VOL. 105 | NO. 7
JULY 2024

Eos

SCIENCE NEWS BY AGU

Rethinking a River

How the West was watered, and how science can set a new course for the 21st century

AGU
ADVANCING EARTH AND SPACE SCIENCES


MATLAB
FOR AI
Boost system design and simulation with explainable and scalable AI. With MATLAB and Simulink, you can easily train and deploy AI models.
mathworks.com/ai
MathWorks®
Accelerating the pace of engineering and science
© The MathWorks, Inc.

CONTENT

From the Editor

One of the most contested water management policies in the United States relies on an ill-informed agreement forged more than a century ago. The 1922 Colorado River Compact "ignored available science and overallocated the river's water," say the scientist-authors of the lead story in this year's policy issue. But it's not too late to change course, they argue in "Fixing the Flawed Colorado River Compact" on p 16.

On the Cover

Credit: Modified by Gabriella Trujillo from her original illustration "Tribes of the Colorado River Basin" for *High Country News*

Eos: Science News by AGU (ISSN 0096-3941) is published monthly except December by the American Geophysical Union, 2000 Florida Ave., NW, Washington, DC 20009, USA. Periodical Class postage paid at Washington, D.C., and at additional mailing offices. POSTMASTER: Send address changes to *Eos: Science News by AGU*, Member Service Center, 2000 Florida Ave., NW, Washington, DC 20009, USA

Member Service Center: 8:00 a.m.–6:00 p.m. Eastern time; Tel: +1-202-462-6900; Fax: +1-202-328-0566; Tel. orders in U.S.: 1-800-966-2481; service@agu.org.

Submit your article proposal or suggest a news story to *Eos* at bit.ly/Eos-proposal.

Views expressed in this publication do not necessarily reflect official positions of AGU unless expressly stated.

Janice Lachance, Interim Executive Director/CEO

Kansas Prairie Streams Are Getting Choked, Maybe for Good

The Konza Prairie Biological Station in Kansas has changed over the past 30 years. Woody vegetation now grows where grasses once thrived. Credit: Walter Dodds

Walter Dodds has watched the Konza Prairie Biological Station landscape slowly change since he started studying it in 1990. Woody vegetation replaced drifts of grasses and wildflowers along the streams, choking their flow and disrupting the ecosystem in this 3,500-hectare preserve in the Flint Hills of northeastern Kansas.

About a decade ago, Dodds, an aquatic ecologist at Kansas State University, and others cleared much of the woody vegetation to help restore the prairie, which is jointly owned by The Nature Conservancy and the university. But the effort has failed to help grasses return, according to a new study published in *Ecological Applications* on how the landscape has fared (bit.ly/woody-vegetation).

Natural cycles in the prairie ecosystem once held woody plants at bay. Then, Konza's 500 species of grasses and wildflowers thrived in a system of checks and balances known as disturbances. These included seasonal weather extremes, grazing animals that regenerated the ecosystem, and fire that cleared spent vegetation and redistributed nutrients.

The balance seems to have shifted, perhaps permanently, Dodds said.

Despite grazing and managed burns, woody vegetation took hold, fundamentally altering the riparian zone. Sun-loving algae, the base of the prairie's aquatic food web, were shaded by the canopy. Across 3 decades, streamflow declined by 40%–50%.

"Along with that, there has been an increase in days with no flow. Therefore, there are strong negative impacts on stream biota as well as less water available for human uses downstream," Dodds said.

The balance seems to have shifted, perhaps permanently.

A Drastic Change?

In 2010, Dodds enlisted dozens of professionals and volunteers to remove woody plants along 4.5 kilometers (2.8 miles) of stream channels. They cleared shrubs and trees with brush cutters and chainsaws. They piled up all the debris and conducted scheduled burns. To regenerate the native plants, they cast bagfuls of seed in the cleared areas.

A decade later, the trees were still gone, and the landscape remained changed. The shrubs not only persisted but also expanded their hold. And the grasses resisted reseeding.

The grassland riparian zone had lost its resilience.

Water quality changed too. Dodds and his colleagues saw huge increases in nitrates after clear-cutting, which can be problematic for human health and cause excess plant growth in waterways. The nitrates flowed downstream, only to be reabsorbed by the rebounding shrubs.

Zak Ratajczak, an ecologist also at Kansas State University and a coauthor of this study, has been researching the landscape-scale effect of woody encroachment using current and historical remote aerial images. In some areas of the prairie, shrub coverage has grown to 45%–50%, despite grazing and periodic burns, he said. The rate of growth for these trees and shrubs has become startling, Ratajczak said.

Dodds conceded that increasing nitrogen availability could have spurred shrub regrowth. Also, modern grazing practices do not fully match conditions of centuries ago, and today's managed fires likely do not replicate the heat and intensity of ones in the past.

But photosynthesis has also changed in light of the shifting climate and atmospheric carbon dioxide enrichment, said Kelly Lyons, a botanist and ecologist at Trinity University in San Antonio who was not involved in the study.

"The process of photosynthesis has an inherent trade-off between water and carbon," Lyons said. "Warm-season prairie-adapted grasses and wildflowers optimize carbon capture and minimize water loss, maintaining an advantage under lower precipitation."

Researchers theorize that with rising atmospheric carbon, encroaching woody species have greater carbon capture and are less disadvantaged, allowing them to get a foothold and spread quickly. Historical disturbances such as frequent fires are no longer keeping shrubs and trees in check.

"Woody expansion is the biggest threat to tallgrass prairies," Dodds said.

"It's getting to the point where it seems like there are very few options to prevent this process from happening," Ratajczak said.

By **Kimberly Hatfield** (@fieldnotes2014), Science Writer

From First Continents to Fancy Countertops

The rock known as gabbro features in many trendy kitchen countertops, where its durability, heat resistance, and bold black-and-white veining make it an attractive option. Its chemistry also made it ideal for creating the early building blocks of the continents, according to a new study published in *Nature Communications* (bit.ly/gabbro-crust).

Early Earth was covered in a hardened shell of dark basaltic crust that crystallized as the planet's primordial ocean cooled. How the lighter and chemically distinct continental crust formed later is still under debate.

"Many people are preparing their dinner on the type of rock that was responsible for making our modern continents."

The new study proposes that gabbros melted within early Earth to form rocks known as TTGs—a mix of tonalite, trondhjemite, and granodiorite—which made up most early continental crust.

"Many people are preparing their dinner on the type of rock that was responsible for making our modern continents," said the study's lead author, Matthijs Smit, a geochemist at the University of British Columbia in Canada. Smit was struck by the revelation while casually cutting an onion for a meal at a friend's house.

The crusts making up the continents and the ocean floor are physically and chemically different. Oceanic crust is thin and dense and made primarily from gabbro and its surface equivalent, basalt. Continental crust, on the other hand, is thicker and less dense and is made from lighter rocks that contain mostly silicate minerals—those that have abundant silicon and oxygen.

According to some theories, continents were first formed mainly by subduction, as one tectonic plate slid beneath another, or by meteorite impacts that fractured and altered the early crust. The new study suggests instead that the early continents formed from the melting of gabbros in crustal regions known as protocontinents roughly 3.5 billion years ago, during the Archean eon.

Archean TTGs are difficult to study, in part because they are so old: Plate tectonics has trundled along for the past 3 billion or so years, subducting, morphing, and eroding TTGs from early Earth and affecting their composition.

(top) A new study suggests that TTG rocks—a mix of tonalite, trondhjemite, and granodiorite, here seen in white—were formed by the melting of gabbros. Credit: Jaana Halla. (bottom) Fragments of ancient continental crust exist in pockets around the world, including in Banff National Park in Alberta, Canada. Credit: Gorgo/Wikimedia Commons, Public Domain

Creating Crust

To dig into the past, researchers looked at data from thousands of TTG samples from locations around the world where the ancient crust is exposed—including in the Rocky Mountains in Canada. These data are detailed in the GEOROC (Geochemistry of Rocks of the Oceans and Continents) data repository at the University of Göttingen in Germany.

"This is a new idea and quite different from previous models."

Their analysis revealed that the TTGs had a distinctive signature of trace elements—a high ratio of the rare earth element lanthanum to samarium and high levels of europium—that indicated that gabbros were the source rocks, Smit said.

This new understanding enabled the researchers to determine that Archean TTGs had formed at the bases of areas of thickened oceanic plateaus above hot regions of the mantle.

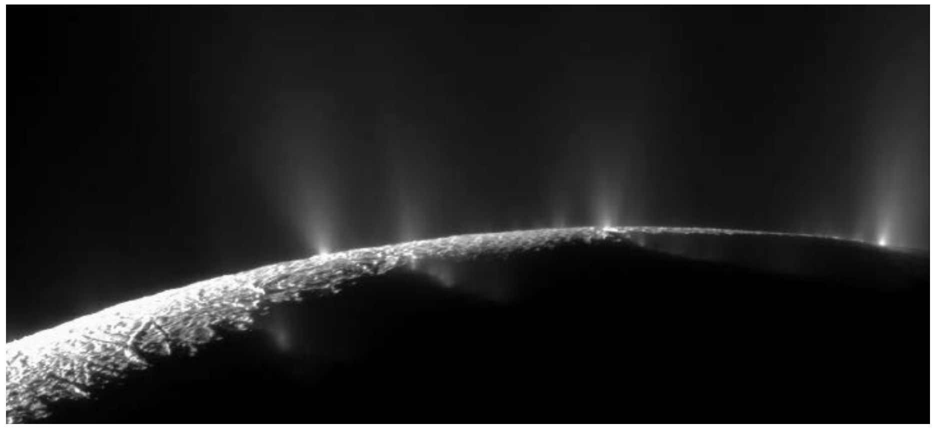
Earlier studies had suggested that Archean TTGs had formed from melting within oceanic plateaus, geochemist Balz Kamber of Queensland University of Technology in Australia wrote in an email. But the new study is the first to identify gabbros as the source.

"The idea had not previously been tested with such a thorough assessment of published geochemical data for TTGs," wrote Kamber, who was not involved in the new study.

Geologist Hugh Rollinson, a professor emeritus at the University of Derby in the United Kingdom who also was not involved in the study, added that he'd like to see a study of areas where such TTGs were exposed on the surface, rather than the latest study's statistical approach to all TTG samples in the GEOROC database. But he stressed that the specific geochemical mechanism proposed in the study was a novel approach to the issue of the formation of Archean TTGs: "This is a new idea and quite different from previous models," he said.

By **Tom Metcalfe** (@HHAspasia), Science Writer

Strike-Slip Faults Could Drive Enceladus's Jets



Jets along Enceladus's tiger stripes regularly eject water, ice, and organic compounds from the moon's subsurface ocean. Credit: NASA/JPL/Space Science Institute, Public Domain

Jets along Enceladus's famous tiger stripes may be punching through the moon's icy shell because strike-slip motion periodically tears the scablike fractures. New research explains how tides between the moon and Saturn force the edges of the stripes back and forth until they split (bit.ly/Enceladus-jets-faults).

Strike-slip motion regulated by tides could govern not just the timing and intensity of Enceladus's jets but also the geological evolution of its south polar terrain, explained Alexander Berne, a geophysics graduate student at the California Institute of Technology in Pasadena and first author on the study.

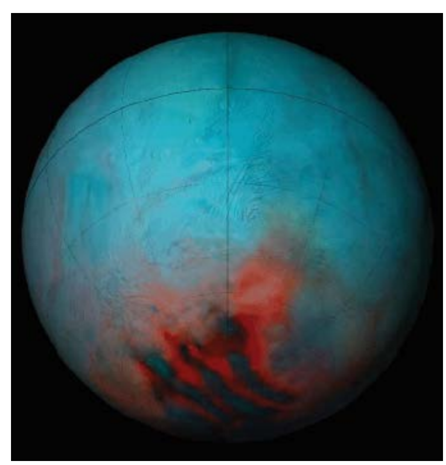
Enceladus's four tiger stripes—named Alexandria, Cairo, Baghdad, and Damascus after locations in *The Arabian Nights*—are roughly 135-kilometer-long fractures in the moon's south polar terrain. Infrared measurements have shown that the stripes are much hotter than their surrounding areas, suggesting the presence of thinner or broken crust or an unknown heating mechanism at those spots.

Images from NASA's Cassini mission revealed intermittent plumes of water, ice, and organic compounds venting from the stripes. The jets are thought to be tapping material from a subsurface ocean.

From Tides to Jets

"Tidal processes have played an important role in Enceladus' evolution, the current presence of a subsurface liquid water ocean, and the spectacular plume activity," explained Sarah Fagents, a planetary scientist at the University of Hawaiʻi at Mānoa in Honolulu who was not involved with the research. But it has been difficult to explain how tides influence the timing and brightness of Enceladus's jets, she said.

The moon's eccentric 33-hour orbit contracts and stretches the icy crust, but between times of maximum crust stress and when a plume's outflow (and thus its brightness)



This global thermal map of Enceladus shows how the four tiger stripes in the south polar terrain are anomalously hot compared with the surrounding crust. Credit: NASA/JPL-Caltech/University of Arizona/LPG/CNRS/University of Nantes/Space Science Institute, Public Domain intensifies is a 6- to 7-hour lag. Moreover, past simulations have shown that if tidal stress were opening the tiger stripes straight apart, like divergent plate boundaries on Earth, peak jet brightness would occur only once per orbit, but the jets instead peak twice.

To unriddle the mystery, the researchers simulated the tidal forces experienced at Enceladus's south pole, inspired by newer earthquake models. "In the last 20 years, very sophisticated numerical models have been developed to model earthquake sequences on Earth along the San Andreas Fault and other places to try to understand the structure of the crust," Berne said. "We adapted that [approach] for Enceladus."

This work is "exactly the type of tricky modeling work we need to understand a body like Enceladus."

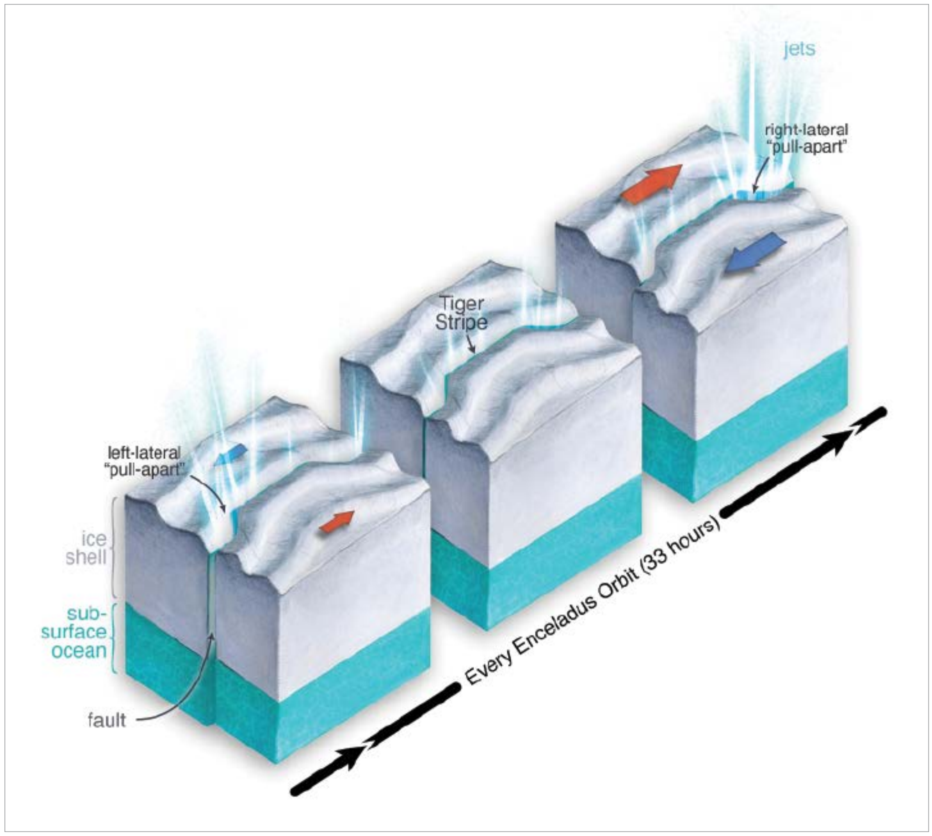
The simulations revealed that for every orbit Enceladus makes around Saturn, the tiger stripes experience two periods of high shear stress from tides. The stress drives strike-slip motion along the two edges of each tiger stripe: Tectonic movement causes blocks of ice to slide past each other, rather than separate or crash together.

