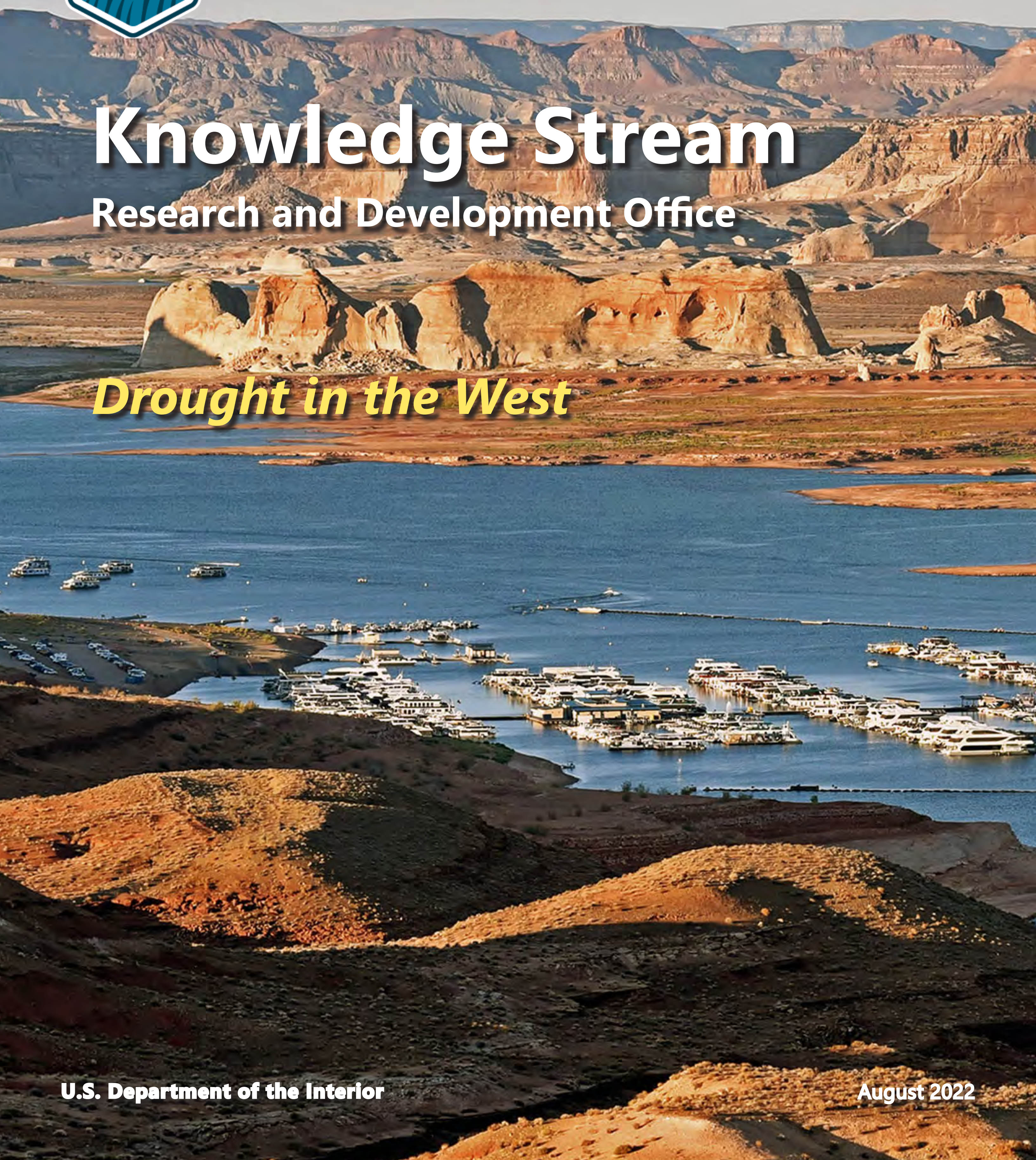
Attachment

BUREAU OF RECLAMATION

Knowledge Stream

Research and Development Office

Drought in the West



U.S. Department of the Interior

August 2022

Message from R&D

Welcome to the Summer 2022 issue of the *Knowledge Stream*! In this issue, we highlight research and innovation activities related to drought in the West. As the Nation's largest wholesaler of water and second largest producer of hydropower, drought strikes at the core of the Bureau of Reclamation's (Reclamation) mission to deliver water and generate power in an economically and environmentally sound manner in the interest of the American public. Drought impacts both the quantity and quality of water available to meet competing objectives. Below-average inflows and depleted reservoir levels reduce allocations and deliveries to customers, degrade the production of clean energy from our hydropower facilities, and make the task of meeting flow and temperature targets for threatened and endangered species difficult. Included in this issue you will find articles about:

- Impacts and challenges of drought across Reclamation
- Drought on the Colorado River
- Research to modernize reservoir evaporation monitoring
- Crowdsourcing better spatially distributed snow estimates
- Projections of future drought conditions
