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One Water, Many Solutions

Scientists and stakeholders engage in broad collaborations and deep research to help ensure safe water supplies.

The Long and Short of Subduction Zones

Power Grids are Vulnerable to Extreme Weather

Heat Stress at the World Cup

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CONTENT

From the Editor

To ensure the availability and sustainability of water resources, water managers and the communities they serve are investing in approaches both broad and deep.

The delegations that help drive the One Water approach to water management are wide-ranging and often serendipitous, as Grace van Deelen explains in “Delegations Drive One Water Dialogues,” on page 18. “One Water,” van Deelen writes, “treats drinking water, wastewater, and storm water as a single, interconnected entity bringing together water utilities, community members, business and industry leaders, researchers, politicians, engineers, and advocacy groups.”

In addition to applying integrated water management approaches, contamination and overuse of shallow groundwater supplies are creating a need for in-depth analysis of the health, safety, and financial concerns associated with accessing deep aquifers, suggest the scientist-authors of “Deep Groundwater Might Be a Sustainable Solution to the Water Crisis,” on page 14.

Meeting water challenges requires intersectional collaboration and data-driven research. This month’s stories show how Earth scientists are already pursuing such approaches and how they are looking to create more.

On the Cover

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Janice Lachance, Interim Executive Director/CEO

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U.S. Power Grids Are Vulnerable to Extreme Weather

When extreme weather and natural disasters such as wildfires and hurricanes descend on a region, the immediate concern is typically damage from the event itself. But the power outages that often accompany such events can be dangerous as well. The wildfires that struck Los Angeles in January left hundreds of thousands of residents without power, and Hurricane Helene caused more than 5 million customers in the Southeast to lose power in September 2024.

A new study published in *PLOS Climate* is among the first to parse how different kinds of extreme events affect power grids in the United States (bit.ly/power-grid-weather).

"We see that power outages are occurring much more frequently with severe weather events than without, even compared to, like, 10 years ago," said Vivian Do, an environmental health scientist at Columbia University and a paper coauthor.

Do and her colleagues found clear regional differences among the types of events associated with outages and gave insights into which kinds of weather are most dangerous for the grid.

Knowing, for example, that heavy rain is more likely to knock out power than severe heat, or that extreme cold and heavy snowfall together are more dangerous than either by itself, could allow residents and authorities to better prepare for outages.

Snow covers power transmission lines in eastern Texas following a blizzard in 2010. Credit: Matthew T Rader/Wikimedia Commons, CC BY-SA 4.0 (bit.ly/ccbysa4-0)

The Worst Time for an Outage

Planning for outages that happen at the same time as severe weather is hampered by a lack of data on how specific weather and power outages relate in a given area, despite the increased risks these overlapping events bring, Do said.

City agencies can assist residents who lose power by offering vital services at shelters, for example, but their strategy is likely to differ when a few feet of snow blankets the ground. "There are so many nuances to preparedness, to response," she explained.

Knowing which scenarios are more likely to affect an area is a necessary first step toward devising strategies to deal with outages.

The researchers compiled county-level data from poweroutage.us, a service that aggregates data on outages from utilities around the country, and compared them with occurrences of wildfires, extreme heat and cold spells, heavy rain and snowfall, and hurricanes.

Between 2018 and 2020, 73% of counties in the dataset saw at least 1 day when a severe weather event and a power outage coincided. Furthermore, 54% of counties in the United States had at least one instance in which two simultaneous natural events occurred at the same time as an outage.

The data did not allow the researchers to prove that any outage was directly caused by a severe event, only that they happened at the same time. Many of the natural events they analyzed are not independent of one another—hurricanes can bring heavy rain and wind, for instance—making it difficult to tease out which, if any, contributed to an outage or dealt the final blow.

Overall, the events most likely to coincide with an outage were hurricanes, followed by snowstorms and heavy rain, though the association varied by region: Rain was a bigger factor in the Northeast and on the Gulf Coast, as well as in Michigan and Southern California, whereas extreme heat events paired with power outages were concentrated in the southeastern states. Heavy snow coinciding with outages occurred most often in counties in the Northeast and in some counties near the West Coast. And though hurricanes were most likely to be associated with an outage, severe rain coincided with the most outages across the country.

Simultaneous severe weather events raised the probability of an outage even more. Of these events, paired severe heat and rain coincided most often with outages across the United States, whereas hurricanes and rain and severe cold and snow were the next most common paired weather combinations associated with outages.

Some counties even saw three simultaneous hazards coincide with outages, such as extreme heat, rain, and hurricanes or severe cold, snow, and wildfires.

Bolstering the Grid

Multiple studies have shown that power outages alone can increase threats to human health—from spoiled food to failing medical equipment to a loss of heat in winter (bit.ly/power-outages-health, bit.ly/NYC-outages-health). These threats become more dire when paired with severe weather.

The kinds of correlations examined in this study could be useful to utility companies, which must allocate finite resources for maintenance and repair and make plans for a range of scenarios, said Ken Cummins, a researcher at the Florida Institute of Technology with experience in grid reliability who wasn't involved in the research. (Cummins is a former science adviser to *Eos.*) But he cautioned that the specific infrastructure used by local electric utilities, which can vary significantly, is also an important factor.

"One thing that would be a problem in St. Louis might not be a problem in Denver or Omaha and would certainly be a different problem in New York City or Long Island," he said.

"Preparedness and response should really be nuanced and consider how the different combinations can bring up different problems for different populations."

Do agreed that a local approach to preparing for both severe weather and outages is paramount, something she argued their research is helping to advance by beginning to prioritize threats. "Preparedness and response should really be nuanced and consider how the different combinations can bring up different problems for different populations," she said.

Cummins questioned why thunderstorms weren't included in the analysis, given that they are the main cause of outages in many places. Though rain, snow, and other kinds of weather play a role, "thunderstorms today outweigh the impact of those things all added together," Cummins said. "They are the majority of outage hours over the United States."

Do said that may be a direction for future work. "A lot of the research in this particular field is still very much in its exposure assessment phase," Do said.

By **Nathaniel Scharping** (@nathanielscharp), Science Writer

Great Barrier Reef Corals Hit Hard by Marine Heat Wave

When an intense marine heat wave sent ocean temperatures soaring in 2023 and 2024, coral reefs around the world bleached. New research on the Great Barrier Reef's One Tree Island shows that more than 50% of surveyed coral colonies that bleached died of heat stress and starvation. And even heat-resistant corals weren't immune.

When corals are stressed by warm water, they can lose the algae that live in their tissues. This process turns the coral white, earning it the name "coral bleaching." Sometimes corals can recover, but if the stress is too intense, they die and eventually crumble into rubble and sand.

"What we noticed in more recent times, when it gets really hot, they often die before they even fully bleach," said marine biologist Maria Byrne of the University of Sydney.

A Global Marine Heat Wave

Record hot temperatures in 2023 were worsened by a strong El Niño. This heat triggered a global coral bleaching event that began in the Caribbean and by early 2024 had reached the Great Barrier Reef. Australian aerial surveys showed that in some areas of the reef, more than 90% of corals were bleached.

Starting in February 2024, Byrne and her colleagues went to the One Tree Island Reef, located roughly 100 kilometers off the coast of Queensland, Australia, to document how the heat wave affected the reef in the months afterward. The island is protected from mainland coastal pollution and tourism, so the effects of the heat wave could be surveyed independent of those stressors.

"When it gets really hot, they often die before they even fully bleach."

Over 161 days, the researchers tracked 462 coral colonies from the peak of the Southern Hemisphere heat wave in February through the winter of July 2024. On four occasions, they dived at two lagoon sites: a shallow channel and a bay connected to the ocean.

Wearing thin stinger suits to protect themselves from jellyfish stings, the researchers swam in pairs along marked transects, one researcher capturing video and the other taking both wide-angle and close-up photos.

The scientists monitored individual corals across surveys using GPS markers and numbered tags. The tags helped them match photos and video from different dives, allowing them to compare changes over time—

One Tree Island Research Station is a key site for studying coral resilience in the southern Great Barrier Reef. Credit: Byrne Lab, University of Sydney whether the corals remained bleached, recovered, or succumbed to disease and algae.

"We match the corals a bit like a jigsaw puzzle," Byrne said. "It did take a lot of time to match all the photos, thousands of them, to individual corals."

When bleaching and algae made corals unrecognizable, Byrne's team had to use natural landmarks—like a giant clam or a patch of soft coral—to track the reef's changing story.

Widespread White

Reef sensors recorded a peak temperature of 30.55°C; higher than satellite readings. This kind of on-site data helps scientists identify coral heat stress and bleaching risks.

In February, almost two thirds of the corals were ghostly white. Even the heat-resistant *Porites,* usually a refuge for turtles, was affected, with seven out of 10 colonies observed showing signs of bleaching.

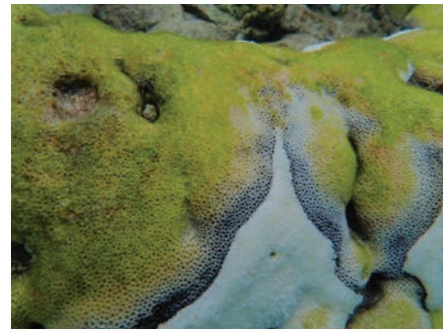
By April, bleaching had intensified, affecting 80% of the coral colonies under study. Though bleaching can contribute to slow starvation over weeks or months, extreme heat can lead to sudden die-offs due to heat stress before the coral even turns fully white. By July, more than half of the observed bleached colonies had died, and only 16% showed signs of recovery.

Different coral species endured different fates: *Acropora,* a fast-growing branching coral, faced near-total collapse after bleaching, with 95% of colonies dead. *Goniopora,* known for its flowerlike polyps, was severely affected by black band disease, a fatal disorder in which a dark stripe separates the animal's healthy tissue from an encroaching microbial mat that leaves a dead skeleton in its wake.

Results of the study were published in *Limnology and Oceanography Letters* (bit.ly/GBR-bleaching).

"The corals that live on One Tree Island Reef are very used to having extreme summers, and to a degree, it's surprising they were pushed over the limit so easily," said Stuart Kininmonth, a coral reef ecologist who manages the University of Queensland's Heron Island Research Station, located 20 kilometers west of One Tree Island. Kininmonth was not associated with the study.

Corals at One Tree Island Reef bleached under extreme heat stress. Credit: Alex Waller/Byrne Lab/University of Sydney



A Goniopora *coral at One Tree Island displays the characteristic strip of black band disease, in which intact coral tissue (green) is separated from the animal's bare skeleton by a black band. Credit: Alex Waller/Byrne Lab/University of Sydney*

The scale of the die-offs and the low recovery rate at One Tree Island Reef show how hard it can be for reefs to rebound from harsh bleaching events.

"The corals that live on One Tree Island Reef are very used to having extreme summers, and to a degree, it's surprising they were pushed over the limit so easily."

Although some species (the stony corals *Goniastrea* and *Pavona*) experienced lower mortalities, surveys also revealed how quickly the reef turned to rubble after coral died, transforming the underwater landscape and ecosystem.

"We've entered a new phase where heat intensities are so frequent—every 2 years instead of every 10—that corals may not have a chance to recover," Byrne said. "Species that didn't bleach may be the ones that survive, leading to a different barrier reef with altered species, ecosystem services, and predator-prey dynamics. We're entering a brave new world."