Strike-slip motion happened roughly 6–7 hours after the peak tidal stress, matching the lag in observed jet activity. What's more, strike-slip motion occurred twice per orbit, a characteristic of jet activity that other tidal simulations had not been able to replicate.

Fagents found the research "persuasive," adding that "the model elegantly explains a key and puzzling aspect of Enceladus' plume dynamics."

"The work made a compelling case that tidally driven strike-slip motion is broadly consistent with the plume activity," said Miki Nakajima, a planetary scientist at the University of Rochester in New York who was not involved with the research.

The simulation showed that areas that slip more match observed hot spots. "This may be indicating that the strike-slip motion helps open the tiger stripes and encourage heat production," Nakajima said.



Strike-slip motion along faults could be linked to jet activity at Enceladus's tiger stripes. Orbital tides between the moon and Saturn pull the faults back and forth, stressing them and causing strike-slip motion. The regular tension along pull-apart zones allows water to rise and feed material to cryovolcanic jets. Credit: James Tuttle Keane

Geologic Evolution

One curious feature of Enceladus's jets is that one of the outflow peaks is brighter than the other. The new simulation reproduced the asymmetry and suggested that the edges of the tiger stripes tend to slip more in one direction than the other during each orbit. More slipping leads to jets that are more intense.

Berne cautioned that the team has not yet pinned down a mechanism that links the strike-slip activity to jet brightness. The study authors propose that strike-slip motion weakens areas along the stripes that have already been stretched and morphed by tides until they eventually pull apart. They plan to explore this possible mechanism more fully in future work.

This work is "exactly the type of tricky modeling work we need to understand a body like Enceladus," said Hamish Hay, a planetary scientist at the University of Oxford in the United Kingdom who was not involved with the study. "The correlation the authors find between fault activity and plume brightness is very intriguing."

Features such as chasmata, rift zones that radiate like bicycle wheel spokes from the south polar terrain, could also have been created by this asymmetrical motion (bit.ly/Enceladus-south-pole).

"This is how geology is created around tectonic faults, like the San Andreas Fault," Berne said. "Our models, even though they only treat the short-term deformation problem, have implications for the long-term evolution of the south polar terrain."

By **Kimberly M. S. Cartier** (@AstroKimCartier), Staff Writer

Extra Carbon Dioxide Helps the Amazon's Lower Layers Thrive—for Now

Plants in the Amazon's understory don't absorb as much carbon as the forest canopy does, but they still play an important role in the rainforest ecosystem. Credit: Dado Galdieri/AmazonFACE

The Amazon plays an essential role in moderating the climate, absorbing a quarter of all the carbon stored in the world's forests. But no one knows how the world's largest rainforest will respond to the increasing amounts of carbon emitted into the atmosphere by humans. Will it absorb more carbon and thrive, or will it reach a tipping point and become a savanna?

Even less is known about the effects of high emissions on the forest's understory—the lower layer of vegetation formed by small trees and shrubs topping out between the forest canopy and the floor.

Though it absorbs just under half as much carbon as the canopy, this layer plays an important role in the forest (bit.ly/forest-floor-carbon). All trees pass through this layer while growing, and other plant species live there throughout their lives.

"These plants are important in ecological relationships," said Sabrina Garcia, a biologist at the National Institute for Amazonian Research, a research center linked to the Brazilian Ministry of Science, Technology and Innovation. "They provide food for animals and also have their share in the carbon sink." Garcia is one of two joint first authors of a new paper in *Plant, Cell and Environment* studying how the forest understory responds to elevated carbon dioxide (CO_2) levels (bit.ly/understory-CO2).

The new study is part of the larger project AmazonFACE. This multimillion-dollar open-air experiment in the Brazilian Amazon will release carbon into the tree canopy via 35-meter-high metal towers to study how the rainforest responds. The first tests are set to run later this year. In the meantime, researchers from the international consortium running the experiment began setting up smaller open-top chambers in the forest in 2019.

Like greenhouses without roofs, these 3-meter-high chambers have transparent walls that encircle forest patches and inject CO_2 into plants' surroundings through a gas line. Researchers used these tools to test the response of the forest's lower layers to carbon-saturated air.

"To see a study like this from a really important ecosystem in the central Amazon is very exciting," said David Ellsworth, an ecologist at Western Sydney University in Australia who was not involved in the research.

Ellsworth, who spent 30 years studying the Amazon and has led experiments exposing vegetation to elevated CO_2 levels, was impressed with the logistics of setting up the chambers in the forest (bit.ly/CO2-chambers). So far, most experiments using this technique have been done on clearings and crops. "To do research like this in the forest is amazing, because it is logistically so difficult to do this kind of study," he said.

Life in the Shadows

Plants in the understory live in the shadows. Typically, only about 5% of sunlight filters down through the canopy.

Researchers hypothesized that plants in the understory would be particularly good at soaking up carbon from the air because they live in a constant state of "hunger" for light.

Their idea was that these plants would use the extra gas to grow larger leaves with more surface area for capturing light, for example.

However, studies to test this hypothesis have been scarce and mostly done with seedlings growing in pots. In the new study, the researchers set up eight open-top chambers in the forest, half under normal conditions and half injected with air containing 250 parts per million of CO_2. This amount corresponds to the extra gas that predictions suggest will be in the atmosphere 50 years from now if emissions follow current trends.

"They are taking the extra CO_2 and depositing it in some structures, for example, increasing their leaf surface."

For a year, they measured the plants' leaf areas, stem diameters, heights, and growth rates. They found that the plants in the understory absorbed the carbon and used it to grow: In 4 months, the understory plants exposed to the extra gas absorbed 67% more carbon and produced 85% more leaves than the other plants.

The researchers think the gas is helping the plants better exploit the erratic Sun flecks they get for photosynthesis. "They are taking the extra CO_2 and depositing it in some structures, for example, increasing their leaf surface," said the study's second joint first author, Amanda Damasceno, who at the time of the experiment was a master's student at the National Institute for Amazonian Research.

Uncertain Future

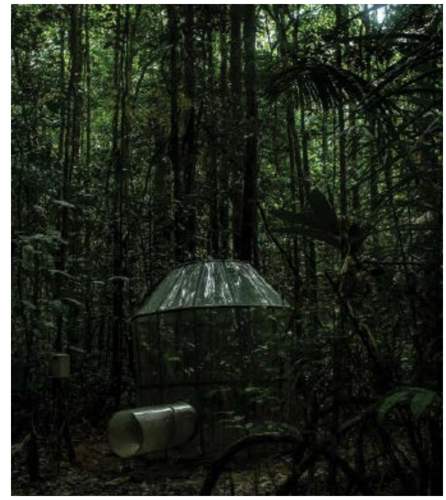
The results might sound like good news at first glance. But the authors highlighted that these effects might change in the long run. As temperatures rise in the changing climate, the plants might not absorb carbon and grow in the same way.

"Will this increase in carbon absorption be, in fact, beneficial for the plants?" Damasceno asked. "To what extent will the plants respond?"

Transpiration is another factor. Just like us, plants sweat to keep their temperature stable, releasing water through small pore-like holes in their leaves called stomata. They use these same structures to absorb carbon from the air. Scientists have suggested that plants could change their transpiration rates in carbon-saturated environments.

When there is a lot of CO_2 in the air, the plants don't need to open their stomata much to absorb the gas. In return, they reduce their transpiration and the amount of water they release into the air.

In the new study, the understory plants maintained their normal transpiration rates. However, Garcia worries that this could change in the long term, possibly altering the region's rain regime. "For now, the understory plants have been shown to be efficient in water use, being able to absorb carbon without losing water," said Garcia. "But this could be a one-off effect."



AmazonFACE researchers set up transparent chambers to pump carbon dioxide around plants in the lower layers of the forest. Credit: Dado Galdieri/ AmazonFACE

Plants exposed to extra carbon dioxide showed higher photosynthesis and growth rates. Credit: João Rosa/ AmazonFACE

Sweating Rain

Amazonian plants are rainmakers. Their transpiration forms so-called flying rivers, kilometers-long streams of moisture that circulate via air currents passing over fields, forests, and cities in South America. The humidity these rivers carry is responsible for much of the rain that falls on the continent.

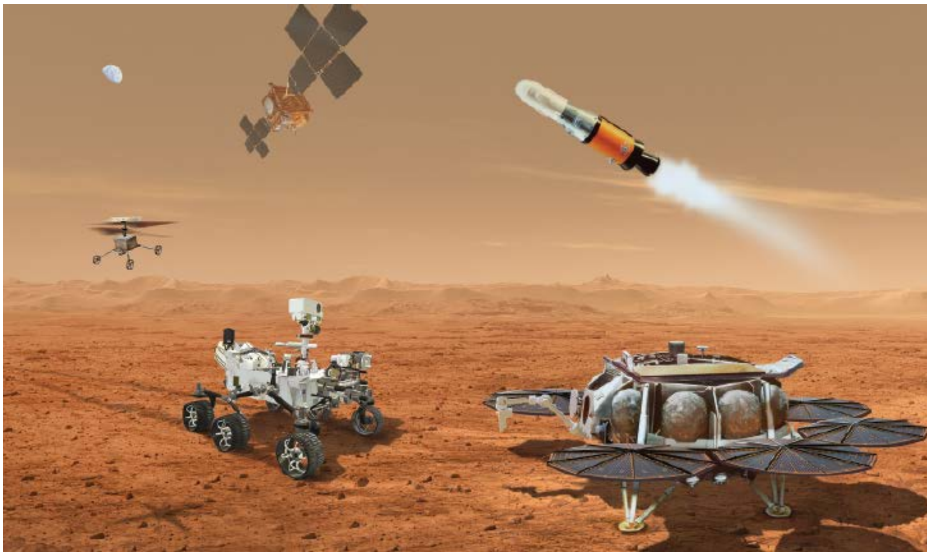
Several studies over the years have suggested that in a carbon-saturated environment with extreme climate change, the Amazon could become a dry savanna, reducing rainfall in South America. Under this scenario, the landscape would become a carbon source rather than a carbon sink.

The researchers will continue tracking the longer-term effects in the experimental area, and they will rely on the results of the larger AmazonFACE experiment to gain a more complete picture of the forest's future.

"We know so little about the climate and the CO_2 responses of tropical vegetation in general and the Amazonian specifically that anything that we do scientifically is a leap forward," said Ellsworth. "This study is a great stepping stone."

By **Sofia Moutinho** (@sofiamoutinhoBR), Science Writer

Mars Mission's Monetary Roller Coaster Hits New Lows



This illustration shows the various activities that could compose a Mars Sample Return mission, a topic of budgetary uncertainty at NASA. Credit: NASA/JPL-Caltech, Public Domain

On 7 February, the Jet Propulsion Laboratory (JPL) in Pasadena, Calif., laid off 530 staff—around 8% of its more than 6,000-person workforce—along with 40 contractors.

February's layoffs were the latest in a series of cutbacks and slowdowns at NASA centers. JPL had already laid off 100 contractors in January, NASA's Goddard Space Flight Center laid off contractors late last year, and work on several projects had slowed or frozen entirely. The sequence was precipitated by the lack of a federal budget for fiscal year (FY) 2024 for several months after the prior year's appropriations ran out.

Virtual Layoffs

On Tuesday, 6 February, JPL employees received a memo from the center's director, Laurie Leshin.

"While we still do not have an FY24 appropriation or the final word from Congress on our Mars Sample Return (MSR) budget allocation, we are now in a position where we must take further significant action to reduce our spending, which will result in layoffs of JPL employees and an additional release of contractors," Leshin wrote. The layoffs would happen the following day.

Barring a few lab-essential personnel, staff and contractors were directed to work from home on 7 February and attend a virtual meeting with their division supervisors explaining the process. Then staff and contractors awaited individual emails saying whether they still had jobs.

Data obtained from California's Employment Development Department show that the majority of February's staff layoffs (71%) affected engineering-related positions. Among those, systems engineers were particularly hard hit, with 117 of 822 engineers losing their jobs, 13% of their workforce. Mechatronics engineers lost the highest fraction (28%) of their workforce (32 of 115).

Leshin told *Space News* in April that though significant, the cuts did not affect JPL's core capabilities. "We worked very hard in spite of having to make the deep cuts and to make sure those capabilities were intact," she said.

Several former JPL employees declined to comment for this story.

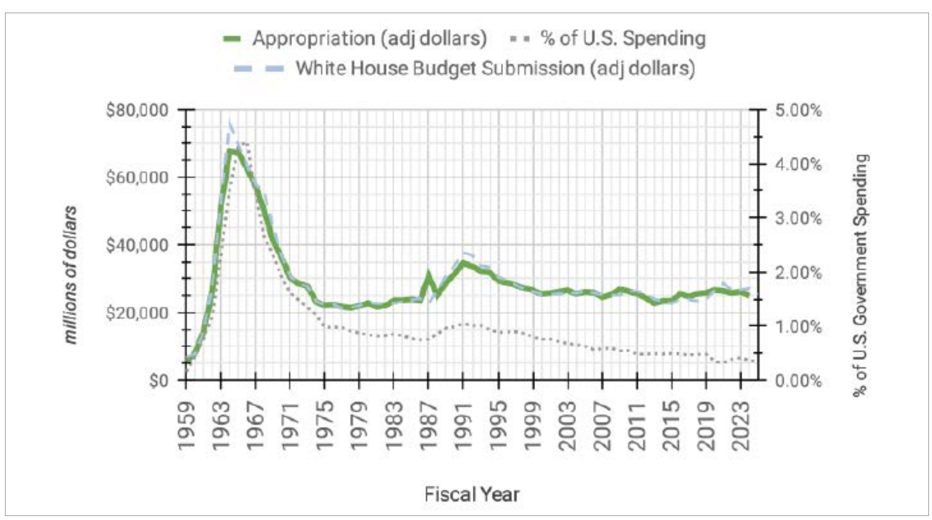
Capping NASA's Budget

On 9 March, Congress passed the Consolidated Appropriations Act of 2024, which provided a budget for NASA and several other federal agencies for FY24. NASA's 2024 budget is $24.875 billion—2%, or $509 million, lower than in 2023.