- Research to improve forecasts

About the *Knowledge Stream*

The *Knowledge Stream*, published by the Bureau of Reclamation's Research and Development Office, is a quarterly magazine bringing mission-critical news about the agency's innovations in the following:

- Science and Technology Program
- Desalination and Water Purification Research Program
- Prize Competitions Program
- Snow Water Supply Forecast Program
- Open Water Data Program
- Reclamation Geographic Information System Program
- Technology Transfer...and more

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Evaluating Water Temperature Modeling and Prediction

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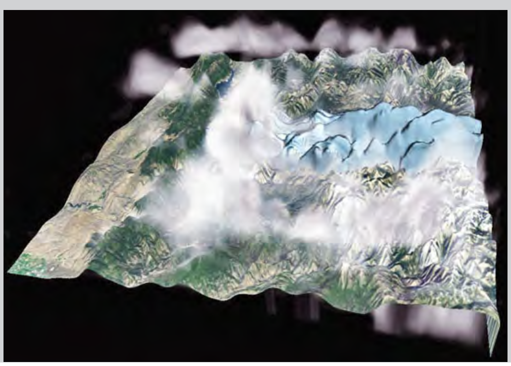

Investigating the potential of Cloud Seeding to Enhance Precipitation

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Front Cover: Photo taken in September 2021, showing drought levels in Lake Powell.

Back Cover: Top photo: Three aerial views of Lake Mead showing drought comparisons and elevation change from 2000 to 2022. Credit: NASA Earth Observatory.
Bottom Photo: Penstocks at Hoover Dam showing the extreme low levels in Lake Mead, April 2021.

The information being offered herein represents the opinion of the author(s) and is not a statement of fact about Bureau of Reclamation findings or conclusions.