By **Anupama Chandrasekaran** (@indiantimbre), Science Writer

Boreal Forests May Be on the Move

Tree distribution in boreal forests like this one at the entrance to Denali National Park, in Alaska, will likely undergo changes in the coming century. Credit: NPS Photo/Tim Rains

Boreal forests comprise the world's largest terrestrial biome—a vast landscape ringing the high latitudes of the Northern Hemisphere. The expanse of trees in this sparsely populated wilderness helps keep Earth's climate stable.

As the planet steadily warms, however, boreal forests will witness a substantial shift in tree distribution, according to a new study published in the *Proceedings of the National Academy of Sciences of the United States of America* (bit.ly/boreal-moves).

"We're not just talking about changing a few patches of trees," said coauthor Ronny Rotbarth, who was a Ph.D. candidate at Wageningen University and Research in the Netherlands when he conducted the study and is now a postdoctoral researcher at the Universität Freiburg in Germany. "Here, we're talking about the entire Northern Hemisphere changing fundamentally because of the climate change that we have caused."

A Glimpse into the Future

The southern, warmer parts of boreal forests are characterized by dense tree cover. Farther north, the drop in temperature inhibits such density and turns lush forests into sparse woodlands.

In the new study, Rotbarth and his fellow researchers analyzed tree distribution across the boreal biome from 2000 to 2020. They employed a stochastic modeling approach using the Moderate Resolution Imaging Spectroradiometer (MODIS), a sensor on NASA's Terra and Aqua satellites.

"It was a great use of long-term satellite data and aligns with other work that has been done in recent years," said Logan Berner, a forest ecologist who studies the Arctic tundra biome at Northern Arizona University and was not involved in the study.

"We're talking about the entire Northern Hemisphere changing fundamentally because of the climate change that we have caused."

The researchers used the 21 years of observational data to simulate changes in the decades leading to 2100. Their models showed a tendency for tree cover to decline in warmer areas and increase in colder areas.

These changes could lead the Arctic away from the temperature-related bimodal tree distribution to a unimodal, open forest state with 30%–50% tree cover before the end of the century. This distribution is much lower than the more than 60% tree cover that warmer boreal forests currently have and higher than the 5%–15% cover of colder forests.

"We didn't really expect that," Rotbarth said. "What was quite surprising was the speed…with which some of these more open, colder boreal forests are becoming denser."

The authors' modeling suggests that colder forests will experience up to a 4% increase in tree cover every decade.

Carbon Emissions and Other Cascading Effects

Changes in tree cover, though, are only one part of the story.

Temperature-driven changes in tree distribution could lead to changes in boreal forests' carbon storage capacity, the authors noted. In the southern region, a loss of tree cover means a loss in biomass carbon storage. Meanwhile, as the permafrost underlying northern forests thaws, it awakens underground microbes that can break down organic materials, releasing carbon into the atmosphere.

This loss of carbon storage will outweigh the amount of biomass gained by tree cover in the colder region, Berner explained. The researchers projected a carbon gain of 11.4%, or 17.7 gigatons, by 2100.

The transition to an open forest will have other cascading impacts, including reductions in biodiversity and water availability, said Zoe Pierrat, a postdoctoral fellow at NASA's Jet Propulsion Laboratory who was not involved in the study but coauthored a commentary on it.

"To me, the biggest concern is the potential impacts on wildfire regimes," Pierrat said.

Two of the biggest climatic drivers of boreal wildfires, she explained, are the lack of available water from snowmelt and increased temperature. In spring, melted snow creates a large pool of water readily available for trees to absorb as they grow in the summer. By fall, these trees could have depleted the water supply and turned dry, creating prime conditions for fire to kindle.

One of "the big questions we need to address in the coming years is, What can we do to these forests so that they can withstand climate change?"

Moving Forward in a Changing Ecosystem

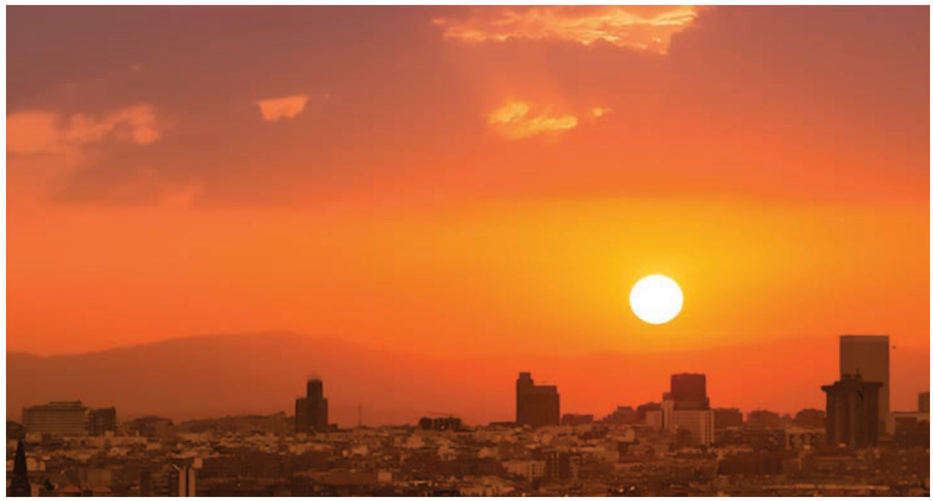
"Temperature alone does not fully explain how climate regulates or controls the ecosystem," Berner acknowledged.

As novel as the study's findings were, he continued, incorporating a wider collection of climate model projections (such as how climate influences the way organisms behave) could strengthen the findings and help scientists better understand the far-reaching effects of future climate.

For Rotbarth, there is still hope. "We should not stop reminding ourselves that we have such an influence on our planet," he said. One of "the big questions we need to address in the coming years is, What can we do to these forests so that they can withstand climate change and increasing pressures from environmental disturbances like fire?"

By **Kristel Tjandra** (@KristelTjandra), Science Writer

Europe Faces Increased Heat Mortality in Coming Decades



In Europe, a rise in heat-related deaths will substantially outweigh any reduction in cold-related deaths by the end of the century, new research finds. Mediterranean countries such as Spain, whose capital, Madrid, is seen here, are particularly vulnerable. Credit: Jose Maria Cuellar/Flickr, CC BY-NC 2.0 (bit.ly/ccbync2-0)

Extreme heat resulting from climate change will become a growing threat in Europe over the next 75 years, new research reports. Without substantial mitigation and adaptation efforts, an additional 2.3 million lives could be lost to extreme-temperature-related causes by the end of the century, with the effects of rising heat outpacing any potential decline in cold-related deaths.

The worst-case scenario projects that the net death burden from climate change will rise by 50%, to about 215,000 deaths per year.

This dire projection comes from a team of researchers led by Pierre Masselot, a statistician and environmental epidemiologist at the London School of Hygiene & Tropical Medicine. Their analysis, published in *Nature Medicine,* examined climate projections and estimated future temperature-related mortality in 854 European cities, each with populations greater than 50,000, across 30 countries (bit.ly/Europe-heat-mortality). The researchers used advanced climate simulations to project daily temperatures for each city and combined the results with statistical data on annual temperature-related deaths in each area.

A 2023 study also led by Masselot found that between 2000 and 2019, about 143,817 deaths in these cities were attributable to extreme temperatures each year (bit.ly/Europe-temp-mortality). The new study considered various warming scenarios and revealed that without substantial reductions in greenhouse gas emissions, extreme-temperature-related deaths are expected to rise. The worst-case scenario—characterized by a lack of substantial emissions reductions and minimal adaptation—projects that the net death burden from climate change will rise by 50%, to about 215,000 deaths per year, by the end of the century. This scenario would result in the aforementioned 2.3 million additional deaths by 2100.

Masselot noted that the consistency of the trend across all scenarios was surprising. "The takeaway is that if cities warm as much as it is projected in the worst-case scenario, it will be very difficult to adapt," he said.

Mitigation Versus Adaptation

The study investigated the potential effects of adaptation strategies designed to protect people from heat, such as using air-conditioning and developing cooling centers. But their results found that deaths would rise even if significant adaptation efforts were implemented.

"In [the] absence of mitigation," Masselot said, "the adaptation to heat would need to be massive to counterbalance this trend."

Mitigation efforts would mostly take the form of reducing greenhouse gas emissions: Masselot said that up to 70% of these extra deaths could be averted by limiting the global average temperature increase to 2°C by the end of the century through reduced emissions in line with the Paris Agreement. However, recent research suggests that Earth is on track to exceed this limit.

Mediterranean Exposure

Currently, extreme cold causes 10 times more deaths than heat does in Europe. However, Masselot explained that though milder winters might mean some northern countries see a reduction in overall temperature-related deaths, the increase in heat-related deaths across the continent will far outweigh this localized effect. The team identified Mediterranean regions, including eastern Spain, southern France, Italy, and Malta, as particularly vulnerable.

The Mediterranean region is more affected because it is a climate change hot spot where temperatures are increasing faster than the global average. "We had a taste of this in 2022 and 2023 when massive heat waves occurred in the region," Masselot said.

The study also considered expected demographic changes in the European Union. For instance, the population of adults aged 80 and above is projected to increase 2.5-fold between 2024 and 2100. Factors such as age are important given older adults' increased vulnerability to heat.

"We need to address both climate change and air pollution, and we can do it through the same means: the decarbonization of our economy and our transport system."

Large cities suffer from the so-called heat island effect, in which city centers can be 4°C–5°C warmer than their surroundings, thanks to a combination of pollution, high insolation (exposure to the Sun's rays), and heat-absorbing materials such as asphalt and concrete. This effect makes large Mediterranean cities particularly vulnerable.

Mark Nieuwenhuijsen, an expert in air pollution and urban planning at the Barcelona Institute for Global Health who was not involved with the research, said scientists shouldn't ignore adaptation strategies. "We could easily reduce the temperatures if we replace a lot of the asphalt with more green space."

Air pollution, by exacerbating the deadly effects of extreme heat, also contributes to health concerns. Nieuwenhuijsen highlighted the importance of reducing air pollution, both to reduce heat-related deaths and to reduce heat itself, because carbon dioxide emissions drive temperature increases. Air pollution causes 300,000 deaths every year in the European Union, far more than heat or cold, and the solutions to both temperature- and pollution-related mortality go hand in hand. "We need to address both climate change and air pollution, and we can do it through the same means: the decarbonization of our economy and our transport system," Nieuwenhuijsen said. "This is the positive message, but we can't wait."

Masselot noted that the next step is understanding how to build resilience to heat, which will be necessary even with immediate mitigation efforts. "That means understanding what makes some cities more resilient to heat than others," he said. "What are the specific characteristics of these cities that we can use to act upon later and can inform policy?"

By **Javier Barbuzano** (@javibarbuzano), Science Writer

Unregulated Industrial Contaminants Detected in Some U.S. Drinking Water

The U.S. EPA regulates levels of more than 90 contaminants in public drinking water, but thousands more chemicals that are potentially harmful remain without health standards at either the federal or state level.

Monitoring data have shown that more than 97 million people in the United States have been served by public water systems that contained detectable levels of at least one unregulated industrial contaminant, according to a new study published in *Environmental Health Perspectives* (bit.ly/US-water-contaminants). And drinking water in counties with higher proportions of Hispanic residents was more likely to have these contaminants.

"This study affirms what environmental justice advocates have been highlighting for decades: Communities of color often have to drink dirtier water," said Lara Cushing, an environmental health scientist at the University of California, Los Angeles who was not involved with the study.

Unregulated but Not Absent

"The number of regulated contaminants in federal law is low relative to the number of potential contaminants that can get into drinking water sources," said Aaron Maruzzo, an environmental health scientist at the Silent Spring Institute in Newton, Mass., and lead author of the study.