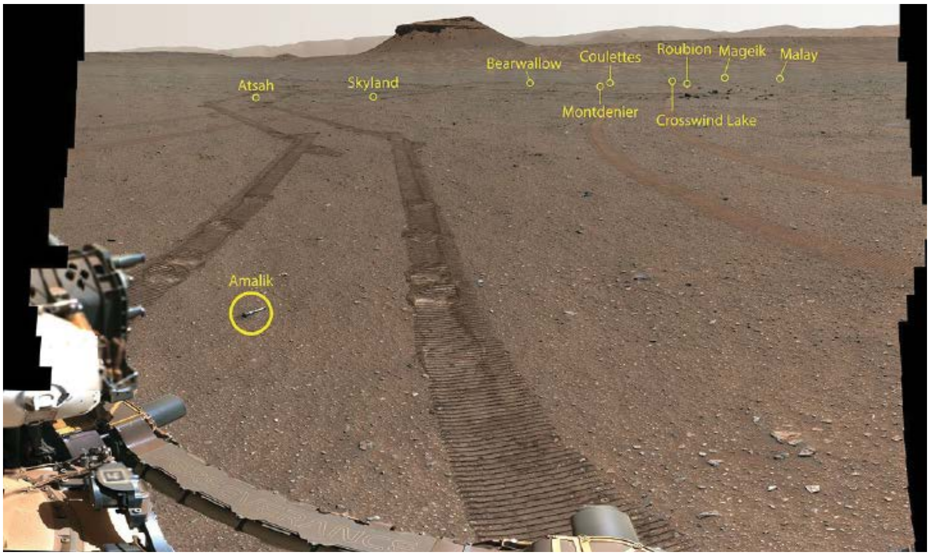
"You can't pursue the program that NASA is directed to do while giving it less money," said Casey Dreier, chief of space policy at the Planetary Society in Pasadena.

"It's good to have a budget, yes," Dreier said. However, when factoring in recent inflation, "the 2% cut actually compounds to a loss of about a billion dollars in buying power since NASA's peak in 2020."

"In a little agency that is doing an awful lot, it makes a big difference," NASA administrator Bill Nelson said about the cut in a call with reporters on 11 March. Nelson blamed the budget constraints on caps put on nondiscretionary defense funding in FY24 and



NASA's appropriation in adjusted dollars (solid green curve) has consistently fallen below the White House's budget request (dashed blue curve) since 2020. The percentage of U.S. spending allocated to NASA (gray dots) can be seen on the right-hand vertical axis. Credit: Casey Dreier, "Historical NASA Budget Data," The Planetary Society



These 10 tubes contain samples of Mars's soil collected at different locations by NASA's Perseverance rover. They await collection by a future sample return mission. Credit: NASA/JPL-Caltech/ASU/MSSS, Public Domain

FY25. The caps were demanded by "a small handful of people in the House of Representatives" as part of a deal to raise the debt ceiling, Nelson said.

Most directorates and divisions received relatively flat funding compared with FY23 levels. Funding for the Artemis program, the Astrophysics Division, and the Near-Earth Object Surveyor in the Planetary Science Division grew slightly, and the VERITAS (Venus Emissivity, Radio Science, InSAR, Topography, and Spectroscopy) orbiter mission is back on the books.

The Science Mission Directorate took the biggest hit, receiving $461 million less than it did in FY23. All of that cut came from the Planetary Science Division, specifically from MSR.

"Mars Sample Return basically became the bank that prevented cuts from every other NASA science project," Dreier said. "That's not a sustainable strategy."

Mars Sample Return on Ice

MSR was allocated at least $300 million, and up to $949 million, in FY24. The lower number was a compromise between the Senate's bill, which initially canceled the mission entirely, and the House's bill, which appropriated the higher amount. The appropriation allows NASA to spend up to the higher amount if money is freed up elsewhere within its planetary science budget.

Leshin's February memo explained that NASA had directed JPL to plan to receive only $300 million for MSR. Staffing cuts were made in anticipation of that, and ultimately, MSR was guaranteed only $300 million.

For the past several years, MSR has been a budgetary flash point. The mission partners with the European Space Agency to collect and return to Earth samples of Mars's soil gathered by the Perseverance rover. Cost overruns, delays, and mismanagement brought MSR under the scrutiny of two independent review boards (IRBs), which advised that the mission as is was not feasible in scope, design, or budget.

"You can't pursue the program that NASA is directed to do while giving it less money."

In response to the second IRB, NASA interviewed dozens of subject matter experts and evaluated 20 mission design proposals. The agency hasn't finalized the mission design or architecture but concluded that a redesigned MSR would likely cost $8–$11 billion and would return samples to Earth in 2040. The agency announced on 15 April that it is soliciting mission architecture proposals to reduce the cost and shorten the timeline.

"The bottom line is, an $11 billion budget is too expensive, and a 2040 return date is too far away," Nelson said in a press conference on 15 April.

The IRB also recommended that JPL retain its MSR campaign-level technical leadership role, but NASA decided to absorb many of those responsibilities into the MSR Program Office at its Washington, D.C., headquarters. The goal of centralizing MSR leadership at the D.C. office rather than splitting it between D.C. and JPL was to improve communication, coordination, and mission development across the NASA centers that would build, test, and run the mission after launch.

NASA initially listed "TBD" as its requested MSR budget for FY25 but has since requested $200 million as it evaluates potential mission architectures.

According to NASA, the plan allows for more flexibility in the mission's construction, launch, and management; solicits innovative and competitive mission architecture proposals; improves communication between NASA and its external stakeholders; increases accountability; and maintains a balanced science portfolio across the agency.

A Bumpy Future

Other high-profile NASA missions have come under congressional fire in the past and gone on to do great things.

The oft-delayed and far-over-budget James Webb Space Telescope was nearly canceled by Congress several times before it launched in 2020. It has since provided unprecedented views of our nearby planetary neighbors and some of the farthest corners of the universe and is poised to usher in a new paradigm of astrophysics. Many planetary scientists believe MSR has the same revolutionary potential for planetary science.

However, JPL has laid off many of the specialists and engineers with the unique knowledge needed to build complex missions. Those engineers may have already found jobs elsewhere or may be wary of returning.

In the present political situation, more cuts may be on the way when FY24 ends in October. The agency also faces uncertainty if a new U.S. president takes office in January.

"NASA is not an agency that depends on or uses mass industrialization or economies of scale," Dreier said. "You lose money, you lose people. Everything slows down or you lose projects."

By **Kimberly M. S. Cartier** (@AstroKimCartier), Staff Writer

Shifting Winter Storms Bring More Flooding to India

Western disturbances describe a system of winds that bring snow and rainfall to northern India during winter months. They originate west of the Hindu Kush and the Himalaya mountains, sometimes from as far away as the Mediterranean Sea, and are vital for ensuring water security across states in northern India.

A new study published in the journal *Weather and Climate Dynamics* found that western disturbances now occur more frequently in summer months, when they were once rare (bit.ly/western-disturbances). Western disturbances in June have become twice as common in the past 20 years as they were during the previous 50.

Typically, western disturbances occur between December and March. That timing benefits farmers and boosts water security, because the heavy precipitation recharges mountain glaciers and snowpack that lose mass in the warmer summer months.

"Winter precipitation is important for livelihoods [in northern Indian Himalayan states] because it ensures water availability in the subsequent spring season," said A. P. Dimri, a climate scientist at Jawaharlal Nehru University who was not affiliated with the study.

The snow and ice associated with western disturbances melt in the spring, making up a large proportion of runoff in the Indus-Ganges river system—an artery that provides water for irrigation, hydropower, and household use for the roughly half a billion people living in its plains.

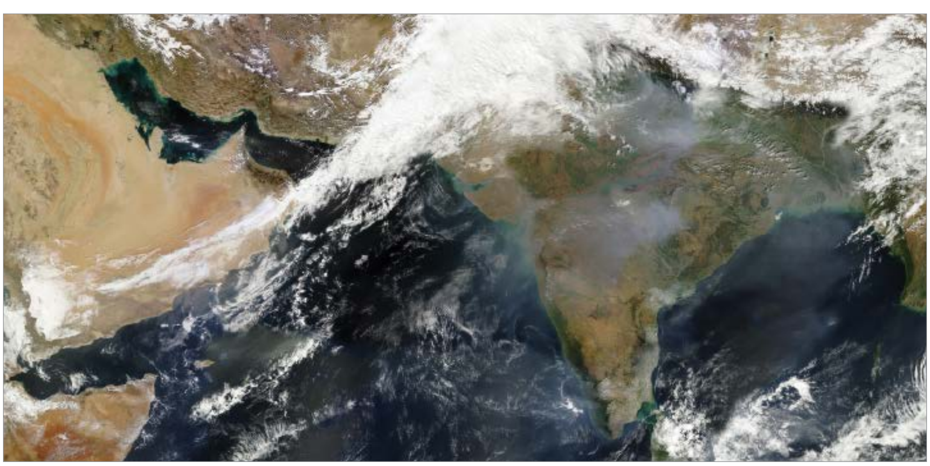
But 70 years of storm track data from a climate hindcast (European Centre for Medium-Range Weather Forecasts Reanalysis version 5; ERA5) show that the western disturbance season has gotten longer. It now stretches into May, June, and July, when the weather pattern can sometimes interact with the summer monsoon, which begins in June. The result is worse flooding.

"We had anecdotal evidence of western disturbances interacting with the monsoon, but now we have been able to show the trend."

"In the winter, the atmosphere is drier because it's colder. So western disturbances have to draw their own water from the Arabian Sea, and typically, they do not cause floods," said Kieran Hunt, the author of the study and a meteorologist at the University of Reading. A lot of the precipitation falls as snow, which melts slowly through the spring. But an overlap between western disturbances and monsoons—which carry about 6–7 times more moisture—can be catastrophic.

"We had anecdotal evidence of western disturbances interacting with the monsoon, but now we have been able to show the trend [in shifting patterns] more clearly," Hunt said. Flash floods in 2013 in the Himalayan state of Uttarakhand claimed around 6,000 lives. They happened in June, when western disturbances struck during the summer monsoon. The same happened in July 2023, leading to floods in many northern Indian states, including in the capital, New Delhi.

The changing pattern of western disturbances is "very concerning," especially because it could result in weather extremes, said Rajib Chattopadhyay, a meteorologist at the Indian Institute of Tropical Meteorology who was not involved in the study.



Recent research illustrates the lengthening pattern of western disturbances, storms, like this one in February 2013, that primarily affect northern India during the winter months. Credit: NASA/Wikimedia Commons

The Climate Link

Western disturbances are steered by the subtropical jet stream, a high-altitude air current.

Climate change has altered the jet stream's movement: Polar regions have become warmer, reducing the temperature gradient between them and the tropical regions to the south. The force that used to draw the jet stream northward before the monsoon season is therefore weaker, extending the time it takes storms to pass over India.

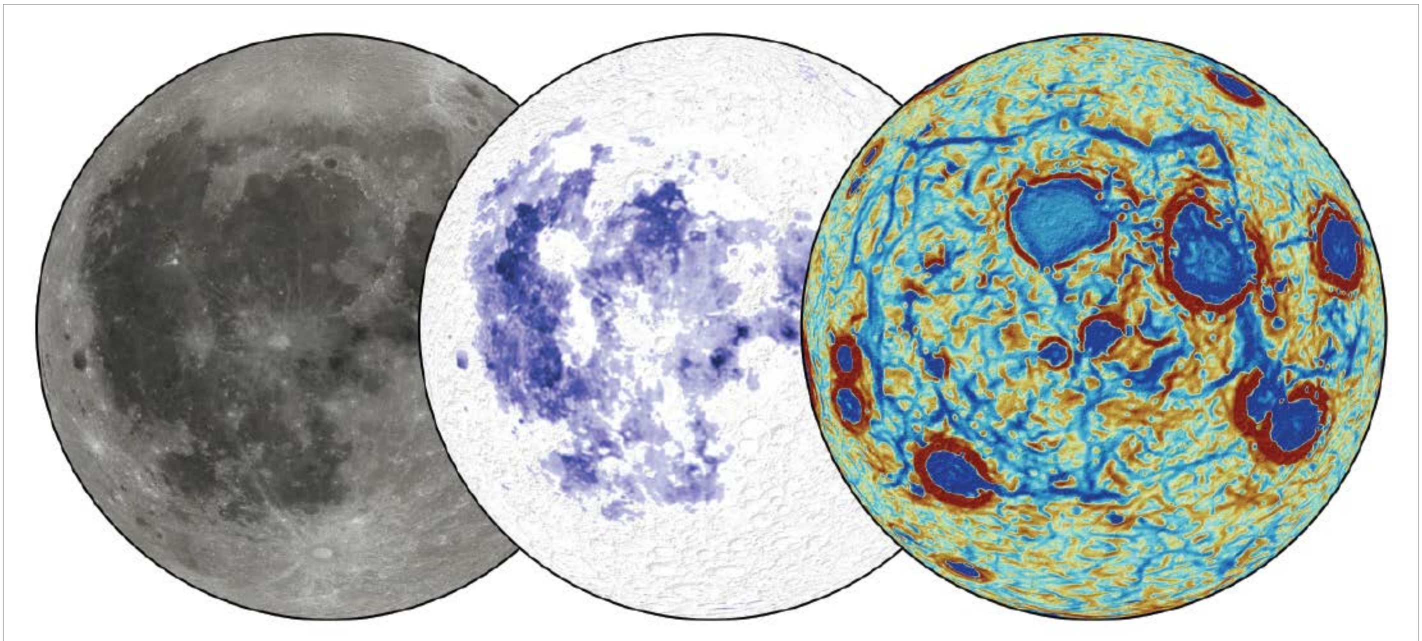
The weakening temperature gradient also means that the jet stream is more susceptible to local factors. One dominant local factor, according to Hunt, is the rapid warming of the Tibetan Plateau. Studies have previously shown that the region is warming at rates almost twice the global average. This makes the plateau warmer than surrounding regions, resulting in a temperature gradient that strengthens the jet stream, intensifying western disturbances and making them more frequent.

Another local factor, according to Hunt, may be the reduction in aerosols over northern India due to air pollution control measures, which has made the local atmosphere warmer and the temperature gradient stronger, also strengthening the jet stream.

"We need to give more attention to western disturbance forecasts," Chattopadhyay said, adding that "it is useful to get some first-order outlook on impending disasters of flash flood, cloudbursts, etc., during monsoon and cold wave or snowfall during other seasons."

By **Rishika Pardikar** (@rishpardikar), Science Writer

The Moon's Mantle Did a Flip—and Scientists May Now Have Evidence



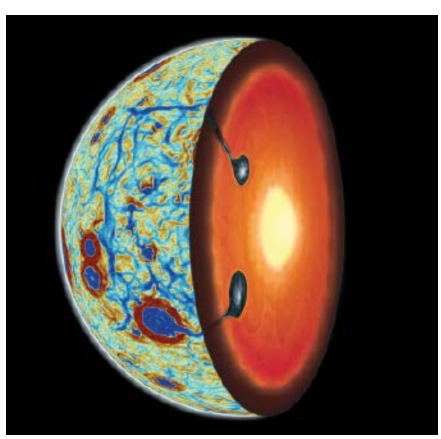
The familiar view of the Moon from Earth (left) shows its nearside dominated by dark volcanic plains, called maria (middle). These maria are surrounded by a mysterious pattern of anomalies (visible as blue lines in a recent gravity map, right). Scientists believe that these lines might be remnants of dense material that sank deep within the Moon billions of years ago. Credit: Adrien Broquet/University of Arizona

For decades, scientists have been intrigued by a strange twist in the Moon's history. Toward its last stages of formation, the lunar mantle likely flipped: Minerals that had formed at its top sank to the bottom, in a process called lunar mantle overturn. The idea emerged from simulations based on the analysis of lunar rocks brought back by the Apollo missions.

