2.34 *2.03 - 2.94*	2.27 *1.98 - 2.65*	0.458	72.35 *60.90 - 86.50*	79.10 *64.50 - 97.00*	0.1742
Cl, mg/L	4.9 *4.3 - 7.2*	6.2 *5.0 - 7.5*	0.106	11.8 *9.2 - 17.5*	73.6 *50.2 - 109.0*	<0.001
Na, mg/L	4.1 *3.0 - 5.7*	4.3 *3.4 - 5.5*	0.463	120.2 *82.3 - 159.2*	70.4 *44.7 - 95.2*	0.002
TDS_{sdc}, mg/L	44.75 *40.67 - 67.06*	46.45 *40.0 - 64.5*	0.796	1,731.6 *1,501.2 – 2,306.3*	1,586.0 *1,140.2 – 1,926.0*	0.031

locally weighted polynomial regression with a segmented regression. Significant downward trends were reported throughout the river basin for bromide, chloride, SO_4, and TDS during 2009-2019; trends in TDS and SO_4 decreased regardless of changes in discharge following the implementation of the voluntary discharge plan. Our results support these findings and expand upon them. We found significant decreasing trends in TDS and SO_4 at an additional two sites (i.e., M61, FM), regardless of adjusting for season or discharge. Kingsbury et al. (2023) used field estimates of TDS which is calculated by multiplying a coefficient (approximately 0.65) by the specific conductance. This multiplier may change over time as it is dependent on the ionic species present. Our work relied on the sum of the concentrations of all measured dissolved constituents, and the findings supported the TDS trends reported by Kingsbury et al. (2023). Our results reinforce the decrease or stable trends in chloride concentrations reported by Kingsbury et al. (2023). Of all the locations included in Kingsbury's analysis (n = 16), chloride concentrations were either decreasing (75%) or exhibited no trend (25%). Trends in bromide concentrations were not considered in our study because the available data did not meet the assumptions needed to perform the statistical tests. In addition, our work also expanded the trends observed by Kingsbury et al. (2023) reviewing long-term trends at an additional four field sites and 10 parameters (temperature, EC, alkalinity, acidity, Fe, Mn, Al, Ca, Mg, and Na) (Table 7).

The Monongahela River basin was historically impacted by AMD, and sampling locations were first selected partly due to locations of AMD treatment facilities (Figure 2). The water quality of a watershed impacted by AMD typically has low pH, high SO_4 concentrations, and high metal concentrations (Fe, Mn, Al, Ca, and Mg). Overall, trends in these parameters in the mainstem either exhibited no trend or were improving. Of the six mainstem sampling locations, 67% showed increasing trends in pH, 83% showed decreasing trends in SO_4, 50% showed decreasing trends in Mg, 17% showed a decreasing trend in Mn (with 83% remaining exhibiting no trend), and 100% showed no trend in Ca. While not conclusive at any sampling site, some increasing trends were determined in Al concentrations; however, no trend was determined in half of the sampling locations (Table 7), and the Theil-Sen's estimator ranged from 0.001 to 0.004 mg/L per year for significant trends (Tables 3-6). Many of these gains are likely related to the voluntary management plan that was implemented by the coal industry. Because the management strategy is not regulated, this independent monitoring is important to communicate the impacts.

The Monongahela River provides drinking water for more than one million people and is the source water for more than 15 drinking water plants (Wilson and Van Briesen 2013). Results suggest widespread improvements in several parameters for which there are secondary water quality standards (i.e., pH, SO_4, TDS_{sdc}) (Table 7), leading to improved taste over time (USEPA 2024). In addition to improvements in drinking water quality, trends suggest additional water quality improvements. Widespread decreasing trends in Cl, Na, SO_4, and TDS_{sdc} concentrations were detected in the Monongahela River basin (Table 7).

The WVDEP maintains a long-term database of water quality through the West Virginia's Ambient Water Quality Monitoring network. As part of a state-wide trend analysis, trends (1996-2012) were determined for several streams in the Monongahela River basin (Monongahela River; Cheat River, CH, Dunkard Creek, DU; Tygart Valley, TV; and West Fork, WF). Results suggested decreases in Mg, Cl, SO_4, and Fe; no trends were determined for Al and Mn (Buchanan and Mandel 2015). Our results look forward to the next decade. We found that, in general, Cl and SO_4 concentrations continued to decline within the mainstem and several tributaries studied by Buchanan and Mandel (2015); we found decreasing Cl trends in DU, TV, and WF and decreasing trends in SO_4 in DU, CH, and WF. Results for Mg were mixed as we found both decreasing trends and no trends. While no trends in Al were previously reported, we found increasing trends in DU and CH. Similarly, decreasing trends in Mn in DU and WF were found in our study, in contrast to no trends reported in 2015. We also did not find decreasing Fe concentrations throughout the basin, as previously reported, but found decreasing trends in DU and WF.

This study only evaluated gradual trends over time using a trend analysis approach. A trend analysis approach is appropriate when treatment systems are widespread, when treatment is implemented progressively, there is little documentation, or when data are only collected at one location (Meals et al. 2011). Only monotonic trends were evaluated, and step changes may exist that were not detected.

Implications for 3RQ and Other Monitoring Programs

As a result of 3RQ monitoring, water quality data were available when the fish kill in Dunkard Creek occurred. Overall water quality in DU has substantially improved over time since the sampling began in 2009. We found a significant increase in pH and alkalinity, significant decrease in EC and acidity, a significant decrease in SO_4 concentrations, significant decreases in metal concentrations (Fe, Mn, Ca, Mg, Cl, and Na), and an overall significant decrease in TDS_{sdc}. Significant increasing trends in Al were observed, but the Theil-Sen's slope ranged from a modest 0.004 to 0.005 mg/L per year. Using monitoring data, WVWRI developed a discharge management approach to reduce TDS. The approach was applied in January 2010 by the coal industry on a voluntary basis (Ziemkiewicz 2015). The management approach remains in use and is attributed to maintaining SO_4 and TDS levels below EPA standards (Ziemkiewicz 2015; Kingsbury et al. 2023). This one example highlights the importance of long-term monitoring to address specific management needs.

Frequent use of collected data is a major characteristic of an effective monitoring program (Lindenmayer and Likens 2010). The 3RQ monitoring network has provided support so that targeted studies can be completed when there is a need. Specific to the Monongahela River basin, WVWRI has completed targeted studies related to TDS trends, trihalomethanes levels, and radium levels in Tenmile Creek (Ziemkiewicz et al. 2022; WVWRI 2024b). Therefore, long-term monitoring programs like 3RQ can support management decisions at the basin-wide or specific watershed level.

Effective monitoring programs must have strong partnerships among scientists, policymakers, and managers (Lindenmayer and Likens 2010). 3RQ is an example of a successful program that combines citizen scientists and grassroots efforts with research partners to maintain monthly sampling at 42 stations (WVWRI 2024a). The effort combines expertise from industry, academic researchers, and citizen groups to respond to impacts of coal and natural gas in the basin (Ziemkiewicz et al. 2022).

Identifying trends in water quality in surface water is important to understand the impact of point and non-point source pollution on ecosystem health (Ouyang 2005). The results reported herein focus on the 3RQ dataset maintained by WVWRI for the Monongahela River basin. The 3RQ program also supports monitoring and reporting in the Southern Allegheny River and its major tributaries (n = 14 sites) as well as in the upper Ohio River basin (WVWRI 2024a). This long-term dataset is unique on such a large scale. Expanding the analysis to the extended 3RQ network would provide information about long-term water quality trends at the regional scale. Statistical advantages related to long-term datasets like these are important in answering questions related to long-term ecosystem dynamics (Fleming 1999). Ultimately, the data are important for identifying pollution sources and evaluating remediation options (Ziemkiewicz et al. 2022). Through the datasets like that provided through 3RQ, we can monitor for seasonal trend changes related to climate change. We also have the opportunity to detect improvements in the larger rivers as headwaters are restored through Bipartisan Infrastructure Law funding for abandoned mine land reclamation.

Conclusion

Long-term water quality trends (2009-2023) were documented in the Monongahela River basin, an important resource for the population in northern West Virginia and southwestern Pennsylvania. Overall, trends in AMD signals in the mainstem either showed no trend or were improving. Of the six mainstem sampling locations, widespread decreasing trends in TDS, SO_4, Cl, and Na were observed, regardless of adjusting for discharge or season; similarly, increasing trends or no trends in pH were observed at all sampling sites. Water quality gains are likely related to the voluntary management plan that was implemented by the coal industry. This independent monitoring through 3RQ is important to communicate the impacts as well as plan for future water management.

Acknowledgements

This material is based upon work supported, in part, by the U.S. Geological Survey under Grant/Cooperative Agreement No. G21AP10620. This research was sponsored in part by the Colcom Foundation, the Statler College of Engineering and Mineral Resources, and the Research Apprenticeship Program. The authors thank Grace Kerr for her contributions.

Data Availability

The data presented in this study are available on request from the West Virginia Water Research Institute, https://3riversquest.wvu.edu/.

Author Bio and Contact Information

Sitraka Jean d'Annie Rabemanjakasoa (corresponding author) is currently pursuing her Ph.D. in Civil Engineering at West Virginia University. She holds a Bachelor of Science in Mining Engineering from the École Supérieure Polytechnique d'Antananarivo in Madagascar and a Master's degree in Civil Engineering from West Virginia University. Sitraka has a robust professional background, having worked in Madagascar for over 10 years. She served as an Environmental Compliance Officer and Report Researcher for the Ambatovy mining project, and as a Civil Engineer for the Toamasina port development project. She may be reached at PO Box 6103, Morgantown, WV 20506 and at sjr0018@mix.wvu.edu.

Sarah Nelson is an undergraduate civil and environmental engineering student at West Virginia University. Currently, she is conducting research with Dr. Leslie Hopkinson at WVU and is a student worker at the West Virginia Water Research Institute. Presenting at two research symposiums and an international conference, the Appalachian Region remains the center of Sarah's focus, and it has fueled her passion for water quality and acid mine drainage remediation. She may be contacted at PO Box 6103, Morgantown, WV 20506 and at sen00006@mix.wvu.edu.

Leslie C. Hopkinson is an Associate Professor in the Wadsworth Department of Civil and Environmental Engineering at West Virginia University, specializing in water resources. She received her B.S. in Biological and Agricultural Engineering at Louisiana State University and her Ph.D. in Biological Systems Engineering at Virginia Tech. Her research focus is in hydrology, reclamation, and ecological engineering. She may be contacted at PO Box 6103, Morgantown, WV 20506 and at Leslie.Hopkinson@mail.wvu.edu.

Rachel Spirnak is a Water Research Project Manager for the West Virginia Water Research Institute. Rachel holds a Master of Science degree in Energy Environments from WVU and a Bachelor of Science degree in Biology from Penn State Behrend. She may be contacted at PO Box 6064, Morgantown, WV 20506 and at rachel.spirnak@mail.wvu.edu.

Melissa O'Neal is the Associate Director for the West Virginia Water Research Institute. Melissa obtained an Associate of Science degree through the Garrett College Natural Resources and Wildlife and Technology Program and a Bachelor of Science Degree in Wildlife and Fisheries Resources from West Virginia University. She may be contacted at PO Box 6064, Morgantown, WV 20506 and at melissa.oneal@mail.wvu.edu.

References

Buchanan, C. and R. Mandel. 2015. *Water Quality Trend Analysis at Twenty-Six West Virginia Long-Term Monitoring Sites*. ICPRB Report 14-6. West Virginia Department of Environmental Protection, Charleston, WV. Available at: https://dep.wv.gov/WWE/watershed/wqmonitoring/Documents/FINALWVTrendReportApril172015.pdf. Accessed October 24, 2024.

Chase, E.H. 2014. Regulation of TDS and chloride from oil and gas wastewater in Pennsylvania. In: *Shale Energy Engineering 2014: Technical Challenges, Environmental Issues, and Public Policy.* Proceedings of the 2014 Shale Energy Engineering Conference, Pittsburgh, PA, July 21-23, 2014, pp. 95-106. Available at: https://doi.org/10.1061/9780784413654.010. Accessed October 24, 2024.

Fleming, R.A. 1999. Statistical advantages in, and characteristics of, data from long-term research. *The Forestry Chronicle* 75(3): 487-489. Available at: https://doi.org/10.5558/tfc75487-3. Accessed October 24, 2024.

Grolemund, G. and H. Wickam. 2011. Dates and times made easy with lubridate. *Journal of Statistical Software* 40(3): 1-25. Available at: https://www.jstatsoft.org/v40/i03/. Accessed November 14, 2024.

Handke, P. 2008. Trihalomethane Speciation and the Relationship to Elevated Total Dissolved Solid

Concentrations Affecting Drinking Water Quality at Systems Utilizing the Monongahela River as a Primary Source during the 3rd and 4th Quarters of 2008. Pennsylvania Dept. of Environmental Protection, Harrisburg, PA. Available at: https://fliphtml5.com/jpml/bzki/basic. Accessed October 24, 2024.

Helsel, D.R., R.M. Hirsch, K.R. Ryberg, S.A. Archfield, and E.J. Gilroy. 2020. Statistical Methods in Water Resources: U.S. Geological Survey Techniques and Methods, book 4, chapter A3, pp. 458. Available at: https://doi.org/10.3133/tm4a3. Accessed October 24, 2024.

Hopey, D. 2014. Report on Water Quality Says Monongahela River No Longer Degraded by Sulfates. *Pittsburgh Post-Gazette (PA)*. Available at: https://research.ebsco.com/c/y2m5o4/viewer/html/fm44bm3nvf. Accessed October 24, 2024.

Kingsbury, J.W., R. Spirnak, M. O'Neal, and P. Ziemkiewicz. 2023. Effective management changes to reduce halogens, sulfate, and TDS in the Monongahela River basin, 2009-2019. *Water* 15(4): 631. Available at: https://doi.org/10.3390/w15040631. Accessed October 24, 2024.

Lindenmayer, D.B. and G.E. Likens. 2010. The science and application of ecological monitoring. *Biological Conservation* 143(6): 1317-1328. Available at: https://doi.org/10.1016/j.biocon.2010.02.013. Accessed October 24, 2024.

Marchetto, A. 2021. rkt: Mann-Kendall Test, Seasonal and Regional Kendall Tests. R package version 1.6. Available at: https://CRAN.R-project.org/package=rkt. Accessed September 17, 2024.

Meals D.W., J. Spooner, S.A. Dressing, and J.B. Harcum. 2011. Statistical Analysis for Monotonic Trends. Tech Notes 6, November 2011. Developed for U.S. Environmental Protection Agency by Tetra Tech, Inc., Fairfax, VA. Available at: tech_notes_6_dec2013_trend.pdf. Accessed October 24, 2024.

Merriam, E.R., J.T. Petty, M. O'Neal, and P.F. Ziemkiewicz. 2020. Flow-mediated vulnerability of source waters to elevated TDS in an Appalachian River basin. *Water* 12(2): 384. Available at: https://doi.org/10.3390/w12020384. Accessed October 24, 2024.

Ott, L. and M. Longnecker. 2001. *An Introduction to Statistical Methods and Data Analysis*, 5th ed. Duxbury Press, Pacific Grove, CA.

Ouyang, Y. 2005. Evaluation of river water quality monitoring stations by principal component analysis. *Water Research* 39(12): 2621-2635. Available at: https://doi.org/10.1016/j.watres.2005.04.024. Accessed October 24, 2024.

Pennsylvania Department of Environmental Protection (PADEP). 2014. *Pennsylvania Integrated Water Quality Monitoring and Assessment Report*. Clean Water Act Section 305(b) Report and 303(d) List. Available at: https://www.pennfuture.org/Files/Admin/2014-Pennsylvania-Integrated-Water-Quality-MonitoringandAssessmentReport.pdf. Accessed October 24, 2024.

Rassenfoss, S. 2011. From flowback to fracturing: Water recycling grows in the Marcellus Shale. *Journal of Petroleum Technology* 63(07): 48-51. Available at: https://doi.org/10.2118/0711-0048-JPT. Accessed October 24, 2024.

Reynolds, L. 2009. Update on Dunkard Creek. USEPA Region 3, Environmental Analysis and Innovation Division, Office of Monitoring and Assessment. Available at: https://archive.epa.gov/region03/archive/web/pdf/dunkard.pdf. Accessed September 17, 2024.

Strager, M.P., J.M. Strager, J.J. Fletcher, C. Yuill, R.N. Eli, J.T. Petty, and S.J. Lamont. 2010. Watershed analysis with GIS: The watershed characterization and modeling system software application. *Computers & Geosciences* 36(7): 970-976. Available at: https://doi.org/10.1016/j.cageo.2010.01.003. Accessed October 24, 2024.

U.S. Army Corps of Engineers (USACE). 2012. Monongahela River Watershed Initial Watershed Assessment. Available at: https://spcwater.org/wp-content/uploads/2020/02/USACE_MonWatershedAssess_2012.pdf. Accessed November 14, 2024.

U.S. Environmental Protection Agency (USEPA). 2000. Guidance for Data Quality Assessment, Practical Methods for Data Analysis. EPA/600/R-96/084. Washington, D.C. Available at: https://semspub.epa.gov/work/06/217322.pdf. Accessed November 14, 2024.

U.S. Environmental Protection Agency (USEPA). 2015. Ecoregions of North America. Available at: https://www.epa.gov/eco-research/ecoregions-north-america. Accessed October 24, 2024.

U.S. Environmental Protection Agency (USEPA). 2024. Secondary Drinking Water Standards: Guidance for Nuisance Chemicals. Available at: https://www.epa.gov/sdwa/secondary-drinking-water-standards-guidance-nuisance-chemicals. Accessed October 24, 2024.

West Virginia Water Research Institute (WVWRI). 2024a. Three Rivers Quest | Home. Available at: https://3riversquest.wvu.edu/home. Accessed

October 24, 2024.

West Virginia Water Research Institute (WVWRI). 2024b. Monongahela River Basin. Available at: https://3riversquest.wvu.edu/monongahela-river. Accessed May 29, 2024.

Wilson, J.M. and J.M. Van Briesen. 2013. Source water changes and energy extraction activities in the Monongahela River, 2009-2012. *Environmental Science & Technology* 47(21): 12575-12582. Available at: https://doi.org/10.1021/es402437n. Accessed October 24, 2024.

Ziemkiewicz, P. 2010. Discharge management to control TDS in the Upper Monongahela basin. In: *2010 West Virginia Surface Mine Drainage Task Force Symposium Papers*. Morgantown, WV. Available at: https://wvmdtaskforce.com/past-symposium-papers/2010-symposium-papers/. Accessed November 19, 2024.

Ziemkiewicz, P. 2015. Coal industry application of discharge management to control sulfate and TDS in the Monongahela River. In: *2015 West Virginia Mine Drainage Task Force Symposium Papers*. Morgantown, WV. Available at: https://wvmdtaskforce.com/wp-content/uploads/2016/01/15-ziemkiewicz.pdf. Accessed October 24, 2024.

Ziemkiewicz, P., M. O'Neal, T. Vandivort, J. Kingsbury, and R. Pell. 2022. Managing TDS and sulfate in the Monongahela River: Three Rivers QUEST. In: *Environmental Impacts from the Development of Unconventional Oil and Gas Reserves*, D. Bain, J. Stolz, and M. Griffin (Eds.). Cambridge University Press, Cambridge, pp. 386-410. Available at: https://doi.org/10.1017/9781108774178.020. Accessed October 24, 2024.

Universities Council on Water Resources
Journal of Contemporary Water Research & Education
Issue 182, Pages 55-69, April 2025

Pluvial Flood Damage Exposure in a Midwestern Metropolitan Watershed: Further Evidence of the Prevalence of Commercial Flood Risk

Steven Shultz

Real Estate and Land Use Economics, College of Business Administration, University of Nebraska at Omaha
Corresponding author

Abstract: Previous research on flood damage risk is updated using expected annual damage estimates from a recent U.S. Army Corps of Engineers (USACE) feasibility study in the Papillion Creek Watershed, Omaha, Nebraska. Across the 500-year floodplain study area encompassing all of the stream reaches in the Watershed, only 25% of 3,587 buildings were risk free. Commercial buildings represent 44% of inventory yet generate 92% of risk, which is double the previously estimated commercial risk based on simplistic modelling. Risk varies by building type, with office and recreation/entertainment buildings generating the highest amount (17% each) followed by industrial (12%), retail and warehouses (both at 11%), and apartments (6%). Mean annual risk values for buildings range from $160 (mobile homes) to $90,152 (recreation/entertainment). Only 11% of buildings in the study area were constructed over the 2005 to 2019 period (after the use of accurate floodplain maps and active floodplain planning), but they generate half of total flood risk. Omaha Area floodplain managers should focus more on commercial building flood risk to reduce the need for costly flood mitigation efforts funded by taxpayers. This research should be replicated elsewhere using either similar USACE feasibility study data, the National Structure Inventory dataset in conjunction with HAZUS-MH flood risk modelling, and/or private sector data from the First Street Foundation.

Keywords: *flood risk, expected annual damage, floodplain management*

Prior research published in this same journal (Shultz 2017) concluded that commercial buildings generated about half of all flood damage risk despite their relative scarcity compared to single-family homes in the 100-year floodplains of two midwestern study site locations (parts of Omaha, NE and Fargo, ND) and that most prior flood risk research in the USA has ignored commercial buildings flood risk altogether. However, these findings were based on relatively simplistic yet commonly employed measures of flood risk that treated all structures in the 100-year floodplain as having an equal (1% chance) of flooding in any given year.

This present research on the nature of urban flood risk takes advantage of a unique dataset created by the United States Army Corps of Engineers (USACE), based on state-of-the art flood risk modelling approaches to estimate expected annual monetary damage to 3,857 buildings and contents in the 500-year floodplain areas of Papillion Creek Watershed in the Greater Omaha, NE metropolitan area which encompasses two counties and population of approximately one million inhabitants. The area is primarily subject to pluvial flood damage, defined as flooding occurring in and around lakes, stream or rivers, and which is noted as being the most common type of flooding in the United States (Resources for the Future 2023).

These data differ substantially from typically available flood damage data that usually measure flood risk simplistically by noting if buildings are with the 100- or 500-year regulatory floodplain

Research Implications

- Almost all flood risk (expected annual damage in monetary terms) in a midwestern metropolitan area subject to pluvial flooding is related to recently built commercial structures.
- Prior analyses of flood risk in the same location but based solely on 100-year floodplain status rather than building specific hydrologic flood modelling, drastically underestimated flood risk.
- Flood risk associated with future commercial building developments within 500-year floodplains should be carefully evaluated to avoid the need for costly flood mitigation projects.
- Recently generated flood risk databases at the building level of analysis should be used to quantify the extent and nature of flood risk in other locations of the country.

boundaries, which is highly limited because such an estimation approach does not indicate the actual probability of building specific flood damages for different types of flood events (from two to 100-year magnitude events). The reality is that there is high degree of heterogeneity of flood risk characteristics for buildings within the same floodplain boundaries. They have different first floor elevation levels, distances from hydrologic features and/or flood mitigation infrastructures, and in many cases have different building materials construction design all of which are known to impact stage damage curves.

Research Objectives

The first objective of this research is to quantify the extent and types of buildings in a midwestern metropolitan area contributing to fluvial flood damage risk (expected annual damage (EAD) to buildings in monetary terms). Evaluated flood risk metrics include: the proportion of total risk (EAD) associated with building types; measures of central tendency of risk values; and flood risk as a proportion of total building value (depreciated structural replacement values). Proportions of total flood risk are a convenient way to quickly assess how different building types contribute to overall flood risk. Actual risk values are useful for evaluating the impacts and magnitude of risk. Flood risk as a proportion of total building value is useful metric to control for the effect of building value on the results.

Flood risk metrics are reported separately for the following building types: single-family homes, mobile homes, offices, hotels, industrial multiple family (apartments), recreation/entertainment structures, restaurants, service stations, special use buildings, and warehouses.

A second and closely related objective is to quantify the impact of improved flood risk modelling by comparing the above flood risk metrics to corresponding findings of a prior (Shultz 2017) study in the Sarpy County portion of the study area. The 2017 findings relied on much more simplistic yet commonly used approaches to estimate annual flood risk where building replacement values are multiplied by 1% for buildings located in the 100-year floodplain to account for their annual probabilistic flood risk.

The third objective is to quantify how building age impacts the relative proportion of flood risk values in the community. In particular, is the flood risk in the study area derived from different building types built before/after 2005 when updated and improved floodplain maps were introduced in the community? The post-2005 era of updated floodplain maps (and the participation in the Federal Emergency Management Agency) (FEMA) Community Rating System of floodplain management) was expected to have influenced the types of buildings built in flood risk areas.

The fourth objective is to evaluate how this research can be replicated in other communities across the United States using similar building specific risk data and flood risk data, which are becoming increasing available nationwide from both public and private sources.

Literature Review: The Extent and Nature of U.S. Flood Damage

Flood Risk Data in the United States at Risk

Flood risk, whether it is predicted (i.e. modelled) or empirically based on documenting prior flood events, can be classified as either direct tangible damage (typically building damage), direct intangible damage, or indirect intangible damage (Merz et al. 2010). The dominant research on flood damage risk in the United States has focused on direct tangible damages, typically building damage, as it is almost aways the largest component of flood damage. Historically, flood risk to buildings has been quantified by: 1) Estimating the impact of flood risk on resale values, often in conjunction with analyses of insurance values and actual damage claims, to gain a better understanding of property owners participation in the National Flood Insurance Program (Kunreuther and Michel-Kerjan 2013; Kousky and Michel-Kerjan 2017); 2) Quantifying past observed flood damage (Pielke et al. 2002; Cartwright 2005; Floodsmart 2016); and 3) Predicting the depreciated structural replacement cost of damages to buildings, which is an approach historically adopted both by FEMA and the USACE when evaluating the net economic development benefits of flood mitigation projects and policies (Scawthorn et al. 2006; USACE 2012). This approach has also recently been adopted by private sector interests including Core Logic and the First Street Foundation. More recently, research has demonstrated the prevalence of flood damage occurring within 500-year floodplain areas (CNT 2014; Kousky and Michel-Kerjan 2017; Office of Inspector General 2017; First Street Foundation 2020). Very recently, FEMA and the USACE have generated a National Structure Inventory that is being used by researchers to quantify flood damage to specific buildings, such as the work by Mostafiz et al. (2021) that focused on residential areas in Louisiana.

Almost all prior academic research and grey literature reports by government agencies and/or think tanks on the extent and nature of flood risk in the U.S. have focused almost exclusively on residential (single-family housing) risk and ignore commercial buildings risk. There are, however, two known studies quantifying the extent and nature of commercial flood building risk in the U.S: 1) Shultz (2017) compared replacement costs of different building types within the 100-year floodplain boundaries of two midwestern cities (Omaha, NE and Fargo, ND) and 2) The First Street Foundation and collaborators quantified flood risk (both structural damage and indirect effects) for some types of commercial buildings in 20 different metropolitan areas across the U.S. (First Street Foundation 2021; Porter et al. 2022).

The Extent and Nature of Commercial Flood Risk in Two Midwestern Cities

Previously Shultz (2017) quantified the extent and nature of potential flood risk in monetary terms to alternative types of buildings in two midwestern locations: Sarpy County, NE (part of the Omaha metropolitan area), and Fargo/Moorhead MN/ND, both of which are subject to fluvial flooding. Flood risk was calculated by multiplying depreciated structural replacement values of buildings by 1% if they were located in the regulatory 100-year floodplain. Commercial buildings represented 13% of all structures in the 100-year floodplain in Sarpy County (Omaha, NE) and 16% in Fargo/Moorhead (ND and MN), yet accounted for half of total potential flood damage exposure in each of the two locations. A major limitation of this prior study was the simplistic assumption that occurs uniformly equally across all buildings in the 100-year floodplain, with each structure having a 1% probability of flooding each year, regardless of its actual elevation and proximity to potential flooding sources. Similarly, all buildings were assumed to suffer identical flood damage regardless of their actual construction materials and/or the existence of flood-proofing measures.

An Evaluation of Commercial Flood Risk Nationally

A recent national study relying on flood risk damage estimates by the First Street Foundation (2020) estimated substantial structural and related economic flood damage estimates for office, retail, and multi-unit residential buildings for 20 different U.S. metropolitan areas and 20 different states. Similar analyses by the First Street Foundation (2021) itself titled 'The 4th National Risk Assessment: Climbing Commercial Closures' and a closely related study by Porter et al. (2022) report that approximately 730,000 commercial buildings across the U.S. generate over $13.5 billion in damage exposure. These estimates were made using the First Street national flood risk model at a 30-meter level of resolution combined with county assessor parcel data, probabilistic flood event estimates, and multivariate depth damage functions (see also Bates et al. 2021). To date, no known independent studies have evaluated the relative accuracy of First Streets' flood risk assessments. However, the American Flood Coalition has noted that First Streets' national flood risk dataset is an important compliment to FEMA flood risk assessments, but that these data should not be used for quantifying flood risk as part of flood mitigation feasibility studies, flood insurance ratings, and/or regulatory floodplain decisions (American Flood Coalition 2024). It should also be noted that alternative proprietary flood modelling efforts across the U.S. are being undertaken by other private sector groups, such as the efforts by Fathom Group which are expected to allow comparisons of the accuracy and/or consistency of First Street flood risk modelling.

While the First Street modelling of commercial flood risk in the U.S. has contributed to a better understanding of the nature of flood risk across the country, it has several limitations. First, only three types of commercial buildings were evaluated (office, retail, and apartment buildings), leaving out a lot of commercial building types that are known to have flood risk. Second, no corresponding structural damage estimates are provided for single-family residential structures in the same 20 study area locations, so it is not possible to compare the relative level of risk between commercial and residential buildings. Third, the study does not cover all locations in the U.S., making it difficult to evaluate the accuracy of flood risk estimates through direct comparisons to commercial flood risk estimates made by the USACE or FEMA in various study locations across the country. Finally, flood risk levels for buildings or sub-areas below entire cities are not available for the public to access and evaluate. First Street does, however, permit the public the opportunity to obtain relative risk factor scores for individual residential properties, via their website.

USACE Estimates of Flood Risk in the Greater Omaha Area

In June of 2021, the Omaha District of the USACE completed a three-year, $3 million feasibility study in partnership with the Papio-Missouri River Natural Resources District (PMNRD), which evaluated alternative flood strategies in the Papio (Papillion Creek) Basin (USACE 2021a).

For such studies, the USACE considers flood mitigation benefits to include avoided damage to the structure and contents of properties within a study area which is defined as 500-year floodplain areas downstream of two proposed flood mitigation dams (Figure 1).

These building-specific flood damage exposure data generated by the USACE were not available for public review and instead was obtained for this research via a 'Freedom of Information Act' (FOIA) request. The resulting data needed to be aggregated across many different and complex Microsoft Excel spreadsheets and then combined with other external data records maintained by county assessors to confirm the accuracy of the data and to integrate it with additional building characteristics.

The methodologies for estimating flood damage exposure estimates are part of well-established 'National Economic Development (NED) Methodologies' which are described in the General Re-evaluation Report (GRR) by the USACE (2021b) and briefly summarized below.

The first step in the estimation of EAD to buildings and contents by the USACE involves quantifying the location, and physical characteristics of structures are obtained through site visits and integrations with county assessor databases. Key site visit data collected include ground floor elevations, building characteristics and uses, and building conditions. The structural information of buildings is used with commercial building cost estimation software to calculate replacement cost new values from which likely rates of depreciation are subtracted to generate depreciated structural replacement values for each building. This entire process is often referred to as 'structural inventory.'

The second USACE approach requires calculating potential flood damage exposure for specific buildings and requires complex hydrologic and hydraulic modelling that is part of the HEC-FDA modelling flood risk management (FRM) approaches. Initially, annual event probability (AEP) damage for individual structures was

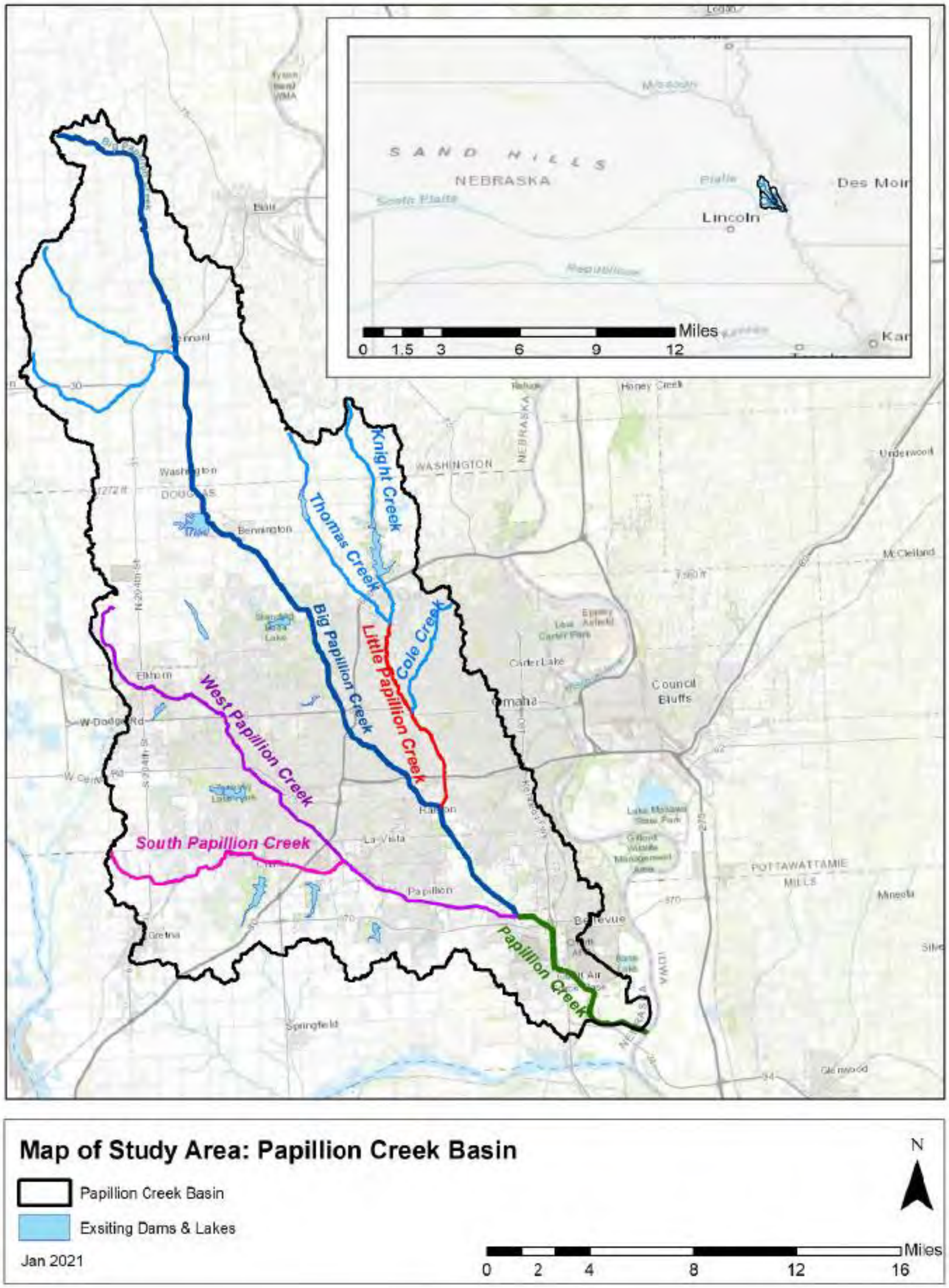


Figure 1. Flood Damage Risk Study Area Map: Papillion Creek Watershed, Omaha, NE (Verbatim from the USACE GRR Study Report, 2021a, p. 3).

calculated for eight alternative hypothetical flood events, ranging from a two-year flood up to a 500-year flood event. These values are based on site specific building information, in particular, location with respect to stream reaches, first floor elevation, historical and expected rainfall data, and streamflow gauge data, as well as both depth damage functions and content to value functions. Estimates are made within pre-identified reaches of sub-basins. AEP values are then converted to EADs by multiplying AEP values for each structure by flood event probabilities and then summing them to get an overall EAD value. This has been a tried and test approach to estimating flood risk that has been used by the USACE in evaluating billions of dollars of flood mitigation projects across the U.S. (USACE 2011; 2012). Its major limitation is that it is very costly to undertake and is therefore applied only to specific project areas being evaluated rather than across large regions or even nationally.

Surprisingly, the EADs generated by the USACE were only briefly reported and discussed in their voluminously detailed project report. Residential versus non-residential EADs for stream reaches and across the entire study area are contained only in a single table (Table 14 in Appendix F/ Economic Analysis; USACE 2021b). Residential EADs for the study area are $2,513,740 based on 2,818 structures versus $14,220,770 for 1,494 non-residential structures, indicating that commercial EADs are 85% of total EADs despite representing only 35% of all structures. These results were not reported in any of the written text of the report, which is surprising as it is assumed this information would be of interest to local stakeholders and floodplain managers.

Methods and Data Collection

This current study undertakes analyses of EAD from flood events in the Papillion Creek Watershed as calculated and reported by the USACE in their 2021 flood mitigation feasibility study. Initially, the USACE refused multiple requests for access to building-specific EAD values used in their flood mitigation feasibility study, but these data were eventually obtained via a FOIA request. The data was provided in a very large excel spreadsheet containing hundreds of poorly defined workbook tabs and thousands of variables, most without explicit data variable definitions or meta-data descriptions which are commonly used in other federal database collections, particularly when the data are used for feasibility analyses and other types of policy decision-making.

A substantial amount of database management work with the USACE-supplied EAD data was required to accurately quantify building damage exposure over time and by building types. First, building and property records needed to be joined across different USACE data spreadsheets and missing and/or repeat data identified and corrected. Second, data records were matched to county assessor property record databases to obtain additional building information (property types, ownership status, and building characteristics) to evaluate the accuracy of the USACE data. Annual Expected Values (AEV) for each flood event were multiplied by the probability of an AEV for each given year (e.g. 1% for a 100-year flood event) and then summed. Resulting EADs across all possible flood events were compared to aggregated EAD values reported by the USACE.

The first reporting task was to summarize the proportion of total EADs by different building classes: single-family homes, mobile homes, and 10 classes of commercial building sub-types (hotels, industrial, multiple-family, office, recreation/ entertainment, restaurants, retails, service stations, special use/miscellaneous, and warehouses). Mean EAD values and EAD values as percentage of total building value are also reported by building types.

These flood risk damage metrics were then compared to the results of a prior flood damage study in the Sarpy County portion of the Omaha metropolitan study area (Shultz 2017) that more simplistically calculated annual flood damage risk as replacement cost values of buildings within 100-year floodplain areas (with an assumed 1% probability of flooding in any given year). EADs are also evaluated by building age (buildings built before and after 2005) to evaluate the proportion of total flood risk in the study area associated before and after the introduction of updated floodplain maps in the study area.

Finally, the strategies to replicate these study results in other parts of the U.S. using other available data and flood risk analyses are discussed.

These included USACE structural inventories (i.e. similar EAD data used by this present study but in other locations), the recently developed 'Natural Structure Inventory' (NSI) dataset developed by FEMA in conjunction with FEMA HAZUS-MH modelling tools, and data and/or analyses from the First Street Foundation (HAZUS 2009).

RESULTS

Data Evaluated and Total Flood Risk Estimates

Data on building specific flood risk in the USACE database contained complete data for 3,857 buildings which is 455 (11%) buildings less than reported utilized by the USACE in their project report. It is not clear whether the USACE misreported their sample size in their report, or if the database they provided had 455 buildings omitted. The annual flood risk for these buildings in the database totals $12.5 million which is 25% lower than the $16.7 million reported in Table 14 by the USACE.

Proportion of Flood Risk by Building Types

Commercial buildings (including apartment buildings) represent 44% of all buildings and 91.7% of all flood risk (single-family residential buildings are 56% of all buildings and only 8.3% of flood risk (Table 1; Figure 2). These statistics differ slightly from what was reported by the USACE (commercial buildings being 85% of risk and residential 15%) which again is likely due to the 455 buildings differential between the USACE report and the actual database. Regardless of which data source is used, the great majority of fluvial flood risk in the Omaha Area is associated

Table 1. Buildings generating fluvial flood risk, Papillion Creek Watershed, Omaha, NE.

	Buildings	**Flood Risk (Expected Annual Damage)**
All Buildings (3,857)	3,857	$12,500,000
Single-Family Residential (including mobile homes)	2,156 (56%)	$1,037,672 (8%)
Commercial (including apartments)	1,701 (44%)	$11,468,616 (92%)
By Building Sub-Types		
Single-Family Residential	2,050 (53.2%)	$1,020,648 (8.2%)
Mobile Homes	106 (2.7%)	$ 17,024 (0.1%)
Apartments	255 (6.6%)	$ 780,675 (6.2%)
Hotel	15 (0.4%)	$ 215,452 (1.6%)
Industrial	144 (3.7%)	$ 1,486,318 (11.9%)
Office	288 (7.5%)	$2,132,837 (17.1%)
Recreation/Entertainment	23 (0.6%)	$2,073,485 (16.6%)
Restaurants	88 (2.3%)	$1,095,897 (8.8%)
Retail	202 (5.2%)	$1,356,334 (10.9%)
Service Stations	126 (3.3%)	$404,572 (3.3%)
Special Use	51 (1.3%)	$490,008 (3.9%)
Warehouses	509 (13.2%)	1,433,038 (11.5%)

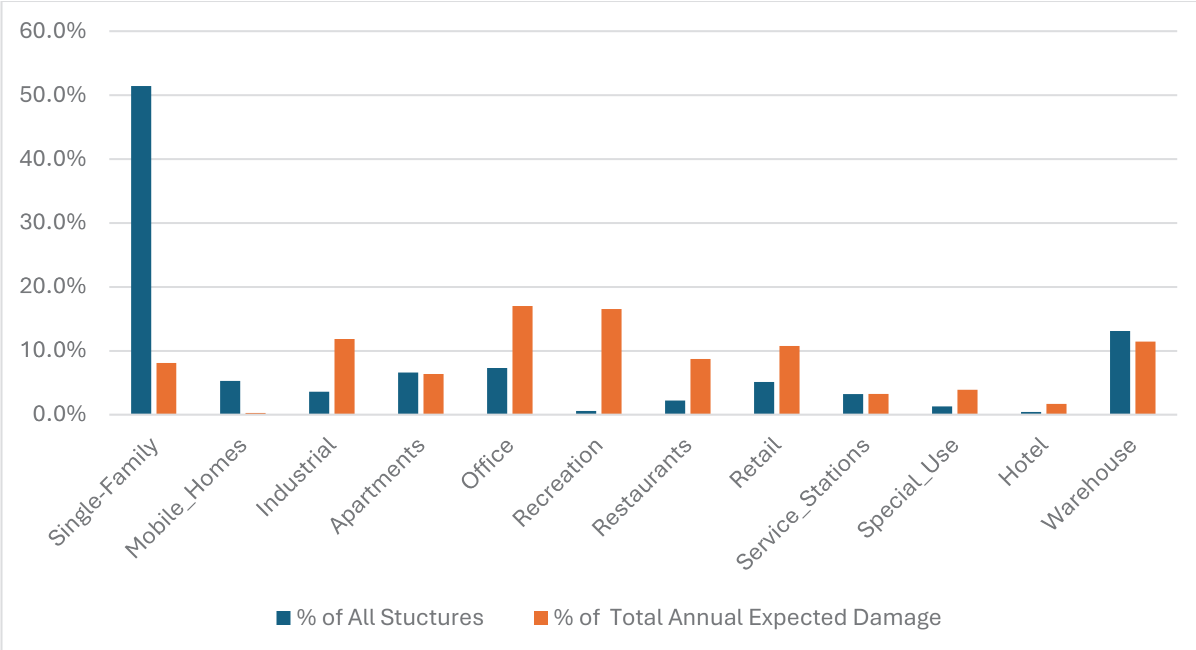


Figure 2. The percentage of buildings and flood risk in the Papillion Creek Watershed.

with commercial buildings.

Single-family homes represent clear majority of all building types with floodplain risk (56% including 3% of mobile homes), but they generate only 8% of total risk, indicating that compared to non-residential properties they are either in less risky areas and/or smaller with lower depreciated structural replacement values. Conversely, commercial buildings (including apartments also known as multi-family residential buildings) are less frequent (44% of all buildings) but representing a staggering 92% of flood risk, indicating that these structures are either disproportionately located in markedly high flood risk areas, and/or have higher than typical replacement values. Of these commercial buildings, the most frequent are warehouses (13% of all buildings) followed by apartments and offices (each representing 7% of all buildings), but the common commercial building types do not correspond directly to building frequency in the floodplain study area. Building types that generate a higher proportion of risk than their frequency include: industrial buildings (12% of risk and 4% of frequency), offices (17%/7%), restaurants (9%/2%), retail (11%/5%) and, most notably, recreation/entertainment structures which are very infrequent (0.6%) yet they are very expensive buildings located in high-risk flood areas and therefore generate 17% of all flood risk. In this case they are two new ice hockey arena entertainment facilities.