To get a sense of the public's exposure, EPA collates data on a selection of unregulated contaminants in drinking water every 5 years. During each data collection cycle, contaminants are selected on the basis of criteria including whether they could occur in drinking water, whether they were monitored in prior cycles, and their potential health effects. Data are collected by all public water systems serving more than 10,000 people, as well as by many smaller systems.

"This study affirms what environmental justice advocates have been highlighting for decades: Communities of color often have to drink dirtier water."

Maruzzo and his colleagues analyzed EPA's monitoring data from 2013–2015 to check the levels of four unregulated contaminants in drinking water supplied by more than 4,800 public water systems.

The researchers analyzed industrial contaminants rather than other chemicals such as disinfection by-products or agricultural chemicals, which have been the focus of other monitoring cycles. They also limited their list to contaminants that were prevalent enough to allow stringent statistical analyses.

Ultimately, they focused on per- and polyfluoroalkyl substances (PFAS), which are chemical compounds used in products such as firefighting foam and food packaging; the industrial solvents 1,4-dioxane and 1,1-dichloroethane; and chlorodifluoromethane (HCFC-22), used as a refrigerant and propellant.

More than a quarter of the public water systems in the dataset—collectively serving more than 97 million people—detected at least one of the four contaminants in the drinking water they supplied.

The most commonly detected contaminant was 1,4-dioxane, which can cause eye and nose irritation at low levels of exposure and may lead to serious kidney and liver issues when present at high levels.

Not Everyone's Drinking Water Is the Same

The study showed that counties with higher proportions of Hispanic and non-Hispanic Black residents were more likely to get their drinking water from public water systems that detected unregulated industrial contaminants. This association persisted across socioeconomic status indicators such as income, homeownership, and proportion of residents in poverty. It could not be explained by how close the public water systems were to sources of the industrial contaminants.

"Unfortunately, we have known from stories from communities of color that environmental justice issues and drinking water quality exist in many places," Maruzzo said. "[Those stories] were completely supported by the data and our analyses."

"This study highlights the urgency of targeted investments and creative ways to help drinking water suppliers, particularly in disadvantaged communities," Cushing said. Minimizing levels of these emerging contaminants in drinking water is vital because

Water treatment facilities can miss unregulated contaminants. Credit: EPA exposure to some of them can have severe health effects.

PFAS, for example, have been associated with increased incidence of various cancers. Widespread concerns about their dangers led EPA to announce the first set of legally enforceable levels for six PFAS compounds in April 2024.

"The problem may actually be worse than we think," Cushing continued. The nature of the data collected by EPA and analyzed in this study meant that some demographic nuances may have been missed, and the inequalities found in this study might actually be more pronounced.

"Looking at the county level can average out some demographic data," said Laurel Schaider, an environmental chemist also at the Silent Spring Institute and a coauthor of the new study. "For instance, we know from prior studies in the California Central Valley, when you look at smaller geographical scales, there can be quite large differences in the demographics of communities that are more impacted by water contamination." Schaider said she anticipated that more recent datasets from EPA will allow researchers to home in on social and demographic inequalities on a much finer scale.

"No data does not mean no problems."

Another issue is that smaller public water systems and private wells may not be required to measure as many potential contaminants as larger systems. "These smaller or private systems may actually be more vulnerable to poorer water quality and have less capacity to deal with contaminants," Cushing said. "No data does not mean no problems."

Next steps should include doing more to protect water sources from being contaminated in the first place, according to Maruzzo. "Also, there should be more support for underresourced communities with water quality issues, so that systems in those communities can treat and test for unregulated contaminants and ensure that they are providing clean drinking water."

By **Adityarup Chakravorty** (chakravo@gmail.com), Science Writer

Extreme Heat and Rain Turned These Arctic Lakes Brown

The field team sampled a lake near Kangerlussuaq, Greenland, that browned after extreme weather events. Credit: Adam Heathcote

Jasmine Saros, a lake ecologist at the University of Maine, has been studying Arctic lakes in Kangerlussuaq, Greenland, since 2013, documenting their various stages of ecological health. She and her colleagues have spent each summer collecting samples and data from the pristine blue waters.

But in 2023, they returned to find that many once-clear lakes had turned brown. Though gradual changes due to climate change are expected, the sudden color shift was a surprise.

Water samples and a look back at weather patterns from the previous year revealed that nine atmospheric rivers that struck the region the previous fall had flushed copious amounts of nutrients into the lakes, altering their color. Whether the change is permanent remains to be seen.

Lake Chemistry

For more than a decade, Saros and her colleagues would paddle out to the middle of each lake on a raft to collect sediment cores and water samples and measure light conditions below the surface. They also tracked dissolved organic carbon levels in the water and observed the microscopic organisms living (and that had once lived) in the lake.

"Every time we went to the lakes, we'd measure hydrogen and oxygen isotopes of the water," Saros said. The ratio of heavy and lighter isotopes of these elements in the samples from 2023 revealed that an unusually large amount of precipitation had fallen on the lakes compared with previous years.

Lake browning often results from high concentrations of dissolved organic carbon, primarily from decaying vegetation. It can also be caused by an increase in iron, typically resulting from natural processes such as weathering of iron-rich soils and rocks into the water, as well as by anthropogenic influences such as agricultural runoff and industrial discharges.

Data from the fifth-generation European Centre for Medium-Range Weather Forecasts atmospheric reanalysis (ERA5)—a global weather hindcast—showed that nine atmo-

Prior to the atmospheric rivers, this lake near Kangerlussuaq, Greenland, had crystal clear water. Credit: Adam Heathcote

spheric rivers had dumped precipitation over the area between September and October of 2022.

Atmospheric rivers are known for transporting moisture, but they can also carry warm air. The ERA data also highlighted that September 2022 was the hottest and wettest September on record in West Greenland since 1940.

By early July 2023, when Saros and her colleagues were back on the lake, dissolved organic carbon levels had risen by 22% compared with the 2013–2023 average. Iron concentrations had increased 1,000%. Other metals, such as aluminum, cobalt, chromium, and copper, had also surged within the lakes.

"Those atmospheric rivers drove not only record precipitation but also record heat," Saros said. Higher temperatures caused precipitation to fall as rain instead of snow. The heavy rainfall saturated the landscape, thawed permafrost, and released organic material and iron into the lakes, turning them brown, she explained.

The study was published in the *Proceedings of the National Academy of Sciences of the United States of America* (bit.ly/browning-lakes).

Ecosystem Transformation

The browning led to a 50% reduction in light penetration into the lakes. Light is critical for phytoplankton that create their energy through photosynthesis, and losing some of it caused some species to shift to mixotrophic behavior, feeding on both light and organic material.

The researchers also found a decline in microbial diversity, with certain species, such as the picocyanobacterium *Cyanobium,* becoming more dominant in the brown lakes, signaling a shift in the microbial community.

"A lot of primary production used to happen at the bottom of the lakes because light penetration was deep," explained Václava Hazuková, a limnologist at the University of Maine and a coauthor of the study. "Now that the transparency is lower, we are seeing a shift of the phytoplankton moving upwards." In shallower waters, they may face higher temperatures and stress, affecting their growth and the entire food web.

Murkier water absorbs more solar radiation than clear water. "You can actually see more heat being trapped in the surface layers of the lake," Saros said.

It is difficult to tell whether these lakes can revert to clear water, according to Saros and Hazuková. "Sunlight can often help in bleaching this brown material," Hazuková said, but future precipitation will continue to influence the lake ecosystem.

"I think what was really stunning about it was how this population of lakes changed in the exact same way, in a similar magnitude. You don't often see that," Hazuková explained. The uniform response of these lakes may suggest that the region is entering a more volatile phase of environmental change, where rapid, large-scale shifts become the norm, though the researchers can't say for sure whether this is the case.

"This research is providing us with new insights into ecosystem resiliency and the impacts of climate change on remote northern lakes."

"Whether this extreme climate event has induced lasting limnological changes, or the lakes return to their previous state soon, this research is providing us with new insights into ecosystem resiliency and the impacts of climate change on remote northern lakes," said Matthew Bogard, a limnologist at the University of Lethbridge in Canada who was not part of the study.

By **Larissa G. Capella** (@CapellaLarissa), Science Writer

Soccer Players Risk Heat Stress in World Cup Stadiums

Estadio BBVA in Monterrey, Mexico, will host four soccer matches during the 2026 FIFA World Cup. Monterrey's daily average temperature will put players at risk of heat stress and dehydration during the tournament. Credit: MX/Wikimedia Commons, CC BY 4.0 (bit.ly/ccby4-0)

During the 2026 FIFA World Cup, soccer teams will play a rapid sequence of games that will take them to 16 cities across Canada, Mexico, and the United States. A team of climate scientists and environmental physiologists evaluated the environmental stresses the teams will experience during the tournament, finding that players will be at very high risk of extreme heat stress during matches played at 10 of the 16 stadiums. Matches at high-elevation stadiums will also put players at risk because of the lower oxygen content in the air.

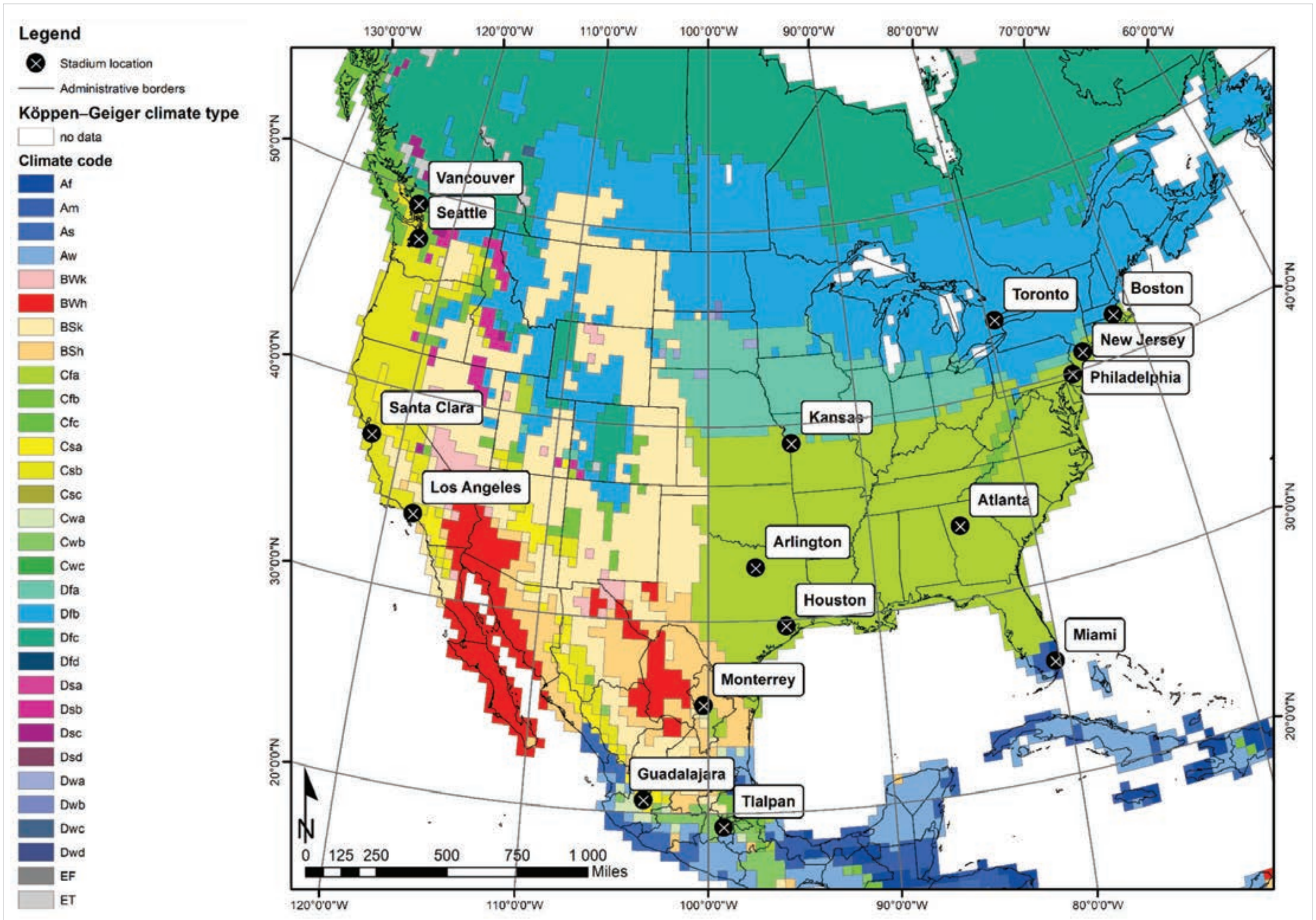
"We hope our results will enable optimization of match schedules at individual venues, taking into account the health risks associated with extreme heat stress, but also the physiological reactions to heat potentially affecting the performance of players on the pitch," said Katarzyna Lindner-Cendrowska, a geoecologist and climatologist at the Polish Academy of Sciences in Warsaw, and lead researcher on the study, which was published in *Scientific Reports* (bit.ly/FIFA-heat-26).