Now a new study published in *Nature Geoscience* offers the first evidence supporting the theory (bit.ly/mantle-overturn).

Four and a half billion years ago, a collection of gases and rocks—remnants of a massive collision between Earth and another object—coalesced into a molten ball that would become the Moon. The lunar surface was initially made up of a vast magma ocean. As it cooled, a natural sorting process began. Metals solidified first, forming the lunar core. Then, minerals started crystallizing, with the denser ones sinking toward the center and the lighter ones rising to the surface and forming the Moon's early crust.

However, during the final stages of crystallization, something peculiar happened. The small bit of remaining magma at the top of the mantle crystallized, forming a layer of ilmenite, a titanium-rich mineral denser than the underlying rock. Scientists theorize that this layer eventually sank, essentially flipping the mantle.



An ilmenite layer may have cascaded into the Moon's mantle in the past. Credit: Adrien Broquet/University of Arizona & Audrey Lasbordes

"You have the top of the mantle that goes down, and then whatever was underneath, that goes up," said Adrien Broquet of the German Aerospace Center in Berlin, who helped lead the new investigation during his time as a postdoctoral researcher at the University of Arizona.

Scientists think that after it sank, some of the ilmenite melted and eventually returned to the surface as titanium-rich lava flows, which were sampled by the Apollo astronauts. This has been the leading theory for the past 50 years, but evidence of the sinking process has been missing.

Matching the Evidence

Researchers realized that NASA's GRAIL (Gravity Recovery and Interior Laboratory) mission, which flew more than a decade ago, might have captured a snapshot of the vestiges of the ilmenite sinking process.

In 2012, GRAIL used two orbiting spacecraft to measure tiny variations in the Moon's gravitational pull. It detected a polygonal pattern of gravity anomalies produced by dense rocks surrounding lunar maria, the dark patches of basalt on the lunar surface's nearside.

Though scientists had been puzzled by the polygonal shapes revealed by GRAIL, it wasn't until one of the new study's team members did a series of computer simulations of how a sinking ilmenite layer would behave that they connected the two. The shapes formed by the sinking ilmenite in the simulations matched what the gravity data were revealing.

The dense rocks spotted by GRAIL are likely the last remnants of the ilmenite layer, which didn't sink uniformly, according to the researchers. Instead, because of the thickness of the underlying mantle, the ilmenite fractured into flat sheets that cascaded downward in a series of waterfall-like structures. These "falls" eventually froze in place as they cooled, preserving their unique form for billions of years.

If true, the gravity data would be the first physical evidence of the ilmenite layer's existence.

"This is one of the most important gravity signals that we have on the Moon, and it was completely unexplained," Broquet said. "This is going to help a lot in future modeling of this process."

Scientists think that the structures left behind by the cascading ilmenite can shed light on the properties of the lunar mantle at the time they formed, the mantle's viscosity in particular. "These ilmenites are sinking into the mantle, but as the Moon cools down, some of these cascades will freeze," Broquet said.

He compared the process to heating a thick liquid, like honey, in a pot: As it gets hotter, it flows more rapidly and forms smaller bubbles. If it cools down suddenly and the bubbles are preserved, they can reveal how quickly the liquid was flowing. Similarly, the geometry of the frozen ilmenite cascades can tell scientists how easily the lunar mantle flowed billions of years ago.

"It's a very interesting idea, but it's very tricky to prove or disprove," said James Tuttle Keane, a planetary scientist at NASA's Jet Propulsion Laboratory who wasn't involved with the new study. (Keane is a science adviser for *Eos.*) "You can create a lot of models to explain gravity observations, and so it's hard to use gravity data alone to separate these things out," he said. Additional observations could put these ideas to the test, whether from modeling, analyzing gravity data, or, ideally, showing that samples from these regions have different geochemistry, Keane added.

When and Where

The researchers dated the ilmenite sinking event by looking at the ages of lunar impact basins. The ilmenite cascades are disrupted by the oldest impact basins on the Moon's nearside, which formed around 4.22 billion years ago, suggesting that the cascades formed earlier. The timing of the sinking is coherent with the later uptick in volcanic activity that brought to the surface the titanium-rich lava flows sampled by the Apollo missions, the authors said.

GRAIL did not detect similar anomalies on the Moon's farside, which has a thicker crust.

"This is one of the most important gravity signals that we have on the Moon, and it was completely unexplained."

This could mean that the features are there but at a depth where GRAIL couldn't detect them. Another possibility is that the ilmenite layer never formed on the farside. Or maybe it formed but migrated toward the nearside, Broquet explained.

A potential trigger for such migration could be a large impact, like the one that formed the South Pole–Aitken basin on the Moon's farside. If such an impact happened when the Moon was crystallizing, which is likely, according to Broquet, simulations show that such an impact can trigger a mass movement toward the antipode of the basin. This, Broquet said, "is exactly where we see the ilmenite in the nearside."

The target landing site for NASA's Artemis III crewed mission to the Moon is the South Pole–Aitken basin, offering an opportunity for collecting samples that could help in testing these ideas, he added.

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

From Newsworthiness to News Usefulness in Climate Change Research

"Climate change doesn't communicate itself" is a lesson only partially learned after decades of research on the topic.

According to the United Nations (UN), communicating climate change "is about educating and mobilizing audiences to take action," a key lever for driving broader change to address and mitigate the climate crisis. Yet such communication has long been neglected by both climate change researchers and the media, and it continues to prove challenging today.

Even into the 21st century, public outreach about climate change was undertaken by only a few scientists. Academic training for such outreach was not a priority, and scientific discourse was regarded as too technical for untrained audiences. In addition, the news media's attention to and coverage of climate change were minimal, and the latter was often limited to portraying incomplete and misleading debates.

Starting about 15 years ago, however, public communication has increasingly been regarded by many climate change scientists as integral to their job—part of a commitment to popularize a topic they see as important—and is a response to incentives from funders and universities. A dedicated field of research, building on insights from the social sciences, has emerged with the objective of alleviating barriers and challenges in climate change communication. Organizations such as the Intergovernmental Panel on Climate Change (IPCC) and the UN have created training materials to guide more effective communication, helping scientists to develop clearer framing and narratives and to convey uncertainties.

Media attention to climate change issues reached record levels in 2021 and remained high in 2022 and 2023 compared with the preceding 2 decades, according to the Media and Climate Change Observatory, which tracks the numbers of related stories appearing in news sources around the world. Initiatives by journalists have encouraged commitments from newsrooms to cover climate news more fully. For example, Covering Climate now, which partners with more than 500 news and media organizations—including *Eos*—across dozens of countries, invites journalists and newsrooms to join its community and to help "drive a public conversation that creates an engaged public."

If the ultimate purpose of coverage of climate change science is to breed action, then delivering information, even if done well, is not sufficient.

As more scientists are actively communicating research findings in climate change science and newsrooms are eager to report on such findings, an ideal opportunity exists to reach the public, especially those for whom news media remain highly trusted sources of information. But does the current approach to such communication achieve its goals of engaging, educating, and mobilizing audiences?

More news coverage of climate change science, reported with intelligible and compelling storytelling, is certainly necessary for raising public awareness. But if the ultimate purpose of this coverage is to breed action, then delivering information, even if done well, is not sufficient: 78% of European citizens consider climate change a very serious problem, for example, but few are willing to make major lifestyle changes to address it. We argue that the current criteria for newsworthy climate science stories are not aligned with those likely to make climate change communication efficient and transformative.

Problems of Current Climate Change Coverage

Mediatization of climate change science—that is, the outward communication of climate change research findings through the mass media—involves selecting which scientific articles are newsworthy. Media outlets' criteria for newsworthiness thus shape which scientific information is presented to the public.

A recent survey of more than 51,000 peer-reviewed scientific articles related to climate change published in 2020, along with roughly 36,000 mentions of those papers in international media outlets, revealed that this filtering is so stringent that only a narrow and limited facet of climate change research is showcased [*Perga et al.*, 2023].

In short, news media depict climate change research as a sentinel and whistleblower for large-scale, observed, or end-of-the-century consequences of climate change for Earth's natural systems. Studies of shrinking glaciers and melting sea ice are popular topics for coverage, for example, and papers on mega-drought, the longer lifetimes of hurricanes in a warming world, and the survival of polar bear populations to the end of this century all ranked in the top 10 most covered studies of 2020.

Long-term and large-scale portrayals of climate change can seem to depict it as happening far away in space and time, creating an emotional and psychological distance that may reduce people's motivation to process and accept information.

On the other hand, human, technological, and social aspects of climate change science—such as quantified assessments of the future of aviation in a carbon-neutral world—as well as local and short-term processes and solutions, are rarely presented in the media [*Perga et al.*, 2023].

Conventional mediatization of climate change research perpetuates perceptions that climate change is mostly a global biophysical problem, undermining how socioeconomic, judicial, philosophical, and technological dimensions are key to creating solutions for mitigation and adaptation. This bias in media reporting was found, for example, to result in systematic underreporting in the United Kingdom and the United States on Working Group III's contribution to the IPCC's Fifth Assessment Report, which focuses on climate change mitigation.

The problem is that this monolithic, biophysically centered portrayal of climate change research in the media overwhelmingly focuses on breaking news that points to the severity of climate change now or in the future. This approach can drive many people to avoid, neglect, minimize, or discount threatening information, and it may reinforce known motivational and cognitive barriers to individual and collective action. For example, the selective exposure effect refers to the tendency for individuals or groups to seek information confirming existing beliefs or interests. This effect implies that people also tend to avoid or ignore inconvenient truths, just as many smokers ignore anti-tobacco messaging and carry on with their behavior.

For media consumers, long-term and large-scale portrayals of climate change can seem to depict it as happening far away in space and time, creating an emotional and psychological distance that may reduce people's motivation to process and accept information. Conversely, discussions of the local aspects or effects of climate change can instill concern and elicit stronger personal processing of information, yet these discussions have been virtually absent from the news media. As a result, even if the media successfully expose readers to climate change research and popularize the idea that climate change is a problem to be addressed, this exposure does not necessarily convert into action, however catastrophic the portrayal of the future.

Another major psychological barrier that limits proenvironmental behaviors and climate action is that individuals and groups often don't feel empowered to act. Preferentially emphasizing the global-scale consequences of climate change, which in the long term appear as though they are determined only by national and international policies (i.e., as modeled in the different IPCC scenarios) or even by other countries, may reduce public perceptions of collective efficacy.

Even if media consumers absorb broadcast content about climate change and feel concerned and capable of acting, it is not a given that they will act. Individuals may not act because the task of influencing change may appear overwhelming or simply a waste of time if they think people in other places—normally envisaged as "other countries"—are also not going to act.

If the purpose of communicating climate research findings is to breed public action, then we are missing our target.

A Self-Reinforcing Symbiosis

Selectivity for newsworthiness occurs in different venues: among scientists and press offices at academic institutions, at publishers and by scientific journals in which scholarly papers are published, and in newsrooms and mass media agencies. The promotional culture and symbiosis among these groups likely explain why climate change communication via the media remains biased toward certain disciplines, spatial scales, and timescales.

The editorial choices of high-profile multidisciplinary journals largely dictate what news readers hear about climate change research.

Media outlets are not just groups of benevolent journalists seeking to inform society; they also must raise revenue. University press offices exist not simply to promote their researchers' work but also to elevate the profile of their institutions. And scholarly journals are interested not only in disseminating cutting-edge research but also in raising revenue through subscriptions and submissions and in priming the metrics that drive the academic publication industry (e.g., impact factors).

Newsrooms frequently rely on press releases from scientific institutions and publishers and judge the newsworthiness of research on the basis of the reputation and name recognition of the journal in which it was published. Journal impact factors can be especially strong predictors of newsworthiness, sometimes more so than the content of articles. *Perga et al.* [2023] found that in 2020, more than 40% of news about climate change research covered studies published in just six high-profile journals—three from the Nature portfolio, two published by the American Association for the Advancement of Science, and the Proceedings of the National Academy of Sciences of the United States of America.

The editorial choices of those high-profile multidisciplinary journals—favoring bio- and geosciences over the social sciences, engineering, humanities, and agriculture and focusing on global versus local scales—thus largely dictate what news the public receives about climate change research. The high degree of redundancy in the reporting of scientific articles within the news media, by which a few articles receive a disproportionate amount of attention, also contributes to the limited diversity of information to which readers are exposed.

Further, high-profile journals—some of which operate under for-profit business models—are most likely to maintain strong press offices and formalized press relations and to promote papers through press releases and commentaries, thereby attracting news media attention. As academic press offices often dedicate more effort to publicizing research appearing in those same top-tier journals, this loop among institutions, publishers, and the media becomes self-reinforcing—and limits the scope of research that is communicated to the public.

Reshaping media coverage of climate change research to inspire action will require the gatekeepers of mediatization to revisit their agendas and approaches. Failing to do so could be seen as a form of greenwashing: claiming a contribution to addressing the climate change challenge by disseminating news about recent research when the real motivation is selling journals and raising institutional profiles.

Reimagining the Mediatization Model

There are levers to pull on the media side that could help with the needed transformation.

These levers include increasing resources to produce more (and more varied) climate coverage, encouraging universities and research organizations to reprioritize the work their press offices push, and providing reporters with extended training on—and incentivizing coverage of—multidisciplinary aspects of climate change science (including, e.g., technological, socioeconomic, and justice aspects).

In addition, as solutions-oriented journalism commonly experiences lower levels of cognitive resistance, media coverage should move away from repeatedly focusing on how problematic and severe human-induced climate change is and instead demonstrate potential ways both to reduce it and to live with it. This coverage must objectively discuss even unpopular aspects of solutions—such as the socioeconomic and environmental costs of mining raw materials to power clean energy sources—and report on both the efficiencies and inefficiencies of proposed ideas.

Furthermore, portrayals of climate change as a global issue should be balanced with place-based communication describing local concerns, impacts, and attempted solutions, which has the potential to resonate more deeply with people and to advance climate initiatives. Remarkable initiatives taking hold in journalism that name and aim to overcome limitations of traditional media models for climate coverage are encouraging signs of progress.

On the institutional and publishing side, academics must assert more control over what climate change–related research is mediatized. The highest-profile journals have disproportionate power in deciding what is newsworthy, and their editorial choices about what research to publish and promote may not always align with the key criterion of news usefulness. Gaining control over what is communicated to raise public engagement requires deflating the power delegated to the publishers and editorial boards of high-profile journals. Reinforcing publications and communications in journals owned by scientific societies, whose editorial boards comprise active academics, is a critical lever with which to do this.

If the usefulness of media coverage of climate change is defined as the ability to engage society in climate action, then the ecosystem of people and organizations involved must work to publish and mediatize more solutions-oriented, locally focused, and interdisciplinary research. The resulting coverage must account for the public's prevailing concerns and resistance to change. In this way, researchers, journals, and news professionals may improve their collaboration and move from being whistleblowers of the problems of climate change to being part of the solution.

References

Perga, M.-E., et al. (2023), The climate change research that makes the front page: Is it fit to engage societal action?, *Global Environ. Change*, *80*, 102675, https://doi.org/10.1016/j.gloenvcha.2023.102675.