Floodplain Risk across Building Types

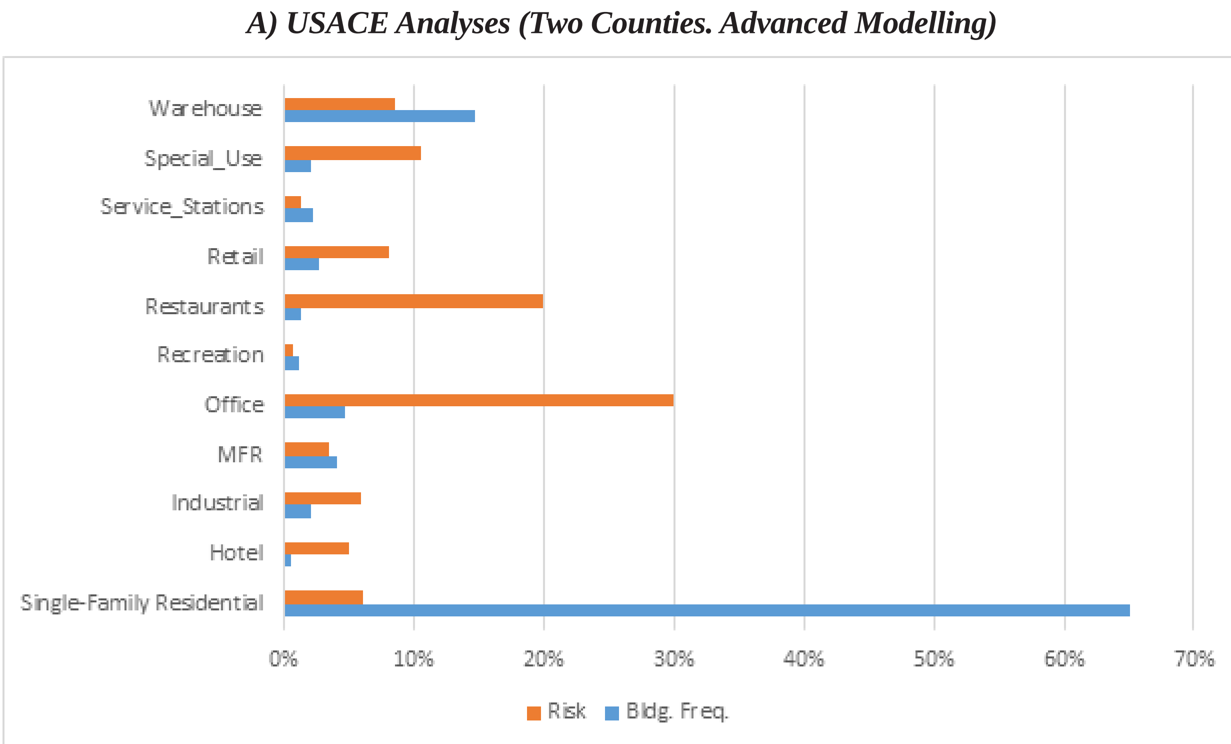
Across the study area (the 500-year floodplain of the Papillion Creek Watershed) 75% of all structures have at least some level of flood risk defined as EAD greater than 0. This supports other recent research and warnings highlighting the need for floodplain managers and property owners to take 500-year flood risk more seriously (Office of Inspector General 2017; First Street Foundation 2020). However, the magnitude of this flood risk is not uniform across building types. For example, for single-family homes, mean risk (EAD) is $498 with a standard deviation of $1,714 (Table 2). Over a 30-year period using a 5% discount this generates a cumulative risk value of $7,600. Among commercial buildings most (7 of 10) building types have 80% or more of their buildings facing annual flood risk with mean EAD values ranging from ($2,756 (warehouses) to $90,152 (recreation/entertainment).

Table 2. Measures of central tendency for building risk (expected annual damage).

	% With Risk	Mean Risk ($)	Median Risk ($)	Standard. Deviation Risk ($)
Single-Family Homes	74%	498	134	1,714
Mobile Homes	53%	160	5	621
Hotel	100%	14,363	5,165	21,620
Industrial	83%	10,322	1,794	27,153
Apartments	78%	3,038	1,187	9,799
Office	84%	7,393	1,504	24,778
Recreation/Entertainment	87%	90,152	4,409	304,503
Restaurants	85%	12,453	522	68,088
Retail	76%	6,715	634	15,221
Service Stations	83%	3,211	949	5,693
Special Use	51%	9,608	63	38,140
Warehouse	81%	2,756	440	7,198

Table 3. Flood risk as a percentage of depreciated structural replacement value.

	Mean	Median	Standard Deviation
Single-Family Homes	0.5%	0.1%	2.2%
Mobile Homes	0.6%	0.0%	2.5%
Hotel	0.6%	0.4%	0.8%
Industrial	1.6%	0.5%	3.0%
Apartments	0.5%	0.3%	2.0%
Office	1.1%	0.2%	2.8%
Recreation/Entertainment	1.6%	0.4%	2.1%
Restaurants	2.5%	0.2%	9.6%
Retail	0.8%	0.1%	2.0%
Service Stations	1.5%	0.5%	2.1%
Special Use	0.3%	0.0%	0.9%
Warehouse	1.0%	0.3%	2.5%



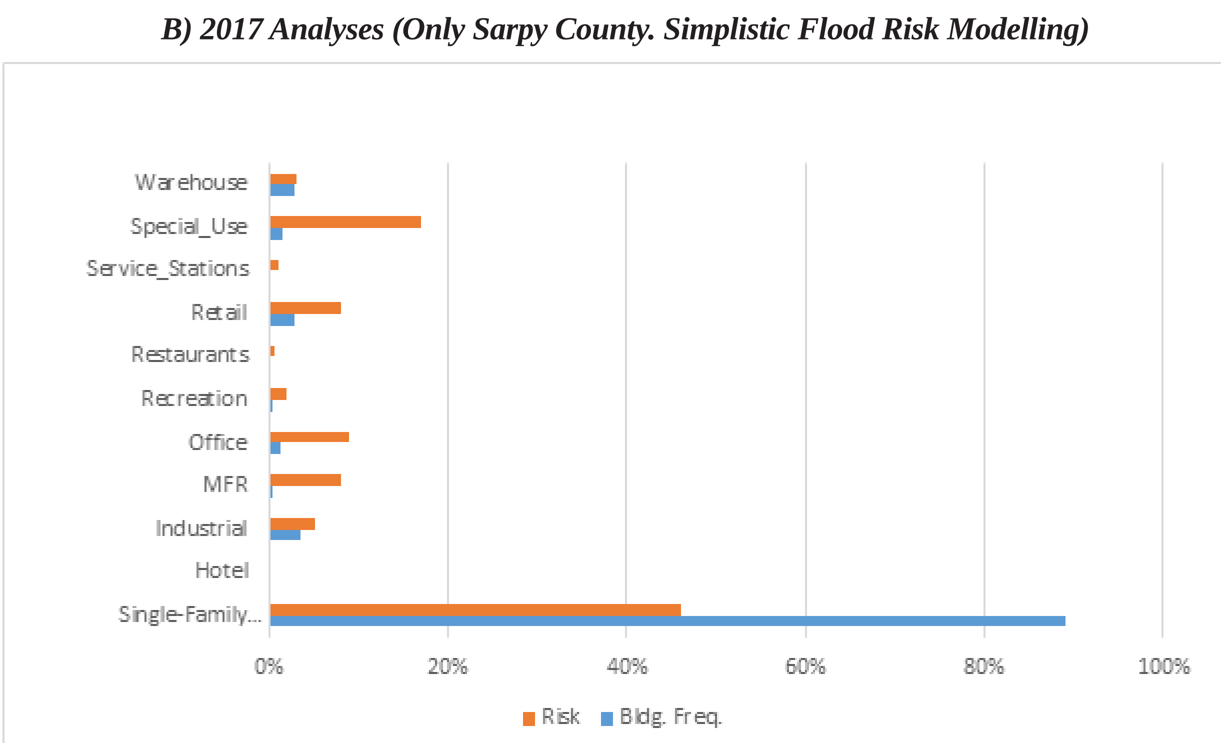


Figure 3. Building frequency and flood risk for Sarpy County: USACE building level analyses versus prior and more simplistic 100-year floodplain estimates (2017).

Risk Values as a Percentage of Building Values

The range in flood risk (EAD) as percentage of building value (depreciated structural replacement value) is from 0.3% with special use buildings to 2.5% for restaurants (Table 3). Some of the lowest percentages of relative building damage are with buildings that are often two or more stories (apartment buildings and hotels) yet there are some cases of single-story buildings such as retail also having low relative risk. Single-story buildings with low percentages of damage, such as warehouses and special use buildings, are likely to have been built with floodproofing measures.

The Impact of Improved Risk Modelling (Comparisons with Prior Results, Sarpy County)

Differences in levels of flood risk as estimated by this current study versus the earlier (2017) study in the Sarpy County portion of the study area are summarized by Figure 3. With the USACE analyses, single-family residential buildings represent 65% of all buildings but only 6% of flood damage risk versus the earlier analyses (89% of buildings and 46% of risk). When comparing specific commercial building sub-types across the two approaches, the largest discrepancy in proportions occurs with single-family homes (the 100-year floodplain approach grossly exaggerates its relative flood risk) and office and restaurant properties (where the 100-year floodplain approach grossly underestimates their relative flood risk). These are markedly different metrics across the two studies, which indicate that whenever possible researchers should not rely on simplistic 100-year floodplain metrics to quantify the extent and characteristics of flood risk in a community, as was undertaken in the earlier study.

Flood Risk over Time (Pre/Post 2005 with Updated Floodplain Maps)

A large majority (89%) of the buildings in the study area were built before 2005 and the use of

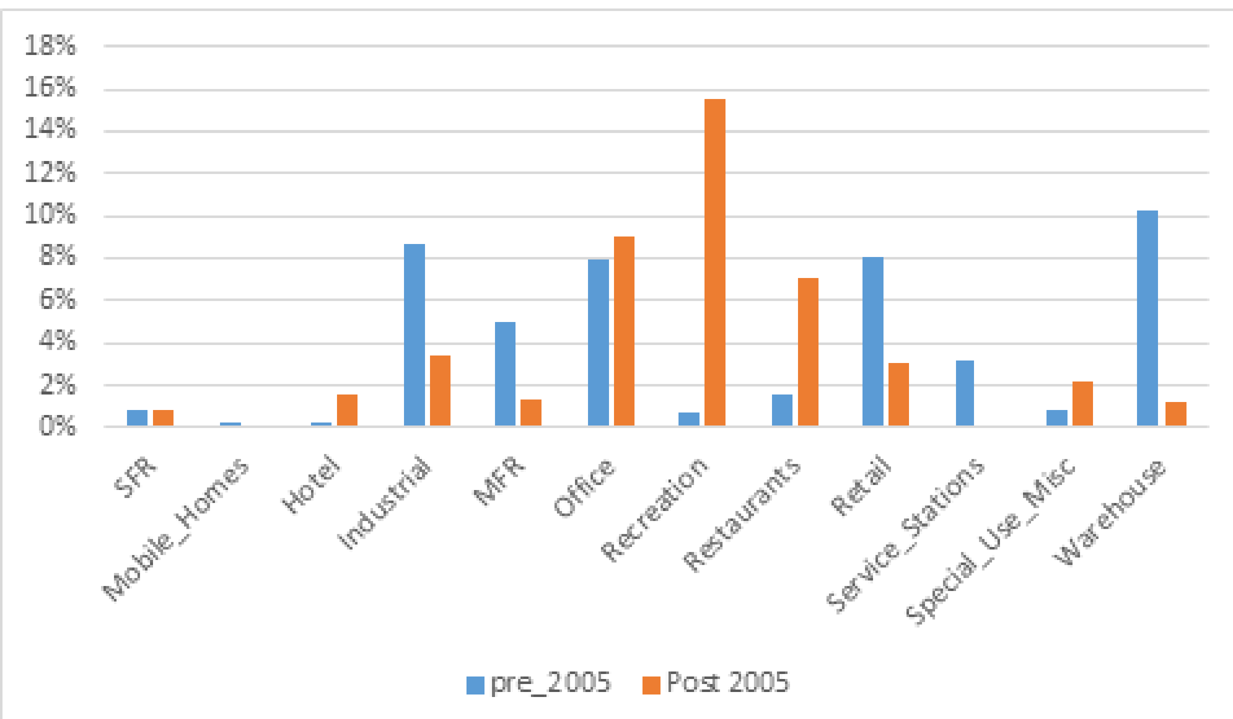


Figure 4. Percentage of flood damage risk by building types, before/after 2005.

updated and accurate floodplain maps, yet they generate 51% of total floodplain risk in the area. Alternatively, the relatively infrequent structures built from 2005 to 2019 (11% of all buildings) generate a disproportionately high amount of damage. This is unexpected since by the year 2005 and onwards floodplain managers, planning agencies, and property developers were for the most part aware of site-specific flood risks in the study area and presumably would have not wanted or allowed the construction of valuable buildings in high flood risk locations unless they had floodproofing designs. In other words, it was expected that most of the flood risk in this study area would have been generated in prior decades when flood risk was not widely understood, and the community was not actively participating in the FEMA Community Rating System designed to avoid flood risks.

However, as shown by Figure 4, recently built flood risk is not uniform across different building types. Single-family home flood risk is identical for homes built before/after 2005 and no mobile homes generating flood risk have been built/established after 2004. Similarly, most flood risk associated with industrial, retail, and warehouse buildings was created (built) prior to 2005. In contrast, most of the flood risk associated with offices, restaurants, and recreational/entertainment facilities is due to recent (post 2005) construction. The recent construction of two large publicly funded ice rink/entertainment venues and several high-profile ,multi-use office buildings (all legally built in the 500-year floodplain) generate the highest relative amount of flood risk. This implies that property owners and/or local floodplain managers and urban planners have done an excellent job regulating risky floodplain development for single-family residential properties but have not done as good a job in avoiding flood risk to commercial buildings.

Conclusions and Recommendations

Implications of the Research Findings

This research has demonstrated that commercial buildings generate the largest amount of fluvial flood risk across a 500-year floodplain study of a mid-sized urban area in the Midwest. It also demonstrated that similar prior research at the same study site which relied on the more simplistic approach of estimating flood risk by accounting for 100-year floodplain location status of buildings (with a 1% chance of flooding per year) combined with building replacement costs, drastically underestimated flood risk and in particular, commercial building flood risk. This updated research, which relied on very complex building specific risk modelling of the USACE, resulted in an approximate doubling of the role of commercial building flood risk.

This research also confirmed the findings and suspicions of many flood risk researchers and policy makers that a great deal of flood risk in U.S. urban areas occurs outside of regulatory 100-year floodplain boundaries. This implies that FRM policies and regulations should place less emphasis on 100-year floodplain classifications and instead focus on flood risk in the 500-year floodplain. Similarly, property developers of and owners of commercial buildings should become better informed about actual flood risk in the 500-year floodplain.

A surprising and unexpected finding of this research is extent to which flood risk has been generated by very recent (2005-2019) building activity, well after the introduction of updated 100-year floodplain maps and the community's active involvement in the Community Rating System of the National Flood Insurance Program. While Omaha area floodplain managers and urban planners have been effective at reducing flood risk for single-family residential homes (and mobile homes) in recent years, they have during the same time allowed so much commercial building development in high-risk flood areas (albeit mostly in the 500-year floodplain), that hundreds of millions of dollars of pending federal/local flood mitigation projects are now deemed required. Interestingly, much of this commercial development with high flood risk was for non-essential structures such as ice rink/entertainment facilities, often with assistance of public funding incentives.

Future Research Needs

Almost all prior academic research publications and policy papers have focused exclusively on single-family residential flood risk, when it does not appear to play a dominant role in total flood risk in Omaha, NE, and, potentially, in other midwestern cities subject primarily to pluvial flood risk. Much of this discrepancy is likely because it has, until very recently, been difficult to obtain detailed flood risk estimates for commercial structures.

Since these findings have not been confirmed in other locations of the country it is recommended that the study be replicated in other locations, particularly in areas of the country facing coastal and hurricane-based flooding. This should focus on quantifying the extent and nature of flood risk generated by all building types, the extent of buildings at risk from flooding in the 500-year floodplain, and when this risk was created (i.e. when at risk buildings were built). Additionally, future research (in Omaha and elsewhere) is needed with regards as to why certain types of commercial buildings (their characteristics) are at particularly high risk from flooding. At this point it is not known whether their high flood risk is due to locational risk, building design, or some combination of these issues. Such research could also help identify the accuracy and reliability of stage damage curves used by the USACE to estimate commercial building flood damage.

There are three feasible sources of data for the aforementioned suggested commercial building flood risk research: 1) Existing USACE flood risk estimates in selected study site locations where they have conducted flood mitigation feasibility studies; 2) The recently updated National Structure Inventory from FEMA and the USACE in conjunction with flood risk modelling tools of the FEMA HAZUS-MH software package (FEMA 2015); and 3) Building specific flood risk estimates generated by the private sector (First Street Foundation and/or the Fathom Group).

Flood Risk estimates by the USACE are likely the most accurate available, but are generated only when they undertake a specific flood mitigation feasibility study in a very limited number of locations. While the USACE does not release resulting building specific risk data to the public, it can potentially be obtained through FOIA requests, as was done with this Omaha research. The National Structure Inventory dataset theoretically offers building replacement cost data for every structure in the country and, combined with floor risk modelling in the open source HAZUS-MH flood risk estimation toolbox, could be used to generate estimated annual damages for all locations of the U.S. However, due to proprietary data concerns with different private sector vendors that supplied necessary input data, building specific data from the National Structure Inventory are only allowed to be used by federal agency personnel or contractors. Therefore, flood risk research using this dataset should likely be initiated by FEMA or other federal agencies. The First Street Foundation flood risk data have already been used to estimate building specific flood risk metrics for at least 20 U.S. metropolitan areas, but this needs to be expanded to a wider range of building types and in additional locations.

Acknowledgements

This research has been a long-term incremental effort that was originally funded by the USGS/Nebraska Water Center 104b program followed by the Institute of Water Resource of U.S. Army Corps of Engineers, and most recently by the Washington County, NE Board of Supervisors and the Papio Valley Preservation Association.

Author Bio and Contact Information

Steven Shultz is a Professor of Real Estate and Land Use Economics in the College of Business Administration at the University of Nebraska at Omaha. He focuses his research activity on the intersection of property values and water resource management and has in the last decade quantified the nature and extent of property-based flood damage resource with funding from county, state and federal agencies and local stakeholders. He may be reached at the following email: sshultz@unomaha.edu.

References

American Flood Coalition. 2024. AFC's perspective on First Street Foundation's Floo Factor Launch. Washington, D.C. Available at: https://floodcoalition.org/2020/06/afcs-perspective-on-first-street-foundations-flood-factor-launch/. Accessed November 17, 2024.

Bates, P.D., N. Quinn, C. Sampson, et al. 2021. Combined modeling of US fluvial, pluvial, and coastal flood hazard under current and future climates. *Water Resources Research* 57 (2): e2020WR028673.

Available at: https://doi.org/10.1029/2020WR028673. Accessed October 28, 2024.

Cartwright, L. 2005. An examination of flood damage data trends in the United States. *Journal of Contemporary Water Research and Education* 130: 20-25.

Center for Neighborhood Technology (CNT). 2014. The Prevalence and Cost of Urban Flooding. A Case Study of Cook County, IL. Available at: https://cnt.org/publications/the-prevalence-and-cost-of-urban-flooding. Accessed October 28, 2024.

Federal Emergency Management Agency (FEMA). 2015. Summary of Databases in HAZUS-MH (General Building Stock). Available at: https://www.fema.gov/summary-databases-HAZUS-multi-hazard. Accessed September 20, 2024.

First Street Foundation. 2020. The First National Flood Risk Assessment. New York, NY. Available at: https://firststreet.org/research-library/the-first-national-flood-risk-assessment. Accessed October 28, 2024.

First Street Foundation. 2021. The 4th National Risk Assessment: Climbing Commercial Closures. Available at: https://assets.firststreet.org/uploads/2021/11/The-4th-National-Risk-Assessment-Climbing-Commercial-Closures.pdf. Accessed October 28, 2024.

Floodsmart. 2016. NFIP Summary of Coverage: Commercial Property. National Flood Insurance Program, FEMA. Available at: https://agents.floodsmart.gov/sites/default/files/fema_nfip-summary-of-coverage-commercial-property-brochure-01-2024.pdf. Accessed November 17, 2024.

HAZUS. 2009. Multi-hazard Loss Estimation Methodology. Flood Model HAZUS-MH MR4 Flood Technical Manual. FEMA (Federal Emergency Management Agency).

Kousky, C. and E. Michel-Kerjan. 2017. Examining flood insurance claims in the United States: Six key findings. *Journal of Risk and Insurance*. Available at: https://doi.org/10.1111/jori.12106. Accessed October 28, 2024.

Kunreuther, H. and E. Michel-Kerjan. 2013. Managing catastrophic risks through redesigned insurance: Challenges and opportunities. Chapter 19. In: *Handbook of Insurance, 2nd edition*, G. Dionne, (Ed.). Springer, New York.

Merz, B., H. Kreibich, R. Schwarze, and A. Thieken. 2010. Assessment of economic flood damage. *Natural Hazards Earth Systems Science* 10: 1697-1724.

Mostafiz, R.B., C.J. Friedland, M.A. Rahman, R.V. Rholi, E. Tate, N. Bushra and A. Taghinezhad. 2021. Comparison of neighborhood-scale, residential property flood-loss assessment methodologies. *Frontiers in Environmental Science* 9: 734294. Available at: https://doi.org/10.3389/fenvs.2021.734294. Accessed October 28, 2024.

Office of Inspector General. 2017. FEMA Needs to Improve Management of Its Flood Mapping Programs. U.S. Department of Homeland Security, Washington, D.C. Available at: https://www.oig.dhs.gov/sites/default/files/assets/2017/OIG-17-110-Sep17.pdf. Accessed October 28, 2024.

Pielke, Jr., R.A., M.W. Downton, and J.Z. Barnard Miller. 2002: *Flood Damage in the United States, 1926–2000: A Reanalysis of National Weather Service Estimates*. National Center for Atmospheric Research, Boulder, CO. Available at: https://sciencepolicy.colorado.edu/admin/publication_files/2002.01.pdf. Accessed November 21, 2024.

Porter J.R., E.G. Shu, M.F. Amodeo, N. Freeman, M. Bauer, I. Almufti, M. Ackerson, and J. Mehta. 2022. Commercial real-estate at risk: An examination of commercial building and economic impacts in the United States using a high-precision flood risk assessment tool. *Frontiers in Water* 4: 875995. Available at: https://doi.org/10.3389/frwa.2022.875995. Accessed October 28, 2024.

Scawthorn, C., P. Flores, N. Blais, H. Seligson, E. Tate, S. Chang, E. Mifflin, W. Thomas, J. Murphy, C. Jones, and M. Lawrence. 2006. HAZUS-MH Flood Loss Estimation Methodology 2. Damage and Loss Assessment. *Natural Hazards Review* 7(2). Available at: https://ascelibrary.org/doi/10.1061/%28ASCE%291527-6988%282006%297%3A2%2872%29. Accessed October 28, 2024.

Shultz, S. 2017. The extent and nature of potential flood damage to commercial property structures in the midwestern United States. *Journal of Contemporary Water Research and Education* 161: 81-91. Available at: https://onlinelibrary.wiley.com/doi/10.1111/j.1936-704X.2017.3253.x/full. Accessed October 28, 2024.

U.S. Army Corps of Engineers (USACE). 2011. HEC-FIA. Flood Impact Analysis Software. Version 2.1. Certification Report.

U.S. Army Corps of Engineers (USACE). 2012. Planning SMART Guide. Available at: https://planning.erdc.dren.mil/toolbox/library/pb/PB2012-02.pdf. Accessed September 20, 2024.

U.S. Army Corps of Engineers (USACE). 2021a. Papillion Creek and Tributaries Lakes, Nebraska. General Reevaluation Report, Final

Feasibility Report. Available at: https://media.defense.gov/2021/Aug/04/2002822908/-1/-1/1/PAPILLION%20CREEK%20GRR%20FINAL%20MAIN%20REPORT.PDF. Accessed October 28, 2024.

USACE. 2021b. Papillion Creek and Tributaries Lakes, Nebraska. General Reevaluation Report. Final Feasibility Report. Appendix F. Economic Analyses. Available at: https://media.defense.gov/2021/Aug/04/2002822918/-1/-1/1/PAPILLION%20CREEK%20GRR%20FINAL%20REPORT-APPENDIX%20F%20ECONOMICS.PDF. Accessed October 28, 2024.

Walls, M.A., S. Pesek, and D. Peterson. 2023. Flooding in the United State 101: Causes, Trends, and Impacts. Resources for the Future, Washington, D.C. Available at: https://www.rff.org/publications/explainers/flooding-in-the-united-states-101-causes-trends-and-impacts/. Accessed October 28, 2024.

Universities Council on Water Resources
Journal of Contemporary Water Research & Education
Issue 182, Pages 70-88, April 2025

Preparing the Next Generation of Water Professionals in New York State: A Review of Educational Programs and Models by the New York State Water Resources Institute

*Rewa Phansalkar[1], Kristen Hychka[1], Chris Bowser[2], Emily Fell[3], Brian Rahm[1]

[1]New York State Water Resources Institute, Department of Biological and Environmental Engineering, Cornell University
[2]New York State Department of Environmental Conservation, Hudson River Estuary Program
[3]New York State Department of Environmental Conservation, Great Lakes Watershed Program
**Corresponding author*

Abstract: Careers in water are critical for sustainable management of this important resource. However, the water sector is facing workforce challenges like skill gaps, aging professionals, and lack of diversity. The New York State Water Resources Institute (NYSWRI) at Cornell University is hoping to address these issues through interdisciplinary and tiered educational models that integrate academic learning about water resources with real-world applications. This article highlights NYSWRI's approaches, including K-12 engagement in partnership with state agencies, university-level training through internships and coursework, and professional development via continuing education, with an emphasis on hands-on research, field experiences, and community collaboration. Despite challenges like the need for consistent evaluation and broader engagement, NYSWRI's educational practices can serve as a starting point for knowledge exchange between water resource research institutes (WRRIs) across the U.S. This article aims to provide models for similar institutions to enhance education and training for workforce development in the realm of water management.

Keywords: *water management, science research, science education, interdisciplinary learning*

Careers in water management, whether in infrastructure operation or scientific roles within state agencies, are vital for sustained access to this critical resource. "Water professionals" come from diverse backgrounds and disciplines, including engineering, ecology, hydrology, environmental science, policymaking, regional planning, finance, and public health, each contributing essential expertise to the comprehensive management of water resources (Pahl-Wostl et al. 2011; Cosgrove and Loucks 2015; Seidl and Barthel 2017). However, the water sector faces a significant decline in maintaining a steady professional workforce, especially in water infrastructure and utilities. The Environmental Protection Agency's America's Water Sector Workforce Initiative predicted that over one-third of the water workforce is set to retire in the next decade (Selna et al. 2006; U.S. Environmental Protection Agency 2020). A 2018 report by the Brookings Institute also highlighted critical skill gaps, issues with hiring, training, and retention, and a lack of diversity and inclusion within the workforce (Kane and Tomer 2018).

Despite the growing recognition that engagement, training, and education in water are critical to addressing workforce challenges, typical science-education programs and initiatives in high schools and universities have limitations (Bloomfield et al. 2018; Luste and Medkova 2019).

Effective water management requires an understanding of both scientific and human dimensions—especially as climate change and existing social inequities further complicate these issues (Abu-Zeid and Biswas 1991; Cosgrove and Loucks 2015; Seidl and Barthel 2017; Lally and

Research Implications

- **Early, hands-on science experiences are crucial for developing environmental identities and inspiring diverse career paths in water science.** Programs like "Day in the Life" and the "Hudson River Eel Project" demonstrate the effectiveness of engaging students early to influence long-term career interests.
- **Tiered educational models that integrate technical training and real-world applications can effectively build essential skills for future water professionals.** The New York State Water Resources Institute's multi-level approach, encompassing university internships and interdisciplinary courses, equips students with practical knowledge and fosters professional networks, addressing critical skill gaps in the water sector workforce.
- **Collaborative and community-based learning initiatives can enhance public awareness and support for water resource management.** Outreach initiatives such as Submerse NY and integrating learning opportunities within professional networks highlight the value of peer-to-peer learning and public engagement in fostering a supportive environment for water professionals to implement effective management strategies.

Forbes 2020)—a skill set that is not adequately developed through traditional school science education (Alsultan et al. 2021). While middle and high school curricula often include water-related topics, learning about water science in the classroom can feel disconnected from real-world applications (Lyons 2006; Hellgren and Lindberg 2017; Amahmid et al. 2019). Similarly, university courses on sustainable water management are limited and have minimal impact (Leendertse and Taylor 2011; Missingham and Mcintosh 2013; Lally and Forbes 2020). The interdisciplinary nature of water careers demands a different approach to water education and training (Kane and Tomer 2018; Burgin 2020; Alsultan et al. 2021).

An interdisciplinary and context-specific mix of educational tools that integrate classroom learning with real-world applications can be highly effective. These methods and models are increasingly implemented through innovative collaborations between K-12 educators, universities, non-profits, research institutions, and state and federal agencies (Pahl-Wostl et al. 2011; Brown et al. 2015; Sadler et al. 2017). Such education typically involves engaging students in citizen science projects, internships, after-school programs, and field workshops (Alsultan et al. 2021). Learnings from these experiments have consistently shown that connecting classroom learning to real-world applications can positively impact student motivation, deepen science content understanding, boost confidence, and develop critical thinking skills (Brundiers et al. 2010; Laursen et al. 2010; Tsybulsky et al. 2018). Projects that address real-world issues, such as providing potable water in developing regions and collaborating with university research labs to assess water quality, have demonstrated how to make science education more meaningful and engaging for high school students (LeVasseur 2014; Alsultan et al. 2021; Kwee and Dos Santos 2023).

Water education must also be tiered, with programs designed to support learning at different ages and levels, beginning with K-12 education, followed by more advanced university-level training, and continuing with public and professional development programs. Identity building starts early, when students first form their understanding of themselves in relation to the environment (Hilander and Tani 2022). Early exposure to water science, particularly through hands-on, real-world learning, can influence career choices in environmental fields (Hunter 2006; Yilmaz et al. 2010; Colvin 2013). As students progress into higher education, the focus shifts to skill development, where they acquire the technical expertise needed for professional careers in water management through applied courses, internships, and fieldwork opportunities (Hodkinson et al. 2006; Parr et al. 2007). Beyond individual skills, professionals require continued training, as well as societal and political support, to implement effective water management initiatives (Cortner 2000; Kedzior 2017). Public outreach and education, along with long-term learning opportunities for both professionals and the public, can help create a supportive social context that contributes to the prioritization of water resource management (Johnson et al. 2014).

Such integrated, tiered models for water education rely on collaboration between multiple entities for their design and execution. Often, research, extension, and educational non-profit entities are well-positioned to coordinate among the various groups involved in water management and facilitate experimental collaborations focused on education and outreach (Pahl-Wostl et al. 2011; Cosgrove and Loucks 2015). The New York State Water Resources Institute (NYSWRI) is an example of such an entity. This article aims to highlight the models used by NYSWRI in three key areas that determine the success of water professionals: 1) identity building at an early age, 2) skill development, and 3) creating a social context where professionals can effectively carry out their work. We also discuss challenges for their effective evaluation and incorporating diversity and equity within them. By doing so, we hope to provide ideas and insights to similar entities—such as cooperative extensions, Sea Grant programs, and USGS-funded water resource research institutes in other states—and inspire those institutions to share their models, fostering learning and collectively equipping future water professionals to address emerging water resource challenges.

The Unique Role and Structure of New York State Water Resources Institute

As a water resources research institute (WRRI) authorized under section 104 of the Water Resources Research Act (WRRA) of 1984, the NYSWRI at Cornell University is part of a Federal-State partnership designed to conduct research, promote technology transfer, and disseminate findings on state and regional water issues. Through the WRRA, NYSWRI is a member of the National Institutes for Water Resources (NIWR), a network of 54 water resource institutes located at land-grant universities and other designated institutions across the United States and its territories. This network collaborates with the U.S. Geological Survey to support research through annual base grants, competitive grants, and the WRRI-USGS Student Internship program. In New York, NYSWRI works closely with the New York State Department of Environmental Conservation (NYSDEC). Through a multi-year Memorandum of Understanding (MoU) between NYSDEC and Cornell University, NYSWRI staff are embedded in NYSDEC offices across the state, with a core presence at Cornell's Ithaca campus.

It is this unique position that NYSWRI occupies at the intersection of state and federal agencies and academia that allows for close collaboration with on-the-ground agency staff, managers, and policymakers—bridging the gap between academic research and practical water management. We can simultaneously leverage connections and expertise both at Cornell and within partner agencies to engage students across disciplines in education practices that are academically robust but also place-based and grounded in application. NYSWRI's position within a network of 54 other institutes of its kind offers the opportunity for the models and methods described in this paper to be adapted by other WRRIs, given their similar circumstances of being located within universities and working closely with government agencies. The following sections outline how NYSWRI's programs operate at various educational levels, using integrated coursework, internships, and community engagement projects to train individuals in addressing water issues across New York State.

1. Building Identity through K-12 Engagement

Early intervention is key to encouraging students, especially those from underrepresented backgrounds, to see themselves as future water professionals. Our programs engage students before college through teacher trainings, field-based initiatives, and creative activities.

Collaboration with State Agencies

Our most direct outreach to students occurs through ongoing collaboration with the NYSDEC to support the state's watershed action agendas, which include extensive educational components. NYSWRI staff embedded in NYSDEC offices lead several educational programs, most notably the "Day in the Life" initiative. Each fall, thousands of students from schools along the Hudson River and Lake Ontario-St. Lawrence River watersheds learn about their environment. Equipped with "seine nets, minnow pots, and water-testing gear," students catch and release fish species, track tides and currents, and test water quality (Hudson River National Estuarine Research Reserve 2024). The data they collect are shared online, linking participants from various locations and enriching classroom studies of water-related environmental issues. This hands-on experience deepens their understanding of the ecosystem and the importance of environmental stewardship (Figure 1).

Although "Day in the Life" is an annual event, NYSWRI staff in the Hudson are engaged year-round in K-12 education, in partnership with the Hudson River National Estuarine Research Reserve at the Norrie Point Environmental Center in Staatsburg, NY. Field trips to Norrie Point complement classroom studies, providing students with practical experiences, such as seining, water quality testing, and canoeing.

The "Hudson River Eel Project" also engages over a thousand volunteers in monitoring the migration of juvenile American eels into Hudson River tributaries (New York State Department of Environmental Conservation 2022). Volunteers—including students, teachers, and local residents—are trained by NYSDEC and NYSWRI staff in data collection and gear maintenance. These sessions teach participants about eel ecology, environmental science, and conservation while contributing to essential baseline data on eel populations, supporting broader scientific studies and conservation efforts.

NYSWRI staff working with the Hudson River Estuary Program (HREP) and the Great Lakes focus on training teachers and developing curriculum resources. Customized workshops in field methods and classroom integration are offered to school districts throughout the Hudson Valley, promoting place-based learning. HREP also provides interdisciplinary lesson plans, organism images, posters, and other materials to educators. In the

Figure 1. High School students conduct field research and stream monitoring as a part of an educational program led by NYSDEC and NYSWRI staff. *Photo by Chris Bowser.*

Great Lakes region, staff collaborate with New York Sea Grant to organize the annual Great Lakes Ecosystem Education Exchange (GLEEE). These workshops demonstrate learning-standard-aligned lessons and hands-on activities on Great Lakes issues such as plastic pollution, coastal resiliency, and climate change (New York Sea Grant, n.d.), featuring presentations by local environmental organizations and experts, connecting educators with their watersheds.

Research in Environmental Education for K-12 Students

In addition to directly working with students and educators through partnerships with NYSDEC, NYSWRI supports environmental education through indirect mechanisms such as funding academic research that engages K-12 students. Our annual Request for Proposals (RFP) offers researchers up to $40,000 to study effective environmental education methods, often involving hands-on student learning activities that are later evaluated. Preference is given to proposals that focus on engaging students from underrepresented groups in STEM, promoting diversity and inclusion in environmental science fields. By analyzing the outcomes of these programs, researchers can identify best practices for engaging diverse student populations in environmental science.

One example is the recently completed "Water Literacy for Lower New York Students" project, led by Dr. Meghan Marrero from Mercy College, which involved over 300 middle and high school students from diverse, primarily urban, and disadvantaged backgrounds in water literacy and watershed science. Activities included interactive webinars, participation in the "It's My Estuary Day" event, and attendance at the National Marine Educators Association (NMEA) Student Conference. Qualitative data from pre- and post-surveys showed that students developed a deeper emotional connection to the ocean and waterways and reported increased awareness of their personal impact on the environment (Figure 2).

Both the "Mid-Hudson Young Environmental Scientists (MH-YES)" program of the Cary Institute of Ecosystem Studies and "The Institute Discovering Environmental Scientists (TIDES)" of the NYSDEC both provide paid summer research opportunity for 12-15 high school students. Students assist in authentic environmental research focused on the Hudson River watershed, investigating water, soil, plants and fish. Mentored by a team of scientists, teachers, and undergraduate students, they collaborate with local community groups. Post-surveys indicated increased confidence in environmental science skills, teamwork, and advanced knowledge of watershed ecology, statistics, and public speaking demonstrated through their research presentations.

K-12 Engagement at Cornell University

NYSWRI has recently begun exploring K-12 education by hosting its first workshop for high school students as part of the broader 4-H Career Explorations program at Cornell University. The 4-H program connects youth to Cornell, sparks career interest, and develops academic and leadership skills through its "Focus for Teens" track, which offers 11 hours of programming over three days. NYSWRI's module, "Dream

Figure 2. Students take part in the National Marine Educators Association (NMEA) conference as a part of Dr. Marrero's project. *Photo by Dr. Megan Marrero.*

Your Landscape Design Studio," introduced students to landscape design fundamentals, site analysis, and the roles of topography, soils, and water flows in design. Staff from the Great Lakes Watershed Program explained watershed functions using a 'wetland in a pan' activity, demonstrating water flow, the functions of natural features like wetlands, and the impact of landscaping choices, highlighting the need for nature-based solutions to address erosion and flooding. Students also learned design skills such as site survey techniques, design charrette processes, visual communication, and sketching. The workshop concluded with students presenting their projects and discussing career pathways in environmental fields. Post-workshop surveys indicated that students felt more curious about the natural and built environment, and more knowledgeable and interested in potential environmental careers (Figure 3).

Involving K-12 Students in NYSWRI Outreach Initiatives

In addition to educational programs specifically designed to engage students, there are often opportunities for K-12 engagement in NYSWRI's regular outreach efforts. For example, WRI's Submerse NY program helps communities enhance flood awareness through physical markers and public art. In Poughkeepsie, a pilot community for Submerse NY, we partnered with the non-profit The Art Effect and the National Art Honors Society to involve high school students in creating artwork that addresses flooding and environmental concerns in the Hudson River. The students' artwork was transformed into removable mural panels and permanently displayed at the Mid-Hudson Children's Museum to raise awareness about climate change and flooding. This collaboration empowered students to creatively express environmental concerns, with the resulting murals highlighting the past, present, and future of the Hudson River ecosystem, aiming to educate and inspire action on environmental issues (Figure 4).

2. Skill Building at the University Level

As students progress through their education, they transition from discovery to commitment. Programs at the university level can offer opportunities for deeper engagement, refining technical skills, and awareness of professional

Figure 3. High school students participate in the "Shoreline in a Pan" activity as a part of a three-part landscape design studio. *Photo by Rewa Phansalkar.*

careers in water resource management. Mentorship and collaboration with professionals in the field and ties with local stakeholders can connect academic learning with real-world water management challenges.

NYSWRI Summer Internship Program

The NYSWRI annual summer internship program is perhaps our most rigorous model for engaging undergraduate and master's students. Open to all Cornell students, the internship program spans ten weeks during the summer. At the start of the summer, NYSWRI staff curate a list of potential projects, providing background materials and research tasks, with outcomes such as posters or reports. Interns select projects based on their skills and interests, and are also assigned secondary projects to broaden their understanding of water resource issues and encourage collaboration.

Interns are paired with NYSWRI staff or faculty from Cornell or external institutions who serve as project leads, meeting weekly to discuss progress. Group meetings further enhance communication skills and critical discussion. The program includes field trips to significant water resource sites like Cornell's water filtration facility, Lake Source Cooling, and local hydroelectric and wastewater treatment plants. Supplemental programming includes panel discussions, guest speakers, and workshops, fostering both practical and broad knowledge of state water issues. Interns often co-author peer-reviewed publications, professional papers, outreach materials, and conference presentations (Figure 5).

NYSWRI Seminar Series

NYSWRI also offers an annual seminar series, titled "Applied Water Research in NYS," led by the institute's director. This series, held every spring, highlights research projects supported by NYSWRI each year. The seven-week seminar is open to both Cornell students and the public, featuring a different speaker each week.

The course includes weekly seminars co-led by invited researchers and NYSWRI staff

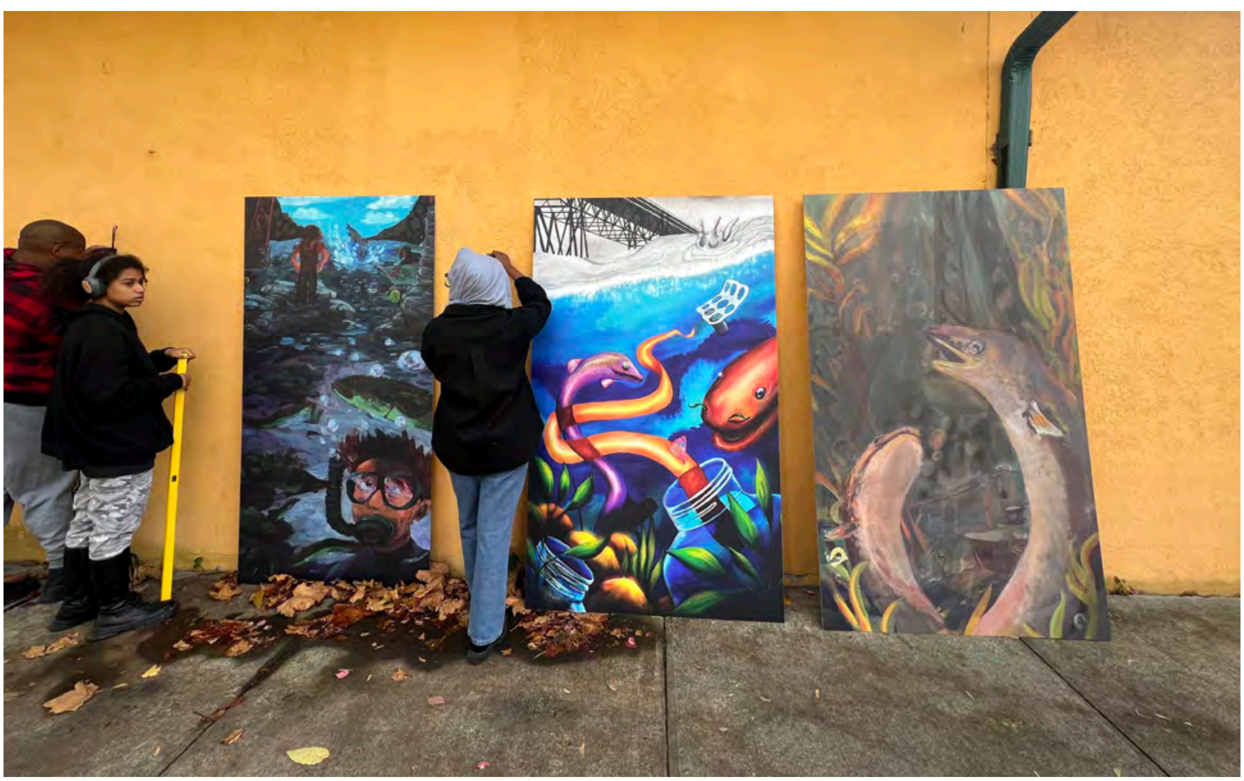


Figure 4. Students install temporary mural panels outside the Mid-Hudson Children's Museum in Poughkeepsie, NY as a part of NYSWRI's Submerse NY program. *Photo by Brianna Estrada.*

who work closely with agencies. Each session covers a specific aspect of water research, such as water engineering, climate and flood resilience, water quality monitoring, and aquatic ecosystems. The seminars are divided into two parts: the first half addresses research questions, study design, data collection, and methods, while the second half focuses on real-world applications and the research's relevance to water policy in New York State. A 15-minute Q&A session concludes each seminar, providing opportunities for direct engagement with the speakers.

Cornell students enrolled for credit are required to attend all sessions, submit bi-weekly reflections on the presentations, and complete a final essay synthesizing their learnings. This course not only expands students' knowledge of real-world water issues but also familiarizes them with applying scientific methods to address critical water management challenges, while raising awareness of potential careers in water. The open format encourages broad participation, bridging gaps between academia, practice, education, and public engagement.