Stadium Swaps Add to Heat Stress

In places where the risks of heat-related illnesses are already high, research has shown that people engaging in intense physical activity such as professional sports are at an even greater risk (bit.ly/sports-heat-risk, bit.ly/football-stroke-risk).

Hot and humid conditions cause an athlete's body to produce more heat than it can dissipate and enhance the risks of extreme dehydration via sweating. Low levels of atmospheric oxygen make it harder to breathe and oxygenate blood, further lowering a body's ability to dissipate heat. These physical responses slow cognitive function and reaction times, inhibit the speed and precision of movements, and reduce concentration. Prolonged activity in these environments can also lead to long-term health conditions and, in extreme cases, death.

These risks are well known by athletic groups. The Fédération Internationale de Football Association (FIFA) considers environmental risks to players, coaches, and spectators ahead of events, typically by measuring the wet-bulb globe temperature (WBGT). If WBGT exceeds 32°C, cooling breaks are mandatory during both halves of a FIFA match. Recent research found that just six of the 16 host cities exceed this threshold during an average year, and each less than 5% of the time (bit.ly/FIFA-hosts-heat).



The 16 stadiums hosting 2026 FIFA World Cup games span nine different climate zones as defined by the Köppen-Geiger climate classification. Changing climate conditions between games will place additional stress on soccer players' bodies. Credit: Lindner-Cendrowska et al., 2024, https://doi.org/10.1038/s41598-024-77540-1, CC BY-NC-ND 4.0, using data from the World Bank Group, CC BY 4.0 (bit.ly/ccby4-0)

(Four more cities exceed this threshold in a hot year.)

But despite its popularity among FIFA and other organizations, WBGT "is considered an imperfect measure of heat load on athletes, as it is prone to underestimating the heat stress level," Lindner-Cendrowska said. Some stadiums don't have a way to measure WBGT on site, and the index itself doesn't consider the additional thermal load if there is high humidity or poor airflow, which makes it harder to cool down, she added.

Lindner-Cendrowska and her colleagues calculated a more precise measure of athletes' heat stress risk by modifying the universal thermal climate index (UTCI) to include biometric data on core body heat, water loss, and oxygen levels of soccer players while playing.

At 10 of the 16 stadiums, UTCI levels for active athletes could exceed 46°C, the threshold for extreme heat stress.

The calculation is similar to the "feels like" temperature on a weather app but for physical exertion.

"UTCI is a measure of the human physiological response to the thermal environment and is considered a better index, as it provides an estimation of how the body feels under a given environmental condition specified by the air temperature, wind, humidity, radiation, clothing, and level of physical effort," explained George Nassis, an environmental physiologist who focuses on cardiovascular and thermoregulatory systems at the University of Kalba in Sharjah, United Arab Emirates.

Nassis, who was not involved with the study, said the researchers' choice to evaluate heat stress risk using a modified UTCI was "most appropriate."

The researchers evaluated hourly average heat stress risk at each 2026 World Cup stadium during the 11 June to 19 July tournament. At 10 of the 16 stadiums, UTCI levels for active athletes could exceed 46°C, the threshold for extreme heat stress.

Midday matches in Houston and Arlington, Texas; and Monterrey, Mexico, put players at the highest risk of heat stress from heat and humidity, with UTCI levels exceeding 50°C, but morning and evening matches at these locations were nearly as risky. In other stadiums, midday matches provided the most risk of extreme heat stress, but shifting matches to other times of day alleviated the risk.

In addition, matches played in Guadalajara and Tlalpan, Mexico, which are at elevations

The matches will take place in nine different climate zones ranging from humid continental regions to subtropical deserts, an "unprecedented" diversity in biothermal conditions.

of 1,566 and 2,240 meters above sea level, respectively, could put athletes at risk due to lower levels of oxygen in the air. Though levels don't vary greatly during the day, oxygen levels are the lowest just after midday in both stadiums.

"This altitude will also impose stress to the body of the coaching and supporting staff as well as to the visitors traveling to these locations from low-altitude locations," Nassis said.

What's more, the logistics of the 2026 World Cup present an additional complication: The 104 matches will take place in nine different Köppen-Geiger climate zones ranging from humid continental regions to subtropical deserts. The researchers called this an "unprecedented" diversity in biothermal conditions.

Teams moving from a low heat stress environment to a high heat stress environment will need to quickly adapt, Nassis said.

"This is a big challenge given that proper heat acclimatization…needs some days to take place," Nassis added. "As a result, some players of these teams may be vulnerable to excessive heat stress that may compromise their health and performance."

Helping Players Stay Cool

Most of the risk can be avoided by strategically scheduling matches at cooler and less humid times of day, the researchers concluded. When hot times can't be avoided, stadiums could use air conditioning in strategic locations at the hottest times to help athletes cool down. The three stadiums that have retractable roofs could cover their fields.

Teams, too, can alter their training regimens to better prepare for the anticipated environmental stress.

"The top two priorities are acclimatization and hydration," Nassis said. Teams could train outdoors or in artificial indoor environments to acclimatize players to anticipated heat conditions. They can also be more vigilant about monitoring hydration and teaching different ways to effectively cool down when overheated. Teams can implement different cooling strategies during halftime and during any WBGT-mandated cooling breaks, which are only 3 minutes long.

"The top two priorities are acclimatization and hydration."

The modifications to match scheduling and training regimens would benefit soccer leagues not just for the 2026 World Cup but for future sporting events, too. The risk of heat stress is increasing around the world because of climate change, which is lengthening and intensifying heat waves and altering precipitation patterns.

"We hope that not only FIFA but also other international sports federations and organizers of major sporting events will find our results inspiring enough to implement precautionary planning, which is essential for ensuring that sporting events are safe and satisfying experiences for everyone—athletes, spectators, and technical staff," Lindner-Cendrowska said.

By **Kimberly M. S. Cartier** (@astrokimcartier.bsky.social), Staff Writer

Deep Groundwater Might Be a Sustainable Solution to the Water Crisis

Groundwater supplies 50% of the world's drinking water and 25% of the water used globally in agriculture. Locally, especially in arid regions of Africa, the Middle East, and elsewhere, these figures can be far higher, making groundwater a critical resource supporting the lives and livelihoods of hundreds of millions of people.

Groundwater is typically sourced from relatively shallow depths belowground, primarily because these sources have historically been easier to locate and access. (The meaning of "shallow" groundwater can vary regionally; here we consider it to mean water within about 400 meters of the ground surface.)

But two key factors contribute to these conventional groundwater resources becoming increasingly unreliable.

First, contamination from natural processes and human activities often compromises water quality and can spread waterborne diseases and hazardous pollutants, especially in near-surface resources [*Li et al.*, 2021]. Second, droughts and overdevelopment result in overuse that places additional stress on these reserves in many parts of the world, further limiting their availability.

The global water crisis threatens access to clean water and food production around the world—and it has scientists, policymakers, and others searching for sustainable solutions.

These issues, together with similar problems affecting surface freshwater resources, are fueling a growing global water crisis. This crisis threatens access to clean water and food production around the world—and it has scientists, policymakers, and others searching for sustainable solutions.

Below the ground, other sources of water—what we call deep aquifers, at depths between 400 and a few thousand meters—remain largely unexplored and untapped. Despite being less widely known, such deep aquifers can hold significant reserves of water, as they do beneath parts of Africa, Arabia, Australia, and the Americas.

Recent studies revealed additional large amounts of deep freshwater in fractured and karstified rock and in consolidated or nonconsolidated porous aquifers. Some of these aquifers even extend offshore in regions such as the Horn of Africa, Sicily, and Tunisia [*Quiroga et al.*, 2023; *Chiacchieri et al.*, 2024; *Bachtouli et al.*, 2023].

This research suggests that deep groundwater may be more common than previously thought, indicating potential new resources in areas where other solutions to the escalating water crisis may not be economically or technically feasible.

What We Know About Deep Aquifers

Under the right conditions of subsurface hydraulic conductivity, surface water recharge, and hydrological gradients within aquifers, groundwater can travel great distances underground and can reside there for long periods. The age of most of the water in the Al Kufrah Basin in Libya, for example, has been estimated to be 30,000 or more years [*Wright et al.*, 1982]. Groundwater can also percolate down well below the surface, sometimes maintaining low salinity (i.e., remaining fresh) as it reaches depths much greater than those of typical water wells.

The quality of this deep groundwater is influenced by the composition of the rock it flows through, the velocity at which it flows, and its residence time underground. In some cases, natural pollutants from the rock, such as arsenic and radioactive elements, contaminate the water, or salts dissolved from rock add salinity. However, in most documented cases of deep-aquifer utilization, the water is safe for drinking and requires minimal treatment. Furthermore, risks of anthropogenically introduced contamination or cross flow are minimized with common modern drilling practices.

Examples of known deep aquifers include those in the Nubian Sandstone Aquifer System, comprising numerous sandstone aquifers holding several thousand cubic kilometers of water down to 3,500-meter depths in northern Africa [*Ruden*, 2016], and the Upper Mega Aquifer System on the Arabian platform [*Abotalib et al.*, 2019], the Great Artesian Basin in Australia [*Fensham et al.*, 2021], and the unconsolidated Kimbiji Aquifer in Tanzania. Deep aquifers have also been tapped in parts of South America and the United States.

Deep aquifer systems with long residence times are virtually immune to pollution and drought compared with surface water and shallow groundwater.

These deep systems with long residence times are virtually immune to pollution and drought compared with surface water and shallow groundwater. The Guarani Aquifer System in South America and the Great Artesian Basin in Australia, for example, have been key sources for drinking water, irrigation, and industrial use for decades to centuries.

Without proper planning, though, aquifers like the Nubian (which should last several centuries with abstraction rates on the order of 1,000 cubic meters per second) can face overexploitation as extraction exceeds natural replenishment [*Ruden*, 2016]. In contrast, the example of the Guarani Aquifer System demonstrates that sustainable management is possible. Shared by Brazil, Argentina, Paraguay, and Uruguay, the Guarani aquifers are managed collaboratively through monitoring, conservation, and contamination prevention, keeping water use within recharge limits and serving as a model for transboundary aquifer management.