Community Needs

Drought Anecdotes from across the West

By Kirk Nelson (CGB), Peter Cooper (CPN), Eve Halper & Valerie Swick (LCB), Dagmar Llewellyn & Carolyn Donnelly (UCB), & Collins Balcomb (MBART)
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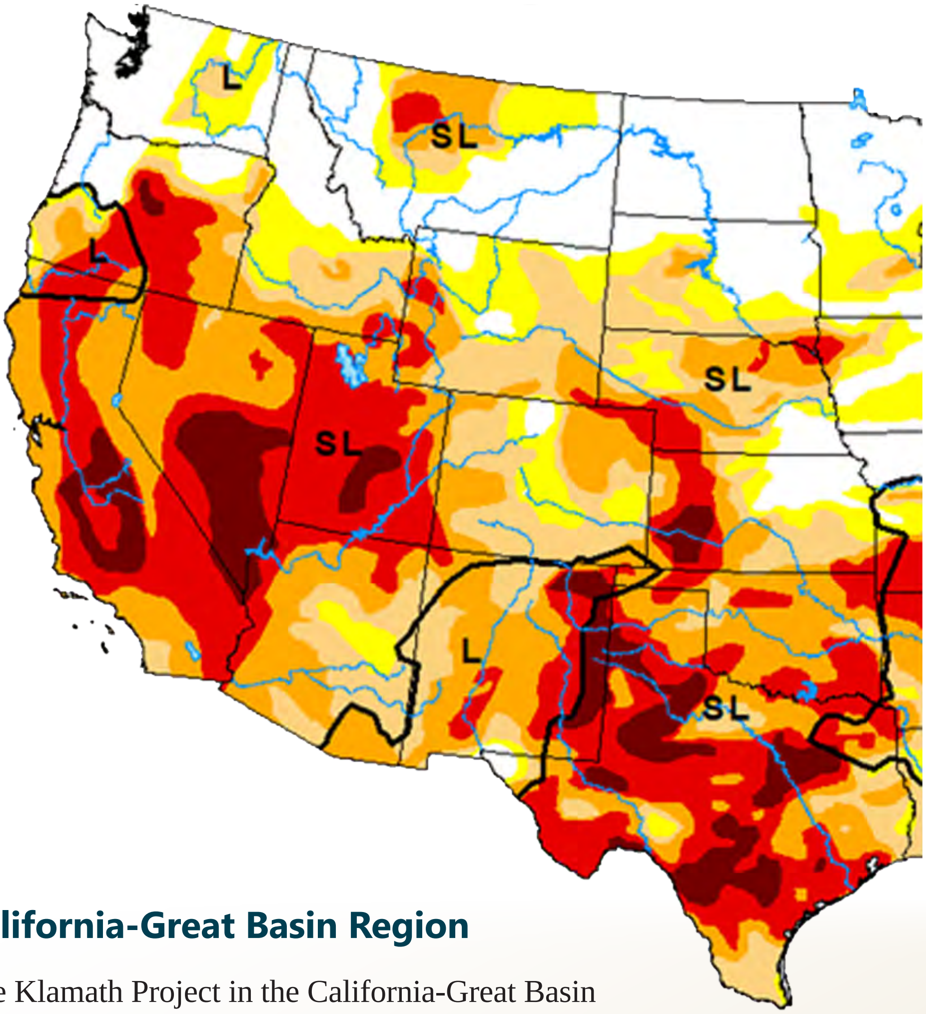
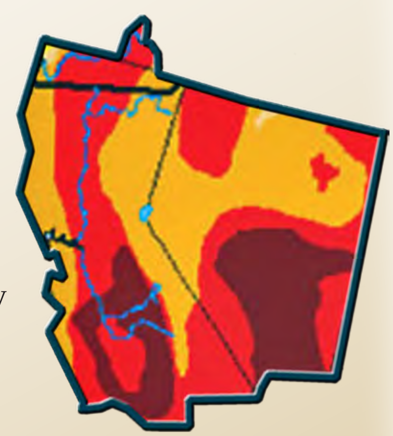


Drought monitor, released July 28, 2022, showing drought conditions of varying severity across most of the Western United States.

California-Great Basin Region

The Klamath Project in the California-Great Basin Region serves multiple objectives, including providing agricultural water, protecting endangered and threatened fishes, and providing water to the Lower Klamath National Wildlife Refuge (managed by the U.S. Fish and Wildlife Service). Consecutive years of recent drought conditions have prevented the Project from meeting all objectives. Refuge wetland acreages have plummeted largely due to the U.S. Fish and Wildlife Service's inability to secure water, which has resulted in the wetlands often remaining dry during the Pacific Flyway southern migration. In a mitigation effort, the owner of a water right of Klamath Project water on a parcel located in Oregon agreed to a temporary 5-year transfer of the water right to the refuge. However, there remains an unresolved issue regarding the volume of water available for transfer. The region has launched a project to evaluate and apply the best available science to estimate the consumptive use of applied water on the parcel to determine the volume of water that will be transferred and delivered to the refuge. This effort is challenging not only because we are working with multiple stakeholders across State lines but because we are also balancing multiple objectives.