Providing Support to Independent Courses

In addition to this independent course offering, NYSWRI supports innovative, interdisciplinary courses through its request for proposals (RFP) process. One such class, "Improving Water Literacy and Education of the Mohawk River Watershed through Art and Science," taught by Dr. Anna Davidson, integrates art and ecology to educate students about the Mohawk River Watershed. The course, a capstone for the Environment and Sustainability Major, involves research, guest lectures, and field trips, including boat rides on the river. Students apply their learning by creating publicly engaged art projects addressing watershed issues such as environmental justice and community awareness. The course also evaluates how incorporating art into environmental

Figure 5. NYSWRI summer interns on a canoe trip in the Hudson River Estuary. *Photo by Chris Bowser.*

education enhances student outcomes through pre- and post-course surveys and interviews.

The "Climate-adaptive Design" (CaD) studio is another such place-based, community-engaged course, resulting from a long-term partnership with Cornell University's Landscape Architecture Department. The studio connects landscape architecture students with riverfront communities in New York's Hudson Valley to explore design ideas for more climate-resilient, ecologically vibrant, and well-connected waterfront areas. Communities express interest through a form-based application process, and Cornell students make multiple field visits before developing their designs, which are then presented to the community for feedback. Operating in the Hudson Valley since 2015, the studio recently completed a pilot along Lake Erie. To date, over one hundred students have gained valuable experience developing design concepts while engaging with community stakeholders. Hundreds of residents in several host communities have learned about climate risks to their waterfronts through the CaD process and have access to design ideas and educational materials produced by the students (Figure 6). HREP staff continue to engage with these communities, working to fine-tune and potentially implement student designs even after the semester concludes.

Integration of Practical Water Management Topics with Classes at Cornell

Rather than funding a new or separate course through our annual RFP, NYSWRI staff often work with Cornell faculty to integrate water-related topics within existing classes. One such initiative is the collaboration with Rhonda Gilmore's class in the Design and Environmental Analysis program. In 2019, NYSWRI partnered with a group of students from the class to develop a public awareness and outreach campaign on Ithaca's water infrastructure, called "Year of Water." The project involved 14 students who conducted research on local water treatment facilities and developed campaign plans and communication materials to effectively relay the information. This included designing large metal "water drop" sculptures packed with information about water resources, creating informational stickers for residence halls, and conceptualizing a water-education mural at the Ithaca Farmers Market in partnership with a local muralist (Figure 7).

These educational materials aimed to inform the Cornell community and Tompkins County residents about the origins and importance of their drinking water and the role of Cayuga Lake in campus cooling. Throughout the course, students toured local water facilities, including the Cornell Water Filtration Plant, Lake Source Cooling Facility, and Cornell's Hydroelectric Plant, providing a deeper understanding of the water infrastructure supporting the campus and surrounding community. Even after the class ended, NYSWRI staff continued to use and further develop the student designs, culminating in the installation of the educational sculptures and mural, promoting awareness of water resource management at Cornell and beyond.

Student Mentorship in Applied Research

Outside of structured courses, NYSWRI staff formally and informally mentor students working on theses and exit projects, often building on summer internship projects. We collaborate with graduate students in professional degree programs such as the Master of Engineering (MEng) and Master of Regional Planning (MRP). One MEng student, a former WRI summer intern, wrote a thesis on *Investigating Flood Attenuation Opportunity from Riparian Restoration and Protection Across New York State*. Previous interns had discovered, through interviews with users, that there was a desire for the New York State Riparian Opportunity Assessment (ROA)—a geospatial tool targeting sites for riparian restoration and protection—to include a flood metric to identify watersheds with high flood attenuation potential. The student applied multivariate statistics on ROA metrics to develop a new flood attenuation score for the tool. They demonstrated the score's usefulness in the Mohawk River region, which directly contributed to their employment at a consulting firm where one of their projects involved directing restoration efforts using geospatial tools.

NYWRI staff also work with undergraduates on theses. One former summer intern in Environment and Sustainability Sciences developed their summer project into an Honors Thesis on *Equity in Climate Adaptation Programs: An Analysis of*

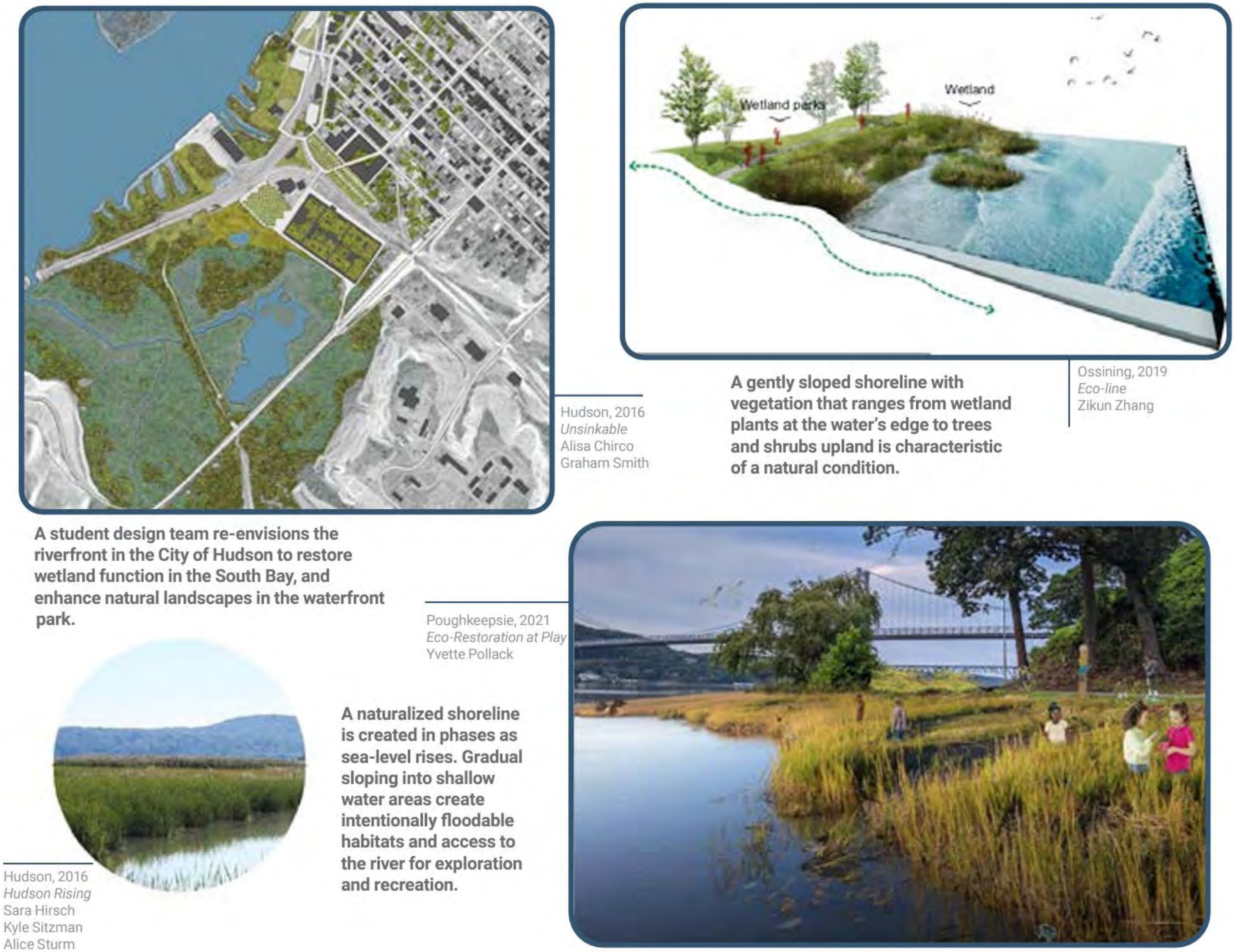


Figure 6. Image from the 2024 Climate Adaptive Design (CAD) Regional Lookbook, depicting student design concepts for a waterfront community by the Hudson River. *Photo by Liz LoGiudice.*

Figure 7. “Water Drop” sculpture depicting water infrastructure at Cornell, created as a part of the Year of Water initiative. *Photo by Blaine Friedlander (Cornell Chronicle).*

Participation in the New York State Climate Smart Communities (CSC) Program. They assessed the equity of the New York State CSC certification and grant programs in terms of municipalities’ access and capacity to participate, based on demographic, economic, political, and spatial trends. One thesis reviewer, an environmental consultant working on adaptation issues along the Lake Ontario shoreline, remarked, “It was so interesting to read this excellent thesis in light of our conversations with communities regarding challenges adapting to fluctuating water levels.” The student presented their work in a session on Social Equity & Human Dimension of Water Management at the American Water Resources Association Annual Meeting.

3. Building a Supportive Social Context through Public Education and Opportunities for Continued Learning

Our public outreach and continuing education programs engage both the general public and professionals outside the traditional academic setting. The world of water resource management is constantly changing, and it is important for water professionals to stay informed, upgrade their skills, and learn from each other. Additionally, without public will and investment, even the most skilled water professionals cannot effectively address water challenges. Engaging the public ensures that water resource management remains a priority, and that necessary funding and policies are in place to support professionals in the field.

Supporting Professional Networks

Beyond student education, NYSWRI staff are actively involved in continuing education and outreach for current water professionals. One example is the creation and development of the New York State Adaptation Practitioners’ Network. This group aims to 1) connect and build relationships among non-profit organizations advising local governments on climate adaptation, 2) share knowledge and advance professional practices in various contexts, and 3) identify processes, models, and tools for high-quality vulnerability assessments and adaptation projects, while exploring how to scale and replicate them. NYSWRI staff co-lead the Learning Network, with a strong focus on peer-to-peer learning. Activities include facilitating a session on funding opportunities under the Bipartisan Infrastructure Law (BIL) with New York State Senate staffers and a multi-part lunch and learn on strategies for managing increased precipitation in the state. NYSWRI staff also create resources to support the network, such as a Quick Guide to assist members in providing feedback on a large state-level climate planning document.

Similarly, in collaboration with NYSDEC, the NYS Floodplain and Stormwater Managers Association, The Nature Conservancy, and Cornell Cooperative Extension Ulster County, NYSWRI is working on strategies and educational resources to expand statewide floodplain manager training. This project focuses on curriculum development, needs assessment, and improving metrics. We completed an inventory of floodplain manager training and resources in New York State and beyond, developed a Body of Knowledge for Floodplain Administrators (FPAs) in New York State, and conducted a gap analysis to identify areas where additional training is needed. To address these gaps, we have developed at least four new training modules. Additionally, we are co-developing program evaluation metrics with stakeholders across the state to align training goals with desired outcomes (Bennett 1976).

In addition to floodplain managers, NYSWRI has also developed targeted training for other water resource professional in the state, including county and municipal highway officials, planners, and natural resource managers on topics such as ditch management, watershed principles, spatial planning tools, and riparian management. During the pandemic, we partnered with the New York Water and Environment Association to provide a series of trainings for wastewater treatment operators and other water managers on COVID-19 monitoring through wastewater analysis. We also collaborated with Public Health faculty and graphic designers to create infographics explaining wastewater-based COVID-19 surveillance.

Public Education and Outreach

Lastly, through community outreach, NYSWRI engages the public in understanding and managing water resources, promoting water conservation, and fostering environmental stewardship – so that careers in water management remain embedded in a social environment where water professionals are supported and valued. Since 2021, we have supported flood resilience efforts through creative outreach methods and public art installations across the state via our Submerse NY program (Figure 8). In partnership with New York Sea Grant, we helped develop MyCoast New York, a portal for collecting and analyzing photos of changing water levels, shorelines, and hazardous weather impacts in New York State. These photos, linked to real-time environmental data, generate reports that help stakeholders such as government agencies, business owners, and residents better understand changing environmental conditions and make informed decisions. In addition, we promoted water resource and infrastructure installations in Ithaca through our Year of Water program. NYSWRI also produces resources to promote water literacy on various topics, such as fact sheets on wastewater surveillance for COVID-19 monitoring and an overview of per- and polyfluoroalkyl substances (PFAS) issues and regulations in New York State. More informally, the director of NYSWRI regularly hosts water trivia as part of a community cruise program on Cayuga Lake, led by the local non-profit Discover Cayuga.

Discussion

We evaluate and adapt educational strategies “in practice, with colleagues and students in the spirit of ‘learning by doing’” (Missingham and Macintosh 2013, 2). Table 1 provides an overview and comparison across programs (Table 1). Through the process of writing this article and engaging in “reflective practice” (Oliver and Dennison 2013, 19), we realize that the core value of much of our programming stems from two main aspects. First, our programs support multiple touchpoints in an individual’s environmental career pipeline—from early learning to continued education and broad water literacy. Second, we work with partners to prioritize educational practices that are directly relevant to real-world water management outcomes. Hands-on research experiences and field visits are integral, especially in our K-12 engagement, as student field observations are used by state agency staff and scientists in their research. Student projects through social science courses are

Table 1. Summary of NYSWRI's major student and public education programs and activities.

	Program	Audience	Location	Duration	Partners	Delivery & Evaluation
Building Identity (K-12)	Day in the Life	~5000 K-12 students, primarily grades 4-9	Multiple locations statewide	1 day annually	HREP (lead), HRNERR, GLWP, CCEs	Watershed staff organize logistics, identify monitoring sites, and train teachers who lead student activities. Evaluation through post-completion surveys.
	Hudson River Eel Project	~1000 K-12 students, local residents	Multiple locations in the Hudson River Watershed	6-8 weeks annually	HREP, HRNERR (lead), local watershed groups	Staff train volunteers via presentations and sessions; volunteers conduct sampling activities. Evaluation through post-completion surveys.
	Great Lakes Ecosystem Education Exchange (GLEEE)	~50 teachers and educators	Multiple locations in New York's Great Lakes Watershed	2-3 days annually	GLWP, NYSG (lead)	Staff and partners organize expert presentations and workshops for teachers to implement water education. Qualitative evaluation through pre and post surveys.
	Dream Your Landscape Design Studio	10-15 high school students	Cornell University	3 days, potentially annual	Tompkins CCE, 4-H Program, GLWP, NYSG	Staff collaborate with 4-H coordinators to offer 11 hours of programming within Cornell's Career Explorations program. Evaluation through a feedback discussion.
	Funded Water Education Courses	K-12, undergraduate and master's students	Statewide	1-2 courses supported annually	Faculty at Cornell and other NYS Universities (lead)	Faculty submit proposals through an annual RFP process; NYSWRI staff provide support. Faculty partners use varied evaluation methods depending on research questions.
Developing Skills (University)	CAD Studio (Long-term Academic Partnerships)	20-30 master's students	Different communities in the Hudson River Watershed	1 semester, varies by community annually	HREP, Cornell University Landscape Architecture (lead), local stakeholders	NYSWRI funds field visits and community engagement; staff facilitate connections and provide follow-up support for implementation. Designs evaluated by faculty, guest reviewers and community partners.
	NYSWRI Seminar Series	4-6 Cornell students, 30-40 public members	Cornell University/ Virtual	7 talks during the spring semester annually	Cornell University Biological and Environmental Engineering	Staff design the course, invite funded researchers as speakers, and manage sessions; seminar is open to the public. Students submit 3 reflections, which are graded by staff.
	NYSWRI Summer Intern Program	4-6 undergraduate and master's students	Cornell University	10 weeks annually	Cornell faculty, local stakeholders, state agency partners	Staff organize and recruit; Cornell faculty and local stakeholders can mentor students on projects. Qualitative feedback surveys are sent out in the 5th and 10th week.
Public & Continuing Education	Public Education Initiatives (Submerse NY, Year or Water)	General public across NYS	Statewide	Ongoing since 2021	NYSG, FEMA, K-12 & Cornell students, artists, local stakeholders	Staff design and provide logistical and financial support to artists and students for creative public outreach and engagement projects. Projects are currently not evaluated for reach.
	Adaptation Practitioners' Network	30+ members from nonprofits and government	Statewide/ Virtual	Multiple sessions throughout the year	Rebuild by Design (lead), SU-EFC	Staff co-lead the learning network & collaborate with experts to design and organize learning sessions and an annual in-person gathering. Evaluated through periodic feedback sessions/ surveys.
	NYS Floodplain and Stormwater Managers Training	Floodplain managers in NYS	Cornell University	Ongoing since 2021	The Nature Conservancy, NYSFSMA, SU-EFC	Staff and partners develop strategies and educational resources for floodplain manager training statewide. Periodically evaluated through participant feedback sessions.

Acronyms: NYSDEC (New York State Department of Environmental Conservation), GLWP (Great Lakes Watershed Program), HREP (Hudson River Estuary Program), HRNERR (Hudson River National Estuarine Research Reserve, NYSG (New York Sea Grant), CCE (Cornell Cooperative Extension), NYSFSMA (New York State Floodplain and Stormwater Managers' Association), RFP (Request for Proposals).

also closely tied to policy and management, with those connections intentionally emphasized as students design and execute their projects.

Alsultan et al., (2021, 3) citing Burgin (2020), stress the importance of engaging in "authentic science" for the most meaningful educational outcomes, providing a framework for assessing our programs. They argue that authentic science depends on "(i) how meaningful or significant the investigation is to the student; (ii) the significance of the work to others, such as members of the scientific community; and (iii) how much the students' activities resemble the practices of the scientific community." In engaging with authentic science, students participate in research question development, study design, data collection, analysis, and dissemination—taking many steps beyond typical school science (Brown et al. 1989; Braund and Reiss 2006; National Research Council 2012; Burgin 2020). While we also strive to provide interdisciplinary learning opportunities beyond the sciences, the concept of authentic science remains a guiding principle for the design and evaluation of NYSWRI's programs.

Our current evaluation approach combines quantitative and qualitative methods, program-specific and varying in scope based on available resources and objectives. Our K-12 programs in the Hudson and Great Lakes regions rely on post-participation surveys, using Likert scales to measure knowledge acquisition and open-ended questions to gather qualitative feedback (Harris et al. 2023). Similarly, teacher development programs, such as the Great Lakes Environmental Education Exchange, use pre- and post-assessments to gauge knowledge gains and intentions to collaborate with peers. We collect detailed qualitative feedback from summer interns at the midpoint and conclusion of their 10-week internship and encourage faculty funded through our RFP process to do the same. These evaluation mechanisms provide valuable insights for refining program content and delivery, effectively measuring short-term impacts. Individual case studies and anecdotal evidence also help illustrate broader impacts. For instance, students who participated in projects like "Day in the Life" or the "Hudson River Eel Project" often pursue environmental science careers, frequently citing these programs as key influences.

Figure 8. Students and visitors on the art trail in Greenport Nature preserve, supported through the Submerse NY program. *Photo by Austen Weymueller.*

While it is possible to assess program effectiveness and knowledge acquisition through the methods described above, evaluating the long-term impact of early education programs presents significant challenges, particularly in measuring behavior change and career outcomes (Phillips et al. 2019). These long-term effects require ongoing access to participants, which is difficult to maintain beyond the program's duration. Privacy concerns, especially for K-12 participants, further complicate the process, limiting the type of data we can ethically collect. Moreover, our broader objectives—fostering both water professionals and water-literate citizens—make it challenging to quantify impacts such as environmental stewardship. While our programs show evidence of influencing career trajectories through anecdotal case studies, the lack of longitudinal data limits our ability to systematically measure the comprehensive outcomes increasingly required by funders and policymakers.

One such outcome is promoting the participation of students from diverse and marginalized backgrounds, particularly given the lack of diversity within the national water workforce (Kane and Tomer 2018). NYSWRI intentionally incorporates Diversity, Equity, Inclusion, and Justice (DEIJ) principles across programs through hiring and recruitment, project development, and programming. Our intern program is an example, where we followed the University of Washington's 6 Steps to Improve Equitable Hiring Practices (https://cdn.uconnectlabs.com/wp-content/uploads/sites/25/2020/09/6-Steps-to-Improve-Equitable-Hiring-Practices.pdf) to assess and amend our practices, strategizing future changes through modifying position descriptions, requiring a short diversity statement, standardizing pay scales with the county livable wage calculator, broadening recruiting, and standardizing candidate evaluation rubrics. We also center water equity in our work, using a Community Agreement for all staff, interns, and mentors to set expectations of respectful and fair treatment, and we encourage equity considerations in all projects with a guide to assist students and mentors. The RFP process for supporting Cornell courses also integrates DEIJ principles by encouraging proposals that address equity issues and involve underserved communities.

For our K-12 programs in partnership with NYSDEC, we avoid collecting personal demographic data from participants but use publicly available data, such as the percentage of economically disadvantaged students in school districts, as a proxy for understanding the inclusivity of our outreach. This approach helps assess whether our programs engage students from underrepresented and economically marginalized communities without infringing on privacy. We have also begun using state-defined Potential Environmental Justice Areas (PEJAs) as a metric to estimate the extent of our programs' reach into historically underrepresented communities. These metrics, while imperfect, provide one approach to evaluating DEIJ outcomes.

To enhance our evaluation capabilities, we hope to develop more structured frameworks for both short-term and longitudinal assessments. Ideally, we could introduce periodic follow-up surveys to track participants' educational and professional trajectories over several years, along with their sustained engagement with water resource issues. Semi-structured interviews could provide rich qualitative data, offering deeper insights into long-term career decision-making and behavior change. For K-12 programs, partnerships with school districts may provide a feasible avenue for regular evaluations without burdening participants or infringing on privacy. Expanding the use of publicly available demographic data, such as metrics on environmental justice areas, could also enhance our understanding of the populations we serve.

Beyond evaluation and promoting diversity, limitations also persist in the scope and design of our programs. While the programs provide substantial field and research opportunities, there is a need for more continuous, long-term engagement to reinforce learning. At the university level, NYSWRI's programs primarily focus on Cornell University, with limited engagement at community colleges and technical institutions, restricting broader equity opportunities across New York State. Sustaining peer-to-peer learning communities is also challenging due to funding constraints and the difficulty of identifying the right geographic and topical focus within a diverse state.

Addressing these challenges requires strategic planning and better capacity allocation. This includes increasing collaboration with community colleges and minority-serving institutions beyond Cornell. We are compiling a list of faculty and courses at potential partner institutions in the state that focus on water research and management and aim to create a 'matchmaking' mechanism through which agency partners and regional staff can develop and pitch projects to these courses. We are also exploring the creation of a small grants program to fund community-engaged courses with field components that integrate collaboration with community stakeholders. Overall, we aim to creatively overcome challenges and adopt more systematic approaches to evaluating educational outcomes over time, while continuing to provide tiered, interdisciplinary educational experiences directly tied to water management outcomes in the state.

Conclusion

Continued investment in education and training for water professionals is critical as the sector faces significant workforce challenges. To contribute to this effort, the New York State Water Resources Institute at Cornell University employs a comprehensive, tiered approach to training future water professionals, spanning K-12 engagement, university-level education, ongoing professional development, and public outreach. By intervening at multiple stages—from identity building in young students to creating a supportive social context for professionals—learners at all levels are better equipped with the skills and knowledge needed to address complex water management challenges. NYSWRI's educational programs emphasize real-world applications, hands-on experiences, and authentic science practices. By connecting education to practical outcomes, such as policy development and environmental stewardship, these initiatives help students recognize the tangible impacts of their work. Additionally, the incorporation of Diversity, Equity, Inclusion, and Justice (DEIJ) principles aims to make educational opportunities more accessible and inclusive, contributing to the diversification of the water workforce.

Nevertheless, there is a need for continuous, long-term engagement to strengthen learning, improve program evaluation, and expand outreach beyond Cornell University. To address these challenges, NYSWRI plans to form partnerships with institutions outside Cornell, develop a matchmaking mechanism for project collaboration, and establish a small grants program to support community-engaged courses.

By refining and systematically evaluating these models, we hope to enhance their effectiveness and broaden their reach. We encourage other institutions to adopt similar approaches and share their experiences, contributing collectively to the advancement of water resource management education. Through intentional reflection, collaboration, and knowledge sharing, institutions involved in water-related research and education can play an important role in supporting a sustainable future for water resources and the communities that depend on them.

Author Bio and Contact Information

Rewa Phansalkar is a regional planner, architect, and researcher based in Ithaca, New York. She is currently an extension associate at the New York State Water Resources Institute at Cornell University, where she works on projects that integrate sustainable urban design, policy, and governance approaches for flood resilience. She studied architecture at the Academy of Architecture, Mumbai, before pursuing a master's degree in Regional Planning at Cornell University. In the past, she has worked with the Aga Khan Agency for Habitat, School of Environment and Architecture, and the Urbz Research Collective in Mumbai. Email: rp589@cornell.edu.

Kristen Hychka is a research and outreach specialist at the New York State Water Resources Institute. Her research and outreach focus on watershed issues, particularly flood resiliency and the management of wetland and riparian systems. She works in partnership with the Syracuse University Environmental Finance Center and the Hudson River Estuary Program to promote statewide assistance to individuals and organizations regarding these issues. Email: kch235@cornell.edu.

Chris Bowser coordinates the education team at the NYSDEC Hudson River Estuary Program and Hudson River National Estuarine Research Reserve. This team implements citizen-science programs like the Eel Project and student initiatives like the Day in the Life of the Hudson and Harbor. Bowser's other experiences include serving as reforestation volunteer with the Peace Corps in West Africa, working as education director for the Sloop Clearwater, and teaching environmental science at Marist and Bard Colleges. Email: chris.bowser@dec.ny.gov.

Emily Fell works as the Eastern Great Lakes Watershed Coordinator for the NYSDEC and WRI. Her background is in natural resources management, and she received her B.S. from the SUNY College of Environmental Science and Forestry. She has been with the NYSDEC and Natural Heritage Trust in this role for seven years prior to joining WRI, and is excited to be a part of the WRI team. Emily grew up within communities in NY's Great Lakes and enjoys working with communities and stakeholders to advance goals of NY's Great Lakes Action Agenda, including water quality, natural resource management, invasive species, resiliency, and stewardship of recreational resources, and works closely with NY Sea Grant to promote Great Lakes Literacy and Stewardship under the Great Lakes Ecosystem Education Exchange. Emily enjoys visits to

the beaches of Lake Ontario, hiking in the Adirondacks, and paddling or tubing within the many rivers and lakes of NY's Great Lakes. Email: Emily.Fell@dec.ny.gov.

Brian Rahm is the director of the New York State Water Resources Institute at Cornell University. From upstate NY, Brian started with NYSWRI in 2010 by focusing on the intersection of engineering, science, and policy associated with potential shale gas extraction in New York State. He has since worked on water resource infrastructure management and policy more generally, and enjoys the challenge of addressing the state's water issues via interdisciplinary research, institutional capacity building, and local stakeholder engagement. Email: bgr4@cornell.edu.

References

Abu-Zeid, M.A. and A.K. Biswas. 1991. Some major implications of climatic fluctuations on water management. *International Journal of Water Resources Development* 7(2): 74–81. Available at: https://doi.org/10.1080/07900629108722497. Accessed October 24, 2024.

Alsultan, J., M. Henderson, A. Feldman, M. Rice, X. Yang, J. Kahler, S.J. Ergas, and K. Ghebremichael. 2021. Participation of high school students in authentic science and engineering experiences with a university-based water research team. *Water* 13(13): 1745. Available at: https://doi.org/10.3390/w13131745. Accessed October 24, 2024.

Amahmid, O., Y. El Guamri, M. Yazidi, B. Razoki, K. Kaid Rassou, Y. Rakibi, and T. El Ouardi. 2019. Water education in school curricula: Impact on children knowledge, attitudes and behaviours towards water use. *International Research in Geographical and Environmental Education* 28(3): 178–193. Available at: https://doi.org/10.1080/10382046.2018.1513446. Accessed October 24, 2024.

Bloomfield, G., K. Bucht, J.C. Martínez-Hernández, A.F. Ramírez-Soto, I. Sheseña-Hernández, C.R. Lucio-Palacio, and E. Ruelas Inzunza. 2018. Capacity building to advance the United Nations sustainable development goals: An overview of tools and approaches related to sustainable land management. *Journal of Sustainable Forestry* 37(2): 157–177.

Braund, M. and M. Reiss. 2006. Towards a more authentic science curriculum: The contribution of out-of-school learning. *International Journal of Science Education* 28(12): 1373-1388. Available at: https://doi.org/10.1080/09500690500498419. Accessed October 24, 2024.

Brown, C.M., J.R. Lund, X. Cai, P.M. Reed, E.A. Zagona, A. Ostfeld, and L. Brekke. 2015. The future of water resources systems analysis: Toward a scientific framework for sustainable water management. *Water Resources Research* 51(8): 6110–6124.

Brown, J.S., A. Collins, and P. Duguid. 1989. Situated cognition and the culture of learning. *Educational Researcher* 18(1): 32–42. Available at: https://doi.org/10.3102/0013189X018001032. Accessed October 24, 2024.

Brundiers, K., A. Wiek, and C.L. Redman. 2010. Real-world learning opportunities in sustainability: From classroom into the real world. *International Journal of Sustainability in Higher Education* 11(4): 308–324. Available at https://doi.org/10.1108/14676371011077540. Accessed December 3, 2024.

Burgin, S.R. 2020. Making science authentic for students: Strategies for integrating real-world research experiences into the classroom. *Journal of Science Education and Technology* 29(3): 402–410. Available at: https://doi.org/10.1007/s10956-020-09824-5. Accessed October 24, 2024.

Colvin, C.R. 2013. Significant Life Experience: Exploring the Lifelong Influence of Place-Based Environmental and Science Education on Program Participants. Dissertation, University of Colorado, Denver, Colorado. (Order No. 3592585). ProQuest Dissertations & Theses Global. Available at: https://www.proquest.com/dissertations-theses/significant-life-experience-exploring-lifelong/docview/1437014333/se-2. Accessed December 3, 2024.

Cosgrove, W.J. and D.P. Loucks. 2015. Water management: Current and future challenges and research directions. *Water Resources Research* 51(6): 4823–4839.

Cortner, H.J. 2000. Making Science Relevant to Environmental Policy. *Environmental Science & Policy* 3(1): 21–30.

Harris, C.B., A.W. Oliveira, B.L.M. Levy, A.R. Berkowitz, and C. Bowser. 2023. The eel connection: Developing urban adolescents' sense of place through outdoor interactions with a local organism. *The Journal of Environmental Education* 54(4): 241–264. Available at: https://doi.org/10.1080/00958964.2023.2216160. Accessed December 3, 2024

Hellgren, J.M. and S. Lindberg. 2017. Motivating students with authentic science experiences: Changes in motivation for school science. *Research* *in Science and Technological Education* 35(4): 409–426. Available at: https://doi.org/10.1080/02635143.2017.1322572. Accessed October 24, 2024.

Hilander, M., and S. Tani. 2022. Meaningful encounters with the built environment as the basis for urban environmental education. *Education Sciences* 12(3): 203. Available at: https://doi.org/10.3390/educsci12030203. Accessed December 3, 2024.

Hudson River National Estuarine Research Reserve. 2024. Day in the Life of the Hudson and Harbor. New York State Department of Environmental Conservation, Staatsburg, NY. Available at: https://hrnerr.org/learn/teachers-educators/. Accessed November 20, 2024.

Hunter, M. A. 2006. Opportunities for environmental science and engineering outreach through K–12 mathematics programs. *Environmental Engineering Science* 23(3): 461–470. Available at: https://doi.org/10.1089/ees.2006.23.461. Accessed December 3, 2024.

Johnson, M. F., C. Hannah, L. Acton, R. Popovici, K. K. Karanth, and E. Weinthal. 2014. Network environmentalism: Citizen scientists as agents for environmental advocacy." *Global Environmental Change* 29: 235–245.

Kane, J. and A. Tomer. 2018. Renewing the Water Workforce: Improving Water Infrastructure and Creating a Pipeline to Opportunity. Brookings Institute, Washington, D.C. Available at: https://www.brookings.edu/articles/water-workforce/. Accessed October 24, 2024.

Kwee, C.T.T. and L.M. Dos Santos. 2023. An international study of high school teachers' experience of incorporating water resources in their teaching. *Frontiers in Education* 7: 1065228. Frontiers Media SA. Available at: https://doi.org/10.3389/feduc.2022.1065228. Accessed October 24, 2024.

Lally, D. and C.T. Forbes. 2020. Sociohydrologic systems thinking: An analysis of undergraduate students' operationalization and modeling of coupled human-water systems. *Water* 12(4): 1040. Available at: https://doi.org/10.3390/w12041040. Accessed October 24, 2024.

Laursen, S., A.-B. Hunter, E. Seymour, H. Thiry, and G. Melton. 2010. *Undergraduate Research in the Sciences: Engaging Students in Real Science*. John Wiley and Sons.

Leendertse, K. and P. Taylor. 2011. Capacity building and knowledge sharing. In: *Water Resources Planning and Management*, R.Q. Grafton and K. Hussey (Eds.). Cambridge University Press, pp. 274–291.

LeVasseur, T. 2014. Teaching sustainability via the environmental humanities: Studying water, studying ourselves. *Journal of Sustainability Education* 7. Available at: https://www.susted.com/wordpress/content/teaching-sustainability-via-the-environmental-humanities-studying-water-studying-ourselves_2014_12/. Accessed October 24, 2024.

Luste, S. and K. Medkova, (Eds.). 2019. Lifelong Learning and Wastewater Treatment in the Baltic Sea Region: Capacity Development Opportunities Observed in the Iwama Project (2016–2019). Lahti University of Applied Sciences, Lahti, Finland.

Lyons, T. 2006. Different countries, same science classes: Students' experiences of school science in their own words. *International Journal of Science Education* 28(6): 591–613. Available at: https://doi.org/10.1080/09500690500339621. Accessed October 24, 2024.

Missingham, B. and B.S. Mcintosh. 2013. Water education for sustainability in higher education. *Journal of Contemporary Water Research and Education* 150(1): 21–28. Available at: https://doi.org/10.1111/j.1936-704X.2013.03144.x. Accessed October 24, 2024.

National Research Council. 2012. *A Framework for K-12 Science Education: Practices, Crosscutting Concepts, and Core Ideas*. National Academies Press.

New York Sea Grant. n.d. New York's Great Lakes Ecosystem Education Exchange. Available at: (https://seagrant.sunysb.edu/articles/t/new-york-s-great-lakes-ecosystem-education-exchange). Accessed October 24, 2024.

New York State Department of Environmental Conservation. 2022. *Hudson River Eel Project Summary Report*. NYSDEC. Available at: https://extapps.dec.ny.gov/docs/remediation_hudson_pdf/082415eelreport.pdf. Accessed November 20, 2024.

Oliver, P. and W.C. Dennison. 2013. Popular education for water sustainability: Three lessons from reflective practice. *Journal of Contemporary Water Research and Education* 150: 18–25. Available at: https://doi.org/10.1111/j.1936-704X.2013.03142.x. Accessed October 24, 2024.

Pahl-Wostl, C., P. Jeffrey, N. Isendahl, and M. Brugnach. 2011. Maturing the new water management paradigm: Progressing from aspiration to practice. *Water Resources Management* 25(4): 837–856.

Parr, D.M., C.J. Trexler, N.R. Khanna, and B.T. Battisti.

2007. Designing sustainable agriculture education: Academics' suggestions for an undergraduate curriculum at a land grant university. *Agriculture and Human Values* 24(4): 523–533. Available at: https://doi.org/10.1007/s10460-007-9084-y. Accessed December 3, 2024.

Phillips, T.B., H.L. Ballard, B.V. Lewenstein, and R. Bonney. 2019. Engagement in science through citizen science: Moving beyond data collection." *Science Education* 103(3): 665–690. Available at: https://doi.org/10.1002/sce.21501. Accessed December 3,2024.

Sadler, T.D., H. Nguyen, and D. Lankford. 2017. Water systems understandings: A framework for designing instruction and considering what learners know about water. *Wiley Interdisciplinary Reviews: Water* 4(4). Available at: https://doi.org/10.1002/wat2.1178. Accessed October 24, 2024.

Seidl, R. and R. Barthel. 2017. Linking scientific disciplines: Hydrology and social sciences. *Journal of Hydrology* 550: 441–452.

Selna, M.W., H.T. Glaser, R.R. Trussell, G.R. Chan, and M. Sullivan. 2006. Declining enrollment has water and wastewater professionals concerned. In: *Proceedings of the Water Environment Federation* Available at: https://www.researchgate.net/publication/228487381_Declining_Enrollment_has_Water_and_Wastewater_Professionals_Concerned. Accessed November 20, 2024.

Tsybulsky, D., J. Dodick, and J. Camhi. 2018. High-school students in university research labs? Implementing an outreach model based on the 'science as inquiry' approach. *Journal of Biological Education* 52(4): 415–428. Available at: http://dx.doi.org/10.1080/00219266.2017.1403360. Accessed October 24, 2024.

U.S. Environmental Protection Agency. 2020. *America's Water Sector Workforce Initiative: A Call to Action*. EPA. Available at: https://www.epa.gov/sustainable-water-infrastructure/americas-water-sector-workforce-initiative. Accessed October 24, 2024.

Yilmaz, M., J. Ren, S. Custer, and J. Coleman. 2010. Hands-on summer camp to attract K–12 students to engineering fields." *IEEE Transactions on Education* 53(1):144–151. Available at: https://doi.org/10.1109/TE.2009.2026366. Accessed December 3, 2024.

Links

Day in the Life: https://cals.cornell.edu/water-resources-institute/watersheds/hudson-river-estuary/education/day-life-hudson-river, https://dec.ny.gov/get-involved/education/teacher-information/day-in-the-life-statewide-events/day-in-the-life-lake-ontario-st-lawrence-river

Hudson River Eel Project: https://cals.cornell.edu/water-resources-institute/watersheds/hudson-river-estuary/education/hudson-river-eel-project

Great Lakes Ecosystem Education Exchange (GLEEE: https://www.nyseagrant.org/gleee

Dream Your Landscape Design Studio: https://www.nys4-h.org/career-explorations-2024

https://docs.google.com/presentation/d/1KkaO_hBCqlC_zVefy6qZRh7PLLtlD1Q6YD8FEwRSwBM/edit?usp=sharing

Funded Water Education Courses: https://cals.cornell.edu/water-resources-institute/resources/grants-funding-opportunities

CAD Studio (Long-term Academic Partnerships): https://cals.cornell.edu/water-resources-institute/watersheds/hudson-river-estuary/climate-change/climate-adaptive-design-process

NYSWRI Seminar Series: https://www.youtube.com/playlist?list=PLh0xmIfBrjAkQCSyetLFk9mM9LnaBlXc6

NYSWRI Summer Intern Program: https://cals.cornell.edu/water-resources-institute/internships

Public Education Initiatives (Submerse NY, Year of Water): https://news.cornell.edu/stories/2022/09/droplet-shaped-sculptures-kick-year-water

Adaptation Practitioners' Network: https://rebuildbydesign.org/nys-adaptation-practitioners/

NYS Floodplain and Stormwater Managers Training: https://nyfloods.org/

Universities Council on Water Resources
Journal of Contemporary Water Research & Education
Issue 182, Pages 89-98, April 2025

Fifty Years of Water Research Projects in California: Keyword Analysis and Qualitative Coding with Natural Language Processing (NLP) Models

Erik Porse

California Institute for Water Resources, University of California Agriculture and Natural Resources

Abstract: Global freshwater resources are increasingly strained in many regions, driven by agricultural expansion, population growth, energy production, and climate change. Research in water science and management seeks to address challenges that industrialized societies face to ensure water of sufficient quality and quantity. What themes have been prominent in water research in past decades and how have these themes changed over time? While the field of water management has often relied on expert judgement to identify research needs, recent analytical tools provide novel opportunities to evaluate the evolution of research priorities in water management. This paper presents a thematic analysis of water research projects in California using keyword analysis with Natural Language Processing models and a database of fifty years of funded research. Results indicate that some themes, such as groundwater management, have remained consistent over time, while others, including aquatic ecosystem management, have emerged more recently with recognized environmental degradation. Research has appeared to respond to changes in water policy priorities and climate variability, with drought-related research projects corresponding to periods of significant drought in California. The analysis demonstrates a replicable methodology for evaluating research themes and outcomes in water research using inductive thematic analysis, which can be applied to more examples from Water Resources Research Act funded projects and other water research initiatives.

Keywords: *National Institutes for Water Resources, Water Resources Research Act, California Institute for Water Resources, artificial intelligence, thematic analysis, content analysis*

Water management challenges in the 21st century require research that addresses questions through analysis, data, theory, and models. Global freshwater resources are increasingly strained in many regions, driven by agriculture, population changes, and energy production (Bijl et al. 2018; Bo et al. 2021). Human-driven changes in land use, urbanization, technology, diet, and wealth alter the availability of freshwater resources, disrupting flows and degrading or depleting surface and groundwater sources (Cosgrove and Loucks 2015; WAPP 2015). Groundwater pumping for irrigated agriculture has particularly affected freshwater availability in some portions of the globe (Rodell et al. 2018; Jasechko and Perrone 2021; Jasechko et al. 2021). While water use efficiency of urban and agricultural uses has increased in many regions, water used for cities and agriculture (water withdrawals) likely exceeds inputs in over 1,800 global watersheds by a total volume equal to 24% of total global freshwater consumption (Motoshita et al. 2020).

Research in water management seeks to address the water scarcity challenges created by industrialized societies, such as ensuring aquatic ecosystem health, reducing or eliminating watershed pollution, developing sustainable and efficient irrigated food systems, and promoting equitable water access (Cosgrove and Loucks 2015; Jepson et al. 2017; Meehan et al. 2020).

Research Implications

- Recent analytical tools in Artificial Intelligence provide novel opportunities to evaluate the evolution of research priorities in water management.
- Fifty years of water research projects funded by the California Institute for Water Resources and its predecessors were evaluated using Natural Language Processing models to understand changing research priorities.
- Research has responded to changes in water policy priorities and climate variability, with drought-related research projects corresponding with periods of significant drought in California.
- The analysis demonstrates a replicable method for evaluating themes in water research that can be applied to more examples from Water Resources Research Act funded projects and other research initiatives.

Improved methods for integrated planning that foster inclusive governance and "soft solutions" can support better regional management of water resources within environmental limits (Gleick 2003; Lund 2006; Biswas 2008; Gallego-Ayala 2013). Research in water and ecosystems has expanded significantly to understand water-related needs of species, including water supply and quality characteristics of streamflow and habitat, which support ecosystem functions (Poff et al. 1997; Poff and Zimmerman 2010; Aznar-Sánchez et al. 2019). Water scarcity, globalization, political trends, and disasters affect the governance of water and organization of institutions that manage water (Saleth and Dinar 2000). Agencies must increasingly consider effects of extreme climate variability and change, such as extended drought, on operations (Gober et al. 2016). The assumptions used to manage water throughout the world are informed by findings from multidisciplinary research.

Within the context of these water management challenges, how has water-related research changed over time and what might the evolution of past research say about future research needs? Such questions can be investigated in several ways. For instance, expert judgement from academics and practitioners can evaluate the evolution of research and posit future trends (Christ 1970). Such assessments have used deductive approaches that synthesize prominent research largely drawn from theoretical frameworks. Within water resources, academic journals have published periodic collections of articles from experts who summarize prominent research themes (Burges 1986; Page and Susskind 2007; Cosgrove and Loucks 2015; Montanari et al. 2015), while countless examples exist of informative literature reviews that focus on comprehensive assessments of existing research on a topic to understand knowledge gaps.

Alternatively, assessments of past research can use inductive approaches that derive themes based on data, with little or no theory or judgement imparted to evaluate themes. As an example, Chen et al. (2022) used bibliometric analysis to assess keywords associated with research over time by collecting keywords from research articles and using expert judgement to categorize prominent themes. When keywords are not predetermined, qualitative research has techniques that can be used to derive keywords from a body of text, which then need synthesized. Thematic analysis is one method for extracting meaning and concepts from data that is broadly applicable to many types of data. Thematic analysis is a method for identifying themes in data, whereby observed data are coded according to a defined and replicable rubric that allows for evaluating the underlying interpretations (Braun and Clarke 2006; Kiger and Varpio 2020). Importantly, thematic analysis seeks to reduce the theoretical context or bias of researchers analyzing the raw data, which can be important when identifying methods to extract keywords or themes from raw data. Only a few examples exist in research for applications of thematic analysis to water resources (Lv et al. 2021; Rahman et al. 2022). The water resources management community can benefit from studies that use emerging, data-driven approaches from qualitative analysis to assess changes in research and management trends over time, which complement expert-driven assessments and have the potential to uncover unaddressed topics.

This paper presents a method to evaluate research themes across historical records of water research projects based on inductive thematic analysis. Using the case study of California and a database of fifty years of historical water research projects funded by the Water Resources Research Act (WRRA) and the State of California, the study: 1) demonstrates a method of thematic analysis using Natural Language Processing (NLP) and machine learning models to identify the focus of water-related research from hundreds of projects based on keyword extraction and qualitative coding analysis, and 2) evaluates changes over time in the focus of these projects. The study describes a replicable methodology that uses a novel application of thematic analysis in the field of water resources to identify keywords from raw data to evaluate changes in research over time. The method can be adapted to program evaluation for research outcomes of the WRRA in other states, along with other state and federal funding initiatives for water.