Repurposing Existing Data and Technologies

Even with the examples above and other recent discoveries, only a handful of deep

Water gushes from a well drilled in Chad during the 2009–2010 United Nations Mission in the Central African Republic and Chad. Credit: Ruden AS

freshwater aquifers have been identified worldwide. The reason is largely that deep-freshwater exploration has never been pursued systematically on a regional scale.

This oversight can be attributed to the fact that most water-scarce countries lack the necessary resources to investigate the subsurface for water and other natural resources. Meanwhile, wealthier nations facing water shortages have focused on more energy-intensive solutions, such as desalination, and countries without water scarcity have directed their investments primarily toward energy exploration, even in low-income, water-scarce regions.

Exploring for deep-groundwater resources today still requires significant technical abilities and investments in data gathering and infrastructure. However, the costs of exploration could be substantially reduced—and the benefits expanded to more people—if existing oil and gas data and technologies were repurposed and shared widely. The process of searching for water is akin to oil and gas exploration, even if the targets are often the inverse: Those searching for groundwater focus, for example, on exploratory boreholes deemed "dry" and unsuccessful for oil and gas production.

A unique opportunity exists at present to broaden the search for deep groundwater, driven by a data revolution spearheaded by open-access policies from governments and academia and by the increased availability of new satellite data and decommissioned oil and gas data. With such data now more accessible than ever, deep-groundwater studies are increasingly feasible [e.g., *Quiroga et al.*, 2023; *Lipparini et al.*, 2023].

Even with accessible oil and gas data, scientists face challenges in repurposing them for groundwater research. One example is

A unique opportunity exists at present to broaden the search for deep groundwater.

Water flows from a well drilled roughly 600 meters underground into the Kimbiji Aquifer in Tanzania. Credit: Ruden AS

the difference in how the oil and gas industry measures water salinity compared with how measurements are done using hydrogeological methods. The industry typically uses indirect methods, such as resistivity measurements and chloride titrations, to obtain generalized salinity estimates sufficient for evaluating hydrocarbon reservoirs. In contrast, hydrogeologists often use direct laboratory techniques that provide detailed information about the broad range of ions and elements in the water, offering more insights into its composition and quality. As a result, additional validations or adjustments of oil and gas data are often required before they are used in groundwater research, making the process more complex.

For oil and gas data to be repurposed effectively in groundwater exploration, such methodological differences and other challenges—which are not widely recognized among water scientists—must be overcome through extensive cross-disciplinary work with oil and gas geoscientists and engineers. The water salinity measurement issue, for example, could be addressed by scientists working together to standardize an additional laboratory-based salinity measurement for samples from future oil and gas boreholes. Such measurements could use methods similar to those applied in water research to ensure the data are more accurate and useful for hydrogeological applications.

Assessments of sustainability must consider renewability on human (i.e., century) timescales.

Renewability and Sustainability

Each promising discovery of a deep aquifer comes with a responsibility: Before it's tapped as a water resource, we must first assess its volume and quality, determine whether it is connected to surface waters, and understand both recent and historical recharge processes. We also must gauge its potential to continue serving as a water source in the decades, centuries, and millennia to come.

Deep aquifers receive large quantities of water during prolonged wet periods but very little during dry stretches. The current climate conditions of the African Sahara, for example, offer little water to the deep subsurface. In contrast, this region had a much wetter landscape between 11,000 and 5,000 years ago that provided more water to deep aquifers.

Amid rising global water demand, deep groundwater remains underrepresented in hydrogeological research and government policies.

The renewability of these aquifers can thus vary greatly depending on the timescale considered. Although current recharge rates may be low or even negligible for many deep aquifers, anticipated climatic changes—resulting partly from Earth's orbital changes, which affect the amount and distribution of sunlight reaching the planet—may replenish them over thousands of years. So viewed with a longer perspective, some deep aquifers can indeed be considered renewable. However, assessments of *sustainability* must consider renewability on human (i.e., century) timescales.

Investigating deep-aquifer renewability over varying timescales requires using high-capacity computing to process extensive regional climate, topographic, geological, and hydrogeological databases that help scientists understand and model key aquifer characteristics. These characteristics include water provenance, infiltration rates, and recharge mechanisms, as well as the climate dependence of these factors; aquifer storage capacity and geometry; climatic conditions at recharge points over extended periods; and the locations of discharge and extraction points relative to recharge areas, along with the time it takes water to travel from source to extraction points.

Renewability is not the only factor determining deep-aquifer sustainability, though. Sustainability is also intrinsically related to usage and fundamentally depends on four key parameters: effective recharge, storage capacity [*Cuthbert et al.*, 2023], discharge, and extraction. If storage capacity is reasonably assumed to be constant on relevant timescales—that is, if we disregard potential effects on capacity from changes in rock porosity and sea level fluctuations (which can, e.g., increase or decrease seawater infiltration into coastal aquifers)—only recharge, discharge, and extraction remain relevant. Natural recharge, as discussed, is highly variable over decades to millennia, and discharge can fluctuate accordingly. Managing aquifer sustainability thus depends crucially on controlling extraction in relation to these two variable parameters.

Research to Support Resource Decisions

Every aquifer is unique, and its feasibility and sustainability as a water resource must be assessed individually within its own local context. Ultimately, decisions about whether to tap deep aquifers may reflect the balance between the need for water and the energy used to acquire it, which involves weighing political, socioeconomic, and regulatory issues, as well as technical considerations.

Energy requirements may vary significantly. Under certain conditions, water from deep aquifers can exhibit artesian flow, naturally reaching the surface without the need for pumping. In other cases, as with shallow groundwater, extracting deep groundwater may require energy for pumping.

Although drawing shallow groundwater may seem like it would always require less energy, the energy needed for extracting deep groundwater can be comparable to, or even less than, that required for shallow sources, especially considering that yield capacities of deep boreholes can exceed those of shallow boreholes by more than 20 times [*Godfrey et al.*, 2019; *Ruden*, 2007]. In addition, in deep boreholes, pumps are typically installed at relatively shallow depths, similar to those in shallow boreholes, because the pressure within the aquifer helps push water toward the surface.

Amid rising global water demand, deep groundwater remains underrepresented in hydrogeological research and government policies. However, some African nations, including Namibia, Somalia, and Tanzania, are taking steps to incorporate deep-groundwater exploration into their water resources plans, either through official policies or with pilot drilling projects.

Given the potential scale of, and return from, deep-groundwater sources—and the scope of growing concerns over water security globally—we suggest that further exploration efforts are needed. These efforts demand interdisciplinary approaches and cross-sectoral collaboration among academic scientists, the oil and gas sector, and governments. With such work, we can not only better understand the resources deep beneath us but also better assess their sustainability and manage them responsibly.

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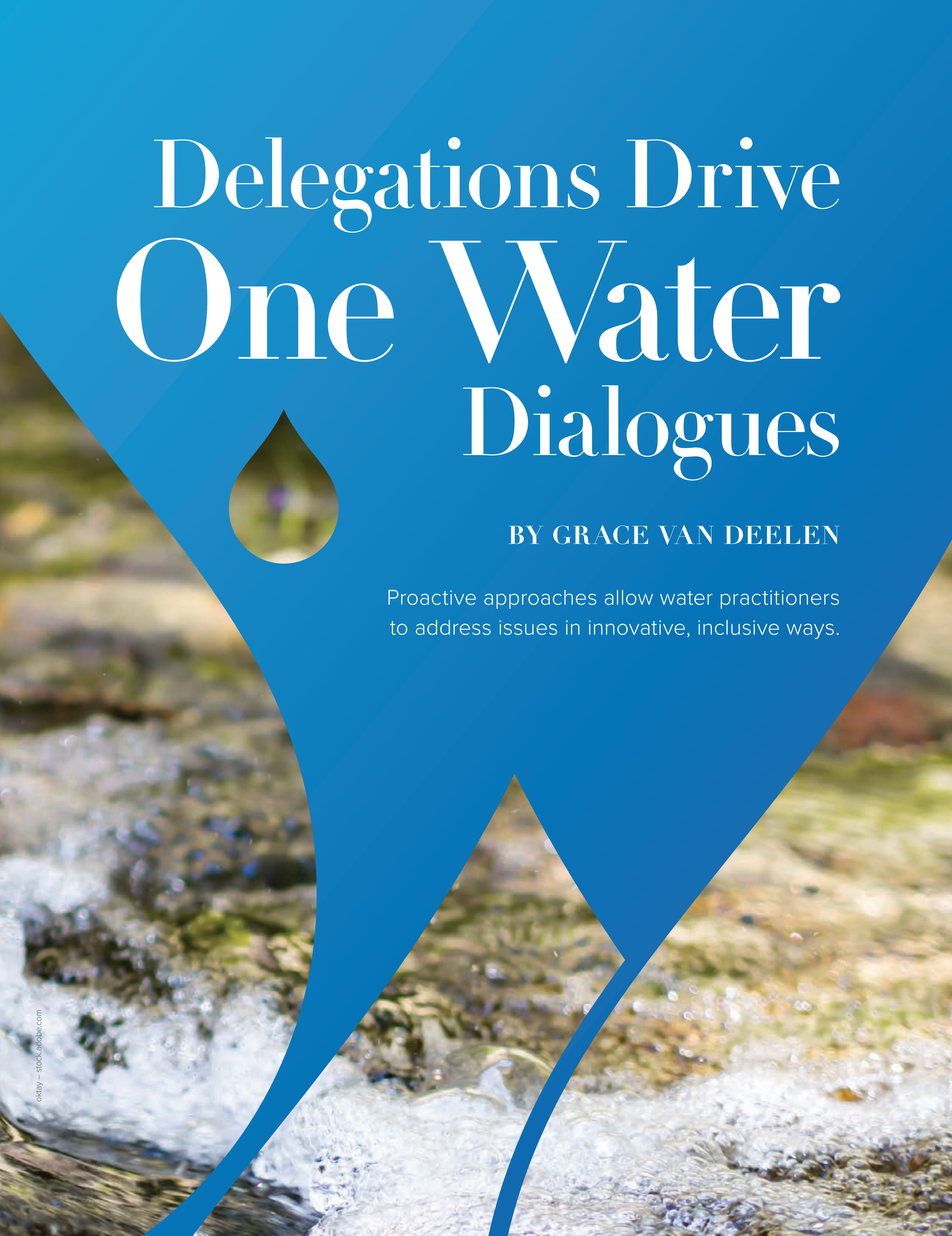
Delegations Drive One Water Dialogues



BY GRACE VAN DEELEN

Proactive approaches allow water practitioners to address issues in innovative, inclusive ways.

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On a summer morning, a storm dropped buckets of rain on the desert outside Tucson, Ariz. Water ran over the dry soil. Most of the water subsequently evaporated, but some parched plants drank their fill. What was left over sank into the ground, percolating into the aquifer below.

A few kilometers down the road, Tucson Water pumped groundwater from the same aquifer to a nearby reservoir, then through its treatment system. A Tucson ratepayer turned on her tap and used a few liters of water to give her dog a bath. The soiled water flowed into Tucson's wastewater system and once again was treated. A portion of that recycled wastewater was released into the Santa Cruz River, where parkgoers enjoyed watching it flow through the city.

In Tucson, as in the rest of the world, every human interaction with water is connected to a broader water system.

But water practitioners haven't always treated their work with the same interconnected approach. Instead, many cities and regions divide their water into three silos: drinking water, wastewater, and stormwater, each managed separately.