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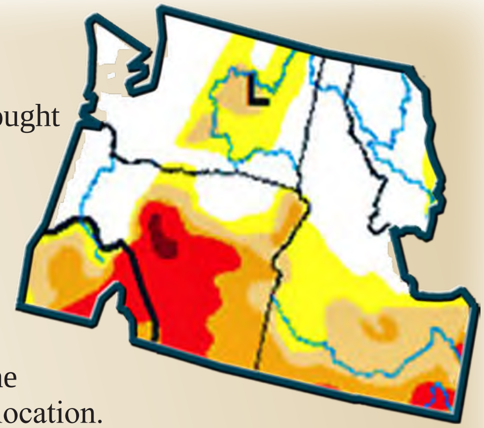
Columbia-Pacific Northwest Region



For nearly 3 years, Crook County in central Oregon, home to the Bureau of Reclamation's Prineville and Ochoco Reservoirs, has been experiencing drought conditions. Much of that time has been spent in the extreme or exceptional drought category according to the U.S. Drought Monitor. Multiple years of drought have resulted in an extremely limited water supply, impacting all who rely on the resources provided by the Crooked River. This season, irrigators received substantially reduced storage allocations, and the uncontracted storage account in Prineville Reservoir, managed in consultation with the U.S. Fish and Wildlife Service and the National Marine Fisheries Service, and utilized for fish and wildlife purposes, received no allocation. Prineville Reservoir contents and tailwater flows below its A.R. Bowman Dam have been at or near record low levels. The irrigation season will end weeks earlier than normal, and the reservoir, which recently dropped below 20 percent of capacity, is anticipated to be near the bottom of active capacity by September. Despite the extremely challenging year, collaboration among the Bureau of Reclamation, its partners, and the many interested parties has been occurring to maximize the benefits of the limited water supply. Users throughout the Ochoco River basin will continue to plan for the worst but will hope for a significant snowpack this winter to help pull the basin out of the unprecedented drought conditions.

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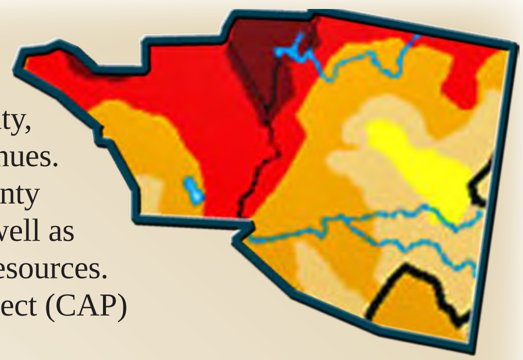
Lower Colorado Basin Region



The Southwest drought has impacted agricultural activities in Pinal County, Arizona, and these impacts are expected to intensify as the drought continues. Located between Arizona's largest cities, Phoenix and Tucson, Pinal County is primarily an agricultural area, supporting beef and dairy industries as well as crops for livestock. Agriculture consumes about 90 percent of all water resources. Many farmers use water from the 300,000 acre-foot Central Arizona Project (CAP) agricultural pool for irrigation.

Due to drought conditions on the Colorado River, this pool was cut in 2022, but some mitigation water was made available to farmers. Under the upcoming Tier 2a Shortage in 2023, however, the CAP agricultural pool will be eliminated, reducing access to water for many Pinal County farmers. The Bureau of Reclamation's (Reclamation) Eloy-Maricopa Stanfield Basin Study is analyzing future water supply and demand for a portion of Pinal County. The study provided three strategies that can help minimize the impact of less water in the future while still allowing agriculture and growth in the county.