Water Research in California

For decades, water-related research in California has sought to inform strategies for better water resources management. Academic researchers study topics of water management and science across the University of California and California State University public systems, which today include 33 campuses and more than 50 local cooperative extension offices and research centers. New technologies and management practices, driven by empirical research, have been critical to supporting cities, agriculture, and aquatic ecosystems in a state with one of the largest water management systems in the world. Water systems across California are highly connected and extend far upstream (Swyngedouw 1997; Lund et al. 2010; 2018). The systems were built to deal with the state's seasonal and limited precipitation. Through the 20th century, the federal and state governments supported creation of large-scale water conveyance infrastructure that moves snowmelt and runoff in northern and eastern parts of the state to areas of higher demand in central, southern, and coastal areas. Across California today, in a year with precipitation near historical averages, half of all water is dedicated to environmental uses for instream flows, 40% of water is used by agriculture, and 10% is used by cities.

The state's diversity of ecosystems, climate, and water demands means that agencies and communities face a myriad of challenges to manage water resources. Research has responded by studying a diversity of topics, from water quality and supply to aquatic habitat and ecosystems to energy and technology, and more. Since the mid-20th century, significant policy, regulatory, and technological developments have changed how water is managed. For example, the Porter-Cologne Water Quality Act (1969) in California and the federal Clean Water Act and its Amendments (since 1972) have established a complex regime to promote water quality through enhanced treatment technologies (Hume 1970; Phaler 1971; Asano 1987; Merhaut 2003; Hawkins 2015). Similarly, large-scale infrastructure projects in the Sacramento-San Joaquin Delta and Colorado River, designed and built decades ago, face continued challenges to manage water scarcity and increasing requirements for environmental water and flows (Medellín-Azuara et al. 2013; Lane et al. 2015; Delfino 2016; Null 2016; Durand et al. 2020). The management of rivers and freshwater ecosystems is being reconsidered to incorporate environmental flow regimes that capture seasonal, volumetric, temperature, and water quality requirements of threatened species (Lane et al. 2017; Stein et al. 2021).

Water Resources Research Act (WRRA) Funding in California

In 1957, the state of California was considering construction of the State Water Project, the large conveyance system that brings water from far Northern California to cities and farms in coastal and inland Southern California as well as the Central Valley. Recognizing the need for new research in California on water resources, the California State Legislature funded the first University of California (UC) Water Resources Center at the University of California Los Angeles (UCLA) to provide training and research for water planning. Soon after, in 1964, the WRRA authorized water research institutes in each state and territory of the U.S. In California, the existing UC Water Resources Center became part of the new network of federal institutes. Located first at UCLA, then led by academics at UC Berkeley, UC Davis, and UC Riverside, the Water Resources Center coordinated research, extension, and education activities, and maintained California's Water Resources Center Archives. In 2011, the Water Resources Center reopened as the California Institute for Water Resources (CIWR), a statewide program within UC Agriculture and Natural Resources (UC ANR) with capacity to support research on campuses across the state.

CIWR and its predecessors have offered grants for water research at California's universities since the 1970s. Since 2011, grants have been awarded through a competitive process, with funded projects recommended by a peer review committee of academic and non-academic participants. The focus and scope of funded projects have evolved. From 1970 to 1999, the California Water Resources Center typically funded a few projects each year by UC researchers. From 1999 to 2008, the program grew with state support and funded 7-20 research projects across five categories including hydrology, ecosystems, water quality, management, and law and policy. Since 2011, CIWR has funded research projects at UC (campuses and extension) and California State University campuses. CIWR has administered nearly $2 million in federal funds, including $1 million to early career researchers, which are all matched by state funding. These grants are only a small part of water research in the state, but grants have focused on early career academics, many of whom have continued their research in the state.

Methods

CIWR archives have records of nearly 250 funded research projects going back fifty years (1970-2025) from which a dataset of project titles was extracted. The compiled database of projects includes those funded from 1970 through 2025 by the UC Water Resources Center (1970-2009) and CIWR (2011-present). Projects were supported by funding from the State of California and the WRRA through 2009, and from WRRA funds with campus matches from 2010 to 2025 at a smaller level of available funding.

Research themes for each decade were identified based on keyword extraction. Keyword and key phrase extraction are important tasks of NLP, which is a subset of Artificial Intelligence (AI) that enables computers to interpret and understand human language (Chowdhary 2020). Methods to identify and extract keywords have grown to analyze proliferating new knowledge, information, and digital content (Sun et al. 2020; Giarelis et al. 2021), including applications to understand emerging scientific research (Mahata et al. 2018). Bidirectional Encoder Representations from Transformers (BERT) is a state-of-the-art deep learning NLP technique that uses both semantic and contextual information to identify keywords.

The open-source *KeyBERT* model uses unsupervised NLP with BERT to identify keywords (Grootendorst 2023). The model includes three main steps. First, the model selects candidate keywords from text of interest using a function to generate potential keywords based on an embedded machine learning model within the *Scikit-Learns* software. The package supports generation of keywords or phrases of varying (*n*) length, where *n* can be a single keyword or a phrase of multiple keywords. Second, a vector containing the frequency of keywords or phrases is generated for each of the candidate keywords based on a sentence transformer model that incorporates BERT, a trained model published by Google that identifies keywords or phrases based on searching both right and left of text to evaluate context (Devlin et al. 2018; Issa et al. 2023). Third, the frequency vector of keywords is compared to the vector of the full document based on cosine similarity (Rahutomo et al. 2012).

To implement the analysis with keyword extraction, project titles were grouped by decade. For each decade, a single text string was compiled with all corresponding project titles without punctuation. The analysis considered unigram (one word) keywords, whereby the frequency vector generated by *KeyBERT* is the list of keywords for analysis. From the initial frequency vector generated by the NLP model, duplicate terms (i.e. hydrologic and hydrological) and geographic names (i.e. California) were removed. The top keywords (up to eight keywords) were recorded in each decade and used to evaluate changes in key terms across decades (Figure 1). Then, a larger set of keywords (40 keywords) for each decade that were identified by the NLP model were grouped into meta categories using content analysis through an iterative manual process. The keywords were categorized into one of twelve themes, which are listed in Table 1. The number of instances of keywords within a theme was then compared across decades (Figure 2), which illustrated how water research interests have evolved.

Table 1. Research themes used to group keywords through qualitative content analysis.

Research Themes
Energy and Technology
Water Quality and Treatment
Climate and Soils
Agriculture
Groundwater
Ecosystems
Watersheds
Recreation
Policy, Planning, and Regulations
Efficiency and Conservation
Flood Management
Hydrodynamics and Hydraulics

Results

Results of the keyword analysis and grouping indicated that while some themes were consistent, other themes have emerged or faded with broader industry and climate trends (Figure 1). For instance, while groundwater is an area of recent high interest due to the Sustainable Groundwater Management Act (SGMA) in 2014 to address chronic overdraft, groundwater research has been prominent for decades in California. "Groundwater" was a top keyword from research in five of six decades, revealing how groundwater has been a consistent challenge for water managers and users in the state for a long time. The keyword analysis also identified how water research in California has been consistently influenced by climate and management realities, with "drought" being a noted research topic in the 1980s, 2000s, and 2010s. This corresponds with several major drought periods in California from 1976-1977, 1987-1992, and 2011-2016.

Other themes are less consistent. From 1970 to 2009, "sediment" was a prominent keyword as research interests increased in early stormwater and water quality management to deal with effects of urbanization. After 1990, however, additional environmental keywords appeared, including "rivers," "salmon," and "ecosystem." This reflects the significant growth in ecosystem-focused work, which recognizes the need to address continued environmental restoration goals in California to reverse decades of environmental degradation. Agricultural water research grew after 2010 with CIWR's relocation as a statewide organization in UC and UC ANR.

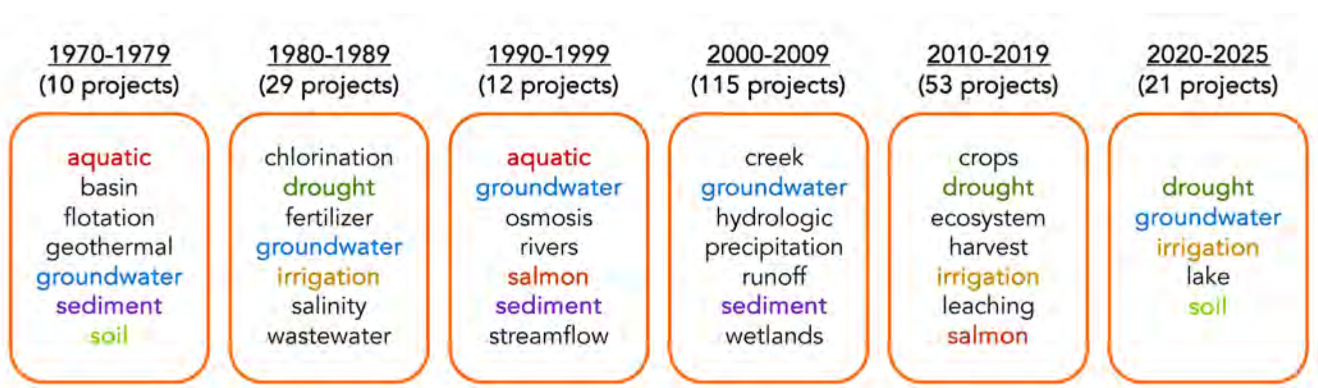


Figure 1. Top keywords of research projects by decade.

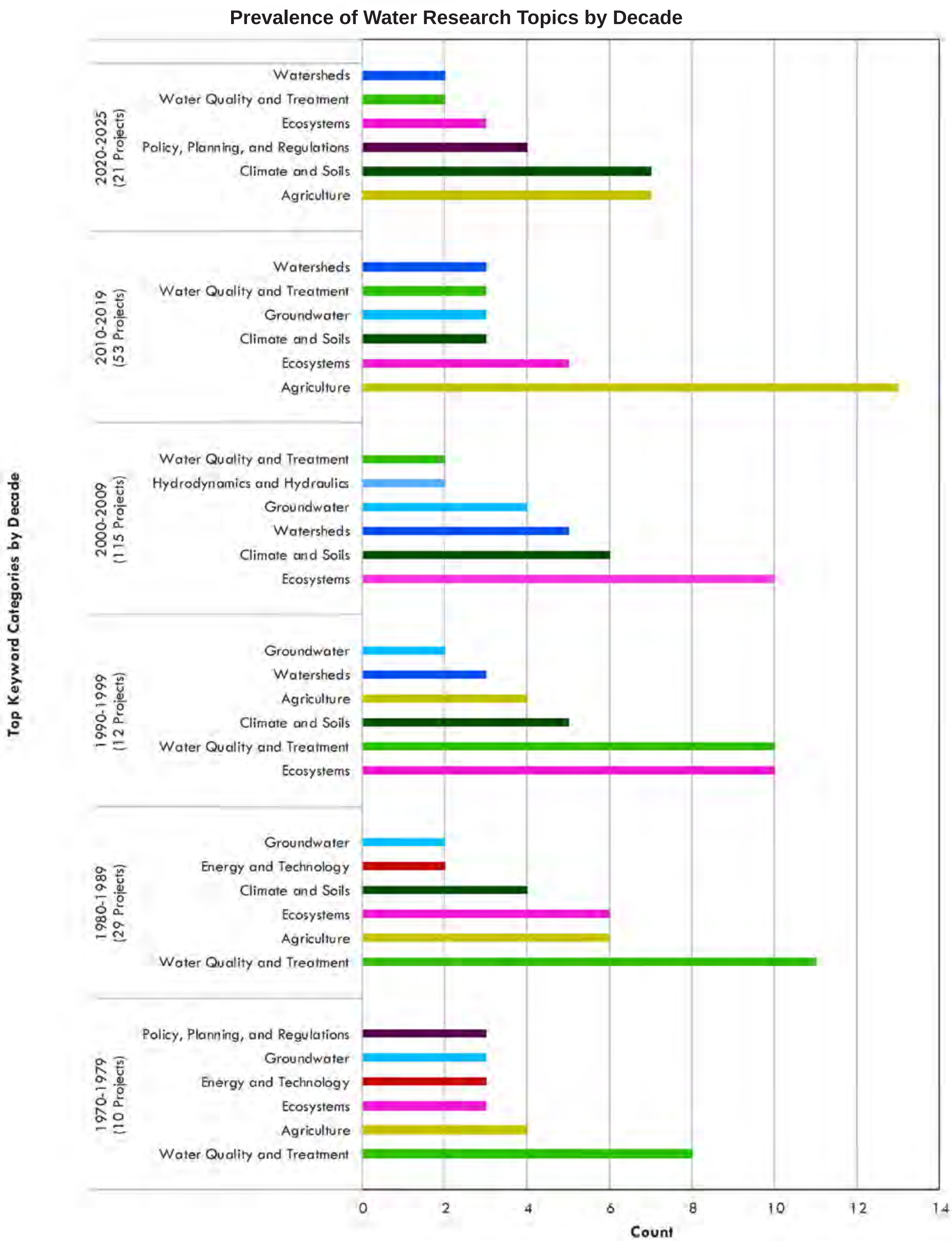


Figure 2. Prominent project themes in each decade based on grouping keywords identified through Natural Language Processing.

Grouping keywords into themes of research revealed additional insights (Figure 2). Across decades, top themes have remained relatively consistent. From 1970 to 2000, water quality and treatment were key themes. During this time, wastewater treatment research expanded significantly, and the state established research for salinity management. Starting in the 1990s, research focusing on ecosystems increased, reflecting broader policy and management challenges associated with long-term decline in aquatic species and renewed focus on managing environmental challenges in the Sacramento-San Joaquin Delta. From 2009 to 2010, statewide infrastructure projects that use the Sacramento-San Joaquin Delta as conveyance to move water to Southern California cities and farms were required to amend pumping operations to address habitat degradation.

Research in agricultural water management increased after 2010, reflecting the growing interest in adapting California's agricultural practices to changing climate conditions and water availability. Climate and soils research is a consistent topic and has grown more prominent since 2020. Recent projects in this area especially incorporate needs to understand climate change effects on water resources, as well as research to understand links between water management, availability, and soil science.

Discussion

The approach helps illustrate how contemporary machine learning and AI tools can be applied to content analysis of resource management research. This is an important reflective task for research programs to ensure that contemporary state and federally funded research is addressing critical questions. For instance, while existing research identifies many past priorities focused on improving utilization of water resources and water quality, recent project titles do not reflect current policy goals for resilience and adaptation, even though such goals may underlie outcomes of ongoing studies. Recent interest in equity as a policy goal is also not reflected. Contemporary tools in both research methods and policy implementation are inadequate to address the ambitious goals sought by ambitious policies such as the *Human Right to Water* (Assembly Bill 685), which was passed in California in 2012 and codified the right for all Californians to "safe, clean, affordable, and accessible" water for consumption and sanitation. Finally, climate change and variability themes are not explicitly reflected in keywords. Reflective studies on existing and future research needs can help align research with emerging industry and management priorities to ensure effective use of public funding for applied research and extension.

Analyzing the results within the context of contemporary issues in water resources management is important. Results from the keyword identification and grouping were evaluated knowing some of the historical policy issues that have arisen over the past decades in California. Additional analysis could contextualize this work even further. For instance, keyword or topical analysis of research projects funded in California from national databases, such as funding records from other federal research agencies, could be collected and compared to WRRA records to understand if WRRA-funded projects are similar to broader research priorities. Alternatively, keyword results could be compared to documented past research priorities gathered from expert judgement or historical strategic research plans.

Conclusions

Global and regional water resources management challenges are increasing in the 21st century. Freshwater resources that support human needs for cities, agriculture, and energy are increasingly overtaxed throughout the globe. In California, continued growth has led water management agencies to seek both supply and demand management solutions, driven or informed by knowledge gained through research and innovations. Using state-of-the-art NLP and machine learning models, the analysis demonstrated a method for using inductive thematic analysis to evaluate the focus of water-related research from projects based on keyword extraction and qualitative coding analysis, and evaluated changes over time in the focus of research projects funded by the WRRA and the State of California.

Results demonstrate how some themes, such as groundwater management, have remained consistent over time, while others, including aquatic ecosystems and species, have emerged more recently with recognition of environmental degradation. Some themes, such as water quality management and drought, reflect policy priorities that are influenced by climate factors or periods of interest in addressing environmental challenges. The analysis demonstrates a repeatable methodology for evaluating changes in research over time, which can be applied to program evaluation for research outcomes of the WRRA and other state and federal funding initiatives for water. California is a laboratory for water management innovations. State and federal support for research are important drivers of innovation. Research being developed by California's current early career academics will forge the water management solutions implemented in future decades.

Acknowledgements

The research was supported by the California Institute for Water Resources (CIWR). The database of project titles was compiled based on data of funded projects from CIWR and its predecessor organizations. University of California Agriculture and Natural Resources

Author Bio and Contact Information

Erik Porse is an interdisciplinary scientist with experience in urban and water resources management. He is Director of the California Institute for Water Resources and Associate Cooperative Extension Specialist in the Agriculture and Natural Resources department at the University of California Davis. Erik has degrees in civil and environmental engineering (water resources), public policy (science and technology), and mechanical engineering and music. In California, Erik has contributed to state and regional studies for safe drinking water, efficient urban water use, groundwater management, water reuse, stormwater planning, and environmental finance. Erik's professional experience includes international work and teaching in Mexico, Europe, Japan, and East Africa, and he has authored over 50 reports and peer-reviewed articles. He may be reached at eporse@ucanr.edu

References

Asano, T. 1987. Water quality management in California. *Water International* 12(3): 124-134. DOI: 10.1080/02508068708686602.

Aznar-Sánchez, J.A., J.F. Velasco-Muñoz, L.J. Belmonte-Ureña, and F. Manzano-Agugliaro. 2019. The worldwide research trends on water ecosystem services. *Ecological Indicators* 99: 310-323. DOI: 10.1016/j.ecolind.2018.12.045.

Bijl, D.L., H. Biemans, P.W. Bogaart, S.C. Dekker, J.C. Doelman, E. Stehfest, and D.P. Van Vuuren. 2018. A global analysis of future water deficit based on different allocation mechanisms. *Water Resources Research* 54(8): 5803-5824. DOI: 10.1029/2017WR021688.

Biswas, A.K. 2008. Integrated water resources management: Is it working? *International Journal of Water Resources Development* 24(1): 5-22. DOI: 10.1080/07900620701871718.

Bo, Y., F. Zhou, J. Zhao, J. Liu, J. Liu, P. Ciais, J. Chang, and L. Chen. 2021. Additional surface-water deficit to meet global universal water accessibility by 2030. *Journal of Cleaner Production* 320: 128829. DOI: 10.1016/j.jclepro.2021.128829.

Braun, V. and V. Clarke. 2006. Using thematic analysis in psychology. *Qualitative Research in Psychology* 3(2): 77-101. DOI: 10.1191/1478088706qp063oa.

Burges, S.J. 1986. Trends and directions in hydrology. *Water Resources Research* 22(9S): 1S-5S. Available at: http://dx.doi.org/10.1029/WR022i09Sp0001S. Accessed December 3, 2024.

Chen, X., H. Chen, L. Yang, W. Wei, and B.-J. Ni. 2022. A comprehensive analysis of evolution and underlying connections of water research themes in the 21st century. *Science of the Total Environment* 835: 155411. DOI: 10.1016/j.scitotenv.2022.155411.

Chowdhary, K.R. 2020. Natural language processing. In: *Fundamentals of Artificial Intelligence*. Springer India, New Delhi, pp. 603-649. DOI: 10.1007/978-81-322-3972-7_19.

Christ, T. 1970. A thematic analysis of the American business creed. *Social Forces* 49(2): 239-245. DOI: 10.2307/2576523.

Cosgrove, W.J. and D.P. Loucks. 2015. Water management: Current and future challenges and research directions. *Water Resources Research* 51(6): 4823-4839. DOI: 10.1002/2014WR016869.

Delfino, K. 2016. Moving water in a highly altered land: California's water infrastructure and environmental degradation. *Duke Environmental Law & Policy Forum* 26: 273-298. Available at: https://scholarship.law.duke.edu/delpf/vol26/iss2/3.

Accessed December 4, 2024.

Devlin, J., M.-W. Chang, K. Lee, and K. Toutanova. 2018. BERT: Pre-Training of deep bidirectional transformers for language understanding. *arXiv*: 1810.04805. DOI: 10.48550/ARXIV.1810.04805.

Durand, J., F. Bombardelli, W. Fleenor, Y. Henneberry, J. Herman, C. Jeffres, M. Leinfelder-Miles, et al. 2020. Drought and the Sacramento–San Joaquin Delta, 2012–2016: Environmental review and lessons. *San Francisco Estuary and Watershed Science* 18(2). DOI: 10.15447/sfews.2020v18iss2art2.

Gallego-Ayala, J. 2013. Trends in integrated water resources management research: A literature review. *Water Policy* 15(4): 628-647. DOI: 10.2166/wp.2013.149.

Giarelis, N., N. Kanakaris, and N. Karacapilidis. 2021. A comparative assessment of state-of-the-art methods for multilingual unsupervised keyphrase extraction. In: *Artificial Intelligence Applications and Innovations*, I. Maglogiannis, J. Macintyre, and L. Iliadis (Eds.). IFIP Advances in Information and Communication Technology, Springer International Publishing, Cham, Switzerland, pp. 635-645. DOI: 10.1007/978-3-030-79150-6_50.

Gleick, P. 2003. Global freshwater resources: Soft-path solutions for the 21st century. *Science* 302(5650): 1524-1528. DOI: 10.1126/science.1089967.

Gober, P., D.A. Sampson, R. Quay, D.D. White, and W.T.L. Chow. 2016. Urban adaptation to mega-drought: Anticipatory water modeling, policy, and planning for the urban southwest. *Sustainable Cities and Society* 27: 497-504. DOI: 10.1016/j.scs.2016.05.001.

Grootendorst, M. 2023. KeyBERT. GitHub. Available at: https://maartengr.github.io/KeyBERT/index.html. Accessed December 4, 2024.

Hawkins, C.P. 2015. The clean water rule: Defining the scope of the Clean Water Act. *Freshwater Science* 34(4): 1585-1587. DOI: 10.1086/684005.

Hume, N.B. 1970. Water quality control in California. *Journal of the Sanitary Engineering Division* 96(4): 873-884. DOI: 10.1061/JSEDAI.0001153.

Issa, B., M.B. Jasser, H.N. Chua, and M. Hamzah. 2023. A comparative study on embedding models for keyword extraction using KeyBERT method. In: *2023 IEEE 13th International Conference on System Engineering and Technology (ICSET)*. October 2, 2023, IEEE, Shah Alam, Malaysia, pp. 40-45. DOI: 10.1109/ICSET59111.2023.10295108.

Jasechko, S. and D. Perrone. 2021. Global groundwater wells at risk of running dry. *Science* 372(6540): 418-421. DOI: 10.1126/science.abc2755.

Jasechko, S., H. Seybold, D. Perrone, Y. Fan, and J.W. Kirchner. 2021. Widespread potential loss of streamflow into underlying aquifers across the USA. *Nature* 591(7850): 391-395. DOI: 10.1038/s41586-021-03311-x.

Jepson, W.E., A. Wutich, S.M. Colllins, G.O. Boateng, and S.L. Young. 2017. Progress in household water insecurity metrics: A cross-disciplinary approach. *WIREs Water* 4(3): e1214. DOI: 10.1002/wat2.1214.

Kiger, M.E. and L. Varpio. 2020. Thematic analysis of qualitative data: AMEE Guide No. 131. *Medical Teacher* 42(8): 846-854. DOI: 10.1080/0142159X.2020.1755030.

Lane, B.A., S. Sandoval-Solis, and E.C. Porse. 2015. Environmental flows in a human-dominated system: Integrated water management strategies for the Rio Grande/Bravo Basin. *River Research and Applications* 31(9): 1053-1065. DOI: 10.1002/rra.2804.

Lane, B.A., H.E. Dahlke, G.B. Pasternack, and S. Sandoval-Solis. 2017. Revealing the diversity of natural hydrologic regimes in California with relevance for environmental flows applications. *JAWRA Journal of the American Water Resources Association* 53(2): 411-430. DOI: 10.1111/1752-1688.12504.

Lund, J.R. 2006. Approaches to Planning Water Resources. University of California, Davis. Available at: https://cawaterlibrary.net/wp-content/uploads/2017/10/lund_water_resource_planning.pdf. Accessed December 4, 2024.

Lund, J.R., E. Hanak, W.E. Fleenor, W.A. Bennett, R.E. Howitt, J.F. Mount, and P.B. Moyle. 2010. *Comparing Futures for the Sacramento-San Joaquin Delta*. Freshwater Ecology Series, v. 3. University of California Press, Berkeley.

Lund, J.R., J. Medellin-Azuara, J. Durand, and K. Stone. 2018. Lessons from California's 2012-2016 drought. *Journal of Water Resources Planning and Management* 144(10): 04018067. DOI: 10.1061/(ASCE)WR.1943-5452.0000984.

Lv, T., L. Wang, H. Xie, X. Zhang, and Y. Zhang. 2021. Evolutionary overview of water resource management (1990–2019) based on a bibliometric analysis in Web of Science. *Ecological Informatics* 61: 101218. DOI: 10.1016/j.ecoinf.2021.101218.

Mahata, D., J. Kuriakose, R.R. Shah, and R. Zimmermann. 2018. Key2Vec: Automatic ranked keyphrase extraction from scientific articles using phrase embeddings. In: *Proceedings of the 2018 Conference of the North American Chapter of the Association for Computational Linguistics: Human Language Technologies, Volume 2 (Short Papers*). Association for Computational Linguistics, New Orleans, Louisiana, pp. 634-639. DOI: 10.18653/v1/N18-2100.

Medellín-Azuara, J., R.E. Howitt, and J.R. Lund. 2013. Modeling economic-engineering responses to drought: The California case. In: *Drought in Arid and Semi-Arid Regions: A Multi-Disciplinary and Cross-Country Perspective*, K. Schwabe, J. Albiac, J.D. Connor, R.M. Hassan, and L.M. González (Eds.). Springer Netherlands, Dordrecht, pp. 341-356. DOI: 10.1007/978-94-007-6636-5_19.

Meehan, K., W. Jepson, L.M. Harris, A. Wutich, M. Beresford, A. Fencl, J. London, et al. 2020. Exposing the myths of household water insecurity in the global north: A critical review. *WIREs Water* 7(6): e1486. DOI: 10.1002/wat2.1486.

Merhaut, D.J. 2003. Runoff water quality in California - Laws, regulations, and their implementation. *Acta Horticulturae* 627: 43-47. DOI: 10.17660/ActaHortic.2003.627.4.

Montanari, A., J. Bahr, G. Blöschl, X. Cai, D.S. Mackay, A.M. Michalak, H. Rajaram, and G. Sander. 2015. Fifty years of Water Resources Research: Legacy and perspectives for the science of hydrology. *Water Resources Research* 51(9): 6797-6803. DOI: 10.1002/2015WR017998.

Motoshita, M., S. Pfister, and M. Finkbeiner. 2020. Regional carrying capacities of freshwater consumption—Current pressure and its sources. *Environmental Science & Technology* 54(14): 9083-9094. DOI: 10.1021/acs.est.0c01544.

Null, S.E. 2016. Water supply reliability tradeoffs between removing reservoir storage and improving water conveyance in California. *JAWRA Journal of the American Water Resources Association* 52(2): 350-366. DOI: 10.1111/1752-1688.12391.

Page, G.W. and L. Susskind. 2007. Five important themes in the special issue on planning for water. *Journal of the American Planning Association* 73(2): 141-145. DOI: 10.1080/01944360708976147.

Phaler, K. 1971. Water quality control in California: Citizen participation in the administrative process. *Ecology Law Quarterly* 1(2): 400-426.

Poff, N.L., J.D. Allan, M.B. Bain, J.R. Karr, K.L. Prestegaard, B.D. Richter, R.E. Sparks, and J.C. Stromberg. 1997. The natural flow regime: A paradigm for river conservation and restoration. *BioScience* 47(11): 769-784. DOI: 10.2307/1313099.

Poff, N.L and J.K.H. Zimmerman. 2010. Ecological responses to altered flow regimes: A literature review to inform the science and management of environmental flows. *Freshwater Biology* 55(1): 194-205. DOI: 10.1111/j.1365-2427.2009.02272.x.

Rahman, M., J.M. Frame, J. Lin, and G.S. Nearing. 2022. Hydrology research articles are becoming more topically diverse. *Journal of Hydrology* 614: 128551. DOI: 10.1016/j.jhydrol.2022.128551.

Rahutomo, F., T. Kitasuka, and M. Aritsugi. 2012. Semantic cosine similarity. University of Seoul, South Korea. Available at: https://www.researchgate.net/profile/Faisal-Rahutomo/publication/262525676_Semantic_Cosine_Similarity/links/0a85e537ee3b675c1e000000/Semantic-Cosine-Similarity.pdf. Accessed December 4, 2024.

Rodell, M., J.S. Famiglietti, D.N. Wiese, J.T. Reager, H.K. Beaudoing, F.W. Landerer, and M.-H. Lo. 2018. Emerging trends in global freshwater availability. *Nature* 557(7707): 651-659. DOI: 10.1038/s41586-018-0123-1.

Saleth, R. and A. Dinar. 2000. Institutional changes in global water sector: Trends, patterns, and implications. *Water Policy* 2(3): 175-199. DOI: 10.1016/S1366-7017(00)00007-6.

Stein, E.D., J. Zimmerman, S.M. Yarnell, B. Stanford, B. Lane, K.T. Taniguchi-Quan, A. Obester, T.E. Grantham, R.A. Lusardi, and S. Sandoval-Solis. 2021. The California environmental flows framework: Meeting the challenges of developing a large-scale environmental flows program. *Frontiers in Environmental Science* 9: 769943. DOI: 10.3389/fenvs.2021.769943.

Sun, Y., H. Qiu, Y. Zheng, Z. Wang, and C. Zhang. 2020. SIFRank: A new baseline for unsupervised keyphrase extraction based on pre-trained language model. *IEEE Access* 8: 10896-10906. DOI: 10.1109/ACCESS.2020.2965087.

Swyngedouw, E. 1997. Power, nature, and the city. The conquest of water and the political ecology of urbanization in Guayaquil, Ecuador: 1880-1990. *Environment and Planning A: Economy and Space* 29(2): 311-332. DOI: 10.1068/a290311.

United Nations World Water Assessment Programme. (WWAP). 2015. *Facing the Challenges: Case Studies and Indicators*. UNESCO's Contribution to the United Nations World Water Development Report 2015, Paris, France. Available at: https://unesdoc.unesco.org/ark:/48223/pf0000232179. Accessed December 4, 2024.

Universities Council on Water Resources
Journal of Contemporary Water Research & Education
Issue 182, Pages 99-114, April 2025

The Regulatory Void of PFAS and Contaminated Sites

Irem Tekogul[1], *David Lampert[2], Farzad Mohammadi[2],
Amandeep Sandhu[3], and Matthew A. Shapiro[4]

*[1]Illinois Institute of Technology Institute of Design; [2]Illinois Institute of Technology Department of Civil, Architectural, and Environmental Engineering; [3]Illinois Institute of Technology Institute for Food Safety and Health, Illinois Institute of Technology Department of Food Science and Nutrition; [4]Illinois Institute of Technology Department of Social Sciences; *Corresponding author*

Abstract: Per- and polyfluoroalkyl substances (PFAS), often referred to as “forever chemicals,” are widely used due to their unique properties. The adverse health impacts of PFAS have been available for the last two decades, but the persistence of inadequate and poorly enforced regulations has led to pervasive environmental contamination. Recent regulatory changes by the U.S. Environmental Protection Agency address PFAS in drinking water under the Safe Drinking Water Act and address PFAS in contaminated sites under the Comprehensive Environmental Response, Compensation, and Liability Act. However, regulatory gaps persist, particularly regarding acceptable risks from sites contaminated with thousands of PFAS. This paper contextualizes PFAS contamination as a “wicked problem,” a multifaceted challenge with no straightforward or obvious solution. In the context of PFAS, we explore failures in current regulatory frameworks and identify strategies for addressing these shortcomings. Based on interviews with experts and our own policy analysis, we conclude that there is an implicit need for policies that account for the diverse and interconnected pathways of PFAS contamination, including groundwater, soil, and food products. A holistic approach to PFAS regulation must emphasize the importance of federal leadership, accountability, and robust research and innovation. This will mitigate the long-term risks to human health and the environment by allowing policymakers to develop more inclusive strategies for remediation and prevention.

Keywords: *PFAS, forever chemicals, policy failure, wicked problems, water pollution, Superfund sites*

PFAS, or per- and polyfluoroalkyl substances, have emerged as a critical environmental and public health challenge. Known as “forever chemicals” due to their extreme persistence in the environment, PFAS contaminate water, soil, and, ultimately, humans. PFAS are a class of thousands of synthetic organic chemicals that have been widely used in industrial and commercial products due to their unique physical and chemical characteristics (OECD 2013; ATSDR 2021). Despite their benefits, PFAS contamination has emerged as a complex, multifaceted challenge due to their persistence, bioaccumulative potential, and widespread exposure in the environment. Due to these unique characteristics, PFAS contamination could pose significant health risks for both present and future generations. Some PFAS are known to be carcinogenic and have been linked to a wide range of diseases such as liver dysfunction and immune system disorders (Lau et al. 2007; Kirk et al. 2018; Fenton et al. 2020). Moreover, PFAS contamination may disproportionately affect low-income communities and communities of color, rendering them more vulnerable to the health impacts of PFAS exposure (Johnston and Cushing 2020), further exacerbating environmental justice issues (Liddie et al. 2023; Watson 2024).

In this context, we classify PFAS regulation as a *wicked problem*, a concept introduced by Rittel and Webber (1973) to describe policy-making issues that are deeply complex, resist definitive solutions, and involve competing stakeholder interests. Unlike “tame” problems, which can be solved through straightforward technical or policy

Research Implications

- The regulatory failures of PFAS are directly related to its complex fate and transport pathways, including various environment-to-human bioaccumulation routes.
- 2. While PFAS contamination in drinking water is a recognized concern, PFAS in soils and sediments are relatively unregulated.
- 3. PFAS policies must anticipate and counter loopholes arising from the substitution of regulated PFAS compounds with one of many unregulated PFAS compounds.
- 4. PFAS contamination disproportionately impacts socio-economically disadvantaged populations.

measures, wicked problems require navigating uncertainty and balancing competing interests, creating a host of problems for policymakers (Head 2022). The extant literature acknowledges that PFAS-related policymaking is challenged by the fact that PFAS defies straightforward problem-solving approaches due to health and environmental complexities (Banwell et al. 2019). At the same time, apart from research on PFAS-laden wastewater sludge (Moavenzadeh Ghaznavi et al. 2023) and agricultural fields (Renella et al. 2025), virtually no other research has employed this frame when discussing PFAS.

The regulation of PFAS exemplifies many characteristics of wicked problems: their widespread contamination impacts multiple sectors and geographies, creating interdependencies that challenge regulatory boundaries; their technical complexity and incomplete knowledge complicate detection, monitoring, remediation, and regulation; and the conflicting priorities of industries, policymakers, and communities result in tension over solutions. Given that PFAS contamination is an ongoing and persistent problem, our use of wicked problem-related framing around PFAS is critical to explain how traditional regulatory approaches have been deficient, particularly in the United States. We engage in a policy analysis and conduct interviews with PFAS-related experts to justify the need for policies accounting for the diverse and interconnected pathways of PFAS contamination, including groundwater, soil, and food products.

PFAS Overview

Legacy PFAS have the basic structure shown in Figure 1a, consisting of a chain of carbon atoms bonded to fluorine atoms and a polar head group; however, newer substitutes have been synthesized to replace these compounds (i.e., GenX), the structure of which is presented in Figure 1b. PFAS in which all hydrogen-carbon bonds are replaced with fluorine-carbon bonds are known as perfluoroalkylated compounds, while compounds that retain some carbon-hydrogen bonds are referred to as polyfluoroalkylated (Atoufi and Lampert 2023). The carbon-fluorine segment of these compounds (sometimes referred to as “the tail”) exhibits both hydrophobic and oleophobic properties, meaning that it repels both water and fats. Conversely, the reactive hydrophilic segment at the other end of the molecule (also known as the head), typically consists of a carboxylic acid, a sulfonic acid, a phosphonic acid, or a methyl functional group. This unique combination of water-repellent and oil-repellent properties, along with a reactive head group, makes PFAS highly effective as surfactants and dispersants. As such, PFAS have been used in firefighting foams, carpets, textiles, chrome plating, semiconductor manufacturing, food packaging coatings, cleaning products, and biocides (ATSDR 2021).

PFAS fate and transport are influenced by their physicochemical properties, including hydrophobic and oleophobic characteristics, as well as the presence of reactive functional groups. Due to their persistence, PFAS remain intact through various environmental pathways, making them both mobile and bioaccumulative. Once released into the environment, PFAS migrate through various pathways, detailed in Figure 2:

- Groundwater Contamination: PFAS leach from contaminated sites, such as landfills, industrial facilities, and fire training areas, into aquifers. Their solubility allows them to form extensive contamination plumes that spread over kilometers, threatening drinking water supplies.
- Soil and Sediment Mobility: PFAS bind

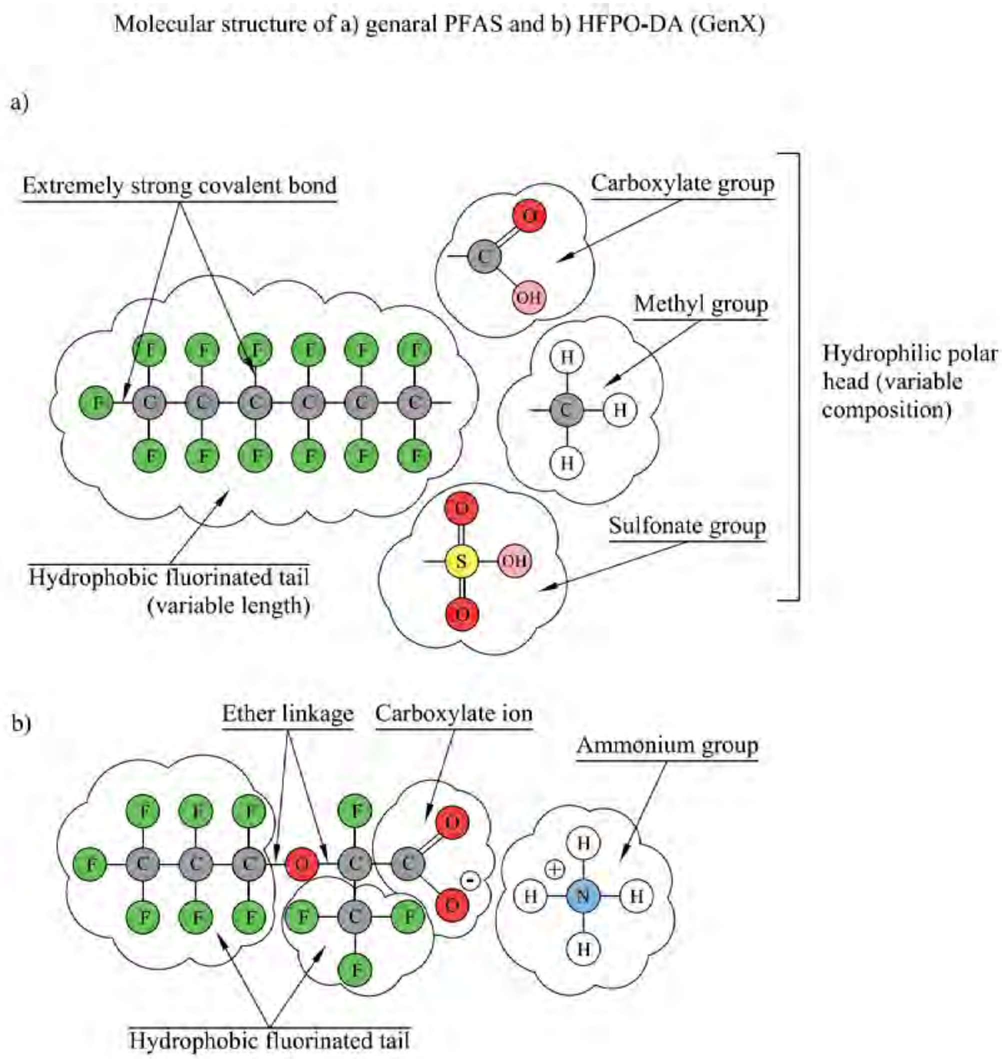


Figure 1. General molecular structure of PFAS

variably to soils and sediments depending on chain length and functional groups. Short-chain PFAS are more mobile, often migrating to groundwater, while long-chain PFAS tend to sorb to organic matter.

- Atmospheric Deposition: Certain PFAS volatilize and disperse through the atmosphere before depositing onto land or water, further contributing to contamination.
- Bioaccumulation: PFAS accumulate in living organisms due to their resistance to metabolic breakdown and reactive functional groups, entering food chains and amplifying the risks of human and ecological exposure.

The intricate interplay of these pathways underscores the challenge we face when attempting to mitigate PFAS contamination, and effective regulatory strategies must account for these diverse and interconnected processes to address the full scope of environmental and public health risks. Furthermore, the wide variety of PFAS allow for ready substitution of similar compounds, making regulations complex.

The Regulatory Void of PFAS

PFAS chemicals have been manufactured and used for decades. At the federal level in the U.S., the regulatory response has been slow to respond

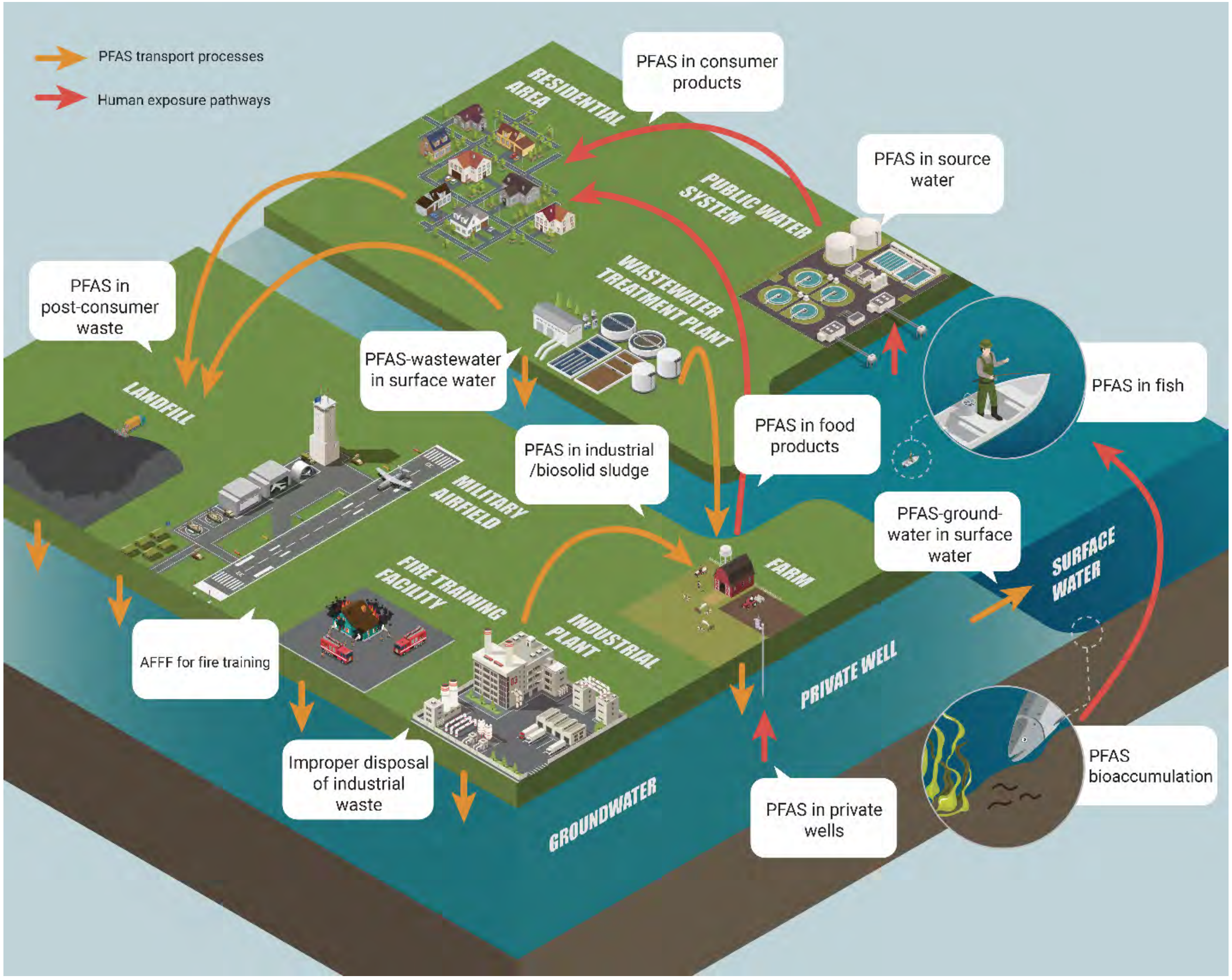


Figure 2. Fate and transport pathways of PFAS

to PFAS (Renfrew and Pearson 2021). While some producers of PFAS have known for years about the potential of certain PFAS to bioaccumulate and negatively impact human and environmental health (Bilott 2020), regulatory inaction, fragmented and underenforced regulations have exacerbated widespread PFAS contamination. Institutionalized ignorance refers to the systematic suppression, omission, or distortion of knowledge within governance systems, often manifesting in scientific and regulatory domains where such gaps are not incidental but shaped by historical, political, and organizational dynamics, and reinforced through mechanisms such as weak regulations, selective research agendas, and entrenched institutional norms (Paul et al. 2022). In the context of PFAS, Richter et al. (2021) argue that institutionalized ignorance has played a role in creating regulatory gaps through the deliberate production, maintenance, and dissemination of uncertainty or lack of knowledge about these chemicals by certain stakeholders, typically those with vested interests. Also contributing to the absence of effective regulatory structures is the suppression of scientific research, the dissemination of misleading information, and lobbying efforts from the private sector (Schwartz 2022). The lack of effective enforcement mechanisms exacerbates environmental injustice and threatens human and environmental health, among a host of other costs (Goldenman et al. 2019; Newell et al. 2020; Cordner et al. 2021).