Marie-Elodie Perga (marie-elodie.perga@unil.ch), **Laure-Anne Pessina, Stuart Lane,** and **Fabrizio Butera,** Université de Lausanne, Lausanne, Switzerland

Read the article at Eos.org

Fixing the *Flawed* Colorado River Compact

By Shemin Ge, Joann Silverstein, James Eklund, Patricia Limerick, and David Stewart

The 1922 Colorado River Compact ignored available science and overallocated the river's water, a decision whose effects reverberate today. Now there's an opportunity to get things right.

The flow of the Colorado River past Hoover Dam is controlled by four water intake towers, two of which are seen here. Credit: Thomas – stock.adobe.com

On 24 November 1922, the Colorado River Commission officially allocated water rights to the seven U.S. states of the Colorado River Basin. The Colorado River Compact and subsequent agreements, collectively known as the Law of the River, eased years of dispute among these states, and they constitute a milestone in the history of the American West.

The 1922 compact provided regulatory certainty for water management. It called for water to be stored and released as needed (most notably with the construction of Hoover Dam), thus supporting a robust era of reservoir building. The reservoirs, in turn, unleashed huge potential for electric power generation and stimulated economic growth throughout the West.

The distinctive "bathtub ring" around Lake Mead is evident in this view overlooking Las Vegas Boat Harbor and Lake Mead Marina in August 2022. Credit: Christopher Clark/U.S. Bureau of Reclamation, CC BY-SA 2.0 (bitly/ccby-sa-2-0)

A root cause of the dire situation today lies in the commission's choice to ignore the best available hydrologic science as it negotiated the original compact.

The terms of the compact, however, were largely the product of development aspirations and political dealmaking, and they relied on optimistic estimations of the amount of water the river could supply that were not supported by existing surveys or science.

Now, more than 100 years later, a lasting water shortage crisis has brought the governance structure outlined in the compact to its knees, and the effects reverberate far beyond the Colorado River Basin. The two largest reservoirs in the United States, Lake Mead and Lake Powell—in Arizona and Nevada and in Arizona and Utah, respectively—have reached historic lows in recent years. This dearth threatens both the water supply and the hydropower generation capacity for tens of millions of users, as well as the nation's food supply and flows critical to maintaining ecosystems.

Municipalities are considering drastic water-saving measures. Farmers and ranchers, who as a group are by far the largest consumers of Colorado River water, face unprecedented challenges and uncertainty. So do the economies and environmental systems that depend on reliable stream discharge for aquatic life and recreation.

It is tempting to place responsibility for the water shortage on climate change, which has resulted in reduced precipitation across the basin, and on population growth that outpaced planners' anticipation of water demands. Indeed, these are important exacerbating factors.

A root cause of the dire situation today, however, lies in the commission's choice to ignore the best available hydrologic science as it negotiated the original compact. As discussions about the availability of Colorado River water continue and a new compact is negotiated over the next few years, planners must not make the same mistake.

The Colorado River Commission signed the Colorado River Compact on 24 November 1922 in Santa Fe, N.M. Pictured here are the members of the commission, including representatives from the seven states of the Colorado River Basin and Secretary of Commerce Herbert Hoover (seated), as well as the executive secretary of the commission. Credit: U.S. Bureau of Reclamation

The Law of the River

Even before the Colorado River Compact was established, the vast American West was a bustling frontier for mineral exploration, agricultural development, and westward expansion. California had already been diverting water from the Colorado to irrigate the fertile Imperial Valley since around 1901. Agriculture in sunny but dry southern Arizona was also booming. Other states envisioned securing more water for future irrigation of farmlands and for urban development.

The commission included eight men, one each representing the Colorado River Basin states—Arizona, California, Colorado, Nevada, New Mexico, Utah, and Wyoming—plus the commission's chair, Secretary of Commerce Herbert Hoover, who later became president of the United States. All parties realized the paramount importance of agreeing on consistent apportionments of the river's water to the states, which would provide needed certainty into the future [*Kuhn and Fleck*, 2019]. That meant estimating the magnitude of the river's discharge.

The main elements of the compact included the following:

1. The Colorado River Basin was divided into the Upper and Lower basins at Lee Ferry, Ariz. The Upper Basin includes four states: Colorado, New Mexico, Utah, and Wyoming. The Lower Basin includes three: Arizona, California, and Nevada (Figure 1).

2. Consumptive water use was divided evenly between the Upper and Lower basins, with each allowed 7.5 million acre-feet (~9.2 billion cubic meters) per year. (One acre-foot is the volume that would cover 1 acre (4,047 square meters) to a depth of 1 foot, or about 1,233 cubic meters.)

Fig. 1. The Colorado River Basin encompasses parts of seven U.S. states as well as the states of Baja California and Sonora, Mexico. Credit: U.S. Geological Survey

The Upper Basin states were obligated to "not cause the flow of the river at Lee Ferry to be depleted below an aggregate of 75,000,000 acre-feet for any period of ten consecutive years."

3. The river's average discharge at Lee Ferry was assumed to be 16.4 million acre-feet per year. Allocating a total of 15 million acre-feet per year would leave the remaining water for future development and for Mexico.

How Much Water Was There?

The allocation of 7.5 million acre-feet per year of consumptive use for each basin was grounded neither in the best available hydrologic calculations nor in climate variability projections. Rather, it was a compromise Hoover proposed between two end-member figures [*Kuhn and Fleck*, 2019]. One end was 8.2 million acre-feet per year, half the assumed annual average discharge at Lee Ferry, derived from a report by the U.S. Reclamation Service (now the Bureau of Reclamation) [*Fall and Davis*, 1922]. The other end was 6.5 million acre-feet per year, a figure proposed and advocated by the Upper Basin commissioners that reflected a roughly 50-50 split of the river discharge at Yuma, in southern Arizona [*Kuhn and Fleck*, 2019].

In the decades following the 1922 compact, a plethora of acts, orders, and agreements were written and signed to fine-tune the compact's provisions, to authorize construction of dams for water storage and power generation, to build water transfer infrastructures, and to resolve interstate and intrastate disputes. Particularly significant was the 1944 treaty between the United States and Mexico—still in effect today—that guaranteed 1.5 million acre-feet of Colorado River water annually for Mexico, bringing the total allocation to 16.5 million acre-feet per year.

In the early 1900s, only a few stream gauges were measuring river discharge in the United States. The middle section of the Colorado River Basin was one of the most remote and inaccessible regions in the nation at the time. In particular, the canyon region from the mouth of Green River in Utah to the Grand Wash in Arizona, covering a water course of approximately 840 kilometers (520 miles), was accessible to wheeled vehicles at only three points [*La Rue et al.*, 1925]. Because of the inaccessibility, no stream gauges were established there until about 1920.

The gauge station at Lee Ferry was established only in summer 1921.

The estimate of Colorado River discharge at Lee Ferry adopted in the compact originated with stream discharge measurements at Laguna Diversion Dam (Figure 2) near Yuma, a water course of approximately

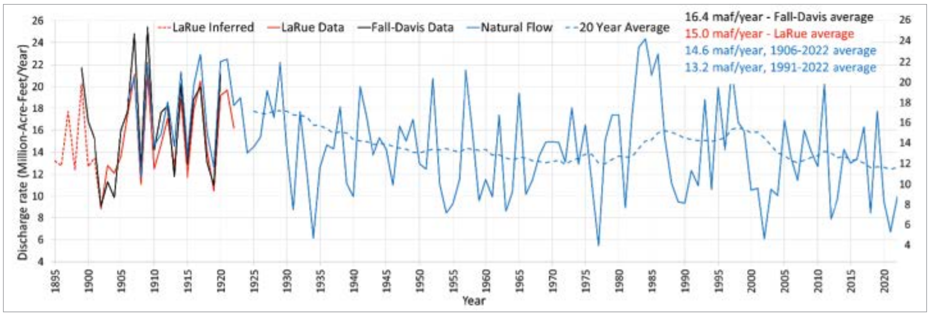


Fig. 2. Colorado River discharge at Lee Ferry, Ariz., from 1895 to 2022. From 1895 to 1920, the data show the difference between La Rue et al. *[1925] and* Fall and Davis *[1922] estimates. The long-term data show the natural discharge and its 20-year running average from 1906 to 2022 (data from U.S. Bureau of Reclamation). Abbreviation maf = million acre-feet.*

1,002 kilometers (622 miles) downstream of Lee Ferry. *Fall and Davis* [1922] derived the value by subtracting the discharge from the Gila River, which enters the Colorado at Yuma, from the measured discharge at Laguna Dam (Figure 1; green dot).

The commission simply assumed that the volume gained by the Colorado from tributaries between Lee Ferry and Laguna Dam was about the same as the volume

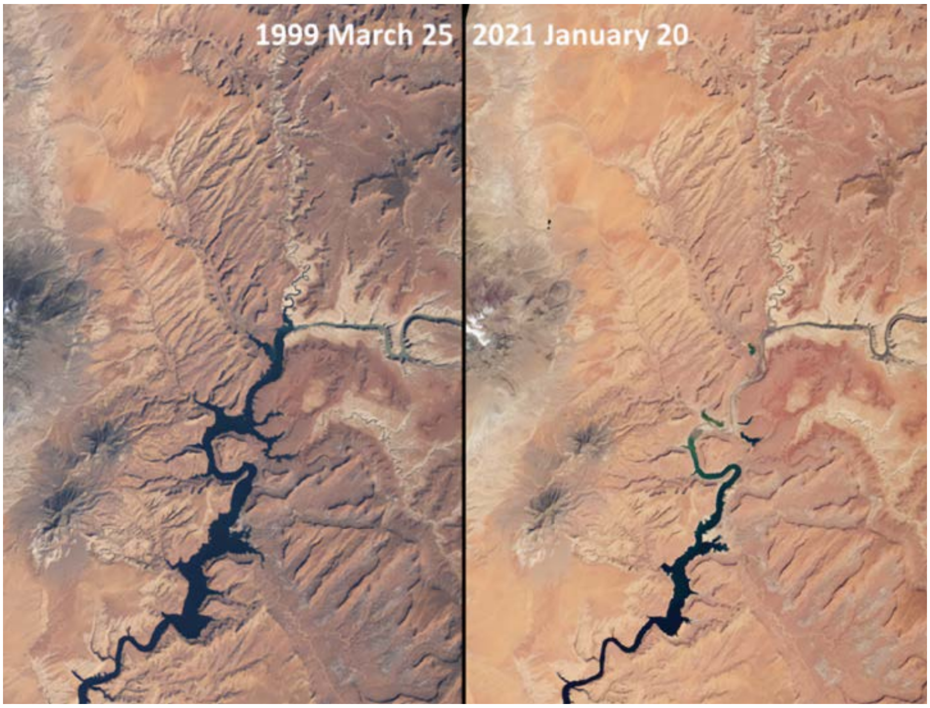
La Rue argued that decisionmakers should use longer-term averages in estimating river discharge.

lost to evaporation over that same stretch of river corridor (black curve in Figure 2).

Even today, it is challenging to estimate water loss due to evaporation and plant transpiration over a vast area of dry land influenced by seasonal floods and varying vegetation covers. It's clear that the commission's assumption, and therefore the estimate of 16.4 million acre-feet per year was informed by grossly optimistic considerations and ignored the more conservative science and more reliable hydrologic data available at the time.

A lower estimate of Colorado River discharge had emerged prior to the compact on the basis of a more rigorous scientific approach by U.S. Geological Survey (USGS) hydrologist Eugene Clyde La Rue [*Kuhn and Fleck*, 2019]. Between 1914 and 1924, La Rue traveled hundreds of miles of the Colorado River and its tributaries to survey dam sites and conduct river discharge measurements. He probably collected more firsthand hydrologic data than anyone and was considered the most knowledgeable Colorado River expert of his generation [*Langbein*, 1975].

Using records from stream gauges and tributary contributions upstream of Lee Ferry, La Rue calculated the average discharge at Lee Ferry to be 15.0 million acre-feet per year between 1895 and 1920. Specifically, he used upstream gauges near Green River, Utah, on the Green River and near Fruita, Colo., on the Colorado River (Figure 1; red dots), combined with his records from several other tributaries, to estimate the discharge at Lee Ferry (red curve in Figure 2).



This comparison of satellite images of the Glen Canyon–Lake Powell region on the Colorado River shows the dramatic change in water level between 1999 and 2021. Credit: Modified from NASA images

How significant is the difference of approximately 1.4 million acre-feet per year between the estimate of La Rue and that of Fall and Davis? It represents nearly 10% of the river discharge assumed in 1922, and it is not far below the estimated reduction in demand needed to meet the recent shortages. At a U.S. Senate committee hearing in 2022 examining short- and long-term solutions to extreme droughts in the western United States, Bureau of Reclamation commissioner Camille C. Touton testified, on the basis of a bureau analysis, that Colorado River Basin states would need to reduce consumption by 2–4 million acre-feet in 2023 to protect hydropower generation at Lake Mead and Lake Powell.

La Rue argued that decisionmakers should use longer-term averages in estimating river discharge. Prior to 1899, there were no stream discharge measurements in the Colorado River Basin. La Rue creatively used water level records from Great Salt Lake in Utah, calibrated against later records of river discharge and lake levels, to infer earlier annual Colorado River discharges back to 1895 [*La Rue and Grover*, 1916; *La Rue et al.*, 1925] (dashed red curve in Figure 2).

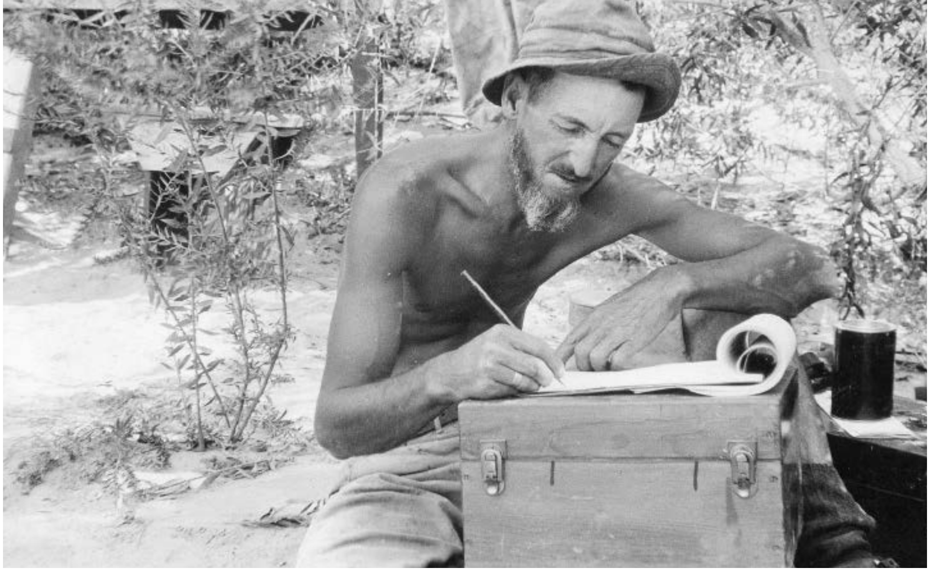
Decades later, La Rue's inferred discharges for those early years were found to be consistent with discharge values estimated from tree ring studies [*Meko et al.*, 2007].