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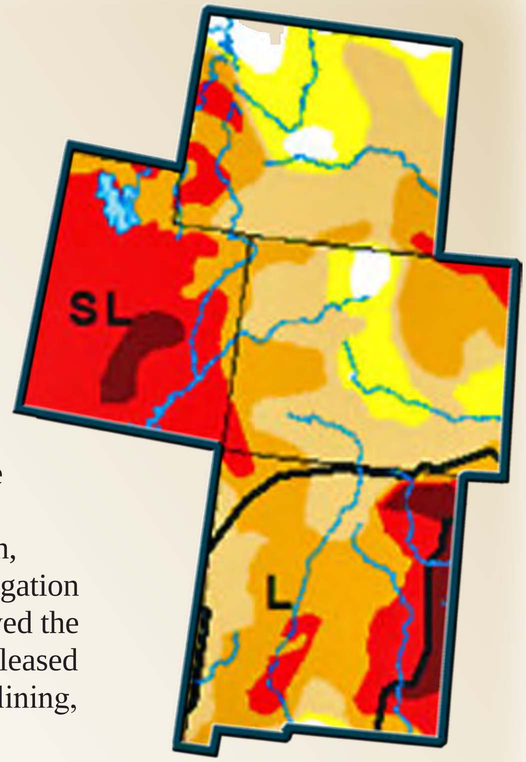
A recent University of Arizona study estimated the contribution of on-farm agriculture and agribusiness to Pinal County's 2016 economic output to be nearly $2.3 billion. Agriculture and agribusiness directly supported and estimated 5,150 full and part-time jobs.

Researchers modeled the impacts of a 300,000 acre-foot reduction in water supplies, assuming that farmers would fallow a combination of wheat, alfalfa, and cotton fields in response. They estimated that this would result in a reduction of 25–32 percent of the county's irrigated acreage. When direct, indirect, and induced effects are included, losses would range from $94 million to $104 million, with 270–480 jobs lost. While time will tell how projections play out, Reclamation planners are actively collaborating with farmers to find viable solutions to water cutbacks.

Upper Colorado Basin Region



Mark Twain is reported to have said "Until I came to New Mexico, I never realized how much beauty water adds to a river." The Rio Grande in New Mexico is sometimes a river without water. In the early 2000s, some low-precipitation years depleted the reservoirs in the Rio Grande in New Mexico—and water shortages have continued, with a few interspersed wetter years. The future promises more of the same—as temperatures continue to increase, snowmelt runoff continues to decrease, extreme storms increase in intensity, and larger and more intense wildfires burn.

Even in the context of two decades of water shortage, 2022 has been particularly challenging. A hot and windy spring blew away much of the forecast snowpack, and record fires burned in the headwaters. El Vado Reservoir, the only reservoir in the system that stores water for irrigation, is now under repairs and cannot store any water. Although the major irrigation district in the Basin, the Middle Rio Grande Conservancy District, delayed the start of its irrigation season by a month, and the Bureau of Reclamation leased water to support endangered species, by mid-May, natural flow was declining, there was no reservoir storage, and the supplemental water supply was insufficient to maintain reach connectivity. The river began to dry in the reaches downstream from Albuquerque. In mid-June, a heat wave made conditions worse. But just as Reclamation was planning a press release to tell the community that the river through Albuquerque would be going dry for the first time in decades, a week of monsoonal storms began! Flow from the rain and decreased temperatures reconnected the Rio Grande downstream from Albuquerque in late June and kept those reaches connected through mid-July. Of course, a single rain system—while blessed—cannot make up for decades of shortage, and the river has started to dry again. Reclamation and its partners are again facing the prospect of the river drying through Albuquerque and continue to collaborate to balance water needs while really hoping for more monsoonal rain.