The U.S. has several regulatory frameworks to protect human health and the environment from chemical contaminants, including the Toxic Substances Control Act, the Safe Drinking Water

Act (SDWA), the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA), and the Resource Conservation and Recovery Act. The SDWA safeguards drinking water in the U.S. by authorizing the Environmental Protection Agency (EPA) to set enforceable National Primary Drinking Water Regulations (NPDWRs) for pollutants, ensuring that public water systems meet health-based standards[1]. CERCLA, or "Superfund," was enacted to address the cleanup of hazardous waste sites. CERCLA gives the EPA the authority to designate chemicals as hazardous substances, thus subjecting them to strict reporting, liability, and remediation requirements. CERCLA primarily addresses legacy contamination and is not a preventive framework, leaving regulatory gaps for ongoing and emerging pollutants.

Recent PFAS regulations have been narrowly focused on specific pathways, and drinking water under SDWA has received relatively more regulatory attention over the past few years compared with PFAS in contaminated sites. Granted, the regulatory focus on PFAS in drinking water has been justified given that water consumption is one of the most significant human exposure pathways for PFAS, particularly for those living near contaminated sites (Hu et al. 2016; Domingo and Nadal 2019). Regarding CERCLA-related updates, the EPA designated two PFAS – PFOA and PFOS – as hazardous chemicals in April 2024 (US EPA 2024b), allowing the EPA "to address more contaminated sites, take earlier action, and expedite cleanups, all while ensuring polluters pay for the costs to clean up pollution threatening the health of communities" (US EPA 2024b)[2].

1 In April 2024, the EPA updated the NPDWR to establish legally enforceable maximum contaminant levels for six different PFAS: PFOA, PFOS, PFHxS, PFNA, HFPO-DA (commonly known as GenX), two or more of PFHxS, PFNA, HFPO-DA, and PFBS (US EPA 2024b).

2 We must note that PFOA had already been voluntarily phased out by eight major PFAS manufacturers under the US EPA 2010/2015 PFOA Stewardship Program, and the last time PFOS was manufactured or imported into the US was in 2006 (US EPA 2024a). Thus, PFOA and PFOS are examples of "legacy PFAS," i.e., persistent PFAS chemicals released into the environment years ago but still hazardous today.

Specific requirements for PFAS at contaminated sites are lacking, as thousands of other types of PFAS besides PFOA and PFOS remain totally unregulated. Leachates from contaminated sites at military airbases, industrial plants, and landfills – all of which contaminate groundwater – affect aquatic wildlife, contribute to bioaccumulation of PFAS, and increase human exposure through ingestion of food products and water (Miranda et al. 2023). Although PFAS contamination is a health risk to a large portion of the population, public awareness of PFAS in the U.S. had been negligible before the EPA's 2024 regulatory updates. A 2023 study found that almost half the respondents to a nation-wide survey had never heard of PFAS and did not know what it was (Berthold et al. 2023). Post-2024, the public has been increasingly exposed to reports on how scientific evidence of PFAS's toxicity was suppressed by 3M to obfuscate the risks to human health (Lerner 2024), as well as whistleblowers' first-hand accounts and complaints about the suppression of scientific evidence by manufacturers of PFAS (Hassanzadeh 2024).

In the absence of clear and robust federal standards and regulations, individual states have taken steps to regulate PFAS. Especially after EPA released its Lifetime Health Advisory Limits for PFOS and PFOA in 2016, the number of US states enacting policies to limit PFAS pollution and reduce consumer exposure has rapidly grown (Brennan et al. 2021). A survey by the Environmental Council of States confirms that there are 29 states with established guidelines for at least one PFAS in at least one environmental medium (Hughes 2024). For example, California's AB 756, the "Safe Drinking Water and Toxic Enforcement Act of 1986," was amended to include PFAS chemicals. This bill authorized the state board to order a public water system to monitor for PFAS. Elsewhere, Virginia (HB1257 2020), Maine (SB64 2021), New Hampshire (HB271 2021), and Delaware (HB 8 2021) have set interim maximum contaminant levels, while other state-based regulations have attempted to address PFAS in firefighting foam, the treatment of PFAS-contaminated water, and the amount of PFAS in consumer good packaging (National Conference of State Legislatures 2025). More recent state-level actions have addressed PFAS-contaminated sludge, such as Maine's ban on using industrial sludge for farming applications (Perkins 2022).

We acknowledge the *EPA's PFAS Strategic Roadmap for 2021-2024*, which focuses on upstream sources of PFAS and holding polluters and other responsible parties accountable for PFAS remediation (US EPA 2021). The *Roadmap*, however, must be accompanied by corresponding levels of federal guidance for PFAS cleanup and remediation. The designation of PFAS as hazardous substances opens the door to the regulation of PFAS-contaminated areas via CERCLA. Decision-making for PFAS cleanup and remediation of contaminated sites can be initiated when EPA-published Regional Screening Levels and Regional Remedial Management Levels are exceeded at a site. In May 2022, for example, the EPA added risk-based values for site cleanups for five PFAS: PFOA, PFOS, HFPO-DA, PFHxS and PFNA. While appearing on Regional Screening Levels and Regional Remedial Management Levels, the *Roadmap* does not offer cleanup standards but merely generic screening values (US EPA 2022). In addition, recent PFAS regulations focused on individual compounds leave a loophole for substitution of new compounds with similar properties, likely including similar environmental and bioaccumulation pathways that could result in no reduction, or potential increases in risk.

The Challenge of PFAS-Contaminated Sites

PFAS contamination is pervasive, as at least one PFAS can be detected in nearly half of US drinking-water samples (Smalling et al. 2023). As well, PFAS have been detected in groundwater-sourced drinking water at more than twice the frequency compared to drinking water sourced from surface water (Hu et al. 2016). Given that groundwater is the main source of fresh water for 155 million Americans (USGS 2019), PFAS contamination in groundwater poses a direct threat to drinking water wells near sources of contamination (Sadia et al. 2023). PFAS contamination of groundwater also poses risks to surface water resources in areas with significant baseflow. Natural biogeochemical processes at interfaces between groundwater and surface water affect PFAS evolution from precursors and create seasonal variations in PFAS levels in lakes (Tokranov et al. 2021). As well, PFAS can travel miles from groundwater sources to surface water, leading to bioaccumulation in fish (McFarlan and Lemke 2024).

There is a clear challenge when addressing PFAS contamination across interconnected environmental media, and the EPA has identified at least 180 Superfund sites that are contaminated with PFAS across the nation, although this number will undoubtedly rise (U.S. Senate Committee on Environment & Public Works 2024). In light of the scale and complexity of these contaminated sites, we acknowledge that even partially remediating contaminated sites is not only difficult and time-consuming, but it is often prohibitively expensive (Brunn et al. 2023). Focusing on "upstream" contributors may help curb PFAS contamination, but there are additional economic challenges for various stakeholders, particularly water and wastewater utilities (Cordner et al. 2021). The EPA estimates the annual cost of compliance with NPDWR to be $1.5 billion, although a cost model developed by the American Water Works Association (AWWA) projects that actual costs could range between $2.6 billion and $3.8 billion per year (Adams et al. 2023; AWWA 2024). The U.S. Chamber of Commerce (USCOC) estimates a cost of $17.4 billion for existing non-federal national priority sites (USCOC 2022). In short, the inclusion of PFAS in CERCLA legislation may enable the EPA to enforce cleanup, but the practicality of enforcement is thwarted by technical issues and economic costs.

Regulatory measures must integrate all stages of contamination, spanning from upstream sources to downstream impacts. The aforementioned regulations focusing on six PFAS-class chemicals in drinking water and two specific ones (PFOA and PFOS) in contaminated sites are focused on drinking water-related targets. Regulations must attend to other critical aspects of PFAS contamination across fate and transport pathways, particularly contamination in the soil, as soil-to-groundwater PFAS can lead to contamination plumes several kilometers long due to their mobility (Evich et al. 2022). Regulations that highlight the connections between soil and groundwater would acknowledge that soil concentrations of PFAS in contaminated sites are orders-of-magnitude greater than typical groundwater concentrations (Brusseau et al. 2020). With at least 8,865 industrial and municipal sites known to produce or use PFAS (EWG 2024), we group the types of contaminated sites presented in Figure 2 under the following four categories:

1. **Military bases, civilian airports, and fire training facilities:** These sites are sources for PFAS contamination due to the use of PFAS-containing aqueous film-forming foam (AFFF). Large amounts of PFAS are discharged into the environment and the soil through the application of AFFF for training purposes or extinguishing fuel-based fires. Indeed, military bases have some of the highest PFAS levels anywhere in the country. For example, PFAS levels at Langley Air Force Base exceeded 2 mg/L (Hayes 2021). Even after the cessation of AFFF use, PFAS persist in the soil and groundwater. Moody et al. (2003) found significant concentrations of PFAS in groundwater at the Wurtsmith Air Force Base in Northeastern Michigan, at least five years after active firefighting had stopped. Groundwater samples contained PFOS, PFHxS, PFOA, and PFHxA, with PFOS concentrations reaching 110 µg/L and PFHxS up to 120 µg/L (Moody et al. 2003), exceeding the EPA advisory of 70 µg/L.
2. **Industrial plants and defunct sites:** Textile, electroplating, semiconductor, paper, and chemical industries are just a handful of the industries known to use PFAS in their manufacturing processes. More than 200 use categories across industry branches and consumer products are identified for 1,400 PFAS (Glüge et al. 2020). Discharges and releases from these manufacturing plants lead to PFAS contamination. Schroeder et al. (2021) found that PFAS emissions from manufacturing plants in Southwest Vermont and Eastern New York State contaminated groundwater and soil over a 200 km² area, demonstrating the widespread environmental impact of industrial PFAS discharges.
3. **Agricultural fields used for PFAS-containing sludge application:** Large-scale contamination of PFAS in agricultural fields is caused by PFAS-contaminated biosolid or industrial sludge applications as fertilizer. As biosolid and industrial sludge applications are common practice, many potential agricultural fields are contaminated with PFAS. One investigation of PFAS concentration at a site in the Western US following a historic biosolid application found that measured soil concentrations were 1 to 2 orders of magnitude higher than PFAS levels in global background soils (Johnson 2022).
4. **Landfills:** When industrial and consumer waste containing PFAS ends up in landfills, site contamination can occurs through leaky liners. PFAS have been widely detected in historic and active landfills (Propp et al. 2021). Furthermore, at municipal solid landfills, PFOA and PFOS have been reported at concentrations of up to, respectively, 1000’s ng/L and 100’s ng/L in the leachate (Solo-Gabriele et al. 2020).

A regulatory framework discounting even one of these four categories would be unlikely to achieve even marginal successes in mitigating PFAS production, use, and remediation. We are thus faced with the challenge of assessing why PFAS-related regulations are no more than, and are quite likely to remain for the foreseeable future, singular and piecemeal.

Methods

To investigate the causes and conditions contributing to the inertia surrounding PFAS-related regulations, we conducted interviews with experts, each of which lasted approximately 30–40 minutes. Expert interviews are a widely recognized method in social and environmental research, offering critical insights from knowledgeable informants, especially when examining complex policy dynamics (Meuser and Nagel 2009).

A snowball sampling approach was employed to identify and recruit participants. This method, which relies on referrals from initial contacts, was chosen to ensure access to a network of individuals with specialized knowledge and diverse perspectives on PFAS management. Snowball sampling is particularly effective in research addressing complex and specialized topics, where expert informants are often interconnected within professional or regulatory communities. In total, our snowball sampling approach yielded eight experts with expertise in PFAS management, environmental regulation, and policy implementation. Detailed in Table 1, these eight individuals possessed high levels of knowledge, and their insights were instrumental in framing the ongoing challenges of PFAS cleanup within the context of regulatory inefficiencies and knowledge gaps.

The interviews were designed to assess expert understanding of PFAS-related challenges, with a specific focus on regulatory frameworks for cleanup and remediation. The interview protocol included questions to explore the following: participants' perceptions of gaps and inefficiencies in PFAS regulatory frameworks; challenges to implementing effective cleanup and remediation strategies; and institutional barriers, including limited knowledge dissemination, competing policy priorities, and inertia in regulatory adaptation. Semi-structured interviews were employed to allow for flexibility when exploring emergent themes during the discussion (Adeoye-Olatunde and Olenik 2021). This approach is particularly well-suited for investigating multifaceted regulatory and policy environments, such as those governing PFAS management, where systemic barriers, institutional inertia, and scientific complexities intersect.

The interview data were analyzed using NVivo content analysis software, facilitating systematic coding and theme identification. An open coding approach was employed, allowing for the development of categories and themes directly from the data (Strauss and Corbin 1998). Open coding is suitable for exploratory studies given its flexibility to uncover patterns and relationships without imposing pre-existing frameworks. This method enabled the identification of recurring themes related to PFAS.

Results

Our analysis of the key informant interviews revealed several themes regarding regulatory failures, presented in Table 2. These themes align with broader concepts of institutionalized ignorance and offer a lens to understand the systemic challenges in addressing PFAS-related issues, such as inadequate enforcement mechanisms, conflicting stakeholder priorities, and challenges in incorporating emerging scientific evidence into policymaking. We consider each problem area and their corresponding challenges in turn.

Policymaking Challenges and Drivers

Federal Vacuum and State Leadership. Interviewees acknowledged the vacuum of federal leadership when it comes to regulating PFAS, in contrast to regulations for other toxic chemicals. In that vacuum, states have stepped up, functioning

Table 1. Interview participants

Participant	Domain	Focus Area
P1	State Environmental Agency	Remediation
P2	Academia - Assoc. Professor	Environmental Engineering
P3	Academia - Assoc. Professor	Environmental Sociology
P4	Academia - Asst. Professor	Environmental Engineering
P5	National Coalition	Consultant - Technical Assistance to community groups
P6	Academia - Assoc. Professor	Environmental Engineering
P7	Academia - Assoc. Professor	Economics
P8	Community Activist	PFAS organizing

Table 2. Regulatory failure-based themes

Problem Area	Specific Challenges
Policy-making challenges and drivers	• Federal vacuum and state leadership • Industry pushback • Public awareness and community activism
PFAS-related challenges	• Feasibility and viability concerns • Classification problems
Burden of cleanup and remediation	• Accountability and responsibility

as the frontier of PFAS regulations According to one interviewee: "lack of federal attention has led states to fill in the gaps." The federal government has been slow to act, and states, especially those that have high concentrations of PFAS in their soil and water, have made significant headway in regulating PFAS (Boden 2020). As some interviewees also pointed out, state leadership is also influenced by increasing levels of public awareness. Some interviewees also argued that the EPA is highly politicized, and that the timeline and scope of PFAS-related regulations are subject to EPA administrators and the whims of the executive branch of the federal government. With regard to the cleanup of PFAS, interviewees referred to the lack of federal guidelines, with one interviewee stating that individual states often look to other states' actions for best practices for cleanup due to a lack of federal guidelines.

Industry Pushback. Interviewees noted how the lobbying efforts of chemical manufacturers and other stakeholders have a clear effect on regulatory decisions. Specifically, regulatory efforts were slowed down due to pushback from industries that use or produce PFAS. Research by Food & Water Watch (2023) finds that federal lobbying disclosures mentioning "PFAS" by eight major PFAS-producing companies totaled $55.7 million, while those by the American Chemistry Council totaled $58.7 million These findings suggest that industry influence may have extended to key policymaking bodies, potentially contributing to the stalling or shutdown of comprehensive PFAS legislation (Food & Water Watch 2023). It should also be noted that, while PFAS-related regulations would likely negatively impact certain industries' revenue stream, a number of other industries have been proactive. One interviewee pointed out that the semiconductor industry, for example, anticipates future regulations and is thus phasing out certain PFAS while developing less harmful replacements. To this point, the World Semiconductor Council (2024) announced that the semiconductor industry has successfully completed the phase-out of intentional uses of PFOA globally. However, substituting PFAS with PFAS-free alternatives is expected to be time-consuming and complicated, taking decades years to research, identify, and implement for the semiconductor industry, with no guarantee of success (Trywhitt Jones 2023; Isaacs 2025).

Public Awareness and Community Activism. Participants agreed that public awareness and community activism applies pressure on state legislators and helps inform state and federal regulations on PFAS. One interviewee involved with community activism stated that the "environmental groups have been fighting for 20 years to get PFOA and PFOS drinking water standards," and claimed that increasing public awareness and engagement have been critical for pushing regulations forward. According to this interviewee, increased access to the internet has made society more knowledgeable and organized but also led to a decline in trust regarding the narratives put forth by the government. The interviewee explained that when "the community groups come online and start collectively organizing, it became impossible for the government to ignore the problem." According to another interviewee, funding streams for PFAS through the National Defense Authorization Act have "been the result of advocacy by legislators in states where they have community groups and impacted residents pressuring them to take action on PFAS." Federal facilities, including military installations where PFAS has been released, must track and collect data on PFAS. Where PFAS levels exceed risk-based values, defense appropriations such as the Defense Environmental Restoration Program can be used to finance remediation. Many well-publicized lawsuits, additional research on PFAS, and grassroots activism have all contributed to increasing public awareness and driving policies. Through a comparative study of two communities impacted by PFAS contamination Garrett et al. (2024) demonstrate that community engagement activism could have significant impact on medical guidelines and state regulations.

PFAS-Related Challenges

Feasibility and Viability Concerns. PFAS in drinking water is viewed by interviewees as a primary concern given its clear, direct health impacts. It also receives more attention as this pathway is better understood given that drinking water is easier to sample, test, and treat. Monitoring and analyzing PFAS in soil matrices are very costly and difficult, and a lack of solid health data and risk assessment is part of the reason for such complexities. One interviewee stated that "the regulations need solid health data, like health impact data and toxicity data to make them an informed decision on regulatory limits. That's lacking for a large group of PFAS because the primary focus has been on just PFOA and PFOS and not a few selected PFAS." Furthermore, interviewees explained that the limitations of current analytical methods play a role in delaying regulatory action. While analytical methods have advanced recently, enabling more frequent detection, such tools are limited to just a few dozen different PFAS (Al Amin et al. 2020). There are thousands currently in existence in the global market.

Additionally, remediation and cleanup of contaminated soils is subject to technical and economic challenges, and existing and affordable technology is seen as the best option. Furthermore, even implementing existing technologies would be very costly and lead to unintended consequences. For example, as one interviewee pointed out, incineration of PFAS could cause it to be emitted into the air, as the incineration of PFAS-containing waste has the potential to release fluorinated greenhouse gases and byproducts from incomplete combustion (Stoiber et al. 2020).

Classification Problems. Differing approaches to designating PFAS represent a significant challenge for the development of PFAS regulations. Interviewees explained that while some scientists advocate for regulating PFAS as a chemical class, industry has responded by pushing for the designation of individual compounds as hazardous substances. One interviewee pointed out that there are additional challenges in treating PFAS as a chemical class, such as differing definitions. She stated that based on some definitions, there are around 14,000 PFAS, but it could be as many as 1 million if by-products are also classified as PFAS. The EPA's CompTox Dashboard, last updated in 2022, currently lists 14,735 compounds. In contrast, under the OECD's 2021 definition of PFAS, recent studies have suggested the total number could range from 6 to 7 million compounds(Gaines et al. 2023; Schymanski et al. 2023). By-products of incomplete PFAS destruction pose a significant challenge, as there are currently no proven analytical methods to detect all fluoro-organic by-products (Horst et al. 2020). Another interviewee argued that certain stakeholder groups push for regulating all PFAS, but that may not be technically practicable due to the breadth of PFAS and the technical difficulties of testing and conducting a risk assessment for all compounds. However, recent scholarship provides a scientific basis for a class-based approach to PFAS regulations (Kwiatkowski et al. 2020), providing an option for treating PFAS as its own chemical class.

Burden of Cleanup and Remediation

Accountability and Responsibility. Agricultural use of wastewater sludge emerged as a significant area of concern among the interviewees. In such cases, determining accountability and responsibility has proven challenging, especially considering how long PFAS stays unchanged in the environment. One interviewee explained that "the people who own those farms now are not the people who made the decision back in the 1980s to spread this sludge … No one knew that there was PFAS." There could also be unintended consequences of new regulations, as more restrictive maximum contaminant levels would drive costs higher and place the burden of water treatment on utilities and end users. Another interviewee pointed out that "[p] eople already struggle to pay for their water bill, so this is going to create new social justice problems." This further complicates the issues related to accountability and responsibility, considering the high costs of treatment, cleanup and remediation. In recent years, there has been a flurry of lawsuits by public utilities against manufacturers of PFAS and settlements which ordered manufacturers to pay billions of dollars to utilities (3M 2023; Chemours 2023).

Conclusion

A central assumption for this paper has been the fact that PFAS contamination exemplifies one of Rittel and Webber's (1973) "wicked problems," and we have subsequently discovered that the regulatory void in managing PFAS contamination can be attributed to several factors:

1. Delayed recognition and response: Institutionalized ignorance and the suppression of scientific evidence delayed the recognition of PFAS as a significant health risk, resulting in decades of unregulated PFAS use and widespread environmental contamination.
2. Fragmented regulations: The lack of a comprehensive federal framework has led to a fragmented regulatory landscape, with states taking varied approaches to PFAS management. This inconsistency complicates enforcement and compliance.
3. Technical and economic challenges: The technical challenges of detecting, treating, and remediating PFAS, combined with high economic costs, hinder effective management. These challenges necessitate the development of advanced technologies and sustainable funding mechanisms.
4. Industry influence: Industry pushback and lobbying have slowed regulatory progress. Thus, effective regulation must prioritize public health and environmental protection over corporate interests.
5. Lack of public awareness: Communities frequently remain unaware of PFAS and its associated health risks, often discovering the dangers only after exposure to PFAS contamination.

Current and future PFAS regulations will have widespread impacts across several domains, particularly when drinking water is treatment is significantly changed, PFAS-free alternatives for agriculture are available, and consumer goods are widely available in PFAS-free form. In light of several interviewees highlighting how PFAS-related regulations will transform the economy over the next ten years, we must be cautious when considering technical feasibility and economic costs. That is, regulations cannot be prohibitively expensive when the marginal benefits of PFAS reduction are negligible, nor can they be delayed given the significant environmental and public health consequences. Recent regulatory efforts by the EPA indicate slight forward movement nationally, but there remains a regulatory void regarding effective and practical frameworks for PFAS management. Specifically, policies must focus on developing additional national standards, holding polluters accountable, investing in research and innovation to address technical feasibility issues, and engaging the public to counter the effects of institutionalized ignorance. Finally, regulating large collections of PFAS as a class would provide a precautionary approach to account for poorly understood bioaccumulation risks arising from substitutions of new PFAS in traditional applications. Only through such holistic and systemic approaches can we mitigate the risks posed by PFAS and protect future generations and the environment.

Acknowledgments

This publication was developed under Assistance Agreement SV-84042101 awarded by the U.S. EPA, grant 2022_IL_Lampert awarded by USGS through the Water Resources Research Act Program, and grant NA24OARX417C0031-T1-01 awarded by NOAA. It has not been formally reviewed by EPA, USGS, or NOAA. The views expressed in this document are solely those of the authors and do not necessarily reflect those of these agencies. EPA and USGS do not endorse any products or commercial services mentioned in this publication.

Author Bio and Contact Information

Irem Tekogul is a Ph.D. candidate at the Institute of Design at Illinois Institute of Technology. Her research focuses on the intersection of design futures, systemic design and wicked problems in policy making. She is the recipient of Foreign Fulbright Doctoral Scholarship. She earned an M.A. in Product design at NABA Milano and a B.Sc. in Industrial Product Design at Istanbul Technical University. She can be contacted at: Institute of Design, Illinois Institute of Technology, 3137 S Federal St, Chicago, IL 60616, itekogul@id.iit.edu.

Dr. David Lampert is an Associate Professor in the Department of Civil, Architectural, and Environmental Engineering at the Illinois Institute of Technology. His research focuses on water quantity and water quality issues, including PFAS contamination. He can be contacted at: Department of Civil, Architectural, and Environmental Engineering, Illinois Institute of Technology, Alumni Memorial Hall, Room 230, Chicago, IL 60616, (312) 567-3544, dlampert1@iit.edu.

Farzad Mohammadi is a PhD student in environmental engineering at the Illinois Institute of Technology researching the fate and transport of PFAS in complex environments. Address: Department of Civil, Architectural, and Environmental Engineering, Illinois Institute of Technology, Alumni Memorial Hall, Room 230, Chicago, IL 60616, (312) 567-3544, fmohammadi@hawk.iit.edu.

Dr. Amandeep Sandhu is an Associate Professor at the Department of Food Science and Nutrition at the Illinois Institute of Technology. Her research is focused on the identification of plant-derived chemical compounds from various fruits and vegetables and the characterization of PFAS in the environment. This work is done using analytical chemistry techniques such as high-performance liquid chromatography and mass spectrometry to identify/quantify. She can be contacted at: Institute for Food Safety and Health, Illinois Institute of Technology, 6502 S. Archer Rd., Bedford Park, IL 60501, (708) 563-8823, asandhu2@iit.edu.

Dr. Matthew A. Shapiro is a professor of political science at the Illinois Institute of Technology. He was trained in political science, economics, and public policy at the University of California at San Diego (B.A.) and the University of Southern California (M.A. & Ph.D), and he earned an M.A. in Korean Studies at Yonsei University's Graduate School of International Studies in Seoul. He can be reached at: Department of Social Sciences, Siegel Hall 116C, Illinois Institute of Technology, 3301 S Dearborn St, Chicago, IL 60616, shapiro@iit.edu.

References

3M. 2023. 3M Resolves Claims by Public Water Suppliers, Supports Drinking Water Solutions for Vast Majority of Americans. 3M News Center. Available at: https://news.3m.com/2023-06-22-3M-Resolves-Claims-by-Public-Water-Suppliers,-Supports-Drinking-Water-Solutions-for-Vast-Majority-of-Americans. Accessed June 22, 2023.

Adams, L., M. Borchers, A. Bui, A. Canida, J. Cornell, Z. Erdal, A. Feffer, et al. 2023. *2023 Water Report*. Black & Veatch. Available at: https://assets.ctfassets.net/6aztiy11c9mv/b8vrPS0zpb9TpTDvKfbzT/44b212aa4e8a81356d67fd039cab0c42/23_SDR_WaterReport_Final__1_.pdf. Accessed April 16, 2025.

Adeoye-Olatunde, O.A. and N.L. Olenik. 2021. Research and scholarly methods: Semi-structured interviews. *Journal of the American College of Clinical Pharmacy* 4(10): 1358-1367. DOI: 10.1002/jac5.1441.

Agency for Toxic Substances and Disease Registry (ATSDR). 2021. Toxicological Profile for Perfluoroalkyls. Toxic Substances Portal. Available at: https://wwwn.cdc.gov/TSP/ToxProfiles/ToxProfiles.aspx?id=1117&tid=237. Accessed April 16, 2025.

Al Amin, M., Z. Sobhani, Y. Liu, R. Dharmaraja, S. Chadalavada, R. Naidu, J.M. Chalker, and C. Fang. 2020. Recent advances in the analysis of per- and polyfluoroalkyl substances (PFAS)—A review. *Environmental Technology & Innovation* 19(1-2):

100879. DOI: 10.1016/j.eti.2020.100879.

American Water Works Association (AWWA). 2024. Estimating the National Cost to Remove PFAS from Drinking Water Using UCMR 5 Data. Available at: https://www.awwa.org/wp-content/uploads/Final-Technical-Memorandum-Updating-National-Cost-Estimate-for-PFAS-Standards-using-UCMR-5.pdf. Accessed April 23, 2025.

Atoufi, H.D. and D.J. Lampert. 2023. Analysis of a passive sampling device to assess the behavior of per- and polyfluoroalkyl substances in sediments. *Environmental Toxicology and Chemistry* 42(10): 2171-2183. DOI: 10.1002/etc.5705.

Banwell, C., T. Housen, K. Smurthwaite, L. Walker, K. Todd, M. Rosas, and M. Kirk. 2019. *The PFAS Health Study Component One: Oakey, Williamtown and Katherine Focus Groups Study*. Australian National University. Available at: https://nceph.anu.edu.au/files/FINAL%20PFAS%20Health%20Study%20Focus%20Groups%20Report%20February%202019_3_0.pdf. Accessed April 16, 2025.

Berthold, T.A., A. McCrary, S. deVilleneuve, and M. Schramm. 2023. Let's talk about PFAS: Inconsistent public awareness about PFAS and its sources in the United States. *PLOS ONE* 18(11): e0294134. DOI: 10.1371/journal.pone.0294134.

Bilott, R. 2020. *Exposure: Poisoned Water, Corporate Greed, and One Lawyer's Twenty-Year Battle against DuPont*. Atria Books.

Boden, S. 2020. Presumptive innocence v. the precautionary principle: The story of PFAS regulation in the United States. *Environs: Environmental Law and Policy Journal* 44: 41.

Bogner, A., B. Littig, and W. Menz (Eds.). 2009. Introduction: expert interviews — An introduction to a new methodological debate. In: *Interviewing Experts*. Palgrave Macmillan UK, London, pp. 1-13. DOI: 10.1057/9780230244276_1.

Brennan, N.M., A.T. Evans, M.K. Fritz, S.A. Peak, and H.E. Von Holst. 2021. Trends in the regulation of per- and polyfluoroalkyl substances (PFAS): A scoping review. *International Journal of Environmental Research and Public Health* 18(20): 10900. DOI: 10.3390/ijerph182010900.

Brunn, H., G. Arnold, W. Körner, G. Rippen, K.G. Steinhäuser, and I. Valentin. 2023. PFAS: Forever chemicals—Persistent, bioaccumulative and mobile. Reviewing the status and the need for their phase out and remediation of contaminated sites. *Environmental Sciences Europe* 35(1). DOI: 10.1186/s12302-023-00721-8.

Brusseau, M.L., R.H. Anderson, and B. Guo. 2020. PFAS concentrations in soils: Background levels versus contaminated sites. *The Science of the Total Environment* 740: 140017. DOI: 10.1016/j.scitotenv.2020.140017.

Chemours. 2023. Chemours, DuPont, and Corteva Reach Comprehensive PFAS Settlement with U.S. Water Systems. Available at: https://www.chemours.com/en/news-media-center/all-news/press-releases/2023/chemours-dupont-and-corteva-reach-comprehensive-pfas-settlement-with-us-water-systems. Accessed April 16, 2025.

Cordner, A., G. Goldenman, L.S. Birnbaum, P. Brown, M.F. Miller, R. Mueller, S. Patton, D.H. Salvatore, and L. Trasande. 2021. The true cost of PFAS and the benefits of acting now. *Environmental Science & Technology* 55(14): 9630-9633. DOI: 10.1021/acs.est.1c03565.

Domingo, J.L. and M. Nadal. 2019. Human exposure to per- and polyfluoroalkyl substances (PFAS) through drinking water: A review of the recent scientific literature. *Environmental Research* 177: 108648. DOI: 10.1016/j.envres.2019.108648.

Environmental Working Group (EWG). 2024. Interactive Map: Suspected Industrial Discharges of PFAS. Available at: http://www.ewg.org/interactive-maps/2021_suspected_industrial_discharges_of_pfas/map/. Accessed April 16, 2025.

Evich, M.G., M.J.B. Davis, J.P. McCord, B. Acrey, J.A. Awkerman, D.R.U. Knappe, A.B. Lindstrom, et al. 2022. Per- and polyfluoroalkyl substances in the environment. *Science* 37(6580): eabg9065. DOI: 10.1126/science.abg9065.

Fenton, S.E., A. Ducatman, A. Boobis, J.C. DeWitt, C. Lau, C. Ng, J.S. Smith, and S.M. Roberts. 2020. Per- and polyfluoroalkyl substance toxicity and human health review: Current state of knowledge and strategies for informing future research. *Environmental Toxicology and Chemistry* 40(3): 606-630. DOI: 10.1002/etc.4890.

Food & Water Watch (FWW). 2023. *PFAS & The Chemistry of Concealment*. Available at: https://www.foodandwaterwatch.org/2023/11/07/pfas-the-chemistry-of-concealment/. Accessed April 16, 2025.

Gaines, L.G.T., G. Sinclair, and A.J. Williams. 2023. A proposed approach to defining per- and polyfluoroalkyl substances (PFAS) based on molecular structure and formula. *Integrated Environmental Assessment and Management* 19(5): 1333-1347. DOI: 10.1002/ieam.4735.

Garrett, K.K., K. Mok, P. Brown, L. Schaider, M. Powers, M. Fitzstevens, A. Amico, C. Osimo, A.

Cordner, and C. Carignan. 2024. REACHing for PFAS solutions: How two communities responded to drinking water contamination. *Journal of Environmental Studies and Sciences*. DOI: 10.1007/s13412-024-00994-2.

Glüge, J., M. Scheringer, I.T. Cousins, J.C. DeWitt, G. Goldenman, D. Herzke, R. Lohmann, C.A. Ng, X. Trier, and Z. Wang. 2020. An overview of the uses of per- and polyfluoroalkyl substances (PFAS). *Environmental Science: Processes & Impacts* 22(12): 2345-2373. DOI: 10.1039/D0EM00291G.

Goldenman, G., M. Fernandes, M. Holland, T. Tugran, A. Nordin, C. Schoumacher, and A. McNeill. 2019. *The Cost of Inaction: A Socioeconomic Analysis of Environmental and Health Impacts Linked to Exposure to PFAS*. Nordic Council of Ministers. Available at: https://www.researchgate.net/publication/345485324_The_cost_of_inaction#full-text. Accessed April 16, 2025.

Hassanzadeh, E. 2024. Whistleblowing Scientist Accuses 3M of PFAS Contamination Cover-up in Minnesota. *CBS News*, November 21, 2024. Available at: https://www.cbsnews.com/minnesota/news/3m-pfas-forever-chemical-whistleblower-kris-hansen/. Accessed April 16, 2025.

Hayes, J. 2021. 'Forever Chemicals' Contamination at Defense Department Sites Threatens Chesapeake Bay Fish. Environmental Working Group. Available at: https://www.ewg.org/news-insights/news/2021/08/forever-chemicals-contamination-defense-department-sites-threatens. Accessed April 16, 2025.

Head, B.W. 2022. *Wicked Problems in Public Policy: Understanding and Responding to Complex Challenges*. Springer Nature, Switzerland. DOI: 10.1007/978-3-030-94580-0.

Horst, J., J. McDonough, I. Ross, and E. Houtz. 2020. Understanding and managing the potential by-products of PFAS destruction. *Groundwater Monitoring & Remediation* 40(2): 17-27. DOI: 10.1111/gwmr.12372.

Hu, X.C., D.Q. Andrews, A.B. Lindstrom, T.A. Bruton, L.A. Schaider, P. Grandjean, R. Lohmann, et al. 2016. Detection of poly- and perfluoroalkyl substances (PFASs) in U.S. drinking water linked to industrial sites, military fire training areas, and wastewater treatment plants. *Environmental Science & Technology Letters* 3(10): 344-350. DOI: 10.1021/acs.estlett.6b00260.

Hughes, S.G. 2024. Processes & Considerations for Setting State PFAS Standards. Environmental Council of the States (ECOS). Available at: https://www.ecos.org/wp-content/uploads/2024/06/2024-ECOS-PFAS-Standards-Paper-Update.pdf. Accessed April 16, 2025.

Isaacs, D. 2025. Consortium Publishes Survey Results of PFAS Discharges to Wastewater. Semiconductor Industry Association (SIA). Available at: https://www.semiconductors.org/consortium-publishes-survey-results-of-pfas-discharges-to-wastewater/#_ftn5. Accessed April 16, 2025.

Johnson, G.R. 2022. PFAS in soil and groundwater following historical land application of biosolids. *Water Research* 211: 118035. DOI: 10.1016/j.watres.2021.118035.

Johnston, J. and L. Cushing. 2020. Chemical exposures, health, and environmental justice in communities living on the fenceline of industry. *Current Environmental Health Reports* 7(1): 48-57. DOI: 10.1007/s40572-020-00263-8.

Kirk, M., K. Smurthwaite, J. Bräunig, S. Trevenar, C. D'Este, R. Lucas, A. Lal, et al. 2018. The PFAS Health Study: Systematic Literature Review. The Australian National University, Canberra. Available at: https://nceph.anu.edu.au/files/PFAS%20Health%20Study%20Systematic%20Review_1.pdf. Accessed April 16, 2025.

Kwiatkowski, C.F., D.Q. Andrews, L.S. Birnbaum, T.A. Bruton, J.C. DeWitt, D.R.U. Knappe, M.V. Maffini, et al. 2020. Scientific basis for managing PFAS as a chemical class. *Environmental Science & Technology Letters* 7(8): 532-543. DOI: 10.1021/acs.estlett.0c00255.

Lau, C., K. Anitole, C. Hodes, D. Lai, A. Pfahles-Hutchens, and J. Seed. 2007. Perfluoroalkyl acids: A review of monitoring and toxicological findings. *Toxicological Sciences* 99(2): 366-394. DOI: 10.1093/toxsci/kfm128.

Lerner, S. 2024. How 3M Discovered, Then Concealed, the Dangers of Forever Chemicals. *The New Yorker*, May 20, 2024. Available at: https://www.newyorker.com/magazine/2024/05/27/3m-forever-chemicals-pfas-pfos-toxic. Accessed April 16, 2025.

Liddie, J.M., L.A. Schaider, and E.M. Sunderland. 2023. Sociodemographic factors are associated with the abundance of PFAS sources and detection in U.S. community water systems. *Environmental Science & Technology* 57(21): 7902-7912. DOI: 10.1021/acs.est.2c07255.

McFarlan, E.L. and L.D. Lemke. 2024. Per- and polyfluoroalkyl substances (PFAS) fate and transport across a groundwater-surface water interface. *Science of the Total Environment* 951: 175672. DOI: 10.1016/j.scitotenv.2024.175672.

Meuser, M. and U. Nagel. 2009. The expert interview and changes in knowledge production. In: *Interviewing Experts*, A. Bogner, B. Littig, and W. Menz (Eds.). Palgrave Macmillan UK, London, pp. 17-42. DOI: 10.1057/9780230244276_2.

Miranda, D.A., A.M. Zachritz, H.D. Whitehead, S.R. Cressman, G.F. Peaslee, and G.A. Lamberti. 2023. Occurrence and biomagnification of perfluoroalkyl substances (PFAS) in Lake Michigan fishes. *Science of the Total Environment* 895: 164903. DOI: 10.1016/j.scitotenv.2023.164903.

Moavenzadeh Ghaznavi, S., C. Zimmerman, M.E. Shea, J.D. MacRae, J.M. Peckenham, C.L. Noblet, O.G. Apul, and A.D. Kopec. 2023. Management of per- and polyfluoroalkyl substances (PFAS)-laden wastewater sludge in Maine: Perspectives on a wicked problem. *Biointerphases* 18(4): 041004. DOI: 10.1116/6.0002796.

Moody, C.A., G.N. Hebert, S.H. Strauss, and J.A. Field. 2003. Occurrence and persistence of perfluorooctanesulfonate and other perfluorinated surfactants in groundwater at a fire-training area at Wurtsmith Air Force Base, Michigan, USA. *Journal of Environmental Monitoring* 5(2): 341-345. DOI: 10.1039/B212497A.

National Conference of State Legislatures (NCSL). 2025. Per- and Polyfluoroalkyl Substances (PFAS) | State Legislation and Federal Action. Available at: https://www.ncsl.org/environment-and-natural-resources/per-and-polyfluoroalkyl-substances. Accessed April 16, 2025.

Newell, C.J., D.T. Adamson, P.R. Kulkarni, B.N. Nzeribe, and H. Stroo. 2020. Comparing PFAS to other groundwater contaminants: Implications for remediation. *Remediation* 30(3): 7-26. DOI: 10.1002/rem.21645.

Organisation for Economic Co-operation and Development (OECD). 2013. *Synthesis Paper on Per and Polyfluorinated Chemicals*. OECD Series on Risk Management of Chemicals. DOI: 10.1787/0bc75123-en.

Paul, K.T., S. Vanderslott, and M. Gross. 2022. Institutionalised ignorance in policy and regulation. *Science as Culture* 31(4): 419-432. DOI: 10.1080/09505431.2022.2143343.

Perkins, T. 2022. Maine Bans Use of Sewage Sludge on Farms to Reduce Risk of PFAS Poisoning. *The Guardian*, May 12, 2022. Available at: https://www.theguardian.com/environment/2022/may/12/maine-bans-sewage-sludge-fertilizer-farms-pfas-poisoning. Accessed May 12, 2022.

Propp, V.R., A.O. De Silva, C. Spencer, S.J. Brown, S.D. Catingan, J.E. Smith, and J.W. Roy. 2021. Organic contaminants of emerging concern in leachate of historic municipal landfills. *Environmental Pollution* 276: 116474. DOI: 10.1016/j.envpol.2021.116474.

Renella, G., P. Carletti, and A. Masi. 2025. Sustainable management of poly- and perfluoroalkyl substances (PFASs)-contaminated areas: Tackling a wicked environmental problem. *Sustainability* 17(2): 510. DOI: 10.3390/su17020510.

Renfrew, D. and T.W. Pearson. 2021. The social life of the "forever chemical": PFAS pollution legacies and toxic events. *Environment and Society: Advances in Research* 12(1): 146-163. DOI: 10.3167/ares.2021.120109.

Richter, L., A. Cordner, and P. Brown. 2021. Producing ignorance through regulatory structure: The case of per- and polyfluoroalkyl substances (PFAS). *Sociological Perspectives* 64(4): 631-656. DOI: 10.1177/0731121420964827.

Rittel, H.W.J. and M.M. Webber. 1973. Dilemmas in a general theory of planning. *Policy Sciences* 4(2): 155-169. DOI: 10.1007/BF01405730.

Sadia, M., M. Kunz, T. ter Laak, M. De Jonge, M. Schriks, and A.P. van Wezel. 2023. Forever legacies? Profiling historical PFAS contamination and current influence on groundwater used for drinking water. *Science of the Total Environment* 890: 164420. DOI: 10.1016/j.scitotenv.2023.164420.

Schroeder, T., D. Bond, and J. Foley. 2021. PFAS soil and groundwater contamination via industrial airborne emission and land deposition in SW Vermont and Eastern New York State, USA. *Environmental Science: Processes & Impacts* 23(2): 291-301. DOI: 10.1039/D0EM00427H.

Schwartz, E. 2022. Too little too late: Underregulation of contaminants of emerging concern. *Environmental Law Reporter* 52(12): 10964-0979.

Schymanski, E.L., J. Zhang, P.A. Thiessen, P. Chirsir, T. Kondic, and E.E. Bolton. 2023. Per- and polyfluoroalkyl substances (PFAS) in PubChem: 7 million and growing. *Environmental Science & Technology* 57(44): 16918-16928. DOI: 10.1021/acs.est.3c04855.

Smalling, K.L., K.M. Romanok, P.M. Bradley, M.C. Morriss, J.L. Gray, L.K. Kanagy, S.E. Gordon, et al. 2023. Per- and polyfluoroalkyl substances (PFAS) in United States tapwater: Comparison of underserved private-well and public-supply exposures and associated health implications. *Environment International* 178: 108033. DOI: 10.1016/j.envint.2023.108033.

Solo-Gabriele, H.M., A.S. Jones, A.B. Lindstrom, and J.R. Lang. 2020. Waste type, incineration, and aeration are associated with per- and polyfluoroalkyl levels in landfill leachates. *Waste Management* 107: 191-200. DOI: 10.1016/j.wasman.2020.03.034.

Stoiber, T., S. Evans, and O.V. Naidenko. 2020. Disposal of products and materials containing per- and polyfluoroalkyl substances (PFAS): A cyclical problem. *Chemosphere* 260: 127659. DOI: 10.1016/j.chemosphere.2020.127659.

Strauss, A.L. and J.M. Corbin. 1998. *Basics of Qualitative Research: Techniques and Procedures for Developing Grounded Theory*. 2nd ed. Sage Publications, Thousand Oaks.