Ignoring Available Science

Data and science characterizing the Colorado were limited in the 1920s, but La Rue's river discharge estimate was known ever since he first published it in a USGS report in 1916. Yet his work only hovered in the background of the commission's negotiations. La Rue made a series of attempts to let the commission know that its perception of how much water was in the river was overly optimistic [*Kuhn and Fleck*, 2019]. In 1920, he tried but failed to facilitate a meeting between USGS and the Reclamation Service because of his concerns over the difference between his estimate, published in the 1916 USGS report, and Fall and Davis's estimate, which first appeared in a preliminary Reclamation Service report in 1920.

As the preparation of the compact was gathering steam, La Rue took the unusual step of writing directly to Secretary Hoover. He received only a thank-you note in return. The commission refused to be distracted by any lower estimate of river discharge and forged ahead with the compact based on Fall and Davis's estimate. The higher estimate, of course, meant more perceived water for everyone, which understandably would make negotiations easier. Whether the commission fully recognized the potential consequences of its inattention to and dismissal of La Rue's lower estimate at the time is unclear.

As the preparation of the compact was gathering steam, La Rue took the unusual step of writing directly to Secretary Hoover. He received only a thank-you note in return.



(top) U.S. Geological Survey hydrologist Eugene Clyde La Rue takes notes while in camp on Diamond Creek, a tributary of the Colorado River in Arizona, in 1923. (bottom) La Rue measures river discharge along Havasu Creek, another tributary in Arizona, also in 1923. Credit: Both: U.S. Geological Survey

Short-Term Measures

In 2007, the Colorado River Basin was experiencing its worst 8-year period of drought in more than a century of continuous recordkeeping. The U.S. Department of the Interior (DOI) issued interim guidelines to address issues related to Lower Basin water shortages and the management of the Lake Mead and Lake Powell reservoirs. These guidelines encouraged voluntary water conservation measures but did not attempt to reallocate water deliveries to compact states.

More than a decade later, as the drought continued, the combined storage in Lake Mead and Lake Powell reached its lowest volume since the 1960s. In 2019, the Bureau of Reclamation established a Drought Contingency Plan, setting an example of collaboration across the Colorado River Basin. The plan required Upper and Lower basin states to work together to address the imminent water crisis and better manage the Colorado River system in the future.

The Lower Basin approach in the Drought Contingency Plan focused on reducing water demand to stabilize water levels in Lake Mead, while the Upper Basin approach focused similarly on maintaining water levels in Lake Powell. The plan also offered recommendations for voluntary water conservation programs to compensate farmers and other water users for reducing their water use without losing their water rights under the Prior Appropriation Doctrine.

In May 2023, DOI announced a deal agreed upon by the three Lower Basin states (and formally adopted by the Bureau of Reclamation in March 2024) to conserve at least 3 million acre-feet of water through 2026 to maintain reservoirs above critical levels. Of that amount, 2.3 million acre-feet will be compensated through funding from the Inflation Reduction Act to support water conservation efforts and enhancements to water system efficiency. The remaining conservation needed for sustainable operation will come from voluntary and uncompensated reductions by the Lower Basin states.

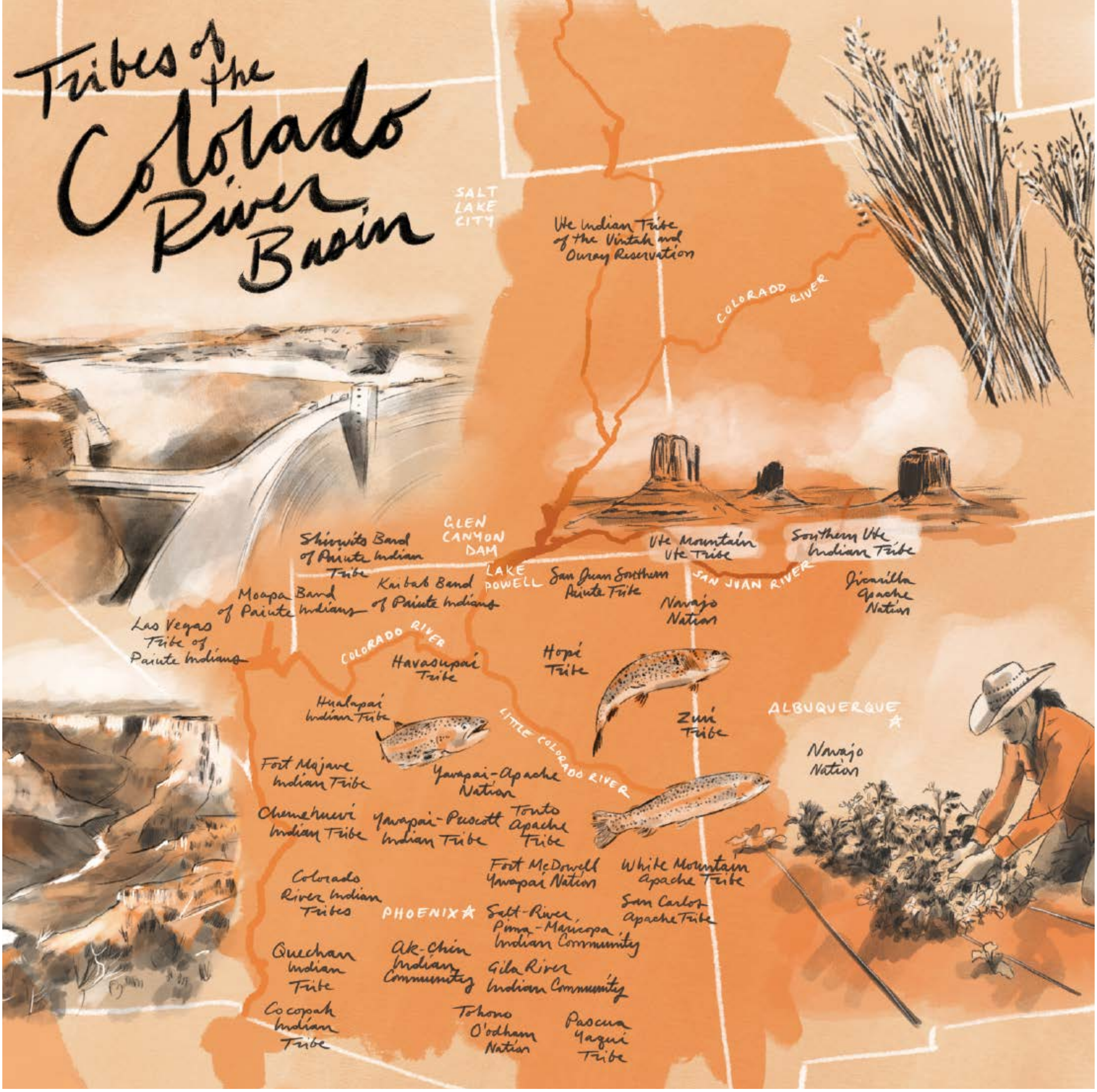
Bring Science—and All Parties—to the Table

The interim management guidelines established in 2007 are set to expire in 2026, the date set for review and reauthorization of the 1922 compact.

Between now and 2026, a window of opportunity exists to rebalance the allocation and availability of water. It is time to

Between now and 2026, a window of opportunity exists to rebalance the allocation and availability of water.

confront the fact that the combination of natural flow and reservoir storage on the Colorado does not provide enough water to meet current demands, as La Rue recog-



Numerous Native American tribes reside in the Colorado River Basin today. Credit: Gabriella Trujillo for High Country News

nized more than 100 years ago. It is time to bring science to the negotiating table.

There is no shortage of examples where science has successfully informed water management policy [*Loucks*, 2021].

Consider the collaboration between Canada and the United States to manage Lake Ontario and the St. Lawrence River. In response to changing needs of various sectors (e.g., recreation, commercial fishing) and natural hydrologic conditions, the *International Lake Ontario–St. Lawrence River Board* [2006] conducted a comprehensive multiyear study to guide revisions to the existing 50-year-old regulations on water levels and river flows for hydropower generation, river navigation, and flood control.

The board engaged the public and experts, addressed issues pertinent to affected Indigenous communities as an integral part of the process, and applied state-of-the-art scientific knowledge to inform the discourse about new regulations.

For example, the 2006 study found that shoreline communities preferred lower lake levels, which minimize damages from flooding and erosion, whereas recreational users preferred higher levels. Meanwhile, scientific research considered in the study indicated that widely varying lake levels in the Great Lakes are favorable for healthier ecosystems [e.g., *Wilcox et al.*, 2007]. Together, the findings required the board to rethink how to balance the interests of shoreline communities and recreational users as well as how to maintain reliable water intakes for hydropower.

The board then devised regulation options that would benefit a greater number of interest groups than the current regulations did and minimize losses for any single group or geographical area. The study also developed adaptation alternatives to help manage climate change–driven uncertainties in future conditions.

There is no doubt that climate change, droughts, and population growth have exacerbated the Colorado River water shortage crisis. It is also obvious that the best available science was ignored more than 100 years ago and water from the Colorado River was overallocated. Negotiators today must learn from history and embrace state-of-the-art science to help reallocate the Colorado River sustainably.

Long-term up-to-date natural discharge data at Lee Ferry are available (Figure 2). As of 2022, the 20-year running average stands below 13 million acre-feet per year, a 20% reduction from what was assumed in the original compact. Further decreases are expected.

Milly and Dunne [2020], considering a moderate greenhouse gas emission scenario (i.e., Representative Concentration Pathway 4.5), predicted that average discharge from the Upper Colorado River Basin between 2016 and 2065 could be 5%–24% less than it was in 1903–2017. *Miller et al.* [2021] projected a 5% decrease at Lee Ferry for the period 2040–2069 relative to 1975–2005. *Li and Quiring* [2022] projected that discharge from the Upper Colorado River Basin would decrease by 2.3%–21.0% due to climate and land use change from 2040 to 2069. The figure of 16.4 million acre-feet per year, an overestimate in 1922, is far from realistic today and in the foreseeable future.

In addition to considering the best available science, all stakeholders—notably including those left out of the 1922 compact—must have seats at the negotiating table. Twenty-nine Native American tribes in the Colorado River Basin were granted rights to water for their reservations by the United States Supreme Court in *Winters v. United States* (1908). And the 1922 compact states: "Nothing in this compact shall be construed as affecting the obligations of the United States of America to Indian tribes." Yet the agreement made no explicit allocations because tribal representatives were not present during the negotiations, and no subsequent water deliveries were made because there was no infrastructure to convey water to tribal lands.

Formally incorporating tribal water rights is a necessity in the challenge of reallocating the Colorado River. A 2018 study conducted jointly by the Colorado River Basin Ten Tribes Partnership and the Bureau of Reclamation found that the 29 tribes have enforceable rights to as much as 2.8 million acre-feet of Colorado River water per year [*U.S. Bureau of Reclamation*, 2018], or more than 20% of the recent average flow of 13 million acre-feet per year.

In addition to considering the best available science, all stakeholders—notably including those left out of the 1922 compact—must have seats at the negotiating table.

The treaty rights of Mexico to Colorado River water also must be included. These rights are mandated by a standing international agreement and are a model for needed bilateral collaboration on allocating the water of the Rio Grande River, which has tributary headwaters in Mexico and the United States.

Realistic Reallocation

Reducing long-term regional allocations will be unpopular, but it is a necessity that negotiators need to accept. The reduced allocations must be embedded in the new compact, and whether designated as percentages of the natural discharge or as specific volumes, they must be based on robust estimates grounded in the best hydrologic and climate science available.

The total allocation also must account for *all* stakeholders and reflect expected declines in discharge over the coming decades. Furthermore, decisions and agreements on reallocation should precede regional- and local-scale actions taken to reduce water use, such as conservation, land use changes, water reuse, and water transfers, so that these actions can be implemented according to revised allocations.

Existing tools used to confront the water crisis, which have been used mostly on a volunteer basis and/or on local scales, have achieved limited success, attesting to the difficulty of the choices ahead and to the need for broader, more enforceable regulations. Remembering Eugene Clyde La Rue's science-based approach and thinking long term will bring much to current negotiations and help sensibly reenvision the Colorado River Compact.

References

Fall, A. B., and A. P. Davis (1922), Problems of Imperial Valley and vicinity, 326 pp., U.S. Gov. Print. Off., Washington, D.C., hdl.handle.net/2027/hvd.32044031907595.

International Lake Ontario–St. Lawrence River Board (2006), Options for managing Lake Ontario and St. Lawrence River water levels and flows: Final report, 146 pp., Buffalo, N.Y., ijc.org/en/glam/options-managing-lake-ontario-and-st-lawrence-river-water-levels-and-flows-final-report.

Kuhn, E., and J. Fleck (2019), *Science Be Dammed: How Ignoring Inconvenient Science Drained the Colorado River*, 288 pp., Univ. of Ariz. Press, Tucson.

Langbein, W. B. (1975), L'affaire LaRue, *U.S. Geol. Surv. Water Resour. Div. Bull.*, April–June, 6–14.

La Rue, E. C., and N. C. Grover (1916), Colorado River and its utilization, *U.S. Geol. Surv. Water Supply Pap., 395*, 231 pp., https://doi.org/10.3133/wsp395.

La Rue, E. C., H. Work, and N. C. Grover (1925), Water power and flood control of Colorado River below Green River, Utah, *U.S. Geol. Surv. Water Supply Pap., 556*, 176 pp., https://doi.org/10.3133/wsp556.

Li, Z., and S. M. Quiring (2022), Projection of streamflow change using a time-varying Budyko framework in the contiguous United States, *Water Resour. Res., 58*(10), e2022WR033016, https://doi.org/10.1029/2022WR033016.

Loucks, D. P. (2021), Science informed policies for managing water, *Hydrology, 8*(2), 66, https://doi.org/10.3390/hydrology8020066.

Meko, D. M., et al. (2007), Medieval drought in the upper Colorado River Basin, *Geophys. Res. Lett., 34*(10), L10705, https://doi.org/10.1029/2007GL029988.

Miller, O. L., et al. (2021), Changing climate drives future streamflow declines and challenges in meeting water demand across the southwestern United States, *J. Hydrol. X, 11*, 100074, https://doi.org/10.1016/j.hydroa.2021.100074.

Milly, P. C. D., and K. A. Dunne (2020), Colorado River flow dwindles as warming-driven loss of reflective snow energizes evaporation, *Science, 367*(6483), 1,252–1,255, https://doi.org/10.1126/science.aay9187.

U.S. Bureau of Reclamation (2018), Colorado River Basin Ten Tribes Partnership tribal water study: Study report, U.S. Dep. of the Interior, Washington, D.C., usbr.gov/lc/region/programs/crbstudy/tws/finalreport.html.

Wilcox, D. A., et al. (2007), Lake-level variability and water availability in the Great Lakes, *U.S. Geol. Surv. Circ., 1311*, 25 pp., https://doi.org/10.3133/cir1311.

Author Information

Shemin Ge (shemin.ge@colorado.edu) and **Joann Silverstein,** University of Colorado Boulder; **James Eklund,** Sherman & Howard LLC, Denver; **Patricia Limerick,** University of Colorado Boulder; and **David Stewart,** Stewart Environmental Consulting Group, Fort Collins, Colo.

Read the article at Eos.org

Show Off Your Data: Enter to Win the Michael H. Freilich Student Visualization Competition

Named after Michael H. Freilich, former director of the NASA Earth Science Division, this competition gives students the chance to demonstrate creative ways to visualize data and present complex problems in the Earth, space and related scientific disciplines.