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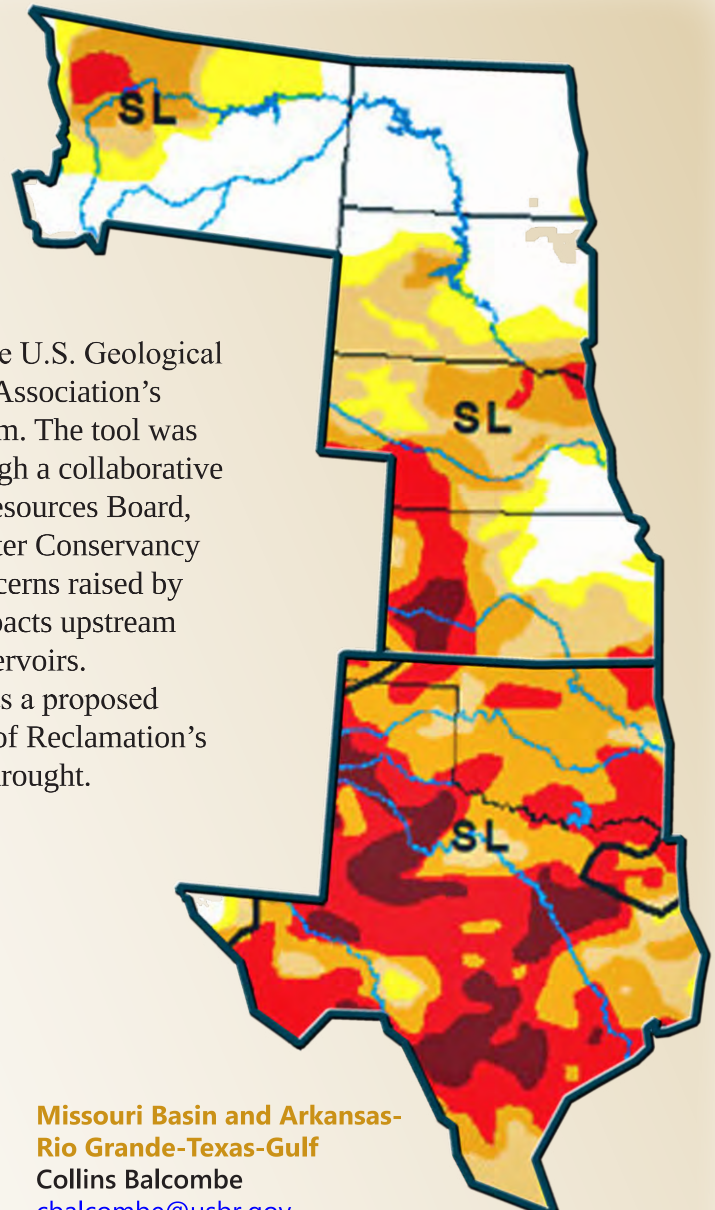
Missouri Basin & Arkansas-Rio Grande-Texas Gulf Regions



With much of the Oklahoma-Texas-Kansas area in severe to exceptional drought, the Bureau of Reclamation's (Reclamation) Oklahoma-Texas Area Office was asked to give a presentation on a new drought prediction tool in a July 14 webinar hosted by the U.S. Geological Survey (USGS) and National Oceanic and Atmospheric Association's (NOAA) National Integrated Drought Information System. The tool was developed under the Upper Red River Basin Study through a collaborative partnership among Reclamation, the Oklahoma Water Resources Board, Lugert-Altus Irrigation District, and Mountain Park Master Conservancy District. The development of the tool stemmed from concerns raised by stakeholders during the last severe drought about the impacts upstream water users were having on storage in Reclamation's reservoirs. Specifically, stakeholders aim to use the prediction tool as a proposed strategy to curtail permitted stream diversions upstream of Reclamation's reservoirs to protect reservoir storage during periods of drought.