Tokranov, A.K., D.R. LeBlanc, H.M. Pickard, B.J. Ruyle, L.B. Barber, R.B. Hull, E.M. Sunderland, and C.D. Vecitis. 2021. Surface-water/groundwater boundaries affect seasonal PFAS concentrations and PFAA precursor transformations. *Environmental Science: Processes & Impacts* 23(12): 1893-1905. DOI: 10.1039/D1EM00329A.

Trywhitt Jones, E. 2023. *The Impact of a Potential PFAS Restriction on the Semiconductor Sector*. Report No. 2022-0737 Rev. 0. SIA PFAS Consortium. Available at: https://www.semiconductors.org/wp-content/uploads/2023/04/Impact-of-a-Potential-PFAS-Restriction-on-the-Semiconductor-Sector-04_14_2023.pdf. Accessed April 16, 2025.

United States Chamber of Commerce (USCOC). 2022. PFOS and PFOA Private Cleanup Costs at Non-Federal Superfund Sites. Available at: https://www.uschamber.com/assets/documents/PFOS-and-PFOA-Private-Cleanup-Costs-at-Superfund-Sites-6.8.22.pdf. Accessed April 16, 2025.

United States Environmental Protection Agency (US EPA). 2021. PFAS Strategic Roadmap: EPA's Commitments to Action 2021-2024. EPA-100-K-21-002. Available at: https://www.epa.gov/pfas/pfas-strategic-roadmap-epas-commitments-action-2021-2024. Accessed April 16, 2025.

United States Environmental Protection Agency (US EPA). 2022. EPA Adds Five PFAS Chemicals to List of Regional Screening and Removal Management Levels to Protect Human Health and the Environment. News Release. Available at: https://www.epa.gov/newsreleases/epa-adds-five-pfas-chemicals-list-regional-screening-and-removal-management-levels. Accessed May 18, 2022.

United States Environmental Protection Agency (US EPA). 2024a. Fact Sheet: 2010/2015 PFOA Stewardship Program. Available at: https://www.epa.gov/assessing-and-managing-chemicals-under-tsca/fact-sheet-20102015-pfoa-stewardship-program. Accessed March 18, 2024.

United States Environmental Protection Agency (US EPA). 2024b. Biden-Harris Administration Finalizes Critical Rule to Clean up PFAS Contamination to Protect Public Health. News Release. Available at: https://www.epa.gov/newsreleases/biden-harris-administration-finalizes-critical-rule-clean-pfas-contamination-protect. Accessed April 19, 2024.

United States Geological Survey (USGS). 2019. Groundwater Quality in Principal Aquifers of the Nation, 1991–2010. Available at: https://www.usgs.gov/mission-areas/water-resources/science/groundwater-quality-principal-aquifers-nation-1991-2010. Accessed April 16, 2025.

United States Senate Committee on Environment & Public Works. 2024. Superfund Sites Identified by EPA to Have PFAS Contamination. Available at: https://www.epw.senate.gov/public/index.cfm/superfund-sites-identified-by-epa-to-have-pfas-contamination. Accessed April 16, 2025.

Watson, A.F. 2024. Remediation for PFAS contamination: The role of CERCLA enforcement in environmental justice. *Georgia Law Review* 56(2). Available at: https://digitalcommons.law.uga.edu/glr/vol58/iss2/7. Accessed April 16, 2025.

World Semiconductor Council (WSC). 2024. Joint Statement of the 28th Meeting of the World Semiconductor Council (WSC). Available at: https://www.semiconductorcouncil.org/wp-content/uploads/2024/06/2024-WSC-Joint-Statement-FINAL.pdf#page=6. Accessed April 16, 2025.

UNIVERSITIES COUNCIL ON WATER RESOURCES
JOURNAL OF CONTEMPORARY WATER RESEARCH & EDUCATION
ISSUE 182, PAGES 115-124, APRIL 2025

National Institutes for Water Resources: Fulfilling the Water Resource Research Act Mission, 2016–2020

Jonathan Yoder

School of Economic Sciences, State of Washington Water Research Center, Washington State University

Abstract: The Water Resources Research Act of 1964 (WRRA) established the network of Water Resource Research Institutes (WRRIs). 60 years on, 54 Institutes carry out water research, education, and science communication for the benefit of the state or territory in which each resides. This article summarizes organizational and fiscal characteristics of the WRRIs and their activities based on Institute reports submitted to the U.S. Geological Survey for the period 2016-2020. The data show that these Institutes are highly diverse fiscally, organizationally, and in the focus of their activities, suggesting that the WRRA provides critical support to sustain the network of Institutes and allows the flexibility to address local challenges in locally relevant and effective ways.

Keywords: *Water Resources Research Act, WRRA, National Institutes for Water Resources, NIWR, water research, water education*

The Water Resources Research Act (WRRA) of 1964 (amended 1984) authorized and supported the establishment of Water Resources Research Institutes (WRRI) at universities or colleges within each state as well as Washington D.C. and the five populated territories (§104(a); WRRA 2021). The intended mission of these institutes is to (i) conduct and support research for effective water resource management, (ii) support education and training of water research scientists, engineers, and technicians for productive water resources fields, and (iii) to disseminate research results to water resource managers and the public (§104(b); WRRA 1984).

Since 1983 there have been 54 WRRIs: one in each state, Washington D.C., the U.S. Virgin Islands, Puerto Rico, and Guam (which includes coverage for the Commonwealth of the Northern Mariana Islands, and the Federated States of Micronesia), and American Samoa (through the Hawaiian Institute). Today, these institutes (hereafter Institutes) are organized through the non-profit National Institutes for Water Resources (NIWR). The NIWR institutes receive regular funding through the WRRA program with annual appropriations managed through the United States Geological Survey (USGS) under their Water Resources Mission Area (USGS 2024a; 2024b). From a practical perspective, NIWR represents the interests of the Institutes that are eligible to receive funding through appropriations under the WRRA program and all WRRIs are members of NIWR. As such, all Institutes described in this analysis are both members of NIWR and are supported under the WRRA program.

This article summarizes the activities, accomplishments, and administrative and funding characteristics of the Institutes based on the data submitted to the USGS for evaluation for the reporting period 2016 through 2020. The intent of this article is to describe the institutional and fiscal foundations in the WRRA, the diversity of Institute structure, funding, and activity borne out of state-level organization and flexibility, and the productivity of the Institutes powered by state-level investment and extramural grant success.

The Institutes report on their activities and

Research Implications

- Water Resources Research Act of 1964 provides consistent funding with cost-share requirements that has, for 60 years, sustained water research, education, and science communication of the 54 Institutes created by and supported under it.
- The organization and fiscal characteristics of the Water Resources Research Institutes varies substantially.
- The federal organization of the Water Resources Research Act program promotes diversity based on local needs and resources.

accomplishments annually and provide five-year summary reports for USGS evaluation. The last set of evaluation reports was submitted to the USGS by each institute in 2023 for the five-year reporting period 2016-2020. The spreadsheet template provided by the USGS and used by Institutes as the basis for reporting is provided in Supplementary Materials.

Several caveats about the data summarized here should be recognized at the outset. First, the reporting guidelines and template that the USGS requires of and provides the Institutes for reporting are driven by USGS goals. They are not intended to be comprehensive but instead represent a balance between the value of comprehensive information and the burden of reporting and assessment. Therefore, the information available to report in this article is somewhat limited. Second, some of the reporting guidelines are open to interpretation. Where this is the case, answers to specific information requests may vary across Institutes solely due to differences in interpretation. Third, some information requests were voluntary. For example, the reporting template allowed but did not require institutes to report their extramural grant awards (other than WRRA) and products that were supported by them. Some institutes reported these products, and others did not. It is therefore likely that some elements of the summary below provide an incomplete picture of Institute activities. Fourth, the data were entered into the spreadsheet by hand by Institute staff three years after the reporting period ended. There is therefore potential for both typographical errors and reporting discrepancies or omissions due to incomplete records. Nonetheless, the data are useful to provide an illustration of the activities and variation across institutes for the reporting period.

Funding and Reporting Background

The WRRA program received a total of $6.5 million annually for fiscal years 2016 through 2019, and $10 million in 2020. These funds are split into two pools: one for 104(b) funds split equally across 52 of the 54 institutes, with two Institutes (Guam and Hawaii) receiving a larger allocation. The other pool of funds supports national competitive grants under the 104(g) program. A small percentage of the funds support USGS administration of these programs. Most Institutes received $92,335 in 104(b) funds per institute in 2016-2019 and $125,000 in 2020, except for Hawaii and Guam, which receive multiple allocations to cover work in supported U.S. territories. Based on the per-Institute limits, the total funding available to the Institutes per year under the 104(b) program was $5,263,095 per year from 2016-2019 and $7,125,000 for 2020, for a total of $28,177,380 over the reporting period.

During this reporting period Institutes were required to provide cost-share of two dollars of non-federal funds for every dollar of federal funds received through this program[1]. This cost-share requirement is satisfied in various ways by Institutes. The program does not pay for Facilities and Administration costs (F&A), so F&A covered by the host university can count toward this cost-share requirement. Many universities provide support to the Institutes that they host by providing personnel funding and other forms of support. Many Institutes also require researchers who receive 104(b) funding to provide cost-share matching, which is often satisfied by in-kind salary matching.

Institutes operate relatively independently, have varying levels and types of institutional

1 The Fiscal Year 2024 budget was $146,895 per institute except for Guam, and the cost-share requirement was dropped from 1:2 federal:non-federal funds to 1:1.

support, are staffed and supported by experts with different expertise and comparative advantages, and face different local water challenges. As a result, Institutes pursue their tripartite mission of supporting research, education, and water science communication in myriad ways. It also follows that the activities and products reported across Institutes vary as well. Taken together, the contributions of these Institutes to the science and management of water resources are both broad and deep, covering the gamut of water management issues across the country with the depth of local and regional expertise that the state-level focus of each individual institute provides.

Project Types and Funding

WRRA 104(b) annual funding applications are organized around "projects." Each annual 104(b) grant proposal may contain one or more identifiable projects for which they request funds. These projects are categorized in various ways, but they are most often categorized as research, education and training, outreach and engagement (also known as information transfer), and administration (Table 1).

Research projects are by far the most numerous, amounting to about three-fourths of all projects proposed as a part of an institute's 104(b) grant proposal. As the category name suggests, these projects are intended to fund water-related research of some form, and may support institute staff or are distributed to other researchers via competitive grant programs or other means. For example, the State of Washington Water Research Center (WRC) has historically held a competitive grant program each year to support up to three small grants. Any faculty or research staff located at a university or college located in Washington State is eligible to submit a proposal. These proposals are reviewed by the WRC Science Advisory Committee, and the top-ranked projects are awarded funds to support a one-year grant project. Other Institutes distribute research funds in other ways.

Education and Training and Outreach and Engagement projects (the latter usually referred to as Information Transfer projects) are likewise intended to support Institutes' missions in those areas. Often, Information Transfer activities relate to the activities and projects that convey and publicize research being carried out at NIWR Institutes or engaging with various stakeholders and the public. Administration projects are projects upon which WRRA 104(b) funds are requested to support the administration of an institute. Based on the number of projects by category in Table 1, Table 2 shows that WRRA 104(b) funding is distributed in roughly the same proportion as project counts, with research projects receiving about two-thirds of annual and cumulative funding. Funding and project counts are distributed similarly for the other project areas as well.

The funding totals reported in USGS (2023) approximate the 104(b) annual totals noted at the beginning of this section and listed in the penultimate line of Table 2. Overall, reported expenditures represent 93% of the funds available. Interannual variation from 2016 through 2019 may be due to variation in the funding requests (which may be lower than the total available funding for an institute) and reporting variation and/or errors across Institutes. It appears from data details (not shown) that there may be several reporting errors in the reported 104(b) funding data, including (apparently) incorrect attribution of funding across

Table 1. WRRA-funded projects by mission category (Count). Based on USGS (2023) Project Overview sheet column B.

Project Category	2016	2017	2018	2019	2020	Total	% Total
Research	228	215	189	193	253	1,078	74
Education and Training	12	13	6	9	10	50	3
Outreach and Engagement	34	29	24	21	24	132	9
Administration	35	37	36	34	37	179	12
Other	5	9	6	5	2	27	2
Total	314	303	261	262	326	1,466	100

years, inclusion of cost-share and/or funds from other sources, and failure to report, so the summary numbers in Table 2 should be taken as approximate.

An important role of the WRRA 104(b) funding is to provide Institutes with a consistent foundation to successfully pursue and attract extramural grant funding for research and outreach. Figure 1 and Table 3 summarize total extramural grant support by year. Table 3 shows that total extramural grant support ranged from about $6 million in 2017 to over $20 million in 2019 and totaled over $56 million for the five-year period. Compared to the $36 million, NIWR Institutes brought in over two dollars of extramural grant funding for each dollar of 104(b) funding. Figure 1 shows that these grant funds were highly variable across Institutes, with some bringing in upwards of a million dollars in a given year and others much less. It is noteworthy that most of the 2:1 cost-share requirement was satisfied by funds other than these grants, so these funds leverage the WRRA program further in support of critical water research for each state and the nation.

Staff, Researcher, and Student Support

A relatively large proportion of the funding listed in Table 2 supports staff, students, and water researchers. Figure 2 provides a synopsis of institute staffing by state, based on a form field that

Table 2. WRRA 104(b) federal funding by project type in nominal U.S. dollars. Percentage of total WRRA 104(b) funds listed underneath dollar amounts. Based on USGS (2023) Project Overview sheet columns B and I. These numbers do not include other WRRA program funds (e.g. 104(g) funds), nor non-federal matching funds.

Project Category		Year					Total
		2016	2017	2018	2019	2020	
Research	$	3,727,667	3,275,514	3,044,987	3,160,353	4,451,747	17,660,268
	%	65.37	68.47	66.94	67.81	67.7	67.22
Education and Training	$	223,966	245,883	144,985	181,581	298,606	1,095,021
	%	3.93	5.14	3.19	3.9	4.54	4.17
Outreach and Engagement	$	776,786	515,206	528,695	482,332	711,716	3,014,735
	%	13.62	10.77	11.62	10.35	10.82	11.48
Administration	$	859,676	601,390	723,606	733,625	1,032,405	3,950,702
	%	15.08	12.57	15.91	15.74	15.7	15.04
Other	$	114,452	146,039	106,887	102,522	81,221	551,121
	%	2.01	3.05	2.35	2.2	1.24	2.1
Total reported	$	5,702,547	4,784,032	4,549,160	4,660,413	6,575,695	26,271,847
	%	100	100	100	100	100	100
Total available 104(b) Funding	$	5,263,095	5,263,095	5,263,095	5,263,095	7,125,000	28,177,380
Reported as % of available	%	108	91	86	89	92	93

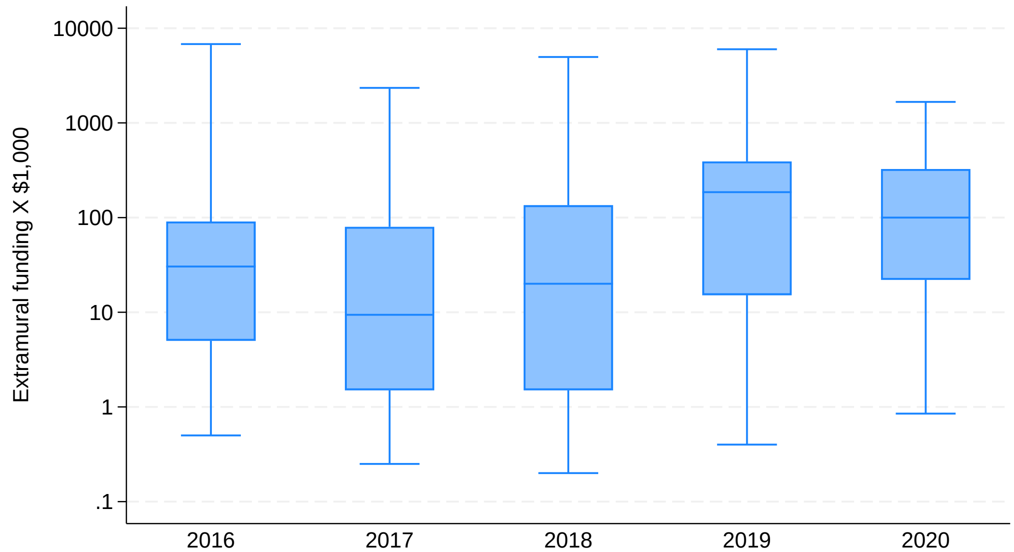


Figure 1. Extramural grant funding based on USGS (2023) Awards-Achievements-Grants sheet.

Table 3. Total grant funding based on USGS (2023) Awards-Achievements-Grants sheet.

Year	Funding ($)
2016	12,034,646
2017	6,298,584
2018	10,909,412
2019	20,242,479
2020	7,270,037
Total	56,755,158

asks for current (2023) numbers for administrative and science staff. For example, Alaska reports the largest total number of administrative and scientist staff, with four administrative staff (not including the director or associate director), and 20 staff scientists, for a total staff of 24. On the other end of the spectrum, 12 Institutes report no staff beyond a director and possibly an associate director. Importantly, the USGS form question supporting this figure does not stipulate the funding source. In particular, this data request does not ask to limit reporting to personnel funded by 104(b), and it is possible that the request was interpreted differently across Institutes.

Table 4 provides a summary of Full-Time-Equivalent positions (FTE) supported by WRRA 104(b) funds specifically, summed over all Institutes, by year. These data summarize how 104(b) funds were used to support staff. Table 4 shows that students represent a large proportion of the personnel supported by WRRA 104(b) funds, followed by administrative staff and science staff. Directors represent a total of 17 FTE-years supported by WRRA 104(b) funds over five years, or almost 3.4 FTE per year during the reporting period.

Together, Figure 2 and Table 4 illustrate that WRRA 104(b) funds do not fully support institute staff. The number of administrative staff and science staff based on Figure 2 is 94 and 165, respectively, but the total administrative and scientist staff FTE supported by WRRA funds per year is 9.3 and 5.7 for administrative and science staff, respectively.[2] Further, out of 54 Institutes, only about the equivalent of three to four full-time directors are supported directly by 104(b) funds. Most are paid from other sources. Many Institutes pay personnel using funding from host

2 To reiterate, the staffing numbers pertain to 2023 at the time of the report, while the WRRA funding FTE numbers pertain to the reporting period 2016-2020. This comparison is valid to the extent that staffing averages across institutes have not changed much in the interim. Due to increased 104(b) funding, however, the WRRA funded FTE for the reporting period may under-represent current (2023) FTE support.

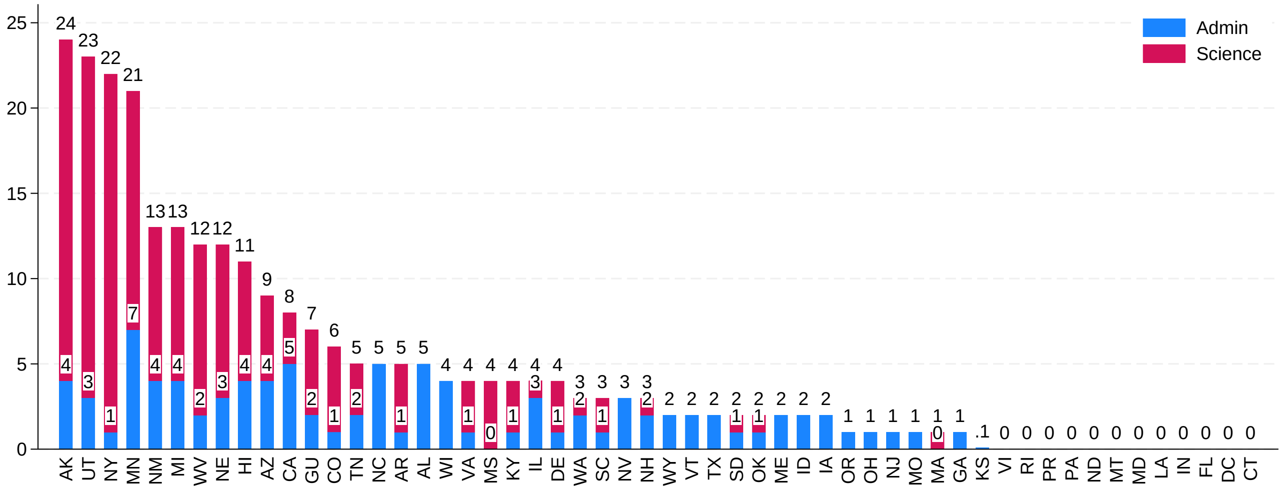


Figure 2: Administrative and science staffing, not including directors and associate directors. Not specific or limited to 104(b) funds. Based on USGS (2023) Institute Background, A7-B8.

Table 4. Staff and student FTE supported by WRRA 104(b) funds (only) over all 54 Institutes. These numbers are the sum of responses to questions in USGS (2023) Institute Background Sheet cells A15-G19.

Position Category	Year					Total
	2016	2017	2018	2019	2020	
Director	3.5	3.3	3.2	3.0	3.9	17
Co-Director	0.3	0.3	0.3	0.3	0.3	1.4
Associate Director	0.3	0.3	0.3	0.3	0.3	1.3
Administrative Staff	6.7	9.1	8.1	11.0	11.0	46
Other Science Staff	4.9	5.2	5.6	5.1	7.6	28
Students	23	23	27	27	36	152
Total	39	57	44	47	60	246

universities, state general and targeted funds, extramural grant programs, or from various other sources. Institute reports do not provide details about other categories of funds, but we can report on some of them. First, university discretionary funds provided to Institutes range from zero, for 32 of the 54 Institutes during the reporting period, to an average of over $800,000/year for one institute. Some pay personnel with discretionary funds and some personnel are supported with non-discretionary funds. However, the definition of discretionary funds varies by Institute.

The data for the student category in Table 4 were provided in response to questions about the administrative background for the Institute. Additional support for students is reported for all project categories shown in Table 1. Table 5 reports the number of students supported through non-administrative projects, disaggregated by educational level. During the five-year reporting period, over 2,000 students are reported to have been supported by 104(b) funds through research, administration, outreach, and research projects. This amounts to over eight students per year per Institute on average.

Institutes are also asked to report the number and rank of principal investigators of research projects supported by WRRA 104(b) funds. Table 6 reports the distribution of positions held by principal investigators of projects supported by WRRA 104(b) funds. Less than one quarter of project principal investigators hold professor ranks, and virtually all the rest represent lower ranked positions and positions associated with earlier-

Table 5. The number of students supported by WRRA projects and funded by WRRA 104(b) funds. Based on USGS (2023) Project Overview Sheet columns J-L.

Educational Level	Year					Total
	2016	2017	2018	2019	2020	
PhD students	129	110	89	119	154	601
MS students	135	139	113	89	137	612
Undergraduates	192	202	220	216	242	1,072

Table 6. Positions held by principal investigators of projects funded by WRRA 104(b) funds. Based on USGS (2023) By Year Summary sheet cells B21-G27.

Position Held	Year					Total
	2016	2017	2018	2019	2020	
Assistant Professor	112	123	116	112	131	594
Associate Professor	80	66	63	65	84	358
Professor	98	83	83	70	103	437
Research Staff, Postdoc	53	50	52	66	87	308
Students	26	24	21	34	28	133
Total	369	346	335	347	433	1,830

career professionals. These results likely reflect the education and training mission of NIWR Institutes instilled by the WRRA. Many Institutes who distribute funds through competitive or non-competitive grant programs emphasize support for early-career professionals in water research and related Institute activities. The WRRA funded FTE for the reporting period may under-represent current (2023-2024) FTE support.

Research Focus, Products, and Audiences

Student and personnel support are provided by WRRA 104(b) funds to produce water research, education, and information transfer for the benefit of their host states. Topic areas, types of products, and audiences are described in this section.

Institutes are asked to associate keywords with individual projects. Figure 3 provides a graphic of the primary and secondary keywords listed for each project. For purposes of this paper the keywords are grouped into six broad categories including [water] Quantity, Quality, Environment, Management, Uses, and Research and Education. Water quantity issues include drought, flooding, and water supply. Quality topics include nutrient management, toxic substances, and nonpoint-source pollution. Environmental topics include surface and groundwater, ecology, and climatology, among others.[3]

Table 7 provides the number of products generated by Institutes organized into various categories. USGS requests that products with associated Digital Object Identifiers (DOI) be reported separately from other products. This table includes the counts of both. Journal articles are the most numerous, followed by theses and dissertations. “Other” contains products that do not fit well within the other categories.

The Institutes engage with a diversity of stakeholders through their activities summarized in Table 7. Figure 4 provides a summary of the categories of audiences that Institutes engage with in their extension, outreach, and conference activities. Academic audiences, water managers, and the general public represent the most frequent audience types.

3 The six broader categories are somewhat arbitrary, and the Quality and Environmental categories have several keywords that could be placed in both or either.

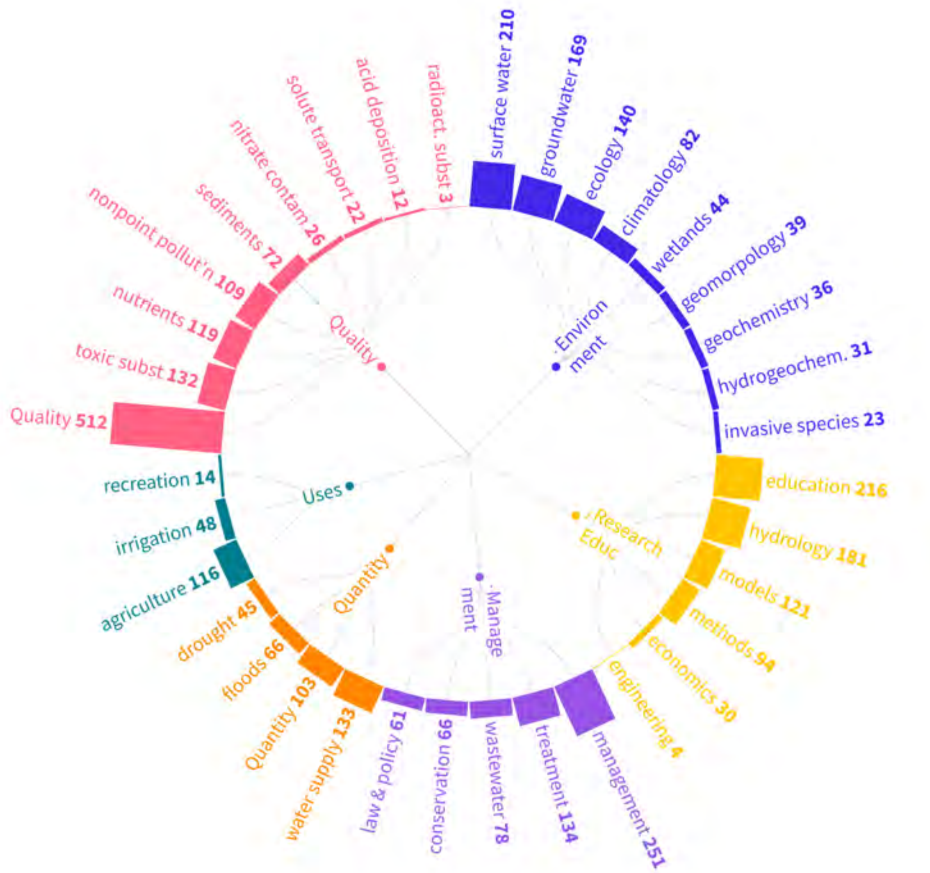


Figure 3. Keyword counts by category. Based on USGS (2023) Project Overview sheet columns V and W.

Table 7. Product count by category. Based on USGS (2023) DOI Products ONLY sheet column B and Other Products sheet column B. Includes the sum of counts from USGS (2023) DOI Products ONLY sheet column B and Other Products sheet column B.

Product Type	Year					Total
	2016	2017	2018	2019	2020	
Journal Article	94	133	156	150	207	740
Thesis/Dissertation	26	39	56	65	64	250
Report	35	32	24	39	29	159
Newsletter	34	31	29	36	28	158
Other	10	23	16	16	38	103
Extension or Tech Bull.	13	15	12	11	16	67
Proceedings Paper	7	13	13	8	6	47
Article/Report in-Prep	5	8	8	4	5	30
Presentation or Poster	6	9	5	2	1	23
Dataset	1	1	2	9	8	21
Webpage or Storyboard	3	6	0	5	6	20
Conference or Workshop	2	6	3	5	3	19
Book	1	5	5	0	2	13
Map or Interactive Map	0	1	1	3	3	8
Tool	0	0	2	0	4	6
Total	145	193	181	200	210	929

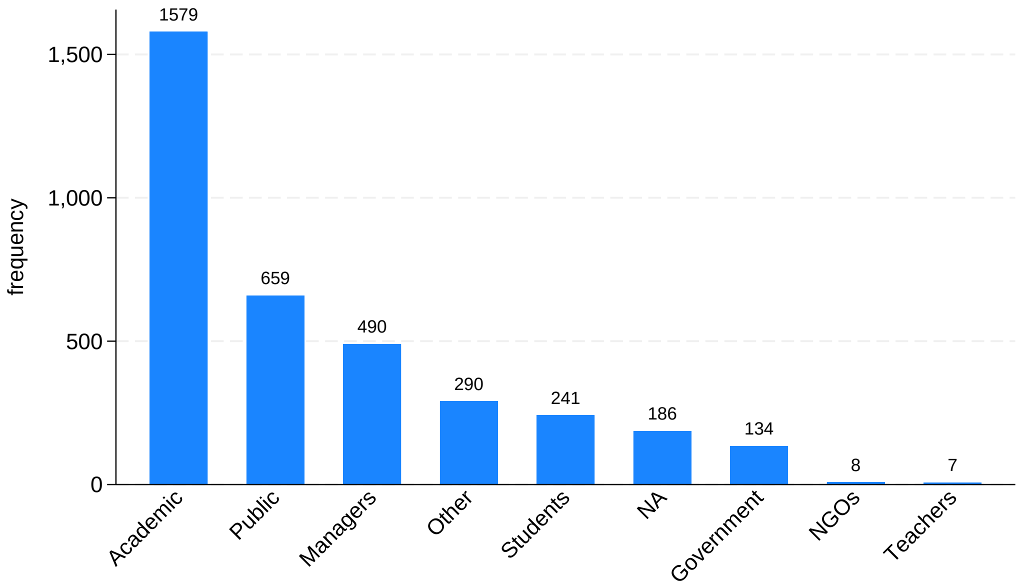


Figure 4. Presentations supported by WRRA 104(b) funds. These include presentations listed as outreach, Extension, and education as well as conference presentations. Based on USGS (2023) Conference Presentation and Education and Outreach Sheets.

Table 8. Achievements, recognition awards, and grant awards received by Institutes and/or the researchers, students, and staff they support. Based on USGS (2023) Awards-Achievements-Grants sheet.

	Year					Total
	2016	2017	2018	2019	2020	
Achievement	43	42	27	31	40	183
Award	65	66	54	59	68	312
Grant	53	42	44	45	43	227

Institutes also reported information about achievements, recognition, and grant awards that were received by Institutes and/or the staff, students, and affiliates that they support with 104(b) funding (Table 8). The achievements category was used widely by Institutes to list significant accomplishments of myriad forms. Awards are generally awards of recognition by associations, departments, colleges, and Institutes. Many of the listings are for achievements and awards earned by students supported by 104(b) funding. In the Award category for example, 206 of the 301 awards listed (68%) were received by students, highlighting the emphasis that the WRRA and the Institutes mission place on training future water professionals.

The number of grants enumerated in Table 8 varies substantially across Institutes, but the average number is slightly less than one extramural grant per Institute per year. The grant funding associated with these grants as summarized in Table 3 and Figure 1 is approximately twice the total of 104(b) funds alone. The consistent 104(b) funding undoubtedly supports successful extramural grant acquisition, which in turn leverages the impact of 104(b) funding.

The spreadsheet template provided by the USGS is a relatively new reporting format for the WRRA program that is condensed and concise relative to the previous full textual report required in previous years. This new spreadsheet approach provides substantial benefits, including the relative ease with which data summaries like those presented here can be generated. However, as noted earlier in this article, there are some reporting deficiencies, and there is room for improvement in the spreadsheet reporting instrument and its use.

Conclusion

For 60 years, the WRRA has provided stable support for a diverse and active set of WRRIs in support of the goals of the Act to provide research, education, and communication focusing on the water science and management needs of each state and territory in the nation. The state-level design and funding of the USGS WRRA program is a foundation for a rich diversity of institute structure, size, mission-area focus, and water resource focus areas, driven by variation in the water research and management needs across states, differences in host state and institutional support, and the comparative strengths and interests of researchers and administration that carry out the work in pursuit of the WRRA mission.

The fact that 54 Institutes remain in existence 60 years after the WRRA was signed by Lyndon B. Johnson is a testament to the stability and value of the distributed water research concept as implemented under the Act. The summary provided here illustrates the value of its relatively modest but consistent base funding as a foundation for leveraging both cost-share funding from states and for successful pursuit of extramural competitive grant funding. Together, the WRRA program and activities it directly and indirectly supports provide valuable water research and educational contributions to state and territory of each Institute in the nation.

The 104(b) program funding has been increasing almost annually since 2020, but the current funding levels are low from a historical perspective. Fiscal year 2024 funding was $15.5 million. In 1967 the program received $3.8 million (Burton 1984; Table 1), which is equivalent to $35 million in 2024 dollars. In 1971 the program received $12.75 million, which is equivalent to almost $100 million in 2024 dollars. While the recent increases in federal funding bode well for pursuing the vision for the WRRA through 2030 laid out in Donohue et al. (2021), returning to historical funding levels in terms of real purchasing power would provide a much stronger foundation for the Institutes to better pursue critical water research, education, and science communication during a time of rapid environmental and demographic change that is changing the fundamentals of natural water systems and our relationship with water resources.

Acknowledgements

This article was supported by WRRA 104(b) funding for fiscal year 2024. I thank Christian Schmidt of the USGS for help acquiring the data and three anonymous reviewers' valuable suggestions and feedback.

Author Bio and Contact Information

Jonathan Yoder has been the Director of the State of Washington Water Research Center since 2014 and holds the Distinguished Professorship for Sustainable Development in the School of Economic Sciences at Washington State University. He can be reached at yoder@wsu.edu.

References

Burton, J.S. 1984. History of the State Water Resources Research Institute Program. U.S. Geological Survey open-file report 84-736. Available at: https://www.usgs.gov/publications/history-state-water-resources-research-institute-program. Accessed November 21, 2024.

Donohue, M.J., E.A. Greene, and D.T. Lerner. 2021. Water Resources Research Act Program—Current Status, Development Opportunities, and Priorities for 2020–30. U.S. Geological Survey Circular 1488. Available at: https://pubs.usgs.gov/circ/1488/cir1488.pdf. Accessed November 21, 2024.

U.S. Geological Survey (USGS). 2023. Water Resources Research Institute Evaluation Report Guidlines FY 2016-2020. Available at https://water.usgs.gov/wrri/files/Evaluation_Guidelines.pdf. Accessed December 3, 2024.

U.S. Geological Survey (USGS). 2024a. Water Resources Mission Area. Available at: https://www.usgs.gov/mission-areas/water-resources. Accessed June 28, 2024.

U.S. Geological Survey (USGS). 2024b. Water Resources Research Act Program. Available at: https://water.usgs.gov/wrri/. Accessed June 28, 2024.

Water Resources Research Act of 1984-(sec. 104) as Amended through P.L. 117-58. 2021. (WRRA). Public Law 98-242. Available at: https://www.govinfo.gov/content/pkg/COMPS-16555/pdf/COMPS-16555.pdf. Accessed June 28, 2024.

Supplementary Material

Supplementary material is available at: https://ucowr.org/supplementary-material/.

Universities Council on Water Resources
Journal of Contemporary Water Research & Education
Issue 182, Pages 19-28, April 2025

Case Study Article

The Virginia Water Resources Research Center's Experience with an Audio Show

Alan Raflo

Virginia Water Resources Research Center

Abstract: This article describes one state water center's 14-year experience in producing a short, audio-based information product and poses key questions for water centers and institutes considering audio technologies to tell their states' water stories. From 2010 to 2024, Virginia Water Radio (VWR), produced by the Virginia Water Resources Research Center, sought to use a short audio show to inform Virginia residents about the abundance, complexity, and use of the state's water resources. Originally designed to be carried by radio stations, VWR evolved into a primarily podcasted show that was accompanied by a blog providing supporting material. The show produced 674 episodes, running weekly from January 2010 through April 2022 and then biweekly until February 2024. Typically between three and six minutes long, the episodes featured sounds and music to introduce and frame the water-related content. Episode subject areas included organisms, geography, weather and climate, organizations, management, history, and water connections in language and music. Achievements included the show's longevity, consistency, breadth of topics, online information accompanying each audio episode, and collaborations with musicians and guest voices. Challenges included finding radio station partners, acquiring permission to use music, finding sounds, describing complex subjects concisely, expanding the show's reach, and balancing staff time among show production, promotion, and evaluation. Questions for water centers or institutes considering an audio product focus on a product's potential value to an organization's programs, staff requirements, evaluation, episode frequency and duration, potential use of sounds and music, role of collaborators, equipment, and technology capacity.

Keywords: *Virginia, podcast, radio, water information*

Imagine the sound of swans calling from a lake. How does that sound connect to Halloween? If you guessed that swans and their water habitats had special significance in Celtic mythology, including myths surrounding the ancient Celtic festival of Samhain that is the precursor of Halloween, you'd be right.

That opening paragraph is a tiny version of an episode of Virginia Water Radio (VWR), a short, audio-based water-information product. This article describes the Virginia Water Resources Research Center's (VWRRC) 14-year experience in producing VWR—the show's origin, production, outcomes, achievements, and challenges. Based on the VWR experiences, the article then identifies key questions for water centers and institutes considering audio technologies to tell their states' water stories.

Originating as a Way to Tell Virginia's Water Story

Virginia has abundant rivers, streams, lakes (most human-constructed), and estuaries (VA DEQ 2024). The VWRRC, established in 1965 at Virginia Tech in Blacksburg, is charged under federal and state law with supporting research, education, and information transfer about those water resources (Commonwealth of Virginia 2024; USGS 2024; VWRRC 2024a). Informing a state's residents about their water can involve exploring water sources and movements, water uses, atmospheric processes, natural habitats, organisms, human health, human history, laws and regulations, economics, politics, and technology (Cech 2009). From 2010 to 2024,

Research Implications

- Modern audio technology offers state water centers and institutes new and creative ways to explore water topics and provide information.
- State-specific sounds and music offer possible options to increase an audio product's information value and aesthetic appeal.
- Format, content, frequency, promotion, and evaluation are interrelated aspects that determine whether an audio product adds value to the programs of a water center or institute.

the VWRRC produced VWR as one way to offer water information to Virginia's over 8.6 million residents (US Census 2024).

As of 2010, the VWRRC had a long history of publishing research bulletins, conference proceedings, a newsletter, and educational reports (VWRRC 2024a; 2024b). Seeking an alternative way to reach audiences, the VWRCC staff began to explore providing information in a short audio format, particularly a format that could be widely and easily accessible. The VWRRC's hiring in 2008 of a media specialist with audio-production expertise gave the VWRRC the capacity to begin its water radio exploration.

On-air examples at the time included "StarDate" (Sand Points 2024) and "The Environment in Focus" (WYPR 2024), showing how a short, regular science segment could fit within a radio station's daily format. Additionally, the weekly "Puzzler" on "Car Talk" was a model for using a question to introduce a short informative segment (Brody and Connearney 2021; CarTalk Digital Inc. 2024). The presence of those shows on public radio stations offered the possibility that a short, water-focused show might appeal to Virginia stations. Beyond the radio broadcast possibility, the availability and growing popularity at the time of blogging (NDMU 2018) and podcasting (Strickland et al. 2021; Berry 2022; Bonini 2022; Chivers et al. 2023) offered affordable means to make a regular audio segment and accompanying information widely available online.

Producing Virginia Water Radio

The VWRRC's media specialist and I began developing VWR in summer 2009, and I recorded the first episode on January 22, 2010. The media specialist created a site on Blogger (a Google-owned blog-hosting site, online at https://www.blogger.com/about/) to host each episode's audio file (MP3 format) and accompanying show notes; the VWR site is http://www.virginiawaterradio.org/. A blog format was chosen to allow each episode to be presented individually, to make episodes easily accessible by number and date, to allow tabs for complementary pages, and to allow presentation of additional information. That information typically included acknowledgments of any special assistance; sources of sounds, music, or images; references; a list of related VWR episodes; and a list of Virginia Standards of Learning that might be supported by information in the episode (VA Dept. Ed. 2024). (Note that Standards of Learning are often referred to as SOLs, but that abbreviation is not used in this paper).

VWR has used episodes of two different formats and lengths. The first, longer format of about eight minutes continued through the first 66 episodes (until June 2011). This format included about four minutes of water-related news, about three minutes of notices about upcoming water-related Virginia government meetings, and an approximately two-to-three-minute segment on water-related sounds or music. The long format used information that I was already compiling for the VWRRC's bimonthly newsletter (*Virginia Water Central*, https://www.vwrrc.vt.edu/publications/) and for a blog on news, events, and information resources (Virginia Water Central News Grouper, https://vawatercentralnewsgrouper.wordpress.com/). By 2011, we had decided that the long format would be hard to maintain weekly, featured too much of one voice, and was not adequately entertaining. So, starting with Episode 67 (June 6, 2011), we based the show specifically on the sounds and music segment, with the following basic format: opening of sound, music, or guest voices introducing the episode topic; VWR host comments (averaging around 300 words) on the topic; and a short closing sample of the sound or music again. This short format resulted in episodes of three-to-six minutes. Episodes were done weekly from January 2010 through April 2022, and biweekly thereafter until February 2024. Figure 1 illustrates the basic details of the show, as presented in a promotional flyer from 2015.

Recording the show took place in the following locations: first, a soundproof recording room available for public use on the Virginia Tech campus in Blacksburg; second, a professional-grade, soundproof recording room used by Virginia Tech's University Relations; third, my work office on the Tech campus; and finally, a room in my home. Recording in the two soundproof rooms was done with mounted microphones and the Pro Tools recording and editing software (https://www.avid.com/pro-tools). Recording in my office space and home was done with a desktop Blue Yeti Professional USB Microphone (purchase price of ~$130 in 2017) and free Audacity software for recording and editing (https://www.audacityteam.org/). Audio files were edited to remove room background sound and clicks or other stray noises, to create a consistent volume for voice and sounds or music, and to ensure playback through standard laptop speakers was of reasonable quality. Audio files were saved in WAV format and then converted to MP3 format using software by NCH (https://www.nchsoftware.com/index.html). The MP3 files are stored online by Virginia Tech.

Figure 1. Flyer used to introduce and promote Virginia Water Radio, as of 2015.

From 2010 to 2011, the VWRRC media specialist did the work of producing the blog entry, using the audio file and text that I produced. From 2011 through 2024, I did all aspects of the show. Average time spent per episode from October 2016 (when record-keeping began) to February 2024 was 11.4 hours per week (ranging from 2.25-30.5 hours), or 0.29 full-time equivalent (FTE).

Sounds used in the show were obtained in four ways: recorded by me with a mobile phone or with a Zoom H1 Handy Recorder (purchase price of about $100 in 2011); recorded occasionally by other Virginians; gathered from public-domain sources, such as the U.S. Fish and Wildlife's National Digital Library (https://digitalmedia.fws.gov/); or gathered from non-public-domain sources that granted permission for use (e.g., Elliott et al. 1997; VDGIF 2008). When making my own recordings, practices to achieve reasonable sound quality included trying to avoid windy conditions when getting field recordings, recording segments of adequate length to allow for later selection and editing, and making and previewing several takes when recording guest voices. For both my recordings and those from other sources, as necessary I used Audacity software editing features to select segments, reduce noise, or adjust volume.

Music sources were recordings for which musicians granted VWR permission for use, recordings made specifically for VWR, and recordings in the public domain. Acknowledgment of sound and music sources and permission to use was given in the episode audio, online show notes, or both.

Occasionally I received the following kinds of assistance: episode research and writing from Virginia Tech students doing internships at the VWRRC; sound recordings from people in different parts of Virginia; and guest voices from Blacksburg neighbors, Virginia Tech co-workers, and middle- and high-school students (from various Virginia localities). For some episodes, faculty members at Virginia Tech or other experts were asked to review scientific content for accuracy, clarity, or both.

The first VWR episode was included in a January 27, 2010, broadcast on WEHC-FM at Emory and Henry College (Emory, Virginia), as part of an hour-long, student-produced show on the environment. Eventually WEHC began to broadcast VWR as a stand-alone segment, and the station continued to do so through VWR's final regular episode in February 2024. From 2013 to 2015, the show usually aired weekly on WUVT-FM at Virginia Tech, and from 2014 through 2024, it was aired weekly by WVRU-FM at Radford University (Radford, Virginia). E-mail requests to have the show broadcast by other radio stations were made on several occasions from 2011 to 2015.

Each completed episode was announced on the VWRRC Facebook and Twitter pages (not continued after Twitter's change to X, due to changes by that social media platform). Starting in September 2017, VWR was made available on Apple Podcasts.