Grand prize winners will receive a $3000 grant to attend the AGU Annual Meeting, up to $3000 to participate in one additional professional development or community outreach opportunity, and more!

The Freilich competition will be open for applications 10 July–10 September 2024.

Get ready to enter with free virtual storytelling workshops sponsored by NASA:

How Do I Even Get Started With Data Visualization?
16 July 2pm ET
This session includes direct, hands-on instruction to help you get started with animated and interactive data visualizations using popular, open-source tools such as those in the R, Python and Javascript open-source scientific computing ecosystems. This is a free 2-hour workshop with a limited number of seats.

Science Storyboarding
6 August 2pm ET
Science is more compelling when told as a story, and visual storytelling can be an especially captivating way of conveying information. To effectively tell a good visual story, it is critical to be able to storyboard—to develop and put together the pieces of the visual narrative. This free 1-hour workshop will provide context, tips and examples of how to storyboard your science into a clear and memorable set of visuals.

AGU
ADVANCING EARTH AND SPACE SCIENCES

A Better Way to Predict Arctic Riverbank Erosion

A permafrost riverbank near Huslia, Alaska, exhibits signs of erosion. Credit: Madison Douglas, with thanks to the Huslia Tribal Council for land access

Arctic riverbanks are typically resilient, thanks to the stabilizing power of permafrost. However, some researchers worry that as river water warms due to climate change, riverbanks in the region will thaw and crumble, which could release stored soil carbon and cause damage to infrastructure near rivers.

But there's a caveat to this concern. Until now, existing models predicted more dramatic rates of Arctic riverbank erosion than have been observed. In a new study, *Douglas and Lamb* set out to determine why.

To do this, the researchers created a model that couples the movement of sediment, such as sand and mud, with permafrost thaw to determine riverbank erosion. Their model reproduces erosion observations on parts of the Yukon River in Alaska. This is because in the real world, erosion is slowed by an insulating layer of thawed sediment. This layer insulates deeper permafrost and limits the pace of bank erosion, so the warmer river water does not immediately wash away newly thawed sediment.

Although the thawed layer does eventually erode, factors like water temperature, flow speed, and soil consistency can affect the buffer layer's longevity and effectiveness. The new model, which takes these variables into account, could be applied to rivers throughout the Arctic to determine how climate change might alter their rates of bank erosion. This, in turn, could help Arctic communities prepare for the effect of eroding rivers. (*Journal of Geophysical Research: Earth Surface*, https://doi.org/10.1029/2023JF007452, 2024) —**Rachel Fritts**, *Science Writer*

Inland Waters Are a Blind Spot in Greenhouse Gas Emissions

Inland waters such as rivers, lakes, reservoirs, and ponds may release copious amounts of greenhouse gases, but this possibility is not well understood.

In a new review, *Yang et al.* summarize what's known about carbon dioxide and methane release from China's inland water and suggest that a widespread monitoring network could help researchers understand this important aspect of climate change.

China is a vast country, covering about 9.6 million square kilometers, with waterways woven throughout. Numerous processes, including thawing permafrost on the Tibetan Plateau, urbanization, and metabolic activity in aquaculture ponds, influence greenhouse gas emissions from the country's waters.

Thawing permafrost releases carbon that's long been trapped in soil, first into water and eventually into the atmosphere. Little is known about how quickly the Tibetan Plateau will warm and what effect it will have on the rate of permafrost thaw.

Meanwhile, China is urbanizing rapidly, and with urbanization comes more concentrated sewage in lakes and rivers. Nutrients from sewage can fuel the growth of microbes, which release carbon dioxide and methane. China has turned largely to hydropower to meet rising electricity demands. Rampant microbial growth is common in the country's dam-formed reservoirs, which number around 98,500.

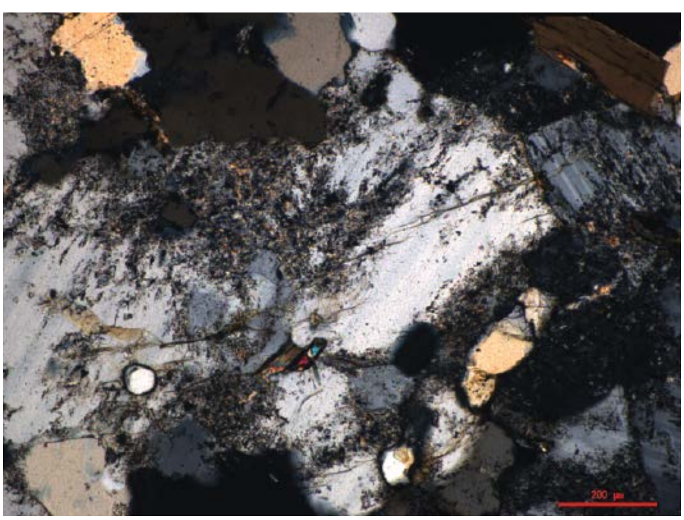
China is also home to about 60% of the world's aquaculture farms. Like sewage, nutrients meant to feed livestock can encourage microbial growth and lead to carbon dioxide and methane emissions. Aerating the water, on the other hand, can suppress the growth of anaerobic microbes, potentially reducing the amount of methane they release.

Scientists need much more information to understand the effects of China's inland waterways on climate change. The researchers suggest constructing an extensive monitoring network and taking frequent readings of the waters' biochemical and biological qualities to shed light on the full impact of China's freshwater systems on global change. (*Journal of Geophysical Research: Biogeosciences*, https://doi.org/10.1029/2023JG007675, 2024) **—Saima May Sidik,** *Science Writer*

Mantle Heat May Have Boosted Earth's Crust 3 Billion Years Ago

Little is known about the nature and evolution of Earth's continental crust prior to 2–3 billion years ago because cratons—stable blocks of lithosphere—older than that are relatively rare.

Cratonic rocks are home to tiny zircon crystals containing radiogenic isotopes of elements such as uranium, hafnium, oxygen, and lead that offer ways of looking billions of years into the past. Both igneous zircons, which crystalize from magma, and detrital zircons, which have an igneous origin and are subsequently transported and altered, can hold information about the rocks in which they formed.



To learn more about the history of Earth's crust, researchers studied grains of zircon embedded in granitoids (seen here under a microscope) from China's southwestern Yangtze Block. Credit: Wei Wang

Lu et al. focus on intact igneous zircons in a new study that examined the geochemical properties of these crystals and their source granitoid rocks in China's southwestern Yangtze Block, a craton thought to be about 3 billion years old.

Previous research has identified an increase in initial hafnium isotopes in both detrital and igneous zircons formed during the transition from the Paleoarchean to the Mesoarchean era around 3 billion years ago. This increase is thought to have resulted from crustal rejuvenation, in which magma was injected into older crustal rocks. Scientists also widely theorize that the increase marks the transition from an immobile crust and mantle to a period of more active plate movement.

The new study challenges this theory. The researchers suggest that the crustal rejuvenation that occurred globally around 3 billion years ago was a result of increased mantle temperatures rather than of widespread tectonic activity.

Isotopic data from the igneous zircons suggest that some of this warmer mantle rock could have melted and pooled at the crust-mantle boundary, independent of any change in tectonic activity. Some of this partially melted magma would have cooled into granitoids like those in the southwestern Yangtze Block.

According to the authors, this process may have played a significant role in continental crust growth. (*Geophysical Research Letters*, https://doi.org/10.1029/2024GL108715, 2024) **—Rebecca Owen,** *Science Writer*

Beneath the Ice: Greenland's Geology Revealed in New Map

Because so much of Greenland's landmass is covered in ice, mapping its geology is a difficult task. Recent advances in remote sensing allowed researchers to extend the geologic map into the island's interior. Credit: Joseph MacGregor

Mapping Greenland's geology is no easy feat. The Greenland Ice Sheet, which covers more than 1% of Earth's land surface and nearly 80% of Greenland's landmass, obscures much of the island's subglacial geology. As a result, scientists have largely interpolated the island's geology from rocks exposed at the ice sheet's margins.

In 2009, Peter Dawes of the Geological Survey of Denmark and Greenland produced the island's landmark geologic map, which is still widely used today. The map has served as a critical tool for documenting geologic characteristics and meaningfully evaluating economic resources on the world's largest island.

In recent years, however, technological advances in seismic imaging, geophysical surveys, and satellite mapping of gravity and magnetic anomalies have created opportunities to improve Greenland's geologic map.

MacGregor et al. used these advancements to redraw Greenland's geologic provinces. Pulling from 19 data sets, the authors delineated an updated map of Greenland's subglacial geology. In addition, they introduced a novel "flow-aware" hillshade (a method for highlighting terrain on a map) based on the idea that an ice mass transfers a topographic signature from the land over which it flows to its surface.

The resulting geologic map clarifies the extent of Greenland's geologic provinces and confirms that a greater variety of provinces exists in the northern part of the island. Three distinct subglacial regions could not be reconciled with the geology at the island's margins. In addition, newly mapped geologic structures offer updated perspectives on how ice flows from Greenland's interior toward its coasts.

The mapping effort also revealed dozens of unusually long, straight, nearly parallel valleys beneath the ice. These valleys are not captured by current syntheses of Greenland's subglacial topography, which raises the possibility that tectonics may have influenced the island's geology more than previously realized.

The authors acknowledge that the updated geologic map is an incomplete representation of Greenland's subglacial geology—and that nothing beats eyes and boots on the ground to examine which rocks are present.

Nevertheless, the work offers a modernized framework for interpreting the landmass's subglacial and solid Earth properties that can be incorporated into a variety of related scientific disciplines. (*Geophysical Research Letters*, https://doi.org/10.1029/2023GL107357, 2024)

—Aaron Sidder, *Science Writer*

Lakes Worldwide Need a Checkup

A rapid loss of ice is just one example of the health issues faced by lakes around the world. Credit: Gesa Weyhenmeyer

Like humans, lakes are living systems that can suffer from a number of health issues, including circulatory and respiratory problems, infections, nutritional imbalances, and heat-related illnesses. Without treatment, these conditions can become chronic, harming lake ecosystems and those who depend on them. More than 12% of the world's human population lives within 3 kilometers of a lake.

In a new study, *Weyhenmeyer et al.* suggest using human health terminology and approaches to assess and treat the world's lake system issues. For example, lakes with multiple health problems could be characterized as having multimorbidity, and regular screenings similar to medical checkups could help detect issues early. These anthropomorphic analogies, the researchers report, may help people better connect with and protect nature.

The team introduced a global classification system modeled after the World Health Organization's human health classification system. The researchers used data from LakeATLAS for nearly 1.5 million lakes worldwide to examine lake maladies of the circulatory (such as flooding and drying out), metabolic (such as acidification and salinization), nutritional, and respiratory varieties—along with other types of disturbances. They found, for example, that roughly 115,000 lakes evaporate twice as much water as they receive, putting more than 153 million people who live near these lakes at risk. Following their analysis, they categorized lake health as ranging from excellent to critical.

Some lake health symptoms, such as algal blooms, fish kills, and floating pollution, are readily visible with satellite or other types of observations. But other concerns can be revealed only with diagnostic tests, which, like those for humans, can be expensive.

The authors recommended additional screening, including testing water samples or installing inexpensive sensors, to get a fuller picture of health. They also noted that many lake health issues are widely recognized but not yet treated, especially in lower-income countries.

They stressed that there is an urgent need to start coordinated, multidisciplinary treatments for unhealthy lakes so conditions do not become chronic or critical. In particular, treating sewage water, mitigating climate change, and counteracting damage done by humans and non-native species should be prioritized. (*Earth's Future*, https://doi.org/10.1029/2023EF004387, 2024) **—Sarah Derouin,** *Science Writer*

A Million Years Without a Megaslide

Earthquakes, volcanic activity, and sediment flux can trigger underwater landslides, which can cause tsunamis on the surface.

Megaslides are extreme versions of these underwater events. The sixth-largest known megaslide occurred in the Surveyor Fan in the Gulf of Alaska around 1.2 million years ago. It was at least 16,124 square kilometers in area, and the preserved volume today is 9,080 cubic kilometers. At the time, before some portions of the slide were subducted or accreted, the volume was at least 16,280 cubic kilometers.

A new study by *Gulick et al.* examines this primeval slide. Using images from seismic reflection surveys and ground truth data from drilling efforts in the Gulf of Alaska, the researchers uncovered evidence of the slide, as well as the seafloor topography from before and after it occurred. Between 0.6 million and 1.2 million years ago, the glacial-interglacial cycle began growing longer, a change known as the Mid-Pleistocene Transition (MPT). The researchers suggest that sediment buildup and flux at the start of the MPT due to great ice extents caused slope instability, meaning that when a large earthquake struck the region, it likely triggered the megaslide. They also noted an absence of megaslides of the same magnitude after this event.

Although seismic activity continues in the region, the slides that do occur are smaller, for several reasons. One is a change in the balance between sediment flux, which can cause slope instability, and seismic strengthening, in which shaking causes sediment to compact, ultimately improving slope stability. In addition, ice streams crossing the continental shelf spread sediment deposits over large areas on the continental slope, leading to less cohesive slides. The continued buildup of sediment along the Alaska margin also reduced the critical wedge taper, which lowers the likelihood of the slope failing. (*Geophysical Research Letters*, https://doi.org/10.1029/2024GL108374, 2024) **—Rebecca Owen,** *Science Writer*

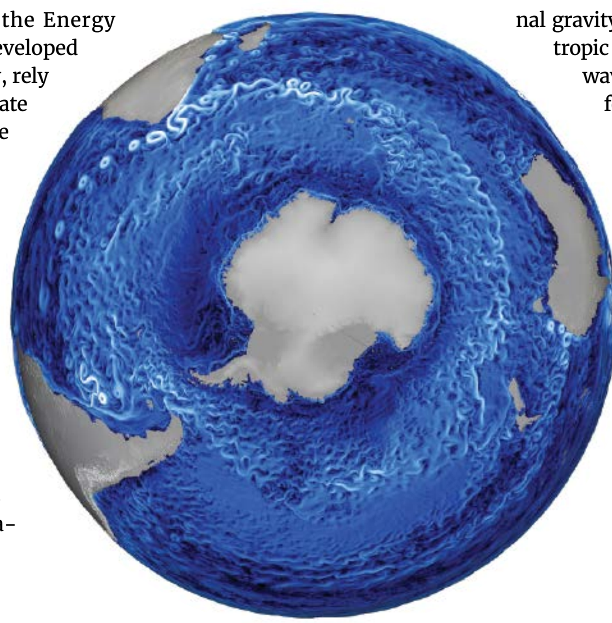
Verifying the Mathematics Behind Ocean Modeling

Global climate models, such as the Energy Exascale Earth System Model developed by the U.S. Department of Energy, rely on many underlying equations that simulate Earth's natural processes. These include the water cycle, carbon dioxide uptake by land and water, and rates of ice melt.

Verifying and validating these equations are crucial for instilling confidence in climate models. Though some discrepancy between model predictions and actual observations is inevitable, the aim is for specific configurations of the model to converge on the correct solution at the rate scientists expect.

Continuous mathematical models must undergo a process called discretization, which converts them into forms that can be numerically solved by computers. Test cases can help with overall verification of a model by extracting subsets of the discretized equations and verifying each term. Measuring the rate at which the numerical solutions of these test cases move toward convergence on the exact solutions (meaning that the errors approach zero) is the gold standard method for model verification. Convergence rates aligning with theoretical expectations is the best guarantee that the discretized equations are coded correctly.