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Key Perspectives

Supporting Collaborative Solutions under Drought and Climate Change in the Colorado River Basin

By Rebecca Smith & Jim Prairie
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In February, an article in Science magazine declared that the Southwestern United States was officially experiencing a megadrought – defined as a drought lasting 20 years or more (Williams et al. 2022). The study used regionally averaged tree-ring reconstructions of soil moisture to show that 2000–2021 was the driest 22-year period since at least 800 CE (Common Era). Beyond analyzing paleo reconstructions, the study also attributed the length and severity of the drought to warming caused by anthropogenic climate change. As studies of prolonged drought in the United States often do, it referenced hydrologic conditions in the Colorado River Basin (CRB) and declining elevations at Lakes Powell and Mead as exhibit A.

This study garnered widespread news media coverage, building on the attention to the August 2021 first-ever declaration of a shortage condition in the Lower CRB. The CRB received renewed attention as the shortage and megadrought story fed into coverage of the Bureau of Reclamation's (Reclamation) spring 2022 actions to protect critical elevations at Lake Powell (more details below). Summer 2022 began another chapter, with national, regional, and local media coverage of the volume of water potentially needed to protect critical elevations at Lakes Powell and Mead, Commissioner Touton's congressional testimony about managing the CRB system in unprecedented times, and the efforts among CRB stakeholders to address rapidly declining reservoir levels. Adding to the complexity of the moment, these public, intra-, and interagency discussions focusing on near-term drought mitigation actions are necessarily happening in parallel with the early stages of planning for operations of Lakes Powell and Mead beyond 2026 (when current operating rules expire);

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in June, Reclamation published a pre-scoping Federal Register Notice requesting input on the anticipated National Environmental Policy Act process and strategies that should be considered for CRB operations beyond 2026.

In this dynamic atmosphere, the Upper and Lower Colorado Basin regions have continued to undertake both standard and specialized technical analyses to inform internal and external partners about acute system conditions and the implications of the ongoing drought. And, though the current circumstances have increased the pace of modeling investigations, it is important to reflect on the work that the UCB and LCB regions have been doing to integrate paleo data, climate change, and drought into technical analyses to support planning and policy since the mid-2000s.

In 2005, in response to the beginning of the drought, Reclamation began working with partners to develop what became the 2007 Colorado River Interim Guidelines for Lower Basin Shortages and the Coordinated Operations of Lake Powell and Lake Mead (Interim Guidelines). To address the potential for continued, frequent, and prolonged low-runoff conditions, the Interim Guidelines, for the first time, specified conditions under which Lake Powell would reduce its annual release below the minimum volume targeted to account for the apportionments of the Lower Division States (Arizona, California, and Nevada) and Mexico and specified when the Lower Division States would be required to take shortages. Critically, the Interim Guidelines also incentivized proactive conservation and enshrined the goal of collaboration before litigation. Studies performed in support of this effort included use of paleo-reconstructed streamflow (Meko et al. 2007) and paleo-conditioned streamflow (Prairie et al. 2008), and they explicitly called for additional research to characterize the potential impacts of climate change on future CRB conditions. This was the first use of paleo data in any major policy development study.

Beginning in 2010, Reclamation and its partners undertook the CRB Water Supply and Demand Study (Basin Study), which was published in 2012. The Basin Study used observations, paleo-reconstructed streamflow, paleo-conditioned streamflow, and streamflow developed from downscaled global climate models in an advanced technical framework to identify vulnerable conditions and potential adaptations to address the future supply and demand imbalance. The technical scope and high level of stakeholder engagement during the Basin Study provided an opportunity for everyone in the CRB to learn about the implications of paleo droughts and climate change on the system.

After back-to-back dry years in 2012 and 2013, Reclamation and its partners again collaborated to increase protection against worsening reservoir conditions. In 2017, Minute 323 to the 1944 Treaty with Mexico, which included the Binational Water Scarcity Contingency Plan (BWSCP). Technical analyses used to develop the BWSCP used a truncated observed record (1931 to 2017 instead of 1906 to 2017) to acknowledge the high-flow pluvial period of the early 1900s was unlikely to recur.