In 2014 to 2015, science curriculum coordinators at Virginia school divisions were e-mailed a chart listing water-related items in Virginia's Science Standards of Learning and VWR episodes that might support teaching and learning of those standards. The coordinators were asked to distribute the information to relevant teachers and to notify VWR if they wished to receive a weekly e-mail announcing new episodes.

Page views of the VWR blog site were monitored, starting in August 2013, with the StatCounter service. The number of downloads for podcasts, starting in September 2017, was provided by Apple Podcast Analytics.

Outcomes

Episode Inventory

Table 1 summarizes the dates, formats, and frequency of VWR's 674 episodes from January 2010 to February 2024. The sound and music segments of about 50 of the first 66 episodes (long format) were redone in later short-format episodes, and about 125 of the 608 short-format episodes were revised and redone as later episodes; as a result, the number of *non-repeated* episodes was about 500. Using a combination of new and revised episodes, VWR provided its recipient radio stations with an episode every week from April 2012 through April 2022, and every other week from May 2022 to February 2024.

Topics

As shown in Table 2 (based on the show's online index of episodes at http://www.virginiawaterradio.org/p/index.html), VWR produced episodes in 18 major subject categories, ranging from Amphibians to Weather, covering almost 400 topics within those categories. Examples of topics within a subject category were Wood Frog (Amphibians), Snow Goose (Birds), Virginia General Assembly (Community and Organizations), Water and the Civil War (History), and Buoyancy (Science). Table 2 also shows the number of episodes within each subject category. The following six categories had the highest numbers of episodes: Rivers, Streams, and Other Surface Waters (89 episodes); Overall Importance of Water (74); Science (74);

Table 1. Inventory of Virginia Water Radio episodes from January 2010 through February 2024.

Dates	Episode Numbers	Format (Long = ~8 min.; Short = ~3-6 min.)	Frequency
1-25-10 through 5-16-11	1 - 66	Long	Weekly
6-6-11 through 4-25-22	67 - 626	Short	Weekly
5-9-22 through 2-5-24	627 - 674	Short (except for nine-minute Episode 674)	Biweekly

Table 2. Inventory of Virginia Water Radio topics from June 2011 through February 2024.

Subject Category	Number of Topics	Number of Episodes
Amphibians	21	28
Birds	53	66
Community/Organizations	25	70
Energy	6	10
Fish	8	8
Groundwater	8	9
History	38	57
Insects	16	19
Invertebrates other than Insects	5	11
Mammals	7	9
Overall Importance of Water	30	74
Plants	23	23
Recreation	14	24
Reptiles	7	7
Rivers, Streams, and other Surface Water	48	89
Science	49	74
Water Quality, including Waste Management and Water Treatment	12	20
Weather/Climate/Natural Disasters	24	70
TOTALS		
18	394	NA

Community and Organizations (70); Weather, Climate, and Natural Disasters (70); Birds (64); and History (57). (Note that summing the total number of episodes per subject category in Table 2 is not applicable, because many episodes were indexed into more than one category or topic).

The topics of some episodes were relatively narrow, such as in Episode 79 (9-12-11) on the Piping Plover. Others episodes explored complicated issues or concepts, such as the U.S. Supreme Court's May 2023 ruling on the Clean Water Act, covered in Episode 658 (6-26-23). Several topics were covered in annually recurring episodes, primarily the following: Virginia General Assembly session previews (12 annual episodes); winter weather preparedness (13); Atlantic tropical storm season previews (10); and year-end reviews of sounds and music used that year on VWR (12).

Starting in 2021, VWR began to group similar-topic episodes into Thematic Series. As of the end of regularly scheduled episodes in February 2024, these series included Groundwater (5 episodes), Human Body and Biology (10), Springtime (7), Trees and Shrubs (18), Water in U.S. Civil Rights History (6), Watersheds and River Basins (7), and Winter (12).

Some episodes presented parts of water-related events or science activities. Examples included a public meeting on the Chesapeake Bay Total Maximum Daily Load (TMDL) (Episode 115, 6-18-12), a Clinch River release of freshwater mussels (Episode 435, 8-27-18), dedication of a high-water marker on the New River (Episode 442, 10-15-18), and an information session of the Virginia Household Water Quality Program (Episode 579, 5-31-21).

Work by university students was part of several episodes. Graduate student research, including projects supported by VWRRC grants, was the focus of eight episodes. Examples of topics included avian malaria (Episode 259, 3-30-15), underground streams (Episode 409, 2-26-18), and water utility customers' trust in water suppliers (Episode 564, 2-15-21). One undergraduate student-related episode featured excerpts of water lessons developed and recorded by students in a Virginia Tech water-resources introductory course (Episode 244, 12-15-14).

Sounds, Music, and Guest Voices

All short-format episodes (since Episode 67) featured sounds, music, guest voices, or some combination of these either as the focus of the episode or as an introduction or frame for the episode's information. The most commonly used sounds were those of frogs and water-related birds, Virginia rivers and other water bodies, and weather.

Musical selections were used both as the main focus of an episode (for example, John McCutcheon's "Water from Another Time," in Episode 67, 6-6-11) and as openings and closings for episodes that also included sounds, guest voices, or both (for example, Torrin Hallett's "Geese Piece" in Episode 335, 9-26-16, on the Canada Goose). Our guiding assumption throughout the duration of VWR was that use of appropriate and relevant music would increase the show's aesthetic appeal, add to its entertainment value, and help reveal water's connections to human culture and history. VWR gained permission to use music from several Virginia solo or group musicians with numerous appropriate songs used in dozens of episodes, as well as from several non-Virginia artists whose music was used less frequently. Six musicians recorded music especially for the show; one of these, Torrin Hallett, also composed 16 original pieces for VWR.

Guest voices were a frequent feature of VWR episodes. Examples included an annual episode where Virginia Tech colleagues or Blacksburg residents called out the names planned for the coming Atlantic tropical cyclone season (e.g., Episode 656, 5-29-23), middle school students calling out water cycle terms (Episode 585, 7-12-21), and high school students calling out mayfly names (Episode 367, 5-8-17).

User Data

According to VWR's StatCounter.com account, the number of unique visits to the VWR site from August 13, 2013 (the start of the StatCounter account) to September 11, 2024, was 20,927, equivalent to 5.2 per day (according to StatCounter calculations) or about 36 per week. Short time periods (a few seconds) reported between page views for certain visitors imply that some of the visitors recorded by StatCounter may not have been legitimate users of the VWR site. Whenever I identified a visitor that seemed non-legitimate, VWR's StatCounter settings were adjusted so as not to record future visits, but the numbers reported here include visits prior to any such settings changes.

According to Apple Podcast Analytics, 1067 plays of various episodes occurred between September 19, 2017 and September 7, 2024, or about three per week. Listener data from radio stations WEHC and WVRU were not available.

One Virginia school division, Montgomery County, Virginia, responded to the water Standards of Learning and VWR episode information sent to science curriculum coordinators in 2014-15, asking to receive VWR's group e-mails announcing new episodes. We have no other data on use of VWR by Virginia school teachers.

Discussion

Achievements

With VWR, the VWRRC developed and maintained for 14 years an audio product that explored a wide range of water topics relevant to Virginia. Using approximately a quarter-time staff FTE, VWR provided two radio stations with a weekly (then biweekly) audio file and provided online users with a detailed blog post accompanying the audio. Sounds acquired at Virginia sites and music about Virginia or by Virginians added state-specific enhancements to each episode. Collaborations with musicians, based on getting permissions and giving prominent acknowledgments, made available a range of musical selections. The show offered writing and speaking experience for university students, a medium for presenting student research, and opportunities for K-12 students, university employees, and local residents to participate as guest voices.

Challenges

The VWRRC's original goal for VWR was to have it available statewide via radio broadcast, but this goal was not achieved despite repeated communications to stations, primarily in the first few years of the show. In addition, visits to the VWR blog site (about 36 per week) and podcast downloads (about three per week) were low. We do not have data on whether these two outcomes were due to the content, length, presentation, or some other reason. The available VWRRC staff time for VWR was required mostly for producing the show: writing concise, informative, and interesting scripts, and recording high-quality audios, were the show's main goals and a significant challenge. The time needed for producing the show limited the opportunities for promotion and for gathering robust evaluation data that might have identified factors behind the show's low numbers of blog visits and podcast downloads.

The potential to gather sounds outside of the Blacksburg area was also limited by available staff time and travel funds. Gaining permission to use certain music was not possible given weekly deadlines or inability to contact musicians. These factors put some limits on potential topics, given the show's sound and music foundation.

Based on these achievements and challenges, I offer below eight key questions that water centers or institutes considering an audio-based information product might want to consider, along with VWRRC's relevant experiences.

Questions for Potential Audio Shows and What VWRCC Experienced with Virginia Water Radio

1. Can an audio product add value to programs of a state water center or institute? In our experience, VWR created an inventory of short information pieces on many water-related topics; that inventory will be available if the VWRCC needs quick access to such information in the future. VWR also helped identify connections between water and a variety of subjects and current issues, for example, the role of water in U.S. civil rights history. Such connections may help the VWRRC identify new ideas and needs for research or outreach.

2. Does the center or institute have adequate staffing to produce, promote, and evaluate an audio product? In our experience, production of a weekly or biweekly episode consumed most of the available staff time, leaving inadequate time for promotion and evaluation. We did engage in various promotion activities, such as contacting radio stations and Virginia school divisions, but

we did not have time for follow-up activities that might have improved responses and the show's reach. We spent considerable time and effort in evaluating the accuracy of VWR episodes (documented in episodes' reference lists and acknowledgment of assistance by subject experts), but lack of formal evaluation by listeners was one of the weaknesses of the program. For water centers and institutes considering or implementing an audio product, a potential model for evaluation could be that described by Chivers et al. (2023), building on the work of Cash et al. (2003). They suggest a framework of four criteria for evaluating science communications: credibility, relevance, legitimacy, and accessibility. Applying the criteria to videos and podcasts, Chivers et al. (2023; pp. 176-177) described the four criteria as follows: credibility refers to "validity, accurateness, and quality of videos and podcasts"; relevance "refers to how salient [or important] a video/podcast is" to a user's needs; legitimacy refers to the source of the information and to whether there is a "presentation of balanced views"; and accessibility refers both to the perception by users of how physically accessible a video or podcast is, and to "whether the content is accessible in terms of their knowledge requirements and learning preferences." From the VWR experience, I suggest adding aesthetic value as a key feature for some audiences. This framework offers a structure for evaluating the quality of a product, in addition to user statistics. The framework could be incorporated into various evaluation tools, such as episode reviews by water scientists and practitioners, outreach to radio stations on what formats meet their needs, and surveys of citizens, teachers, or other groups.

3. What frequency of episodes is desirable, and can the show be maintained consistently? For VWR, a weekly schedule allowed covering more topics and a quicker response to current events, but the weekly deadline became difficult to sustain over a long period, particularly with limited staff time. The switch to a biweekly schedule for VWR offered more time to work on long-term projects, find sounds, get music permissions, record guest voices, obtain adequate and correct information, and retain energy and enthusiasm for the project. Regardless of frequency, though, having a regular schedule was important for meeting radio station expectations and presenting the public with a reliable product.

4. What duration of episodes will help meet the goals of a center or institute? Long, medium-length, or short segments all have advantages and disadvantages depending on purpose, content, intended audience, and available resources (Osborne 2023). In our experience, the three-to-six minute format was sustainable and flexible enough to accommodate many subjects and their related sounds and music. An important unresolved question is what impact that time format had on radio station acceptance of the show or on podcast listener levels.

5. Do sounds and music increase the value and reach of a water-related audio show? This was VWR's fundamental assumption, and we considered it the essence of the show, but we did not evaluate this formally. VWR's experience offers an example for other centers and institutes interested in how they might use sounds and music to accompany the information they provide to their citizens.

6. How can collaborators add value to the audio product? VWR benefitted from collaborations for getting music, expanding the geographic range of sounds, having various guest voices, and reviewing episode drafts for accuracy. The early partnership with WEHC helped VWR get started and, if the station's facilities had been nearby, might have brought additional benefits of recording space, access to music, and promotion.

7. Can the center or institute get the equipment needed? In our experience, equipment was not a big barrier. VWR's microphone for episode recording was inexpensive but highly effective; a laptop computer was the recording and editing device; the editing software was free (although one could pay for a more advanced brand); the mobile recorder was a phone or a relatively inexpensive hand-held field recorder; and the recording quality in an office and home was adequate, although a recording studio—if available—can offer better quality and more recording options, such as interviews.

8. Does the center or institute have the capacity to stay current in hosting and distribution technology and options? From our experience, this is a vital consideration for product quality, distribution, and

evaluation. A key decision is how one makes a show available, particularly whether to use a blog site, podcast host, or both; each has its advantages (Gunn 2024). A likely challenge is needing to respond when technology changes; for example, VWR chose an accessible blog site in 2010, but as podcasting developed, it presented new choices. Cost is an issue: podcast hosts typically have monthly fees (Strickland et al. 2021).

Conclusion

Affordable tools exist for water centers and institutes to use audio to provide information about water and other natural resources. Broadcasting offers possibilities if a center or institute can collaborate with one or more radio stations, while podcasting presents broad options for formatting, frequency, and distribution of audio products. The 14-year experience of VWRRC's VWR raises questions and provides lessons about content, production, and distribution for other centers and institutes considering audio as an alternative way to tell their state's water story.

Acknowledgements

The author thanks Patrick Fay, Lesley Howard, Daniel McLaughlin, and Kevin McGuire for their advice and assistance with this manuscript; Kevin McGuire and Stephen Schoenholtz for long-time support of Virginia Water Radio; and many collaborators for helping make Virginia Water Radio possible. The work reported in this paper was supported by the federal Water Resources Research Act through the U.S. Geological Survey and by the Virginia Water Resources Research Center. The views expressed in this paper are solely those of the author and do not necessarily reflect those of the funding agencies.

Author Bio and Contact Information

Alan Raflo is a research associate at the Virginia Water Resources Research Center, where he has worked since 1997 on the center's newsletter, inventories of state water legislation, responses to citizen enquiries, and other water-information projects. He has an M.S. in Water Resources from Iowa State University and a B.S. in Economic Biology from Clemson University. He can be contacted at araflo@vt.edu, or 210 Cheatham Hall (0444), Virginia Tech, Blacksburg, VA 24061, USA.

References

Berry, R. 2022. What is a podcast? In: *The Routledge Companion to Radio and Podcast Studies*, M. Lindgren and J. Loviglio (Eds.). Routledge, London, Chapter 40.

Bonini, T. 2022. Podcasting as a hybrid cultural form between old and new media. In: *The Routledge Companion to Radio and Podcast Studies*, M. Lindgrenand and J. Loviglio (Eds.). Routledge, London, Chapter 2.

Brody, S. and P. Connearney. 2021. 'Car Talk' Ends Its Radio Run. Here's What Ray Magliozzi Hopes You'll Remember. WBUR, Boston, MA, September 25, 2021. Available at: https://www.wbur.org/news/2021/09/25/car-talk-click-clack-ray-tom-magliozzi. Accessed June 24, 2024.

CarTalk Digital Inc. 2024. Car Talk. Available at: https://www.cartalk.com/. Accessed June 24, 2024.

Cash, D.W., W.C. Clark, F. Alcock, N.M. Dickson, N. Eckley, D.H. Guston, J. Jäger, and R.B. Mitchell. 2003. Knowledge systems for sustainable development. *PNAS* 100(14): 8086-8091. Available at: https://www.pnas.org/doi/full/10.1073/pnas.1231332100. Accessed June 28, 2024.

Cech, T.V. 2009. *Principles of Water Resources: History, Development, Management, and Policy*, 3rd Edition. John Wiley & Sons, Inc., Hoboken, N.J.

Chivers, C-A., K. Bliss, A. de Boon, L. Lishman, J. Schillings, R. Smith, and D.C. Rose. 2023. Videos and podcasts for delivering agricultural extension: Achieving credibility, relevance, legitimacy and accessibility. *Journal of Agricultural Education and Extension* 29(2): 173-197. Available at: https://doi.org/10.1080/1389224X.2021.1997771. Accessed June 5, 2024.

Commonwealth of Virginia. 2024. Code of Virginia § 23.1-2628. Available at: https://law.lis.virginia.gov/vacode/title23.1/chapter26/section23.1-2628/. Accessed September 12, 2024.

Elliott, L., D. Stokes, and L. Stokes. 1997. *Stokes Field Guide to Bird Songs: Eastern Region*. Little, Brown and Company, Boston, MA.

Gunn, D. 2024. Blog vs. Podcast: Which One is Better for You and How to Decide. BloggingPro, January 22, 2024. Available at: https://www.bloggingpro.com/blog-vs-podcast/#gref. Accessed June 14, 2024.

Notre Dame of Maryland University (NDMU). 2018. History of Blogging. Available at: https://online.ndm.edu/news/communication/history-of-blogging/. Accessed June 24, 2024.

Osborne, A. 2023. 5 Ways Podcast Length Impacts Listener Engagement. CoHost, November 2, 2023. Available at: https://www.cohostpodcasting.com/resources/branded-podcast-length-impacts-engagement. Accessed September 5, 2024.

Sand Points Arts and Cultural Exchange (Sand Points). 2024. Space 101.1 FM/StarDate. Available at: https://www.space101fm.org/program/stardate/. Accessed June 24, 2024.

Strickland B.K., J.M. Brooke, M.T. Zischke, and M.A. Lashley. 2021. Podcasting as a tool to take conservation education online. *Ecology and Evolution* 11(8): 3597-3606.

U.S. Census Bureau (US Census). 2024. Virginia. Available at: https://data.census.gov/profile/Virginia?g=040XX00US51. Accessed June 21, 2024.

U.S. Geological Survey (USGS). 2024. Water Resources Research Act Program. Available at: https://www.usgs.gov/programs/water-resources-research-act-program. Accessed June 21, 2024.

Virginia Department of Education (VA Dept. Ed.). 2024. K-12 Standards and Instruction. Available at: https://www.doe.virginia.gov/teaching-learning-assessment/instruction. Accessed June 19, 2024.

Virginia Department of Environmental Quality (VA DEQ). 2024. Draft 2024 Integrated Report. Draft 305(b)/303(d). Richmond, VA. Available at: https://www.deq.virginia.gov/our-programs/water/water-quality/assessments/integrated-report. Accessed June 21, 2024.

Virginia Department of Game and Inland Fisheries (VDGIF) and Lang Elliott/NatureSound Studio. 2008. The Calls of Virginia Frogs and Toads Compact Disc. Virginia Department of Wildlife Resources (formerly VDGIF), Richmond, VA.

Virginia Water Resources Research Center (VWRRC). 2024a. History and Mission. Available at: https://www.vwrrc.vt.edu/about/. Accessed June 21, 2024.

Virginia Water Resources Research Center (VWRRC). 2024b. Publications. Available at: https://www.vwrrc.vt.edu/publications/. Accessed June 21, 2024.

WYPR. 2024. The Environment in Focus. Available at: https://www.wypr.org/show/the-environment-in-focus. Accessed June 24, 2024.

Universities Council on Water Resources
Journal of Contemporary Water Research & Education
Issue 182, Pages 29-34, April 2025

Research Note

Water as a Natural Souvenir

Grace Winningham

Institute for Water & Watersheds, Oregon State University

Abstract: This research note explores the significance of natural souvenirs in tourism, emphasizing their contribution to cultural and environmental sustainability. Through a mixed-methods approach including a literature review and oral histories, the study examines how natural souvenirs, particularly water-based ones, foster souvenir-person-place bonding, enhance destination branding, and promote sustainable tourism practices. The findings highlight the unique and authentic nature of water souvenirs, which serve as powerful reminders of travel experiences and strengthen emotional connection to destinations. Additionally, the study discusses the role of natural souvenirs in differentiating destinations, leveraging unique attributes for branding, and stimulating interest through word-of-mouth marketing. Also addressed are concerns about environmental impact, advocating for responsible collection practices that support conservation and local economies. Overall, this study underscores the ability of water souvenirs to enhance the tourism experience while promoting the preservation of cultural and natural heritage.

Keywords: *place-based souvenirs, mementos, spirituality, sustainable tourism*

A significant aspect of tourism is the collection of natural souvenirs: an item gathered from nature, such as a shell, rock, flower, or a handful of sand. Unlike mass-produced mementos, each natural souvenir carries with it a piece of the place from which it was collected, adding a level of uniqueness and authenticity to the object. People collect natural souvenirs during outdoor activities such as hiking, camping, or walking along the beach, or while traveling great distances for religious pilgrimages. Beyond sentimental value, they can be used for decorative purposes, incorporated into art, displayed as a reminder of the beauty of the natural world, or provide a connection to spirituality. Given the popularity of this practice, especially in an era of increasing awareness of sustainability, it is crucial to investigate the broader implications of natural souvenir collection on tourism and the environment. How do natural souvenirs, particularly water-based ones, foster a stronger souvenir-person-place bond, enhance destination branding, and promote sustainable tourism practices? Understanding these dynamics is critical for informing sustainable tourism practices that minimize environmental harm while maximizing economic and cultural benefits for local communities. The purpose of this research is to qualitatively explore how natural souvenirs contribute to cultural and environmental sustainability, emphasizing water souvenirs and their role in souvenir-person-place bonding, promoting destination branding, and supporting sustainable tourism.

Methods

A comprehensive literature review was conducted to gather existing knowledge on the role of natural souvenirs in tourism, their impact on cultural and environmental sustainability, and their significance in destination branding and sustainable tourism practices. Prior research was identified using Google Scholar as the primary search platform, employing key phrases such as “souvenir,” “natural souvenir,” “sustainable tourism,” “destination branding,” and “destination

Research Implications

- Water is a natural souvenir to memorialize an event, place, or spirituality.
- Water souvenirs are important to local economies.
- Water souvenirs define the identity of geographic locations.

marketing." All sources directly or adjacently related to the field of natural souvenirs were selected for review, and notably all literature had been published later than 2011, highlighting the recency of this subtopic within tourism research. The review included academic journals, books, and credible online sources. Key topics explored in the literature review included the concepts of souvenir-person-place bonding, the economic and cultural implications of natural souvenirs, and the environmental considerations associated with their collection and commercialization. Significant gaps were identified in the literature, specifically a lack of articles focused specifically on natural souvenirs, and no mention of water-based souvenirs. A 2022 literature review on souvenirs in tourism (Li 2023) makes no mention of water-based souvenirs, highlighting a gap in both water and tourism research.

Oral histories were gathered from two subjects who voluntarily reached out to Oregon State University. These stories were included in the research to provide qualitative insights into the personal experiences of individuals who have collected natural souvenirs during their travels. The histories were analyzed to explore recurring themes and personal narratives related to natural souvenir collection. The information collected was combined with findings from the literature review in a mixed-methods approach which allowed for a more holistic understanding of this understudied topic.

Results

Souvenir-Person-Place Bonding

Souvenir-person-place bonding refers to the intricate relationships between the three concepts, highlighting how souvenirs serve as tangible reminders of a traveler's experiences and memories associated with a particular destination. Souvenirs play a crucial role in tourism by allowing individuals to recall memorable experiences, often through items that are uniquely tied to the place visited (Swanson and Timothy 2012). In a similar fashion, natural souvenirs - such as shells, rocks, and small samples of water or sand - serve as powerful reminders of the place-based natural environment. Mass-produced items, on the other hand, tend to simply bear the name of a destination, rather than embodying the authentic essence of the natural heritage of a geographic location (Pabian et al. 2020).

Effective souvenir-person-place bonding requires souvenirs that are unique and authentic, reflecting the local culture, environment, and traditions. This authenticity enhances tourist satisfaction, fosters a deeper connection with the destination, and supports the sustainability of cultural and natural heritage through responsible tourism practices (Duan et al. 2023). By representing the unique and tangible attributes of a place, natural souvenirs play a crucial role in maintaining the cultural and environmental integrity of tourist destinations.

This connection rings especially true for Suzanne Bircher who took a road trip by car with three girlfriends from the University of North Carolina at Charlotte, north to Canada and then back down and across the United States to Coos Bay, Oregon. "The trip I took in 1971 was the biggest trip of my life," she recalls, "That is where I saw the Pacific Ocean for the first time, and that has been my only trip to the West Coast." As a memento of the journey, Suzanne filled an empty apple juice bottle with some sand and ocean water. Fifty-three years later, the bottle remains, sitting atop her dresser. "I don't know if you have seen the East Coast beaches or the Appalachian Mountains," she adds, "but they are very different than the West Coast mountains and beaches. I guess I kept my saltwater souvenir because the memories of that trip have stayed with me for a lifetime, and I am a bit of a pack rat."

Suzanne's story underscores how authentic and unique souvenirs, particularly those derived from the natural environment, contribute to enhancing tourist satisfaction and establishing a deeper connection with a destination. Her saltwater souvenir addresses the gap in literature by demonstrating how water-based natural souvenirs can foster a long-term emotional bond with a place, acting as a powerful reminder of personal experiences. This highlights how natural sample collection can play a crucial role in honoring the environmental integrity of a place, preserving both fond memories and a deep respect for the West Coast's natural landscapes.

Destination Branding

Destination branding (place branding) refers to the creation and maintenance of a strong place identity that differentiates itself from that of competitors (Ruiz-Real et al. 2020). And what is more distinctive and unique than a natural souvenir that represents the inherent features of a geographic location? Natural souvenirs create emotional connections with a destination, enhancing the experience for tourists, and serving as a constant reminder of the memories made on their trip - perhaps even prompting a revisit. When travelers return home with natural souvenirs, they can serve as conversation starters, prompting discussions about the trip and generating interest in the destination through word-of-mouth marketing, which can be a powerful tool for destination branding.

Geologist Todd Jarvis helped a small community in Utah site a new well targeting an undeveloped limestone aquifer on the western slope of the Uinta Mountains in 1998. The well was drilled to approximately 1,600 feet and suddenly started flowing water at the ground surface. "Being that the well location was a few hundred feet higher in elevation than the nearby Weber River, it was a surprise the well flowed. During the course of well and aquifer evaluation, the water tasted better than any of the other wells I had worked on over the previous 15 years of my career in groundwater engineering. I collected many samples of the water for analyses for drinking water quality. But the well flowing at such a high elevation above the Weber River suggested the water may not be hydraulically connected to the river, so I also had water samples age dated which suggested "old" or "fossil water" on the order of 20,000 years. Town residents referred to the water as dinosaur water or springs of eternal life once they learned more about the new well. I suggested the town consider marketing the water to a bottled water company, which it did, and it was marketed as the most expensive bottled water in the United States. The well and flowing water was so unique that I collected my own sample in an iced tea bottle that I still have after 25 years."

Destination marketing organizations themselves can leverage natural souvenirs as promotional tools to attract tourism. Gift shops and tour experiences in Israel boast opportunities to purchase or collect small vials of water from the Jordan River which resonate with religious tourists and enhance the destination's branding as a site for spiritual pilgrimage (Jerusalem Spirit Gift Shop n.d.). Similarly, salt and mud from the Dead Sea are renowned for their therapeutic properties due to the high mineral content. These properties are highlighted in promotional campaigns that emphasize the health and wellness benefits of visiting the region (Tourist Israel 2012). The Fountain of Youth in St. Augustine, Florida is another example of the ways in which water souvenirs define the identity of geographic locations and add value to local economies - charging upwards of $20 USD for adult admission to see the Fountain (St. Augustine Ponte Vedra 2024). Beyond the physical location, hundreds of listings appear on eBay advertising bottles of water collected from the Fountain of Youth (eBay 2024).

In short, natural souvenirs can serve as mementos from places of significant cultural and religious importance, offering visitors unique opportunities to connect with the destination, and enhancing the marketability of a place.

Sustainable Tourism

Sustainable tourism emphasizes the need to minimize the negative impacts of tourism on the environment while maximizing the benefits for local economies. A research study of natural souvenir collection in Poland found that 80.7% of young people on tourist trips bring souvenirs back home, and 61.4% collect natural souvenirs (Pabian et al. 2020). Even in the age of technology and mass production, natural souvenirs continue to be collected and cherished by even the younger generations. This research study, however, goes on to take a negative stance toward the collection of natural souvenirs suggesting its violation of the law, potential hazards to life and health, and destruction of the environment (Pabian et al. 2020). Although it is always important to check local laws and regulations or consult park rangers or other authorities before collecting natural souvenirs, the article provides no evidence that all natural souvenirs are harmful or destructive.

In fact, natural souvenirs can play a significant role in promoting sustainable or ecotourism by encouraging responsible travel behaviors and fostering environmental awareness. The Global Ecotourism Network (GEN) defines ecotourism as “responsible travel to natural areas that conserves the environment, sustains the well-being of the local people, and creates knowledge and understanding through interpretation and education of all involved (visitors, staff, and the visited)” (Global Ecotourism Network 2016). One of the primary ways natural souvenirs contribute to sustainable tourism is by promoting the responsible collection and consumption of natural resources. Tourists who collect natural souvenirs can often develop a deeper appreciation for the environment and its preservation, which can lead to more environmentally conscious behaviors, both during their travels and when they return home. Through encouraging tourists to directly engage with nature, destinations can foster a greater understanding of the importance of conservation efforts, and the need to protect natural habitats.

In addition to the promotion of environmental awareness, natural souvenirs can support the livelihoods of local communities by creating economic opportunities related to sustainable tourism practices (Soukhathammavong and Park 2019). Local artisans and businesses, for example, can craft and sell items made from natural materials that are authentic to the region, helping discourage the wasteful mass production of ordinary souvenirs made of toxic or environmentally harmful materials.

Interpreting Results

The findings above underscore the critical role of water in forming a bond between souvenir, person, and place. This triadic relationship highlights how souvenirs act as physical embodiments of travel experiences, creating a tangible connection to the memories associated with a destination. The narrative of Suzanne Bircher vividly illustrates this phenomenon - her retention of a bottle filled with sand and water from the Pacific Ocean for over fifty years exemplifies how natural souvenirs can evoke powerful, enduring memories. This case demonstrates that natural souvenirs carry an authenticity and personal significance that mass-produced items often lack. The ability of such souvenirs to capture and retain the essence of a place supports the idea that they can significantly enhance tourist satisfaction and deepen the emotional connection to the destination. This bond not only enriches the tourist experience but also promotes the sustainability of cultural and natural heritage through responsible tourism practices, as noted by Duan et al. (2023).

The role of water souvenirs in destination branding is particularly noteworthy, serving as distinctive and authentic representations of a location, differentiating it from other destinations. The example of Todd Jarvis and “dinosaur water” from Utah illustrates how a unique natural feature can be leveraged to create a compelling brand identity. By marketing the well water as the most expensive bottled water in the United States, the town capitalized on its unique attributes to attract attention and visitors. This approach not only enhances the destination’s brand, but also fosters a deeper connection with visitors, who bring home a piece of the place in the form of a natural souvenir. Similarly, the marketing of Jordan River water and Dead Sea mud highlights how natural souvenirs can be integrated into promotional strategies to enhance a destination’s appeal, especially for religious and wellness tourism. These examples demonstrate that natural souvenirs can play a significant role in word-of-mouth marketing, as tourists share their unique finds to others, thereby generating interest and potentially attracting more visitors.

In addition, the discussion around sustainable tourism and natural souvenirs presents a more nuanced perspective. While some studies express concerns about the environmental impact of natural souvenir collection, evidence suggests that responsible collection practices can mitigate these risks. The study by Pabian et al. (2020) points to a high prevalence of natural souvenir collection among young tourists in Poland, indicating a continuing interest in these items despite the availability of mass-produced alternatives. This interest underscores the importance of promoting responsible collection practices to ensure sustainability. By fostering an appreciation for the environment among tourists, natural souvenirs can promote conservation efforts and highlight the importance of protecting natural habitats. Furthermore, the economic opportunities created for local artisans and businesses through the sale of natural souvenirs can support sustainable tourism practices and reduce reliance on mass-produced, environmentally harmful souvenirs.

Discussion

The concept of water souvenirs fits neatly into the framework of ecosystem services, particularly within the category of cultural services, which emphasizes non-material benefits that people obtain from ecosystems through spiritual enrichment, cognitive development, and aesthetic experiences (Ryfield et al. 2019). Water, as a natural souvenir, provides individuals with a tangible link to a place, fostering a deep emotional connection to natural landscapes and experiences. This connection can enhance appreciation for natural environments and encourage behaviors that promote their preservation. In the context of sustainable tourism, water-based souvenirs offer a unique opportunity to highlight a destination's natural heritage, providing a sense of place and potentially enhancing tourist satisfaction.

However, there are limitations to the study. A significant gap exists in research specifically focused on natural souvenirs, with water-based souvenirs being especially underexplored. The lack of literature on this topic provides limited historical context on the longstanding practice of natural souvenir collection. The keywords chosen may have led to the exclusion of older studies or studies in other disciplines that could have applications to water souvenirs.

Additionally, the reliance on oral histories, while valuable for providing qualitative insights, limits the generalizability of the findings. The small sample size and self-selecting nature of the oral histories may have introduced biases, as those who choose to share their stories may have particularly strong emotional attachments to their souvenirs, which may not reflect the experiences of a broader population. This highlights the need for more diverse data collection methods, such as surveys or case studies, that can provide a more comprehensive understanding of the topic.

Conclusion

This study aimed to explore how natural souvenirs, particularly water-based ones, foster souvenir-person-place bonding, enhance destination branding, and support sustainable tourism. Through a mixed-methods approach that combined a literature review and oral histories, it was found that water souvenirs play a unique role in preserving memories, fostering emotional connections to destinations, and promoting sustainable tourism practices. These souvenirs allow travelers to bring home a piece of the natural environmental, providing authentic reminders of their experiences while promoting a deeper appreciation for the cultural and environmental heritage of the places they visit.

The findings indicate that water souvenirs not only enrich the tourist experience but also contribute to destination branding by leveraging unique environmental features. Moreover, by encouraging responsible collection practices, water souvenirs can align with the principles of sustainable tourism, ensuring that future generations can continue to engage with these meaningful mementos without harming the environment.

Looking ahead, it is evident that additional research is necessary to fully understand the impact of natural souvenirs on the environment and local economies. Future studies should research the history of natural souvenirs and their cultural importance through time, the broader environmental impacts of natural souvenir collection, and best practices for the sustainable collection and commercialization of these souvenirs. Natural souvenirs hold the potential to shape the future of tourism in a way that honors and protects the natural world, which makes it especially important to continue to invest time and research into these precious physical representations of the environment and the memories made in it.

Acknowledgements

Funding for this research was derived from a grant to Oregon State University through Section 104(b) of the Water Resources Research Act.

Author(s) Bio and Contact Info

Grace Winningham is a fourth-year undergraduate honors student at Oregon State University double majoring in Environmental Science & Economics. Her previous research efforts focused on media portrayals of natural gas, and she is especially interested in topics that intersect environmental and economic issues. She will graduate in June 2025. Contact Grace at gracewinningham4@gmail.com or by mail at Institute for Water and Watersheds, 234 Strand Agricultural Hall, Oregon State University, Corvallis, OR 97331.

References

Duan, Z.Y., S.-K. Tan, S.-W. Choon, and M.Y. Zhang. 2023. Crafting a place-based souvenir for sustaining cultural heritage. 2023. Heliyon (5): e15761. Available at: https://doi.org/10.1016/j.heliyon.2023.e15761. Accessed October 28, 2024.

eBay. 2024. Fountain of Youth Water for Sale. Available at: https://www.ebay.com/sch/i.html?_from=R40&_trksid=p4432023.m570.l1312&_nkw=fountain+of+youth+water&_sacat=0. Accessed October 28, 2024.

Global Ecotourism Network. 2016. What Is (Not) Ecotourism. Available at: https://www.globalecotourismnetwork.org/what-it-is-not-ecotourism/. Accessed October 28, 2024.

Jerusalem Spirit Gift Store. No date. Jordan River Water. Available at: https://jerusalem-spirit.com/collections/jordan-river-water. Accessed October 28, 2024.

Li, F. 2023. Souvenir in tourism research: A literature review and future agenda. Tourism Critiques 4(1/2): 15-27. Available at: https://doi.org/10.1108/trc-09-2022-0022. Accessed October 28, 2024.

Pabian, A., A. Pabian, and A. Brzeziński. 2020. Young people collecting natural souvenirs: A perspective of sustainability and marketing. Sustainability 12(2): 514. Available at: https://doi.org/10.3390/su12020514. Accessed October 28, 2024.

Ruiz-Real, J.L., J. Uribe-Toril, and J.C. Gázquez-Abad. 2020. Destination branding: Opportunities and new challenges. Journal of Destination Marketing & Management 17(1): 100453. Available at: https://doi.org/10.1016/j.jdmm.2020.100453. Accessed October 28, 2024.

Ryfield, F., D. Cabana, J. Brannigan, and T. Crowe. 2019. Conceptualizing 'sense of place' in cultural ecosystem services: A framework for interdisciplinary research. Ecosystem Services 36(April): 100907. Available at: https://doi.org/10.1016/j.ecoser.2019.100907. Accessed October 28, 2024.

St. Augustine Ponte Vedra: Florida's Historic Coast. 2024. Fountain of Youth. Available at: https://www.floridashistoriccoast.com/things-to-do/history/fountain-youth/. Accessed October 28, 2024.

Soukhathammavong, B. and E. Park. 2019. The authentic souvenir: What does it mean to souvenir suppliers in the heritage destination? Tourism Management 72(June): 105-116. Available at: https://doi.org/10.1016/j.tourman.2018.11.015. Accessed October 28, 2024.

Swanson, K.K. and D.J. Timothy. 2012. Souvenirs: Icons of meaning, commercialization and commoditization. Tourism Management 33(3): 489-499. Available at: https://doi.org/10.1016/j.tourman.2011.10.007. Accessed October 28, 2024.

Tourist Israel. 2012. Dead Sea. Available at: https://www.touristisrael.com/dead-sea/289/. Accessed October 28, 2024.

Universities Council on Water Resources
Journal of Contemporary Water Research & Education
Issue 182, Pages 3-11, April 2025

Perspective Piece

The Golden Age of Water (1964-2025)

Dr. Gerald Joseph McAdams Kauffman, Jr.

University of Delaware

Six decades ago, the golden age of water began in the United States when President Lyndon Baines Johnson signed the Water Resources Research Act (WRRA) of 1964. This led to the founding of the National Institutes for Water Resources (NIWR) and Universities Council on Water Resources (UCOWR). Sixty years ago, these two water organizations formed to represent the 54 water research institutes at land grant universities (NIWR) authorized by the WRRA and the over 60 water research institutions of higher learning in North America (UCOWR). This paper traces the 60-year evolution of these associations that conduct water research locally, regionally, and nationally in United States, from the Great Society of the 1960s, the Clean Water Act years of the 1970s and 80s, and the watershed movement of the 1990s into the 21st century.

Overview

The year 1964 was pivital in American history. It was the year of escalation in the Vietnam War and the year of the British Invasion on American airwaves. It was also the year of the Great Society, President Johnson's sweeping vision for social justice policies, based on his predecessor, President John Fitzgerald Kennedy's legacy. On July 2, 1964, he signed the Civil Rights Act, after Congress passed it by 2 1/2 to 1 in the House and 3 to 1 in the Senate. The Act prohibited discrimination based on race, color, religion, sex, and national origin in the workplace and in schools.

In 1964, science and environmental protection were popular with Americans. It developed from the quest for science and a college education with the GI bill, when veterans returned home from World War II. It followed President Dwight David Eisenhower's 1956 push to build the interstate highway system that linked America from coast to coast—America's biggest public works project ever. It followed the space race in 1958 and the Sputnik moment when the Americans and Soviets raced to the moon and President Eisenhower pushed for a change in the way that kids were educated in America in math and science. And it followed the publication of *Silent Spring* in 1962, when marine biologist Rachel Carson wrote a best selling book about the dangers of chemicals in society. President Kennedy, himself a former naval officer with a deep appreciation for the ocean, publicly supported Carson's work and became interested in cleaning up our nation's waters. He followed up on a 1959 report from Senator Mike Mansfield (D-MT) that said water scarcity was the biggest problem in the American West, a 1961 report he commissioned by the National Academy of Sciences recommending more water research and jobs training by our nation's universities, and a 1963 article in the journal *Science* that recommended strengthening our nation's colleges to train more engineers and scientists (Revelle 1963).

Building on President Kennedy's water initiative, on July 17, 1964 President Johnson signed the WRRA that established a network of "water resources research and technology institutes

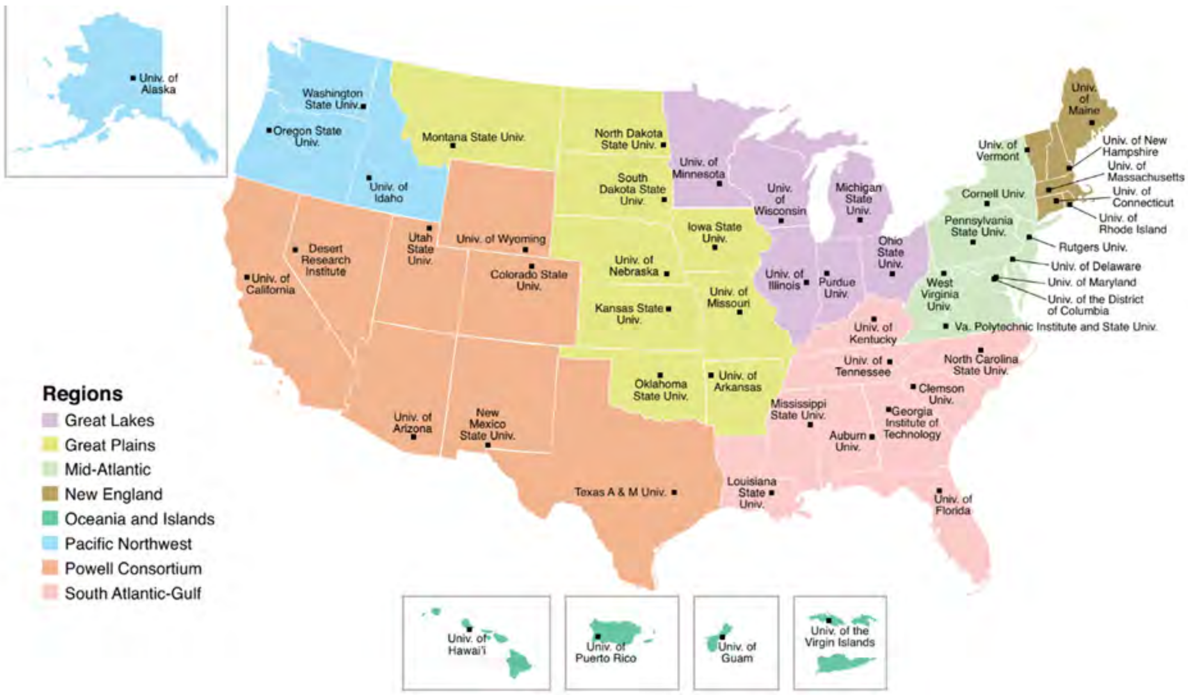


Figure 1. Network of Water Resources Research Institutes in the United States.

or centers…" at public institutions that stretch from Maine on the Atlantic to Micronesia in the Pacific (Figure 1). The 1964 WRRA was based on the 1862 Morrill Act that established land grant colleges and the 1887 Hatch Act that formed state agricultural experimental stations. It was reauthorized in 1984 and in the 2021 Bipartisan Infrastructure Law. The water research institutes are authorized by federal laws passed during the administrations of Abraham Lincoln (1862), Grover Cleveland (1887), Lyndon Johnson (1964), Ronald Reagan (1984), and Joe Biden (2021). The Congressionally chartered land grant water research institutes assist the Nation and States in augmenting their water resources science and technology to: (1) conduct research into the nation's water challenges and (2) train future scientists and engineers for water resources careers. As President Johnson signed the law he said: "abundant, good water is essential to continued economic growth and progress . . . and Congress has found that we have entered a period in which acute water shortages are hampering our industries, our agriculture, our recreation, and our individual health and happiness."

The 1964 WRRA appropriation administered by U.S. Geological Survey (USGS), a science bureau within the Department of the Interior, has been successful over the last six decades. One of the first WRRA research students supported was University of California Los Angeles graduate student Elinor Ostrom who researched regional planning and water wars in Southern California and, after moving to Indiana University, was awarded the Nobel Prize in economics for game theory. The WRRA invests in water resources and river basins that support a trillion dollars of economic activity in the U.S. such as outdoor recreation, agriculture, drinking water, and water-related jobs. (Donohue, Greene, and Lerner 2021). Clean water supports fishing ($42 billion), hunting ($23 billion), and bird watching ($46 billion) and outdoor recreation totaling $140 billion nationally for boating, paddling, and sailing. The Delaware River Basin supports $22 billion in economic activity and 600,000 jobs. The Chesapeake Bay, as the nation's largest estuary, supports a trillion dollar tourism, fishery, and agriculture economy. The Colorado River supplies drinking water for 40 million Americans, a $1.4 trillion economy, 16 million jobs, and 12% of U.S. Gross Domestic Product. The 54 WRRA institutes at our nation's colleges, with over 10 million alumni, supported over 25,000 student water research projects that work to protect the health, safety, and welfare of the American public.