That approach is not meeting the needs of many communities. And a different approach, called One Water, is beginning to take its place.

One Water treats drinking water, wastewater, and stormwater as a single, interconnected entity and attempts to manage it holistically, bringing together water utilities, community members, business and industry leaders, researchers, politicians, engineers, and advocacy groups.

In a One Water approach, the Tucson ratepayer, water utility, and parkgoer are equal stakeholders, and water practitioners attempt to create a water system that works well for each of them.

"Partnerships and collaboration are at its core," said Scott Berry, director of policy and government affairs at the US Water Alliance, a nonprofit membership organization dedicated to advancing a "One Water future for all."

A holistic, inclusive approach is not without obstacles, though. Different stakeholders bring different priorities and practices and may have cultural, historical regulatory, and organizational barriers that keep them from collaborating effectively.

To navigate such challenges, water stakeholders from varied sectors across the United States come together at an annual conference (soon to be held every 18 months), the One Water Summit, hosted by the US Water Alliance. About 70% of attendees come as part of a delegation, a peer group, typically organized by region, whose members want to work together on U.S. water issues.

These delegations are the lifeblood of the summit and uniquely mirror the One Water approach: They're meant to be highly collaborative, allowing stakeholders with very different priorities to come together and work toward a common cause. Though the framework is hindered by funding constraints and a lack of engagement from some sectors, delegations have provided a valuable opportunity for sharing knowledge and bringing One Water projects to fruition.

"It's a way to test the waters of collaboration away from the normal sphere of influence."

Siloed Systems

In the water sector, siloed systems are the norm. The inertia they engender can be hard to break when trying to build collaborative networks.

In some cases, siloed approaches contribute to unaligned regulations, which can limit a collaboration's success, explained Caity Peterson, a research fellow at the Public Policy Institute of California's Water Policy Center.

For example, someone working on a wastewater problem must navigate both environmental and health regulations. A One Water program might involve potable reuse, or recycling wastewater into drinking water by purifying it, filtering it, and diverting it to groundwater or reservoir supplies. Such a project needs to ensure that the recycled water complies with environmental regulations that govern water quality for irrigation and other nonpotable uses. But once that water is destined for a drinking water supply, it must

Recycled water flows into the Santa Cruz River in Arizona as part of the Santa Cruz River Heritage Project. Credit: Tucson Water also comply with health regulations. “A little bit of streamlining” of those regulations can bolster collaboration, Peterson said.

Siloed jurisdictions can present another challenge for water practitioners. Though the flow of water respects no political or system boundary, water managers do work within such jurisdictions, said Sarin Pokhrel, a water resource engineer for the Environment and Protected Areas Ministry of Alberta, Canada. (Some local governments within Alberta, such as Edmonton, where Pokhrel is based, use a One Water approach.)

British Columbia, where Pokhrel previously worked, is home to an array of jurisdictions: Municipalities govern water via local bylaws, Indigenous communities manage their own water, and districts follow broader regional plans. Unifying plans under a single framework that all levels of water management can follow is very challenging, he said.

The US Water Alliance added the delegation structure to its annual conference in 2016 as a way for water practitioners to overcome these barriers and move toward One Water ideals. Berry, who leads delegation work at the US Water Alliance, said he thinks of the delegation system as an opportunity for stakeholders to “road test” collaborations.

“It’s this idea of getting a bunch of folks together who may not work together often, or who may even be at odds with one another,” he said. “It’s a way to test the waters of collaboration away from the normal sphere of influence.”

> “We can come together in ways that would be almost impossible at home.”

Organizers of the One Water Summit encourage delegations, which can be assembled by anyone with the interest, ability, and time to recruit fellow delegates, to attend. Delegation members can register at a discounted rate, and the summit provides opt-in programming specifically for delegates. Around one thousand people and 20–40 delegations attend each year. Membership in any one delegation has ranged from fewer than 10 to almost 50 people, Berry said.

The first half day of each summit is dedicated to “peer exchanges,” where delegations present their work to each other. These presentations range from showcasing a particular success to workshopping a problem that the delegation is facing, Berry said.

At the 2023 Tucson summit, for example, the Tap into Resilience delegation hosted a peer exchange to brainstorm how to scale up distributed water infrastructure, a type of ultralocal water system meant to be more affordable than conventional water systems. The Climate Action delegation shared strategies for utilities to use capital investments to make progress on their climate plans. And the New Jersey delegates hosted a discussion about how delegations can build relationships with state governments to advance One Water.

At an end-of-summit plenary, delegations are invited to announce “commitments to action” for the coming year.

“The entire plenary, you’re surrounded by all this amazing work that’s going to be happening in all these different places,” Berry said. “You get a sense that you’re not alone and that there are opportunities for collaboration.”

Commitments to action range from informal directives to full proposals. Delegations at the 2023 summit committed to developing new One Water plans for their cities, improving community engagement around water issues, sharing what they’d learned with local leaders and policymakers, and constructing new green stormwater and water treatment facilities. Delegations that return to the subsequent summit are encouraged to share how they’ve progressed on their commitments.

One Water, Many Networks

Water practitioners report a strengthening of the depth and breadth of their collaborations as a result of participating in a delegation.

“I felt like I really got to know people in a different way, not just as colleagues but as friends,” said Rebekah Jones, communications director for the Iowa Soybean Association’s Iowa Agriculture Water Alliance, who attended the 2023 One Water Summit as part of the delegation from Iowa. Jones deepened her relationships with colleagues at the city of Cedar Rapids and Des Moines Water Works and especially enjoyed meeting members of a delegation from Hawaii, who shared how critical water is to Hawaiian culture and livelihoods.

Jennifer Walker of the Texas delegation, director of the Texas Coast and Water Program at the National Wildlife Federation, said she feels the same after attending multiple summits. When a delegation convenes away from their home community, “everybody has a little bit more time to focus on the content, spend some time together, and build relationships,” she said.

Because Texas is such a large state, the delegation venue is crucial for getting Texas stakeholders, including nonprofits, utilities, engineers, consultants, elected officials, and community members in the same room.

The delegations are building relationships among people who don’t work together day-to-day, said Michelle Stockness, executive director of the Freshwater Society, a nonprofit based in Saint Paul, Minn. Stockness attended the 2023 summit as a member of the Minnesota delegation. “We’re building those relationships so that we can talk about hard things a little more easily.”

“We can come together in ways that would be almost impossible at home,” said Candice Rupprecht, a water conservation program manager for the city of Tucson and member of the Tucson delegation, in a 2019 presentation.

Strengthened relationships have sparked meaningful progress on One Water projects across the country.

At the 2023 conference, the Iowa delegation held an educational session for other summit attendees about urban and rural collaboration via an exercise about a fictional town called Farmersville and its picturesque Crystal River. Attendees attempted to fix a water quality problem in Farmersville—a suddenly odorous and murky Crystal River—while playing a role that was different from their real-life job. For example, a water researcher could act as mayor, and a utility staff member could role-play a farmer.

In the scenario, the urban community blamed rural farmers for soil erosion and nutrient pollution, whereas farmers accused the city of industrial pollution and ineffective waste management. Workshop attendees had to navigate these concerns as they developed a plan to improve water quality.

“It got people thinking out of the box about what it’s like to be in someone else’s shoes,” Jones said.

In New Jersey, water practitioners had already formed a coalition of community members, nonprofit organizations, government entities, and utilities when the delegation from the state began attending the summit in 2016. Participating as a delegation supplemented the group's holistic effort, said Paula Figueroa, director of the Jersey Water Works Collaborative and a former New Jersey delegate. For the New Jersey delegation, the summit is an important source of energy to balance the sometimes draining, difficult work of advancing a One Water approach, she said.

After the 2022 summit, Figueroa noticed that two leaders, one a New Jersey utility staff member and the other an employee of the Jersey Water Works Collaborative, began to collaborate, inviting each other to more events and sharing the other's work. The new relationship increased the visibility of a shared, primary project: replacing lead service lines across the state.

The summit offers delegations opportunities for interstate cooperation as well. Following conversations between the Pittsburgh and Milwaukee delegations at the 2022 and 2023 summits, delegates from Pennsylvania and Wisconsin held a dedicated learning exchange in Milwaukee the following year.

Some water issues in Pittsburgh would have taken 2 or 3 years each to solve, but as a result of knowledge gained in the Wisconsin exchange, "we were able to complete five or six problems in 2 or 3 years," said Jamil Bey, founder of the UrbanKind Institute and a longtime member of the Pittsburgh delegation. "That learning exchange model is really powerful."

At the Tucson, Ariz., One Water Summit in 2023, the Minnesota delegation shared concerns about water quality and distribution. Credit: Michelle Stockness

The event in Milwaukee helped inform a new approach to addressing stormwater reclamation in Pittsburgh, for instance, said Kelly Henderson, who was part of the Pittsburgh cohort that attended the learning exchange.

One of the locations the group visited was Green Tech Station, a former brownfield site that the Northwest Side Community Development Corporation, a nonprofit in Milwaukee, had transformed into a stormwater reclamation facility. Green Tech Station can capture more than 380,000 liters of stormwater each time it rains—water that is then used to irrigate trees on the site. The facility also includes a prairie ecosystem with native plants, a pavilion to host educational programming, and a collection of artwork.

"Most of the most vulnerable people who are having water issues, they don't have the resources to participate."

Henderson, executive director of Grounded Strategies, a nonprofit focused on community-driven vacant lot reclamation, found Green Tech Station so inspiring that she decided to create something similar in Pittsburgh. Grounded Strategies, along with partners from the Department of City Planning in Pittsburgh and the Pittsburgh Water and Sewer Authority and elsewhere, recently received a $55,000 grant to start the project. As they plan the site, they'll be in close contact with the group that constructed Green Tech Station, Henderson said.

Delegations can also facilitate cooperation between stakeholders with different immediate interests.

In 2017, for instance, the Tucson delegation committed to a lofty goal: returning perennial water flow to the Santa Cruz River. At the time, the stretch of the river in downtown Tucson flowed only during rainstorms.

Rupprecht, the Tucson Water conservation manager and four-time Tucson delegation member, said delegation members were key to advocating for Arizona's Drought Contingency Plan, a change in state law that increased recycled water recharge credits. Under the Drought Contingency Plan, Tucson Water can receive credits for 95% of the water released into the Santa Cruz River, then use those credits in the future to secure additional water supply.

Within a year, Tucson Water's Santa Cruz River Heritage Project had released enough recycled water to the river that it flowed anew for the first time in almost 80 years. The new stretch of perennial river restored plants, revitalized a ciénaga (wetland) ecosystem, and provided new habitat for wildlife such as herons, native toads, coyotes, and dragonflies.

Inclusivity Obstacles

Though many delegations have made tangible progress toward One Water goals, barriers still exist to achieving full cross-sector engagement.

"With something like One Water…if you don't do a good job of building those relationships and building those ties between sectors, then there's a risk it could be just some pleasant marketing but not really delivering the outcomes that it's supposed to deliver," Peterson said.

One major barrier is money. Attending the summit comes at a financial cost that can be too high for underfunded organizations. "It's all about money," said Pokhrel, the Alberta engineer. "Do we have enough budget? Do we have enough resources to fulfill this?"

"Most of the most vulnerable people who are having water issues, they don't have the resources to participate," Bey said. "There's a minimum threshold for organizational capacity that you have to have to connect you to these types of conversations."

The US Water Alliance tries to help delegates from underfunded organizations attend the summit with a tiered registration fee system. "If you're a small nonprofit, you're going to pay less than a private company or a large urban utility," Berry said. "The people who are more resourced, who can afford to pay more, do pay more, and that helps us subsidize the cost for the folks who are less well resourced."