For computational efficiency, ocean models typically split their governing equations into a 3D baroclinic component that models slow internal gravity waves and ocean currents and a 2D barotropic component that models fast surface gravity waves. The barotropic component assumes the form of shallow-water equations.



The Model for Prediction Across Scales–Ocean (MPAS-Ocean) reveals ocean currents and eddies. Credit: Los Alamos National Laboratory/Flickr, CC BY-NC-ND 2.0 (bit.ly/ccbyncnd2-0)

Bishnu et al. present a collection of test cases focused on these equations.

To develop the test cases, the authors drew on their experience developing the Model for Prediction Across Scales–Ocean (MPAS-Ocean), which is used to simulate ocean activity and study how it is affected by anthropogenic climate change. They note that their test cases are meant to verify the accuracy of the model (to ensure that the discretized model equations are implemented correctly), rather than to validate the results (to ensure that the model predictions resemble real-world observations).

The researchers reviewed the theoretical foundations of the shallow-water equations alongside the discretization methods, offered an overview of the test cases to ensure reproducibility, and demonstrated that the convergence rates match the anticipated predictions.

These test cases will enable other researchers to assess their models' components without the need for excessive computational power, the authors write. In addition, the test cases could be useful for broader fluid dynamics problems and serve as instructional tools for studying and developing ocean models. (*Journal of Advances in Modeling Earth Systems*, https://doi.org/10.1029/2022MS003545, 2024) **—Nathaniel Scharping,** *Science Writer*

When Extreme Drought Becomes Commonplace

Water levels in Lake Oroville, Calif., dropped to 38% capacity in May 2021. The drought conditions driving the decrease have become more common in California and across the western United States since 2000. Credit: Frank Schulenburg aka wikiphotographer/Flickr, CC BY-SA 2.0 (bit.ly/ccbysa2-0)

Every Thursday at 8:30 a.m. Eastern time, the U.S. Drought Monitor (USDM) publishes a map of drought conditions across the United States. Established in 2000, the USDM combines measurements of physical variables like soil moisture and runoff with reports of drought effects like fallow fields and reductions in municipal water supply.

Though generated by experts and informed by data, it is in some ways a subjective interpretation of drought conditions, and it carries significant political and economic ramifications—the USDM informs state declarations of emergency, as well as drought relief payments issued by the U.S. Department of Agriculture.

The USDM classifies localities into six drought categories, ranging from "none" to "exceptional." Each category is based on thresholds of event rarity. Some weeks, the placid white representing normal conditions blankets much of the country; other weeks, splotchy maroon pockets of exceptional drought pop off the map like blistered burns.

Li et al. assessed weekly USDM reports from 2000 to 2022 to determine whether the monitor is adequately capturing changes in the climate. This is the first effort to quantitatively link shifting drought behavior to the USDM and its drought class frequency guidelines. The authors analyzed trends across six hydroclimate variables and evaluated whether these changes were reflected in the USDM's drought threshold percentiles.

The results showed that across the country, but particularly in the West, drought occurred more frequently than the thresholds suggest it should in a stationary climate, or one whose parameters don't change over time. These findings mirrored trends in hydroclimate variables over the study period. Across large swaths of the West, the USDM record shows a prolonged dry period. The thresholds are designed so that exceptional drought should occur just 2% of the time. But for the first 23 years of the century, some places experienced it in up to 18% of the time.

The findings confirmed that the expert opinions of the USDM are capturing climate variability and trends toward warmer and drier conditions, particularly in the Southwest.

But the authors note that the results also raise important questions about how drought classifications based on historical data will apply to future conditions in a warmer climate. Can exceptional drought be defined the same way in the past, present, and future? The interpretation of this question, and the subsequent application of drought thresholds, will increasingly challenge policymakers and could have costly ramifications for drought-stricken communities. (*AGU Advances*, https://doi.org/10.1029/2023AV001070, 2024) **—Aaron Sidder,** *Science Writer*

Alerting Communities to Hyperlocalized Urban Flooding

As climate change continues to warm the planet, scientists expect natural hazards such as flooding to increase. Urban flooding can be caused by extreme precipitation events, storm surges, or high tides, with dangerous and expensive consequences for public health and infrastructure.

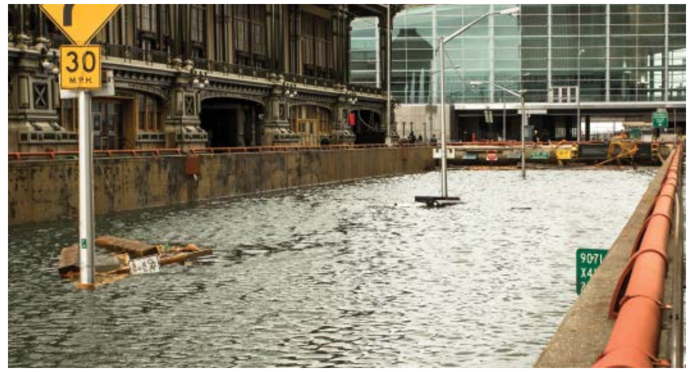
Urban flooding hazards are complicated by the heterogeneity of cities—various types of land use, development, surfaces, and drainage systems can all change how water moves. Flooding can be localized to areas as specific as a block or a street corner and change quickly, making it difficult to monitor hyperlocal floods distributed across a city in real time. Crowdsourced flood reports from citizens (such as social media posts) are helpful during such events, but the coverage and accuracy can be spotty given that they require human witnesses to register events. Some water level sensors present logistical challenges. For example, pressure sensors installed in sewers are susceptible to damage and require frequent maintenance. Existing camera-based sensing sometimes requires high power or provides low-quality images.

In a new study, *Mydlarz et al.* present their design for a low-cost, accurate, and robust flood sensor that can be deployed throughout cities.

The solar-powered sensors are part of a project called FloodNet, a New York City cooperative developing a combination of hardware, open-source software, visualization, and community engagement tools to provide real-time and quantitative flood information to various stakeholders, including city agencies, community members, and researchers. The sensors can be easily mounted to street sign poles or walls, and they measure water depths with better than 25-millimeter accuracy using an ultrasonic range finder. The sensors transmit the data to a central server every minute using a Long Range Wide Area Network (LoRaWAN) or a cellular network, allowing them to be installed independently of existing network infrastructure. The total cost of each sensor is around $200.

The researchers created a public-facing data dashboard that allows community members and city agency personnel to visualize the data in close to real time and to access historical data. Alerts can be triggered to warn community members and emergency responders when floods are detected.

To date, the team has deployed 87 FloodNet sensors across all five boroughs of New York City, which recorded 360 flood events between October 2020 and May 2023. The team is now fine-tuning data analysis tools and flood detection thresholds and expanding the sensor network. They noted that their aim is to release flood data to stakeholders in real time, with the goal of making that data meaningful for actionable use. (*Water Resources Research*, https://doi.org/10.1029/2023WR036806, 2024) **—Sarah Derouin,** *Science Writer*



A new kind of low-cost sensor could more quickly and effectively alert people in urban areas about localized flooding. Credit: Patrick McFall via Flickr, CC BY-SA 2.0 (bit.ly/ccbysa2-0)

Members of the FloodNet team install a sensor designed to provide real-time flood information to community members, researchers, and agencies in New York City. Credit: Veroneque Ignace

U Y K A R E P H S Y B M G T H N D C G C O M P A C T P W F G
S T I F M J D E A F X K N A B R E V I R O Z Q B H Z R O I F
E P P C I Z S L O E A V I G H G A M S R D P K P A H J G B E
V O C C M L B I A U G W Y F A B M A O I A Y K T B V A B B M
I L C R H T K D T K Z R U H K W I T E V R R G J D G W F O J
T I Z E V V F Z S U E F G Y T Z T F O E O I E I E A B N F A
A C Y T A J D A V U F P P M Y U C V P R L O T W T L O O I H
I Y N O A J O I R Y O I O V H O T Y D E O F I E B C F K H A
T G S Z R W X L J M U X K W C H F H C T C D R J Z E Z Q S R
I K M B Q Q N L Z G E F U F E S V O Q G K S A A B W N I Y W
N Y G Q N G W G M A D R J V E L N B U X U S E M K R I M W F
I H O L U N H K Y D V E S K S G L X T P N B A F S O S P A B
B Y D P G I W H A T U W K V I E H B P Z P V C Y Y D A E T K
H D O C X M T P G M B C T O X O B L T O O F E R C A B R E T
A R G H J O M Q M L J I N E H H Y Y Q G Y J O U H N N I R C
Y O Z K G Y O A B M S G O O F U S E V D Y G W H S F T A Y Q
H P J Y Z W D R L O R O W U M U F L K Z C F P W Y T Q L S F
F O C R N R G I A O U L E R U T L U C I R G A J Q N N V X T
K W Q F E O Z J K L V O C S Q P B S L N D I R A R T O A T I
Q E E V E P A R E B A R S L R R C C W E J R Z M D P I L T W
D R O W Z K I T M L X D B O E Y Z P Y O B A O W B N T L Q A
F O F E S V N J E A R Y K F O W L X Q G O X Y B F T A E Z E
H V W I R S R L A G X H P I S Q I Q M L V I N A V Q E Y S G
M G I H A R O N D L B Q J V I X G I F T T Q F K J T R L C R
B S S O N H F R G A K H J G R L E E F E R R Y I I X C K L A
T U D F C Z I P R Y C L I M A T E M L F I R E R G J E Y A H
M D Z F H B L W S E U D L D A R I Z O N A C S V C O R N X C
B D Q D E M A D Q R T D T Q J L U J I A V S U I V H M U E S
Y U A P R P C G Z S U Z J J V I S E R O S I O N K R Z X R I
S U A E S J B E L A N D U S E S J Y H T M U Y S Y U D T N D

Word Search: Dams, Reservoirs, and Policy

U	Y	K	A	R	E	P	H	S	Y	B	M	G	T	H	N	D	C	G	C	O	M	P	A	C	T	P	W	F	G
S	T	I	F	M	J	D	E	A	F	X	K	N	A	B	R	E	V	I	R	O	Z	Q	B	H	Z	R	O	I	F
E	P	P	C	I	Z	S	L	O	E	A	V	I	G	H	G	A	M	S	R	D	P	K	P	A	H	J	G	B	E
V	O	C	C	M	L	B	I	A	U	G	W	Y	F	A	B	M	A	O	I	A	Y	K	T	B	V	A	B	B	M
I	L	C	R	H	T	K	D	T	K	Z	R	U	H	K	W	I	T	E	V	R	R	G	J	D	G	W	F	O	J
T	I	Z	E	V	V	F	Z	S	U	E	F	G	Y	T	Z	T	F	O	E	O	I	E	I	E	A	B	N	F	A
A	C	Y	T	A	J	D	A	V	U	F	P	P	M	Y	U	C	V	P	R	L	O	T	W	T	L	O	O	I	H
I	Y	N	O	A	J	O	I	R	Y	O	I	O	V	H	O	T	Y	D	E	O	F	I	E	B	C	F	K	H	A
T	G	S	Z	R	W	X	L	J	M	U	X	K	W	C	H	F	H	C	T	C	D	R	J	Z	E	Z	Q	S	R
I	K	M	B	Q	Q	N	L	Z	G	E	F	U	F	E	S	V	O	Q	G	K	S	A	A	B	W	N	I	Y	W
N	Y	G	Q	N	G	W	G	M	A	D	R	J	V	E	L	N	B	U	X	U	S	E	M	K	R	I	M	W	F
I	H	O	L	U	N	H	K	Y	D	V	E	S	K	S	G	L	X	T	P	N	B	A	F	S	O	S	P	A	B
B	Y	D	P	G	I	W	H	A	T	U	W	K	V	I	E	H	B	P	Z	P	V	C	Y	Y	D	A	E	T	K
H	D	O	C	X	M	T	P	G	M	B	C	T	O	X	O	B	L	T	O	O	F	E	R	C	A	B	R	E	T
A	R	G	H	J	O	M	Q	M	L	J	I	N	E	H	H	Y	Y	Q	G	Y	J	O	U	H	N	N	I	R	C
Y	O	Z	K	G	Y	O	A	B	M	S	G	O	O	F	U	S	E	V	D	Y	G	W	H	S	F	T	A	Y	Q
H	P	J	Y	Z	W	D	R	L	O	R	O	W	U	M	U	F	L	K	Z	C	F	P	W	Y	T	Q	L	S	F
F	O	C	R	N	R	G	I	A	O	U	L	E	R	U	T	L	U	C	I	R	G	A	J	Q	N	N	V	X	T
K	W	Q	F	E	O	Z	J	K	L	V	O	C	S	Q	P	B	S	L	N	D	I	R	A	R	T	O	A	T	I
Q	E	E	V	E	P	A	R	E	B	A	R	S	L	R	R	C	C	W	E	J	R	Z	M	D	P	I	L	T	W
D	R	O	W	Z	K	I	T	M	L	X	D	B	O	E	Y	Z	P	Y	O	B	A	O	W	B	N	T	L	Q	A
F	O	F	E	S	V	N	J	E	A	R	Y	K	F	O	W	L	X	Q	G	O	X	Y	B	F	T	A	E	Z	E
H	V	W	I	R	S	R	L	A	G	X	H	P	I	S	Q	I	Q	M	L	V	I	N	A	V	Q	E	Y	S	G
M	G	I	H	A	R	O	N	D	L	B	Q	J	V	I	X	G	I	F	T	T	Q	F	K	J	T	R	L	C	R
B	S	S	O	N	H	F	R	G	A	K	H	J	G	R	L	E	E	F	E	R	R	Y	I	I	X	C	K	L	A
T	U	D	F	C	Z	I	P	R	Y	C	L	I	M	A	T	E	M	L	F	I	R	E	R	G	J	E	Y	A	H
M	D	Z	F	H	B	L	W	S	E	U	D	L	D	A	R	I	Z	O	N	A	C	S	V	C	O	R	N	X	C
B	D	Q	D	E	M	A	D	Q	R	T	D	T	Q	J	L	U	J	I	A	V	S	U	I	V	H	M	U	E	S
Y	U	A	P	R	P	C	G	Z	S	U	Z	J	J	V	I	S	E	R	O	S	I	O	N	K	R	Z	X	R	I
S	U	A	E	S	J	B	E	L	A	N	D	U	S	E	S	J	Y	H	T	M	U	Y	S	Y	U	D	T	N	D

Search up, down, forward, backward, and on the diagonal in the grid above to locate the words listed below.

acre-foot
agriculture
algal bloom
Arizona
basin
California
climate
Colorado
compact
dams
discharge
erosion
farmers
Hoover Dam
hydrologic
hydropower
Imperial Valley
initiatives
IPCC
Lake Mead
Lake Powell
land use
Lee Ferry
policy
ranchers
recreation
river
riverbank
Utah
water
water supply
Wyoming

See p. 31 for the answer key.


Real-time Measurements of NH_3 Vapor — Anywhere
PI2103 Ammonia Gas Concentration Analyzer
The ideal solution for atmospheric, urban, and indoor air quality research and monitoring applications.
• 1Hz real-time measurements
• Superb sensitivity and accuracy
• Long-term stability
• Automatic water corrections
• Small footprint, easy to install and maintain
PICARRO
PI2103
www.picarro.com
PICARRO