Water research in the U.S. is a national priority. The drought in the East continues into 2025 after six months with little precipitation, a record stretching back to the first National Weather Bureau rain gauges in 1894. Unprecedented flooding from Hurricane Ida in September 2021, Hurricanes Helena and Milton in 2024, and the Ohio River Basin floods in Spring 2025 drove Americans away from their homes in Delaware, Pennsylvania, Florida, North Carolina, and Kentucky. The West saw the worst drought in 400 years, since the Indigenous people and the Spanish lived on the land, and then atmospheric rivers flowed from the Pacific and flooded San Francisco and Seattle. A snow drought continues in the Sierra Nevada in the "water towers of the west." And in the winter of 2025, micro-drought driven wildfires consumed the canyons in Los Angeles along the Pacific.

In 1965, by resolution of the Governor and Delaware General Assembly, the Board of Trustees established the University of Delaware Water Resources Center (UDWRC) on campus with three directors over the years: Dr. Robert Varrin, Chair of the Department of Civil and Environmental Engineering (1965-1995), Dr. Thomas Sims, Dean of the College of Agriculture and Natural Resources (1995-2015), and Dr. Gerald Joseph McAdams Kauffman, Jr., Associate Professor, Biden School of Public Policy & Administration (2015-2025). In 2024, we celebrated the 60th anniversary of the WRRA and in 2025 we commemorate the 60th anniversary of the UDWRC. With federal, state, local, and philanthropic cost sharing, UDWRC supports Delaware, Delaware State University, and Delaware Tech students in water research concerning PFAS (per- and polyfluoroalkyl substances), and lead in drinking water, coastal and riverine flooding, harmful algal blooms, and water economics, all important issues in Delaware and the Delaware and Chesapeake Bay watersheds.

Universities Council on Water Resources (UCOWR)

The 1950's space race turned to an emphasis on math and science here on Earth, but in the 1960's there was little emphasis on hydrology as a science (Scott 1988). In August 1962, Professors David Todd (University of California Berkeley) and Warren Hall (University of California Los Angeles) invited 20 scientists including V. T. Chow (University of Illinois), R. K. Linsley (Stanford University), and M. G. Wolman (Johns Hopkins University) to an intercollegiate symposium to discuss the state of hydrology at Lake Arrowhead, California. The 19 universities at this first conference defined hydrology as "the science that treats the waters of the Earth, their occurrence, circulation and distribution, their chemical and physical properties, and their reaction with the environment, including their relation to living things . . ." On November 26, 1962, 16 universities met to form the Universities Council on Hydrology (UCOH) with membership from Caltech, Iowa, University of California Los Angeles, Idaho, University of Southern California, Washington, Wisconsin, Utah State, Illinois, Colorado State, Cornell, Arizona, Georgia Tech, Stanford, Johns Hopkins, and Michigan State. In 1964, the UCOH reformed as UCOWR to recognize "the interdisciplinary nature of the field."

The mission of UCOWR is to address water resources challenges through sharing expertise, fostering leadership, and developing interdisciplinary collaborations (UCOWR 2025). The Board of Directors is supported by staff at Southern Illinois University in Carbondale, Illinois. UCOWR connects member institutions through conferences and webinars, recognizes water resources scholarship, teaching, and outreach through annual awards, and publishing the *Journal of Contemporary Water Research and Education (JCWRE)*. Over 60 institutions with a water education and research mission in North America are UCOWR members. UCOWR and NIWR cosponsor annual forums such as the Joint 60th Anniversary Conference with AWRA on September 30, 2024 in St. Louis and annual conferences in June 2025 at the University of Minnesota and June 2026 in San Antonio, TX. At the annual conference, the UCOWR Board presents national water awards such as the Warren A. Hall Medal, Friends of UCOWR, Ph.D. Dissertation Awards, Education/Public Service Award, and *JCWRE* Paper of the Year.

National Institutes for Water Resources (NIWR)

Federal action on water resources research goes back to the 1950s and the Eisenhower administration. In 1957, Sol Resnick formed the University of Arizona Institute of Water Utilization and served as director until 1964 when the Arizona Water Resources Research Center was established (AWRRC 2014). In 1959, Senator Mike Mansfield (D-MT) informed the Western Democratic Senators conference that water was the greatest resource problem facing not just the West, but the entire nation. Senators Murray, Mansfield, and Anderson then introduced Senate Resolution 48, recommending water research legislation to the Interior Committee chaired by Senator R. Kerr (D-OK) and Senator T. Kuchel (R-CA).

In January 1961, just before President John F. Kennedy's inauguration, President Eisenhower's Bureau of Budget sent a bill to Congress to establish river basin planning commissions. On February 23, 1961, in a message to Congress, President Kennedy directed the National Academy of Sciences to review federal programs to strengthen their water research capabilities. In 1961, Professors Castle, Burgess, Krygier, and Warren petitioned the Oregon Board of Higher Education to authorize the Water Resources Research Institute at Oregon State University as one of the first water institutes in the nation (Jarvis 2019). In 1962, the WRRA was drafted based on the January 1961 Report of the Select Senate Committee on Water Resources chaired by Senators Kerr and Kuchel (Caulfield 1987). Revelle (1963) wrote in the journal *Science* about a shortage of qualified water research scientists and recommended that Congress and the White House pass new water legislation to strengthen university based water research.

In early 1964, Senator Anderson drafted a WRRA bill (Strong 1964) supported by Dr. J. Fisher (Resources for the Future), Dr. J. Geyer (Johns Hopkins), and Stephen Dedijer, a Russian scientist and emigree who wrote in the *Journal of Atomic Scientists* that scientist knowledge shared by all citizens—not just the elite—is essential to democracy (Caulfield 1987). In Spring 1964, the WRRA was redrafted with Title I water research grants to land grant universities and Title II grants of $1 million to centers of excellence at non land grants, foundations, and public agencies. Hawaii Representative Thomas Gill expressed his concern about depleted water tables, water pollution, and water supplies that make knowledge of water critical to this life source. Interior Committee chair Senator C. Anderson modeled the WRRA after the 1887 Hatch Act that created land grant agricultural experimental stations popular with conservative rural legislators like Representative Compton White of Idaho (Sowards and Lacabanne 2017). Speaking at New Mexico State University, Senator Anderson maintained federal water research was underfunded at 0.7% of budget compared to oil and gas industry research and development at 3%, chemical industry at 6%, and auto industry at 12.5% (Caulfield 1987). Representatives. C. Brown (R-OH), W. Aspinall (D-CO), J. Saylor (R-PA), and O. Teague (R-TX) thought the WRRA would better coordinate federal water research to prevent duplication and hailed universities for diverse expertise with ‘‘an ideal setting for water resources research.’’ In June 1964, the WRRA (HPL 88-379) was supported by Colorado State University President Dr. William Morgan, the Association of Land Grant Colleges and State Universities, Harvard, John Hopkins, Georgia, and Stanford, and Council of State Governments (Caulfield 1987) and Cal Tech professor and UCOH chair Dr. D. Todd (UCOWR 1964) who wrote to the Secretary of Interior and endorsed the WRRA, as it "provided the opportunity to significantly increase . . . research in water resources at universities throughout the United States."

On July 16, 1964 President Johnson signed the WRRA to assist the Nation and States in augmenting their water resources science and technology to: (1) assure supplies of water sufficient in quantity and quality, (2) discover practical solutions to the Nation's water resources problems, (3) assure protection of environmental and social values…with water resources management, (4) promote more effective coordination of the Nation's water resources research program, and (5) promote the development of a cadre of trained research scientists, engineers, and technicians for future water resources problems. President Johnson stated: "The Water Resources Research Act of 1964, which I have approved today, fills a vital need. Abundant, good water is essential to continued economic growth and progress. The Congress has found that we have entered a period in which acute water shortages are hampering our industries, our agriculture, our recreation, and our individual health and happiness…by the year 2000 there will not be enough usable water to meet the water requirements . . . of . . . Arizona, California, Colorado, Delaware, Idaho, Illinois, Indiana, Iowa, Kansas, Louisiana, Michigan, Minnesota, Montana, Nebraska, Nevada, New Jersey, New Mexico, New York, North Dakota, Ohio, Oklahoma, Oregon, Pennsylvania, South Dakota, Texas, Utah, Wisconsin and Wyoming. . . . It will create local centers of water research. It will enlist the intellectual power of universities and research institutes in a nationwide effort to conserve and utilize our water resources for the common benefit. The new centers will be concerned with municipal and regional as well as with national water problems." In 1964 and 1965, state water resources research institutes were established at most of the land grant university campuses in the U.S.

In 1971, the Water Resources Task Force of the Department of the Interior concluded: "interregional institutional research will strengthen the overall research effort in water resources evaluation and provide a protective umbrella for projects that might be regarded as too controversial for a specific investigator of an institution to undertake." In the 1970s, the WRRA was amended to: (1) add technology development as a water research purpose, (2) form the Office of Water Research and Technology (OWRT), (3) develop technology transfer methodologies "to make information gained from water research generally available," (4) encourage regional consortiums to increase effectiveness of a nationwide network of institutes, and (5) "cooperate closely with other colleges and universities . . . in developing a statewide program to resolving state and regional water problems."

By 1983, amendments to the 1964 WRRA broadened the charter to 54 institutes in the 50 states, District of Columbia, Puerto Rico, U.S. Virgin Islands, and Guam to: (1) oversee competent research that addresses water problems or expands the understanding of water phenomena and (2) aid the entry of new research scientists into water resources fields, helping to train future water scientists and engineers, and transferring results of sponsored research to water managers and the public.

In 1984, during the Reagan Administration, the Secretary of the Interior, James Watt, and Office of Management and Budget (OMB) Director, David Stockman questioned federal water programs such as the 1978 Water Research and Development Act and 1965 U.S. Water Resources Council Act following the trickle-down economics theory to defund federal Agriculture and Interior programs they thought were state issues. Opposing the Administration, Congress voted to reauthorize the Water Resources Research Act of 1984 (P.L. 98-242) following Senator Abdnor's subcommittee legislation and Congressman McNulty's House leadership. Overriding President Ronald Reagan's veto, Congress passed the 1984 WRRA amendments and the Secretary of the Interior delegated oversight of the WRRA to the USGS.

At the 1987 National Water Institute Directors meetings in Arlington, Virginia, Colorado State University political scientist Dr. H. P. Caulfield (1987) looked back to 1984 and observed the 54 water institutes should support WRRA reauthorizations without regard for political ideology as the Enlightenment valued science and "scientific thinking dominates much modern intellectual thought" and "this honorific role of science gives water research a strong presumption of public worth." Dr. Caulfield continued: "It is essential, as I see it, that the whole water research community find a consensus for the water research program it wants to see reauthorized. . . . different interests within the community will need to bargain . . . to arrive at a consensus that all feel makes good sense and is capable of being sold to the political community. Finally, the water research community needs to stand solidly together in the . . . political process. . . . The 54 state institutes provide a widespread base for distributive politics that not all very worthwhile federal programs are fortunate enough to possess."

On December 4, 1989, Dr. Paul Godfrey (Massachusetts Water Research Center), Dr. Patrick Brezonik (Minnesota Water Resources Center), and Dr. Paul Zelinsky (Clemson Water Research Institute) signed articles of incorporation by the Commonwealth of Massachusetts that established the National Association of Water Institute Directors, NAWID (later NIWR), that provided representation for state water research institutes to implement the WRRA of 1984.

In FY99 the federal WRRA appropriation to the 54 NIWR institutes was $4 million, institutes provided local matching funds of $71 million (38:1 local match), and USGS funded 800 research projects averaging $54,000/project (NIWR 2000). In August 2007, the Water Institute Directors Panel (2007) at the Western States Water Council in Bozeman, MT discussed the western institutes such as Arizona, Idaho, and Montana which preceded the 1964 WRRA. They also pointed out that NIWR institutes collectively supported $120 million in water research between 1964 and 2007, the largest water education program in the Nation, that supported 1000 students, 1000 publications, and 280 conferences with 150,000 participants. John H. Marburger of the White House Office of Science and Technology Policy (OSTP) formed a Subcommittee on Water Availability/Quality co-chaired by Robert Hirsch (US Geological Survey) and Rochelle Araujo (Environmental Protection Agency Office of Research and Development) and requested Federal agencies "develop a coordinated, multi-year plan to improve research to . . . control water availability and quality and . . . to ensure an adequate water supply for the Nation's future."

Table 1. Board of Directors of the National Institutes for Water Resources.

Position	2015	2019	2024
President	Sharon Megdal, Arizona	Alexander "Sam" Fernald, New Mexico	Gerald McAdams Kauffman, Delaware
President-elect	Rick Cruse, Iowa	Daniel Devlin, Kansas	Yu-Feng Forrest Lin, Illinois
Past President	Brian E. Haggard, Arkansas	Stephen Schoenholtz, Virginia	Jeffrey Peterson, Minnesota
Executive Treasurer/Secretary	John C. Tracy, Idaho	Todd Jarvis, Oregon	India Allen, Van Scoyoc Assoc.
At-Large Representative	Doug Parker, California	Susan White, North Carolina	Linda Weavers, Ohio
New England Region	John Peckenham, Maine	Leon Thiem, Rhode Island	Michael Dietz, Connecticut
Mid-Atlantic Region	Steve Schoenholtz, Virginia	Kaye Brubaker, Maryland	Brian Rahm, New York
Southeast Region	Kirk Hatfield, Florida	Kirk Hatfield, Florida	John Schwartz, Kentucky
Great Lakes Region	John Lenhart, Ohio	John Lenhart, Ohio	Keith Cherkauer, Purdue
Great Plains Region	Daniel Devlin, Kansas	Daniel Devlin, Kansas	Stephanie Ewing, Montana
Pacific Northwest Region	Todd Jarvis, Oregon	William E. Schnabel, Alaska	Nicole Misarti, Alaska
Powell Consortium	Alexander "Sam" Fernald, New Mexico	Alexander "Sam" Fernald, New Mexico	Karen Schlatter, Colorado
Islands and Oceana Region	S. Khosrowpanah, Guam	Darren Lerner, Hawaii	Tao Yan, Hawaii
USGS			
USGS Office of Planning	Jerad Bales, Reston, VA	Robert Joseph, Austin, TX	Robert Joseph, Austin, TX
Director, WRRA Program	Kimberly Dove, Reston, VA	Earl Greene, Baltimore, MD	Christian Schmidt, State College, PA
Chief Office Acquisition/Grants	Sherri Bredesen, Reston, VA	Sherri Bredesen, Reston, VA	
Grant Specialist Grants	Kimberly Dove, Reston, VA	Kimberly Dove, Reston, VA	

(Marburger 2007).

On July 17, 2014, USGS celebrated the 50th anniversary of the WRRA, noting its federal agency partners, universities, state/local governments, and especially President Johnson who signed the WRRA. In 2014, Dr. Sharon Megdal, Director of the Arizona WRRC (2014) and president-elect of NIWR stated: “The water research partnerships fostered by the WRRA are unparalleled . . . fifty years later, the Water Resources Research Institutes, in partnership with the USGS, continue to fulfill their roles assigned by Congress in 1964. They have produced path-breaking research, developed innovative information and technology transfer programs, and provided training to more than 25,000 students in their 50-year history.” On June 9, 2015, the Senate passed S. 653 sponsored by Senators Cardin and Boozman reauthorizing the WRRA program at USGS.

USGS released a 10-year strategic plan (2020-2030) for the WRRA Program setting priorities for: (1) Water Scarcity/Availability, (2) Water Hazards/Climate Variability, (3) Water Quality, (4) Water Policy, Planning, Socioeconomics, (5) Ecosystem/Drainage Basin Functions, (6) Water Technology/Innovation, and (7) Workforce Development/Water Literacy (Donahue, Greene, and Lerner 2021). In November 2021, President Biden signed the Bipartisan Infrastructure Law passed by the House (228 Yea, 206 Nay) and Senate (69 Yea, 30 Nay) that reauthorized WRRA with a 1:1 federal/state match, five-year evaluation studies, and authorized appropriations of up to $12 million for the Section 104b (base grants) and $3 million for Section 104g (special topic grants) programs in FY22-25. In FY24, Congress provided $15.5 million in WRRA funding and USGS awarded grants totaling $14.4 million in year four of a five year authorization to 54 NIWR institutes with $8.3 million in Sec. 104b and $6.1 million in Sec. 104g grants matched by $13.7 million in state/local funds for 245 water research projects (NIWR 2024) and USGS awarded six Sec. 104g Aquatic Invasive Species, nine PFAS, and seven general research grants. In 2024, the House and Senate Appropriations Committees requested $16.5 and $15.5 million, respectively, for the FY25 WRRA budget.

Over 15 years, WRRA funding by Congress doubled from $6.5 million in FY10 to $15.5 million by FY24. White House budget requests in the USGS budget were zero from FY10-14, $3.5-$6.5 million from FY15-17, zero from FY18-21, and $11-$15 million from FY22-24. Congress passed WRRA appropriations in the Interior budget at $6.5 mil (FY10), $6.49 mil (FY11), $6.49 mil (FY12), $3.27 mil (FY13), $6.5 mil (FY14), $6.5 mil (FY15), $6.5 mil (FY16), $6.5 mil (FY17), $6.5 mil (FY18), $6.5 mil (FY19), $10 mil (FY20), $11 mil (FY21), $14 mil (FY22), $15.5 mil (FY23), and $15.5 mil (FY24).

The National Institutes for Water Resources are

Figure 2. Past Presidents of NIWR and UCOWR organizations at the 60th anniversary conference in St. Louis, MO, September 30, 2024.

Figure 3. On February 23-26, 2025, over 80 Directors, Delegates, and staff met at the annual National Institutes for Water Resources annual meeting in Washington, D.C.

governed by Bylaws through a Board of Directors from eight regions and an Executive Committee who serve three-year terms as President-elect, President, and Past President (Table 1). During 2013-2026, NIWR Presidents were 2013-14 Brian Haggard (Arkansas), 2014-15 Sharon Megdal (Arizona), 2015-16 Rick Cruse (Iowa), 2016-17 Stephen Schoenholtz (Virginia), 2017-18 Sam Fernald (New Mexico), 2018-20 Daniel Devlin (Kansas), 2020-21 Doug Parker (California), 2021-22 Kevin Wagner (Oklahoma), 2022-23 Nicole Misarti (Alaska), 2023-24 Jeffrey Peterson (Minnesota), 2024-25 Gerald McAdams Kauffman (Delaware), 2025-26 Yu-Feng Forrest Lin (Illinois), and President-elect 2026-27 Linda K. Weavers (Ohio). On September 30-October 2, 2024, we commemorated the 60th Anniversary of three water associations at the Joint AWRA/UCOWR/NIWR Conference in St. Louis, MO (Figure 2). On February 23-26, 2025, over 80 Directors, Delegates, and staff met at the annual National Institutes for Water Resources annual meetings in Washington, D.C. (Figure 3).

Concluding Remarks

The 54 National Institutes for Water Resources are Congressionally authorized by the Water Resources Research Act of 1964 and 1984, as amended (42 USC 10301 et seq.). We have been in existence for six decades, celebrating our 60-year anniversary in 2024. The WRRA law states: "Subject to the approval of the Secretary of the Interior . . . one water resources research and technology institute, center, or equivalent agency . . . may be established in each State (. . . includes the Commonwealth of Puerto Rico, District of Columbia, Virgin Islands, Guam, American Samoa, Commonwealth of the Mariana Islands and Federated States of Micronesia) at a college or university which was established in accordance with the Act approved July 2, 1862 (12 Stat. 503) [7 U.S.C. 301 et seq.] and the institute in such State shall . . . be established at the one such college or university designated by the Governor of the State . . ." The 54 Institutes, at land grant schools that stretch halfway across the world, exist to assist the public in addressing water problems as our core mission by law. It is in our nation's educational institutions—elementary and high schools, vocational and trade schools, and community colleges and universities—where we have opportunities to gain scientific knowledge and obtain meaningful employment to provide for our families and contribute to the betterment of our nation. This was the vision of President Johnson and Congress in enacting the WRRA in 1964, and the ongoing goals of the organzations of NIWR and UCOWR. As we look back to the historic year of 1964 where civil rights and the principles of scientific water research became the law of the land, we look ahead cogently to the next 60 years of good and civil water science and policy in the United States.

Author Bio and Contact Information

Dr. Gerald Joseph McAdams Kauffman, Jr. is Director of the University of Delaware Water Resources Center in Newark, Delaware, Associate Professor in the Biden School of Public Policy & Administration, and President of the National Institutes for Water Resources (NIWR). He can be reached at the University of Delaware Water Resources Center, DGS Annex 261 Academy St., Newark, DE 19716. jerryk@udel.edu.

References

Arizona Water Resources Research Center (AWRRC). 2014. *Water Resources Research Center History, 1964-2014.* WRRC 50th Anniversary. Tucson, Arizona.

Caulfield, Jr., H.P. 1987. *Purpose, Accomplishments, Challenges, Thoughts, and Ideas on the Water Resources Act.* May 6, 1987 Annual Meeting, National Association of Water Institute Directors. Arlington, Virginia.

Donohue, M.J., Greene, E.A., and Lerner, D.T., 2021. *Water Resources Research Act Program—Current Status, Development Opportunities, and Priorities for 2020–30*. U.S. Geological Survey Circular 1488.

Jarvis, T. 2019. *Institute for Water & Watersheds*. Oregon State University. Corvallis, Oregon.

Marburger, J.H. 2007. *A Strategy for Federal Science and Technology to Support Water Availability and Quality in the United States.* Report of the National Science and Technology Council Committee on Environment and Natural Resources. Available at: https://obamawhitehouse.archives.gov/sites/default/files/microsites/ostp/NSTC/fed_st_strategy_for_water_9-07_final.pdf. Accessed April 30, 2025.

National Institutes for Water Resources (NIWR). 2000. *Program of the National Institutes for Water Resources 2000 Executive Summary.*

Revelle, R. 1963. Water resources research in the federal government. *Science*. 142(3595): 1027-1033.

Scott, V.H. 1988. History of Universities Council on Hydrology and Universities Council on Water Resources. *Journal of Contemporary Water Research and Education* 77(1): 7-11.

Sowards, A.M. and B.M. Lacabanne. 2017. *I*nstituting water research: The Water Resources Research Act (1964) and the Idaho Water Resources Research Institute. *Water History* 9: 295-316.

Strong, B. 1964. *Concept, Legislative History and Implementation of the Anderson Water Resources Research Act*. Remarks, Benton Strong, Staff, U.S. Senate, Interior, and Insular Affairs Committee, Western Resources Conference, July 16, 1964.

Universities Council on Water Resources (UCOWR). 1964. UCOWR Newsletter. Iowa City, Iowa. Issue No. 1.

Universities Council on Water Resources (UCOWR). 2025. *About Us*. Available at: https://ucowr.org/about-us/. Accessed April 30, 2025.

Water Institute Directors Panel. 2007. Western States Water Council. Bozeman, Montana.

Universities Council on Water Resources
Journal of Contemporary Water Research & Education
Issue 182, Pages 12-18, April 2025

Perspective Piece

Institutional Aspects of Assessing Surface Water Availability

Ralph A. Wurbs

Texas A&M University

Water resources of river and reservoir systems are shared by many people for diverse, sometimes complimentary but often competing purposes. Effective water management requires a thorough understanding of water availability assessed from a reliability or frequency perspective. The great variability inherent in river system hydrology and the complexities of managing constructed facilities are important considerations in assessing capabilities for meeting water needs. The following two institutional dimensions highlighted in this article are also crucial in water availability modeling.

Infrastructure ownership, regulatory authorities, water rights, contracts, treaties, interstate compacts, and other institutional aspects of water development, management, allocation, and use must be modeled within computer-based quantitative assessments of water availability.

Effective implementation of a water availability modeling system requires collaboration of a water management community that includes government agencies, consulting firms, university researchers and educators, and diverse other entities.

The Texas experience in water management and associated water availability assessments illustrates these two institutional perspectives. Texas provides an informative study of river and reservoir system water management relevant nationwide and worldwide (Wurbs 2024a).

A 1984-1988 research project at Texas A&M University (TAMU), titled *Optimizing Reservoir Operations in Texas*, was sponsored by the cooperative federal/state research program of the Texas Water Resources Institute (TWRI) and U.S. Geological Survey authorized by the Water Resources Research Act of 1964 (Wurbs 2021; 2024b). The Brazos River Authority (BRA) served as nonfederal sponsor. This was the beginning of continuing endeavors to develop and apply the Water Rights Analysis Package (WRAP) discussed in this article. Extensive use of the modeling system over many years has greatly contributed to improving water management throughout Texas (Wurbs 2024a). The modeling system continues to be improved and expanded.

The TWRI, Texas Commission on Environmental Quality (TCEQ), Texas Water Development Board (TWDB), U.S. Army Corps of Engineers (USACE), National Institute for Global Environmental Change, and other agencies have sponsored research at TAMU since 1988 to either expand capabilities of WRAP or investigate specific water management issues employing the modeling system. TCEQ sponsored research at TAMU to expand and improve WRAP during 1997-2002 and continuously from 2005 through the present. With 2,800 employees, TCEQ is the largest state environmental regulatory agency in the United States.

WRAP and the Water Availability Models

WRAP is a set of generalized simulation models and auxiliary software for supply reliability, streamflow and storage frequency, and other analyses that can be applied anywhere in the world. Water resources development, management, regulation, and use in a river basin or region under a priority-based water allocation system are simulated and analyzed. Basin-wide impacts of water resources development projects and management practices are accessed. The modeling system facilitates assessments of hydrologic and institutional water availability and reliability in satisfying requirements for municipal, industrial, and agricultural water supply, hydroelectric energy generation, environmental instream flows, and reservoir storage. A routinely applied simulation component of WRAP is based on a monthly computational time step. A daily time step version of the simulation model currently being implemented provides additional capabilities for simulating environmental flow requirements and reservoir flood control operations. WRAP is documented by six manuals published as TWRI technical reports (Wurbs 2009; 2024b; 2024c; 2024d; 2024e; Wurbs and Hoffpauir 2024). Wurbs (2005b) presents an extensive literature review and compares WRAP with other models. A lengthy bibliography of TWRI technical reports, TCEQ reports, graduate student theses and dissertations, journal papers, and book chapters is provided as an appendix in the WRAP reference manual (Wurbs 2024b).

WRAP software, publications, and training courses are accessible at the TAMU WRAP website (https://wrap.engr.tamu.edu/). WRAP training courses presented at TCEQ, TWDB, and TWRI facilities and elsewhere in Texas and abroad have now essentially been replaced with online courses at the website. An introduction to WRAP employing the fundamentals manual (Wurbs 2024d), with student projects, is included in a TAMU graduate course in water resources systems engineering.

The WRAP website interlinks with the TCEQ water availability models (WAM) website. TCEQ maintains input datasets, called WAMs, for the WRAP simulation model at the WAM website along with an array of information regarding water right administrative procedures, environment flow standards (EFS), and water availability modeling. TWDB also maintains an extensive array of databases and information online.

Fifteen major river basins and eight coastal basins of Texas are modeled with twenty WAMs. These WRAP input datasets available at the TCEQ WAM website simulate naturalized stream flow at 14,800 sites and other aspects of river system hydrology combined with operation of 3,400 reservoirs and other constructed facilities in accordance with 6,235 water rights, two international treaties, five interstate river compacts, federal/state water supply contracts, water supply and hydroelectric energy agreements, and environmental flow standards.

TCEQ as lead agency, TWDB, and Texas Parks and Recreation Department (TPRD) with the assistance of university researchers and about ten consulting engineering firms created the water availability modeling system during 1997-2002 pursuant to Senate Bill 1 (SB1) enacted by the Texas Legislature in 1997 (Wurbs 2005a; TCEQ 2023). A committee representing the three agencies adopted the generalized WRAP modeling system developed at TAMU over the preceding several years along with compiling an extensive list of required additions and improvements to WRAP to be performed under contract with TAMU.

WRAP simulation input datasets (WAMs) were developed by consulting firms for each major river basin or combination of adjacent basins. The consultants applied WRAP with the WAMs to simulate specified alternative water management scenarios. Geographic information system capabilities were developed at the University of Texas to support data compilation.

TCEQ and its partner agencies and consultants have continued to update and improve the WAMs (TCEQ 2023). TCEQ has continued to sponsor WRAP research and development at TAMU. WRAP User Group conferences are conducted periodically by TCEQ or in collaboration with TCEQ hosted by river authorities or consulting firms. The WRAP Subcommittee of the Surface Water Committee of the Texas Water Conservation Association provides expert advice for improving WRAP capabilities for addressing various complexities and issues.

Development and continual improvement of the WRAP/WAM modeling system have been driven primarily by water allocation and statewide and regional planning endeavors administered by TCEQ and TWDB. River authorities, other water agencies, and their consultants also apply the modeling system in operational and project planning studies. Agency and university research studies have investigated a diverse array of water management issues employing the modeling system.

The WRAP/WAM modeling system combines simulation of river system hydrology, constructed facilities, and institutional practices. The following institutional perspectives are illustrated by the following synopsis of water management in Texas. (1) Modeling of complex institutional capabilities and practices is a necessary component of the simulation model. (2) The modeling system is implemented within a collaborative framework of decision-support needs, funding sources, and agency jurisdictions and responsibilities.

Water Management in Texas

Water management in Texas is driven by dramatic spatial and temporal hydrologic variability, rapid population growth, declining groundwater supplies, and intensifying demands on river and reservoir systems. Dams, reservoirs, conveyance systems, and other constructed facilities along with effective planning, water allocation, and resource management capabilities are essential for providing reliable water supplies, reducing flood damages, protecting ecosystems, and providing other water-related services. Numerous water development projects, most constructed during the 1940s-1980s era of large-scale water project construction nationwide, are operated throughout Texas to regulate extremely variable river flows for beneficial purposes. Other projects are in various stages of planning and development. Effective water management requires integration of improvements in both operation of constructed facilities and institutional capabilities for planning, allocation, and management of both water and other related resources.

The major rivers and largest cities in Texas are shown on the map of Figure 1. Mean annual precipitation ranges from less than 10 inches at El Paso in West Texas to over 55 inches along the border with Louisiana. The population of the state increased from three million people in 1900 to 9.6 million in 1960 to 20.9 million in 2000 and 29.7 million in 2020. TWDB projects a future statewide population of 33.9 million in 2030 and 40.2 million in 2050.

Conservation storage in about 3,400 reservoirs with capacities of 200 acre-feet or greater is authorized by water rights. These storage authorizations do not include flood control and surcharge storage capacity. About 97% of the licensed storage capacity is contained in 195 major reservoirs located wholly or partially in Texas with storage capacities of 5,000 acre-feet or greater. These 195 major reservoirs contain storage capacities, excluding surcharge storage, of 58,872,700 acre-feet with 40,129,600 acre-feet in 192 reservoirs allocated to conservation (water supply, hydropower, recreation) storage and 18,743,100 acre-feet in 36 reservoirs allocated to flood control (Wurbs 2024a).

River authorities, water districts, and cities are directly responsible for supplying water to the citizens of Texas. These local and regional agencies own and operate storage, conveyance, and treatment facilities and contract for water supply storage in federal reservoirs. Water management is a collaborative effort of many local, regional, state, and federal agencies and private sector entities.

The 1940s-1980s nationwide era of federally dominated basin-wide planning and construction of large-scale water projects has transitioned to a greater focus on operation, maintenance, and rehabilitation of a massive inventory of aging constructed facilities concurrently with dramatic growth in regulations to protect the environment. State water right systems and other water allocation mechanisms continue to grow in importance with intensifying demands on limited resources. A shift from federal and local community dominance to increased state-level responsibilities in water resources planning and allocation, funding, and environmental protection has occurred. Advances in computer-based decision support technologies are improving capabilities for managing hydrologic variability and future uncertainty. Institutional changes are driven by politics, economics,

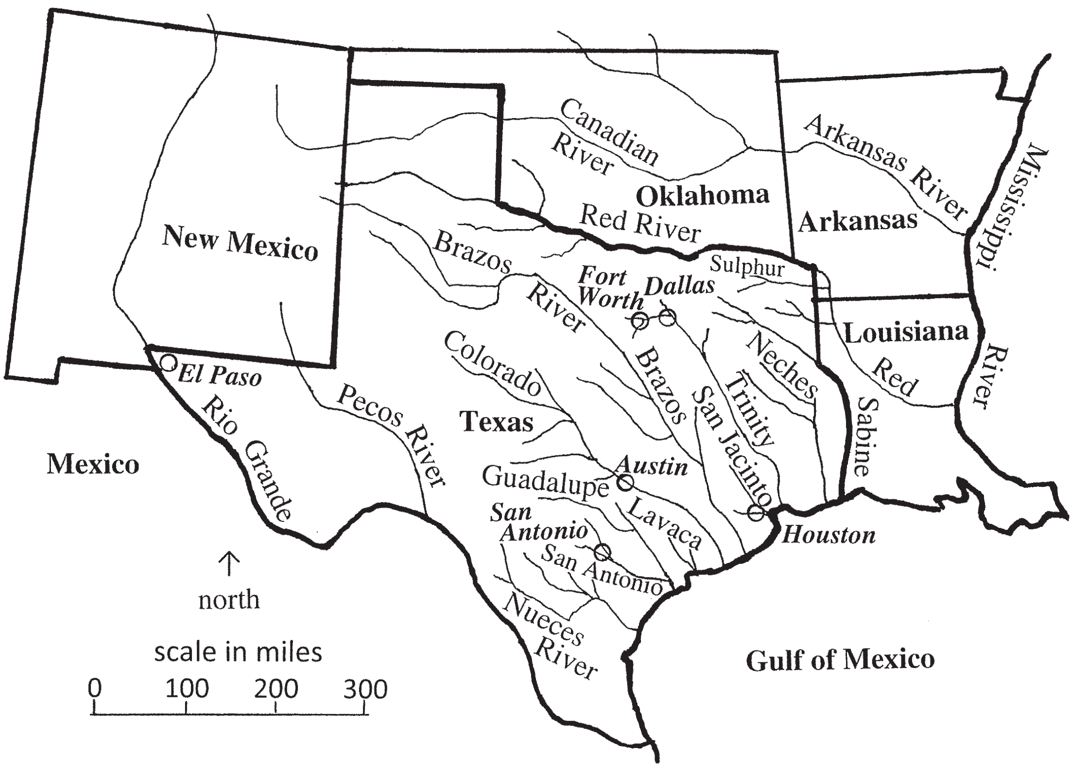


Figure 1. Major rivers and largest cities of Texas.

technology, resource availability, and often by floods or droughts (Wurbs 2020).

The waters of the Rio Grande above Fort Quitman, 90 miles south of El Paso, were allocated between the U.S. and Mexico in 1906. A 1944 treaty allocates Rio Grande waters from Fort Quitman to the Gulf of Mexico between the two nations. About 14.8% and 11.9% of the storage capacity in the 195 major Texas reservoirs are contained in International Amistad and Falcon Reservoirs operated by the International Boundary and Water Commission. The TCEQ Rio Grande Water Master Office administers distribution among Texas water right holders of the U.S. allocation of the water stored in the two reservoirs and flowing in the Rio Grande. Five interstate river compacts administered by compact commissioners with support from TCEQ allocate water between Texas and neighboring states (Wurbs 2024a).

About 27.7% and 78.3% of the conservation and flood control storage capacity of the 195 major reservoirs are contained in 30 reservoirs owned and operated by USACE. Impoundment of water at the oldest and newest USACE reservoirs in Texas began in 1943 and 1991. Costs allocated to flood control are borne by the federal government. Under provisions of the Water Supply Act of 1958, costs allocated to water supply are repaid by nonfederal sponsors. River authorities, water districts, and cities that have contracted for the water supply storage capacity of USACE reservoirs are paying for use of storage capacity, not delivery of water. These nonfederal sponsors sell water, not storage capacity, to cities, industries, and other customers under various agreements. The Bureau of Reclamation has constructed five reservoir projects in Texas, which are now owned and operated by two river authorities, a water district, and two cities.

State and Regional Water Planning

A devastating 1950-1957 drought ended by extreme flooding in April-May 1957 motivated creation of the TWDB by a legislative act in 1957. TWDB with about 400 employees is responsible for statewide planning and administering grant and loan programs for local communities. Agency staff completed the first state water plan in 1966 and plan updates in 1969 and 1984. Motivated by drought conditions during 1995-1996, the Legislature in 1997 enacted water management legislation known as SB1 which included adding local stakeholder-guided consensus-based regional planning to the TWDB statewide planning process and also authorized development of a water availability modeling system.

Pursuant to the 1997 SB1, the state was divided into 16 regions with planning groups representing diverse water interests guiding planning for each region. Sixteen regional plans and a consolidated statewide plan are updated in a five-year cycle with a 50-year future planning horizon. Reports documenting the 2002, 2007, 2012, 2017, and 2022 regional plans and consolidated state water plan are available at the TWDB website. Completion of the next regional and state water plans is scheduled for 2027. TWDB staff and consulting firms perform technical studies that include applying the WRAP/WAM modeling system to evaluate water supply capabilities and impacts of proposed strategies and projects under various scenarios.

SB1 planning focuses on water supply and environmental protection needs and capabilities. The Legislature in 2019 authorized TWDB creation of a similar planning process for flood mitigation. The new flood planning process has a five-year cycle and 15 regional planning groups. The first set of 15 regional flood plans was completed in March 2024. The first statewide flood plan was submitted to the Legislature in September 2024.

Water Rights

Water rights in Texas evolved over several centuries into an unmanageable assortment of poorly recorded and often conflicting riparian and prior appropriation strategies. The severe 1950-1957 drought motivated a massive lawsuit that resulted in establishing water rights for the Texas share of the Rio Grande below Fort Quitman. The Water Rights Adjudication Act of 1967 created a process to convert existing water rights into a prior appropriation permit system for the rest of Texas that was completed by 1990. TCEQ administers both the allocation system for the Texas share of water in International Amistad and Falcon Reservoirs and the different allocation system applicable for the remainder of Texas.

Surface water is owned by the state. A water right holder has no ownership of water but only a right to store water in reservoirs and withdraw the water for beneficial use. Water rights can be sold or leased subject to TCEQ approval. Any organization or person may apply to TCEQ for a new right or change in existing water right. TCEQ will approve the application if unappropriated water is available, the proposed beneficial need for water will be supplied at an acceptable level of reliability, existing water rights are not impaired, efficient water conservation will be practiced, and proposed actions are consistent with relevant SB1 statewide and regional water plans. During the 1968-1990 adjudication process, priority dates were established based on historical water use. Since then, priorities are based on the dates that applications are received by TCEQ.

Currently 6,235 water rights are defined by 4,892 certificates issued pursuant to the adjudication process and 1,343 water use permits issued later. Typically, over 100 applications for new permits or modifications to existing rights are under review by TCEQ at any time. Many are not approved. Water conservation plans are required for water rights. More complex rights also include periodically updated system water management plans.

TCEQ approved in 2016 a water use permit application and associated system operation plan prepared by the BRA and consultants that is more complicated than most water rights. Modifications to BRA water rights approved in 2016 significantly increase water supply capabilities. The system water use permit and management plan combine multiple-reservoir operations of a 12-reservoir USACE/BRA reservoir system with use of unregulated flows entering below the dams and return flows, coordination with groundwater sources, interbasin conveyance, water conservation, and environmental flow requirements. Combining firm and interruptible water commitments as facilitated by WRAP/WAM simulations is a major feature of the plan. BRA initiated further studies in 2024 for constructing an off-channel reservoir.

Permit applicants and their consultants apply relevant WAMs in preparation of permit applications and associated water management plans. TCEQ staff apply the modeling system in evaluations of the proposed new or amended water rights.

Environmental Flow Standards

The importance of protecting instream flows for fish, riverine ecosystems, wetlands, and freshwater inflows to bays and estuaries has been recognized in Texas since the 1980s. Efforts to formulate and implement EFS intensified pursuant to legislation enacted in 2001 as Senate Bill 2 (SB2) and in 2007 as Senate Bill 3 (SB3). SB2 created the Texas Instream Flow Program (TIFP) jointly administered by TWDB, TCEQ, and TPWD to improve capabilities for protecting aquatic ecosystems. SB3 created an accelerated process for establishing EFS for priority river systems using best available information and science. EFS for selected river systems are created by appointed science teams and stakeholder committees subject to public review and final approval by TCEQ.

The SB3 process results in EFS that are incorporated by TCEQ in the WAMs. EFS metrics and rules that vary with location, season, and hydrologic condition govern curtailment of diversion and/or storage of stream flows by junior water rights. EFS have subsistence, base, and high pulse flow components. The SB3 process includes periodically reevaluating and updating the EFS.

EFS are incorporated in the WAMs with a priority based on the date TCEQ receives recommendations from the science team. TCEQ may not issue a permit for a new appropriation or amendment to an existing water right if any EFS would be impaired. Holders of existing senior water right permits are not required to curtail appropriations of water to maintain junior EFS.

Conclusions

Water availability assessment capabilities are essential for effective water management. Institutional considerations are relevant to other types of computer modeling as well as to other regions of the nation and world. For example, the 1997 SB1 also created a groundwater modeling program within TWDB that reflects institutional perspectives that are very different but analogous to those associated with surface water discussed in this article.

With increasing demands on limited water resources, water allocation systems have become an essential component of water management. Water allocation and planning are integrally related. Shared modeling tools facilitate integration of planning and water allocation as well as connecting with other aspects of water management.

Modeling systems include computer programs, databases, organizations, people, and decision processes. Compilation and management of voluminous data may be necessary. A modeling system is constructed rather than just a model.

Model development is a dynamic evolutionary process. As long as a modeling system continues to be applied, its development is never completed. Model development is a process of continual expanding and improving to address evolving needs and objectives.

Author Bio and Contact Information

Dr. Ralph A. Wurbs was employed in the USACE water development program for nine years prior to joining the TAMU faculty in 1980. His teaching, research, and administrative service at TAMU have been recognized by an endowed professorship, graduate student fellowship endowed by former students named in his honor, several teaching awards, and various other awards including the Outstanding Research and Innovation Award of the American Academy of Water Resources Engineers (AAWRE) and inaugural Texas Water Lifetime Achievement Award. He is a Founding and Honorary Diplomate of AAWRE and Fellow of ASCE. He was an associate director of TWRI in 2007-2012 and for many years a TAMU Delegate to UCOWR. He may be contacted at r-wurbs@tamu.edu or by mail at Zachry Department of Civil and Environmental Engineering, Texas A&M University, College Station, Texas 77843.

References

Texas Commission on Environmental Quality (TCEQ). 2023. Water Availability Models. Available at: https://www.tceq.texas.gov/permitting/water_rights/wr_technical-resources/wam.html. Accessed October 22, 2024.

Wurbs, R.A. 2005a. Texas water availability modeling system. *Journal of Water Resources Planning and Management* 131(4): 270-279.

Wurbs, R.A. 2005b. *Comparative Evaluation of Generalized River/Reservoir System Models*. Texas

Water Resources Institute Technical Report No. 282. College Station, TX. Available at: https://wrap.engr.tamu.edu/wp-content/uploads/sites/84/2022/07/ModelsReviewTR282.pdf. Accessed October 22, 2024.

Wurbs, R.A. 2009. *Salinity Simulation with WRAP*. Texas Water Resources Institute Technical Report No. 317. College Station, Texas. Available at: https://wrap.engr.tamu.edu/wp-content/uploads/sites/84/2020/12/SalinityManual.pdf. Accessed October 22, 2024.

Wurbs, R.A. 2020. Institutional framework for modeling water availability and allocation. *Water* 12(10): 2767. Available at: https://www.mdpi.com/2073-4441/12/10/2767. Accessed October 22, 2024.

Wurbs, R.A. 2021. Water rights analysis package modeling system. *Texas Water Journal* 12(1): 68-90. Available at: https://twj-ojs-tdl.tdl.org/twj/index.php/twj/issue/view/375/53. Accessed October 22, 2024.

Wurbs, R.A. 2024a. *Managing Water in River and Reservoir Systems: Water Resources, Institutional Practices, and Constructed Infrastructure in Texas*. ASCE Press, Reston, Virginia. Available at: https://ascelibrary.org/doi/book/10.1061/9780784485385. Accessed October 22, 2024.

Wurbs, R.A. 2024b. *Water Rights Analysis Package (WRAP) Modeling System Reference Manual*. Texas Water Resources Institute Technical Report No. 255, 15th Edition. College Station, Texas.

Wurbs, R.A. 2024c. *Water Rights Analysis Package Modeling System Users Manual*. Texas Water Resources Institute Technical Report No. 256, 15th Edition. College Station, Texas.

Wurbs, R.A. 2024d. *Fundamentals of Water Availability Modeling with WRAP*. Texas Water Resources Institute Technical Report No. 283, 11th Edition. College Station, Texas.

Wurbs, R.A. 2024e. *Water Rights Analysis Package River System Hydrology*. Texas Water Resources Institute Technical Report No. 431, 4th Edition. College Station, Texas.

Wurbs, R.A. and R.J. Hoffpauir. 2024. *Water Rights Analysis Package Daily Modeling System*. Texas Water Resources Institute Technical Report No. 430, 5th Edition. College Station, Texas.