A little funding can go a long way to help include historically marginalized voices. With help from a grant from the US Water Alliance, for instance, in 2023 the Minnesota delegation was able to invite representatives from the Indigenous-led nonprofit Honor the Earth, as well as community members from the Environmental Justice Coordinating Council (EJCC). Members of EJCC had previously attended the 2022 One Water Summit in Milwaukee, where they had committed to working on issues of environmental health in Minnesota, particularly the impact of per- and polyfluoroalkyl substances (PFAS) on drinking water.

"Providing funding for community and tribal members was really important to get the people we wanted to be there and have that diverse representation of multiple perspectives," Stockness said.

"Providing funding for community and tribal members was really important to get the people we wanted to be there and have that diverse representation."

Delegates from Honor the Earth and EJCC could not be reached for comment in time for publication.

Berry and some past delegates said they feel that the agriculture industry is underrepresented at the summits, too. Agriculture is a huge element of the water system, responsible for about 70% of freshwater use worldwide. The proportion of agriculture practitioners at the summit is "still not as big as it could be, or should be," said Sean McMahon, a sustainable agriculture consultant who has been involved in coordinating the Iowa delegation for five summits.

City utilities make up the majority of membership in the US Water Alliance, and urban organizations dominate the summit—a dynamic that may make the rural agriculture community feel ostracized, Peterson said. If members of the agriculture community are not engaging in a collaboration, that might mean the benefit of participating is not clear to them.

As in the fictional Farmersville, agriculture communities and urban water suppliers may not always see eye to eye. Farmers may be frustrated with what they see as overly restrictive regulations in an already difficult economic environment, whereas urban utilities prioritize delivering clean drinking water to their ratepayers.

The agriculture sector often gets cast as a villain and may feel that it must defend

Shown here is Green Tech Station in Milwaukee, a former brownfield site that was restored as a water reclamation system. In April 2024, members of the Pittsburgh delegation visited Green Tech Station as part of a learning exchange. Credit: Northwest Side Community Development Corporation itself against other water practitioners who aren't familiar with the hardships of farm operations, Peterson said. Making clear to farmers the mutual benefits of a One Water approach could improve collaboration. For instance, many sustainable agriculture practices both benefit farm finances and improve downstream water quality.

McMahon recommended that delegation leaders reach out to agriculture associations to find champions of improving water quality and water use efficiency. "If you're framing your proposal like, 'Come help us talk about these complicated issues from your perspective,' it's like a wide-open door to have really powerful conversations," said Jones.

Clare Lindahl, chief executive officer of the Soil and Water Conservation Society, a member of the Soil and Water Conservation delegation, and a board member of the US Water Alliance, said her delegation has had success building relationships across the urban and rural divide by emphasizing the value of water to all stakeholders. "The water is the bridge," she said.

"The water is the bridge," she said.

When a highly diverse group of stakeholders makes it to the summit, collaboration can lead to what Figueroa called a "healthy push and pull": Everyone sitting around the table may have different expectations, goals, and work practices.

Delegations have found that defining common goals and outlining clear responsibilities are the best way around that.

For example, the New Jersey group has centered its conversations around four shared goals: having effective and financially sustainable water systems; empowering stakeholders and ensuring that they are well-informed; building successful, beneficial green infrastructure; and creating smart combined sewer overflow control systems.

"That's our North Star, and that has helped us," Figueroa said.

"It's hard to break down silos if your objectives aren't clear," Peterson said. Being "really candid and clear about who's involved, what the roles are, and what the responsibilities are for the beginning, middle, and end of the project" can help, she said.

Berry said he has high hopes for the future of delegations. He imagines an eventual Colorado River delegation that would include stakeholders from throughout the Colorado River Basin. Other dreams include a Great Lakes delegation and a Mississippi River delegation. "There's so much ground to cover," he said.

"It's both a resources and money question, and it's a relationship question," Berry said.

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Read the article at Eos.org

A Seafloor Spreading Slowdown May Have Slashed Sea Levels

If the entire East Antarctic Ice Sheet—including Denman Glacier, pictured here—melted today, sea level would rise by about 36 meters. Between 15 million and 6 million years ago, deepening of Earth's ocean basins may have caused a sea level change of similar magnitude, but in the opposite direction. Credit: NASA

Today we are witnessing rapid global sea level rise attributable mostly to climate change–driven melting of ice sheets and glaciers and thermal expansion of seawater. However, sea level change also occurs over millions of years as geological processes gradually reshape Earth's ocean basins and change their total storage volume.

Dalton et al. home in on a period from 15 million to 6 million years ago. Prior research had revealed that ocean crust production dropped by 35% during this period. This reduction, mostly resulting from a global slowdown in seafloor spreading, caused ocean basins to deepen.

In the new work, the researchers considered various possible initial conditions for the area and ages of ocean crust, as well as crust destruction rates, calculating that the ancient seafloor spreading slowdown would have resulted in a sea level drop of 26–32 meters. This amount is comparable to the sea level change that would result today if the entire East Antarctic Ice Sheet (the largest on Earth) melted, but in reverse.

In addition, the researchers calculated that heat flowing into the ocean from the hot mantle beneath would have decreased by about 8% overall from 15 million to 6 million years ago, with an even greater drop (35%) in hydrothermal flux near oceanic ridges. They suggest this drop may have caused significant changes in the ocean's chemistry.

In previous work, some of the same researchers proposed that the 35% slowdown in crust production could have led to decreased volcanic emissions of greenhouse gases, and thus to global cooling, during the same period. If this decrease occurred, sea level could have fallen by more than 60 additional meters, thanks to thermal contraction of seawater and more water being held in continental ice sheets.

Only limited evidence of sea level changes over the past 15 million years is available from coastal rock layers. Nonetheless, the new calculations are consistent with interpretations of existing sequence stratigraphy data gathered from coastal New Jersey and offshore Nova Scotia, the researchers write.

They add that although this is not the first study to estimate past sea level changes on the basis of shifting plate tectonic speeds, it covers a more recent period at a finer resolution and with greater statistical certainty than most prior studies. (*Geochemistry, Geophysics, Geosystems*, https://doi.org/10.1029/2024GC011773, 2025) **—Sarah Stanley,** *Science Writer*

Deep Beneath California's Sierra Nevada, Earth's Lithosphere May Be Peeling Away

Crustal rocks deep underneath the Sierra Nevada in California are in the process of foundering, or sinking into the mantle. Credit: Dicklyon/Wikimedia Commons, CC BY-SA 4.0 (bit.ly/ccbysa4-0)

The processes that form continental crust from the denser rocks of the upper mantle may make the lower lithosphere denser than the underlying mantle. One theory holds that the lower lithosphere splits away and sinks into the mantle in a process called foundering. Conclusive evidence of foundering, however, has been hard to come by.

Peering deep under California's Sierra Nevada, *Schulte-Pelkum and Kilb* discovered new evidence of lithospheric foundering in progress.

The team imaged the lower crust and uppermost mantle beneath the Sierra Nevada with receiver function analysis, which uses seismic waves that change as they cross structures beneath the surface.

They also studied earthquake data from the Advanced National Seismic System Comprehensive Earthquake Catalog, or ComCat. They found a band of seismicity in the central Sierra, in which small earthquakes (ranging in magnitude from 1.9 to 3.2) occur at the unusual depths of 40 kilometers and greater.

Differences in receiver functions along the mountain range revealed a distinct layer in the mantle, which grows gradually less distinct farther north. This observation aligns with the existing hypothesis that a section of the lithosphere beneath the southern Sierra sank (foundered) millions of years ago.

The researchers found no evidence of this layer in the northern Sierra, indicating foundering has yet to progress to that region.

A slab of colder continental lithosphere also has the capacity to crack, rather than to stretch and flow like hot material typically found at such depths. This likely also explains the presence of such deep earthquakes in the central Sierra, according to the authors.

The results of this work align with those of previous studies that found a gradient Moho, rather than a sharply defined crust-mantle boundary, under the Sierra. It also matches previous suggestions that a cold mantle anomaly under the Great Valley region to the west may be dense lithosphere lost to the foundering process. Foundering has been ongoing in the Sierra for at least 3 million years according to this hypothesis, and the researchers say it may be progressing northward.

This region provides evidence of a process of differentiation that occurs throughout Earth's crust, they argue. (*Geophysical Research Letters*, https://doi.org/10.1029/2024GL111290, 2024) **—Nathaniel Scharping,** *Science Writer*

Ceres's Organics Might Not Be Homegrown After All

The dwarf planet Ceres is the largest object in our solar system's asteroid belt, and it may have remnants of a subsurface ocean.

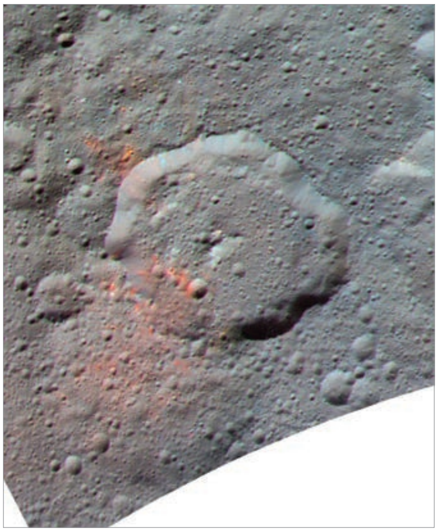
In 2017, researchers reported that NASA's Dawn spacecraft had discovered complex organic compounds on Ceres, including in the 50-kilometer-wide Ernutet Crater. They suggested that the compounds, which consist of long chains of carbon atoms, were most likely produced by chemical processes on Ceres.

However, as more Dawn data were analyzed, a lively debate grew over whether these organics had indeed formed on the dwarf planet or were delivered by organic-rich asteroids that crashed into its surface.

Now, *Sarkar et al.* present a new analysis that supports an external, asteroid origin for Ceres's complex organic compounds.

The researchers scanned Ceres's surface in search of any organic compound hot spots that earlier studies may have missed. First, they applied a machine learning approach known as a deep neural network to images captured by Dawn's Framing Camera, probing for reddish, visible-wavelength signatures of potential organic-rich sites. Then, they further analyzed those sites using data from Dawn's Visual and Infrared Spectrometer, specifically looking for infrared light at 3.4 micrometers—a telltale sign of the chain-like compounds they sought.

The deep neural network revealed several reddish, previously undetected sites of interest across Ceres's surface, but only two of



Areas colored red in this composite image of Ernutet Crater on Ceres are associated with evidence of organic material. New research suggests this material originated on asteroids that collided with the dwarf planet. Credit: NASA/JPL-Caltech/UCLA/MPS/DLR/IDA

the new sites, which are likely associated with the main deposit at Ernutet crater, exhibited the signal of complex organic compounds.

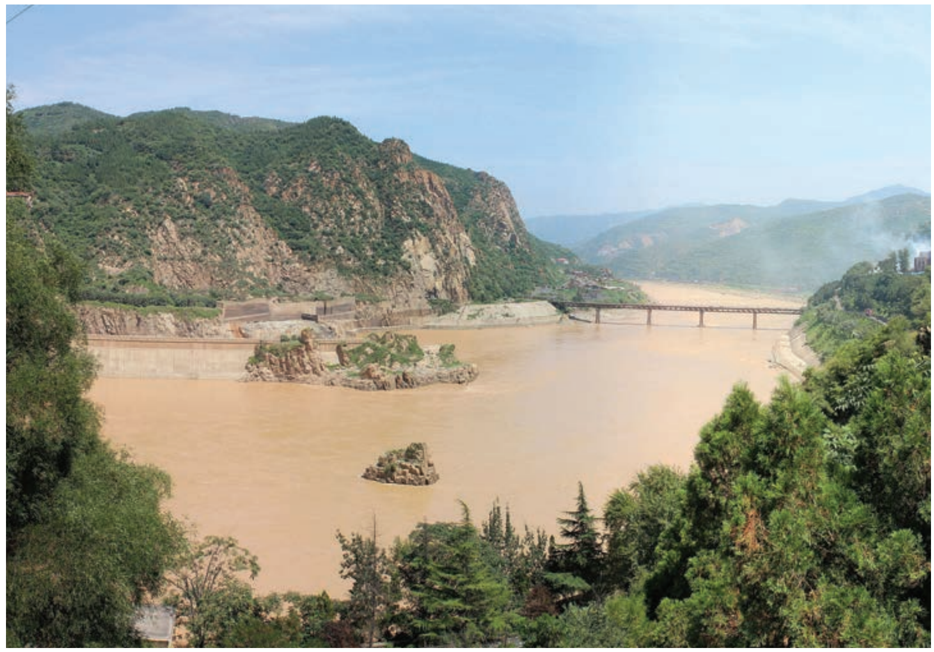
Taking a closer look at the previously known sites, the researchers found that the organic compounds appear to be limited to the upper layer of Ceres's surface. In addition, they did not find geologic features, such as fracture systems or volcanic structures, that might indicate the materials came from Ceres's interior.

Instead, the new data suggest that the organic compounds were more likely deposited by organic-rich asteroids that crashed into Ceres, while traveling slowly enough that at least some of the organics remained intact after impact.

Organic compounds like those found on Ceres are thought to be the building blocks of life. Although these findings don't suggest that Ceres has ever harbored life, they deepen understanding of the history and distribution of organic compounds in the solar system.

The researchers note, however, that the debate may not yet be resolved; it is still possible that organic compounds are produced on Ceres but have so far escaped detection capabilities. (*AGU Advances*, https://doi.org/10.1029/2024AV001362, 2025) **—Sarah Stanley,** *Science Writer*

Tracing Metals from Earth to Water to Life in the Yellow River



China's Yellow River transports sediments and other materials thousands of kilometers and is a cornerstone of adjacent ecosystems. Credit: fading/Wikimedia, CC BY-SA 3.0 (bit.ly/ccbysa3-0)

The Yellow River, which stretches from the Tibetan Plateau to the Bohai Sea in China, is so called because of the color lent by massive amounts of suspended sediments along its 5,400-kilometer length. Its waters, sediments, and nutrients support more than 100 million people and many endemic plant and animal species. China's "Mother River" also transports metals such as iron, cobalt, arsenic, and platinum, a process with important implications for the health and evolution of downstream ecosystems.

Wang et al. analyzed the metal content of water, particulate, and sediment samples collected from 57 locations along the Yellow River and its tributaries. They also extracted microbial DNA and fish tissues from the samples. Their goal was to assess how metal abundances varied throughout the river, its sediments, and local biology, or what the researchers refer to as the area's "Earth-river-life complex."

In total, the authors identified 62 metals, with abundances spanning 10 orders of magnitude. Alkali and alkaline metals were the most common, and platinum and lanthanide metals were the least common. The types and relative abundances of different metals were consistent across the water, sediment, and biological samples. (Gold, iridium, and palladium, however, were more abundant in the water than in the solid crust, which the authors attribute to human activities such as mining and smelting as well as to natural processes such as evaporation.)

Less toxic metals were more abundant, particularly in sediments, though the researchers detected elevated levels of highly toxic arsenic in their samples. Further, they identified 324 different metal-resistance genes in the river microorganisms studied. These genes allow organisms to survive in areas with toxic concentrations of metals and reflect how microbial life has adapted to such hazards.

The researchers suggest that their study and similar work can offer useful information for updating regional water- and diet-related health guidelines, for example, to account for the high levels of arsenic identified. (*Water Resources Research*, https://doi.org/10.1029/2024WR037961, 2024) **—Nathaniel Scharping,** *Science Writer*

Trees Can Cool Cities, but Only with a Little Help

Because trees can cool cities by providing shade and evaporating water into the atmosphere, greening city streets is an often-touted strategy for climate change adaptation. But trees provide benefits only if they're healthy, and physical variations in urban environments mean that not all trees have the same chance to thrive.

Wilkening and Feng identified cityscape features in Minneapolis–Saint Paul that set trees up for success and that may cause them to struggle. The researchers used data from the ECOSTRESS sensor aboard the International Space Station to map the summer afternoon canopy temperatures. Then they applied machine learning to assess the relationship between these temperatures and various environmental factors, including proximity to water, urbanization, traffic exposure, and surrounding land cover.

Trees, such as these in Minneapolis–Saint Paul's Loring Park, help cool cities, but not always as much as might be expected. Credit: Warren LeMay/Flickr, CC BY-SA 2.0 (bit.ly/ccbysa2-0)

They found that proximity to blue and green spaces (areas with water or vegetation) improved tree health, whereas trees in areas with a lot of built structures and impervious surfaces fared worse.

Using this analysis, the researchers created and calculated the combined urban tree index (CUTI)—a metric that considers the fraction of land covered by tree canopy along with the temperature and health of the canopy—to determine how much an area benefits from its trees. The CUTI scale ranges from 0 to 1, with 0 meaning no benefit and 1 meaning maximum benefit.

In urban areas where the surroundings will likely cause trees to do poorly, city managers will need to plant more trees and attend to them more carefully than in areas where trees thrive naturally, the authors concluded.

That approach may be particularly relevant to historically disadvantaged communities, which often have few trees. Planting trees in these areas is a step toward correcting environmental injustices, the authors say, but those trees must also be nurtured for communities to benefit from them. (*AGU Advances*, https://doi.org/10.1029/2024AV001438, 2025)

—Saima May Sidik, *Science Writer*

Modeling the Long and Short of Subduction Zones

Tectonic Plates at subduction zones typically move just a few centimeters per year. But when accumulated stress at these convergent boundaries releases suddenly, the plates can slip several meters and cause some of Earth's largest earthquakes. The timing and location of such megathrust earthquakes depend on factors such as the shape, roughness, composition, and fluid content of the fault.

Aside from the danger they pose, such earthquakes disrupt the slow, long-term changes occurring at subduction zones. The cycle of sudden earthquakes and slow plate movement makes it difficult for scientists to create a single computer model that accurately combines all of these features. Seismic cycles and long-term deformation are typically modeled separately, and models that do try to simulate both processes don't capture along-strike variations, which help dictate the size of a megathrust earthquake.

Fang et al. describe a new subduction model that can better capture both long-term tectonics and short-term earthquakes and that agrees with existing observations. The model combines several factors, such as buoyancy forces that drive plate motion; diffusion and dislocation creep, which describe material flow in the mantle; and the friction between tectonic plates, to more accurately capture the mechanics of subduction across both time and fault length.

The Oregon coastline, seen here, sits above the Cascadia megathrust. Motions along this and other megathrust boundaries have been difficult for scientists to model because of the drastically different timescales of slip that occur through time. Credit: Rob DeGraff/Flickr, CC BY-NC-ND 2.0 (bit.ly/ccbyncnd2-0)

The new model, which simulates movements along a 4,040- × 660-square-kilometer thrust fault area, predicts plate movement of around 5 centimeters per year and ruptures with around 10 meters of slip every several hundred years. The model also accounts for how greater rupture length correlates with earthquakes of greater magnitude. (*Geophysical Research Letters*, https://doi.org/10.1029/2024GL110821, 2024)

—Rebecca Owen, *Science Writer*

Alaska's Lakes and Ponds Reveal Effects of Permafrost Thaw

Summit Lake in central Alaska is fed by the Gulkana Glacier, which can be seen in the background. Credit: Eric Levenson

As climate change warms the Arctic, permafrost is thawing, and carbon trapped within the soil is moving into the atmosphere. Permafrost stores twice as much carbon as the atmosphere, but the degree to which this frozen carbon will thaw and accelerate climate change has remained a point of scientific inquiry. Taking widespread on-the-ground permafrost measurements is not logistically feasible in the remote Far North.

By documenting Alaska's lakes and ponds in unprecedented detail, *Levenson et al.* show where and how water bodies can signal underlying permafrost thaw, providing a step toward a straightforward, easily applicable method for keeping tabs on how the Arctic is changing.

Thawing permafrost can shift erosion rates, vegetation growth, and soil permeability, which can cause lakes to form, grow, and drain. To examine how the relationship between lake area and the extent of intact permafrost varies across Alaska, the researchers used images taken nearly daily at 10-meter resolution by the Sentinel-2 satellite to identify and track changes in more than 800,000 bodies of water across the state.

They report that thawing permafrost appears to reduce the size of lakes in landscapes untouched by glaciers where bedrock is not exposed at the surface. Conversely, in areas that were recently carved by moving glaciers, lake area sometimes increases as permafrost thaws. In some cases, no clear relationship between the two exists.

Receding glaciers usually leave behind new lakes; however, the formation of these lakes may be delayed until permafrost thaws and new depressions can form. The rugged topography and less permeable sediment in glacial landscapes could also explain why lakes in glaciated and unglaciated regions react to permafrost thaw differently, the researchers say.

The authors are not the first to consider the relationship between lake area and permafrost thaw, but they are among the first to describe how a lake's response to ongoing thaw depends on its geologic history. The researchers say the dataset they produced, which they call the Alaska Lake and Pond Occurrence Dataset, could greatly simplify research aimed at investigating how permafrost is changing as the Arctic warms. (*Geophysical Research Letters*, https://doi.org/10.1029/2024GL112771, 2025) **—Saima May Sidik**, *Science Writer*

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- A statement on teaching philosophy and mentorship.
- Contact information for three professional references.

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Dear *Eos*:

The first thing that impresses those who trek up to the ruins of Machu Picchu—other than the spectacularly biodiverse transition landscape between the Peruvian Andes and the Amazon Basin—is that they are not really on top of the world. Machu Picchu (Old Mountain, in Quechua), located approximately 3,000 meters above mean sea level, is itself surrounded by towering mountains that rise to about 4,000 meters above mean sea level. More than 600 years ago, the Inca harnessed natural springs originating at higher elevations to supply water to their homes and irrigate terraced fields in this mountaintop sanctuary.

In these images from July 2024, one can see evidence of canals crisscrossing the ruins that eventually drain to the Urubamba River in the Sacred Valley below. Evidence of active aqueducts, fountains, and irrigation canals also can be seen in the nearby Inca villages that have been continuously inhabited for the past several centuries. One good example of such Indigenous hydroengineering lies in the village of Ollantaytambo, which has water derived from Andean glaciers perennially running through it.

World over, people have used mountain water towers as a source of water for millennia, taking advantage of the power of the water cycle to raise water, the capacity of mountains to store it, and the force of gravity to release it—maintaining fertile landscapes of running fresh water. Throughout the Mediterranean, the Romans and the Moors left lasting legacies of their extensive network of aqueducts and canals, some of which are still functional.

Roughly half of humanity today depends on water derived from rapidly dwindling mountain water towers, many of them still glaciated or periglaciated. With anthropogenic land use changes in mountain habitats altering their capacity to hold and release water, and ongoing global warming accelerating glacial mass loss, water security will get precarious over time. The world's mountain water towers need immediate protection from the multipronged threats eroding their unique water-holding capacity.

—**Bopi Biddanda,** Robert B. Annis Water Resources Institute, Grand Valley State University, Muskegon, Mich.