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In 2019, the Drought Contingency Plan (DCP) was authorized by the United States Congress. Among other things, the DCP complemented the BWSCP in requiring contributions to Lake Mead by Lower Division States at higher elevations (starting at Lake Mead elevation 1090, 15 feet above the first shortage condition specified in the Interim Guidelines). The DCP also established a mechanism for Reclamation's upstream reservoirs to release water to Lake Powell under low reservoir conditions for later recovery. The technical analyses that supported development of the DCP used a truncated observed record (1988–2017 instead of 1906–2017) that aligned with a regime shift in runoff efficiency (McCabe et al. 2017), and which was more representative of the ongoing drought than Reclamation's typical studies, which relied on the historical record, including the early pluvial period. Analyses at the time showed that the DCP reduced the risk of reaching critical elevations, but it did not entirely eliminate it.

Annual streamflow from 2020 through 2022 (estimated) has been about 60 percent of the long-term average – one of the lowest 3-year spans in the observed record. DCP-authorized releases were from upstream reservoirs in 2021 and 2022 to protect Lake Powell from falling below elevation 3490. In 2022, Interim Guidelines shortages and DCP contributions were required from Arizona and Nevada, with required contributions and reductions from Mexico, to bolster Lake Mead. Greater cutbacks under existing policy will be required in 2023. In May, historically low reservoir elevations and near-historic low-runoff conditions prompted Reclamation, with agreement from its partners, to reduce Lake Powell's previously determined water year release to protect critical infrastructure at Glen Canyon Dam that could be compromised if 2023 is dry. In June, a new flavor of technical analysis was explored: in addition to "How will these actions reduce risk?", answering "What will it take to avoid critical elevations?" is providing helpful, clarifying context to the ongoing efforts to identify further protective actions.

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Lake Mead July 2000 | Lake Mead July 2022 | Lake Mead July 2000-2022

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Behind the modeling for official studies, and behind the scenes of the public activities described in the media, the UCB and LCB regions devote significant energy to improving our models, developing and integrating research, and working with our partners to interpret technical results. Below is a brief summary of some of our recent work.

Mid-Term Planning

In mid-term planning applications (looking 1–5 years into the future), our standard hydrologic input has been the 30 traces generated by the Colorado Basin River Forecast Center (CBRFC) in their Ensemble Streamflow Prediction product. The 30 traces are based on temperature and precipitation from 1991 to 2020, in line with the World Meteorological Organization's "standard reference period" for current climate. We have completed several research projects in the past 5 years to develop new mid-term hydrologic inputs, and we are continuing to work with the CBRFC and stakeholders to explore scientifically sound ways of aligning mid-term inputs with drought under climate change. We are also working to monitor experimental products (Baker et al. 2022) and, in the meantime, direct our audience to the lower portion of the distribution of potential system conditions in recognition that we are best served by planning with dry years in mind.

Long-Term Planning

For long-term planning, which looks 5 to 50 years into the future, we use hydrology ensembles that capture a wider range of uncertainty than used in mid-term modeling. As described above, we have used paleo-reconstructed, paleo-conditioned, climate change projections, and truncated observed records in previous studies, and we are working to develop additional planning ensembles based on more recent climate projections and also custom scenarios designed to capture specific statistical features of interest. Recognizing that we will not be able to reduce hydrologic uncertainty (among other uncertainties), we have also developed research and in-house capabilities to understand and implement decision making under deep uncertainty planning methods (Smith et al. 2022).

In unprecedented times, the UCB and LCB regions continue the technical work that supports planning at multiple time scales. Whether the context is standard modeling or special studies, we work to provide sound technical information. While the pace and urgency have increased in recent years, we always strive to conduct technically sound studies, advance our methods, and support our partners in pursuit of collaborative, sustainable solutions in the CRB.

Drought Monitoring

Advances in Estimating Reservoir Evaporation

By Kathleen Holman; with partners, Desert Research Institute & Texas A&M University
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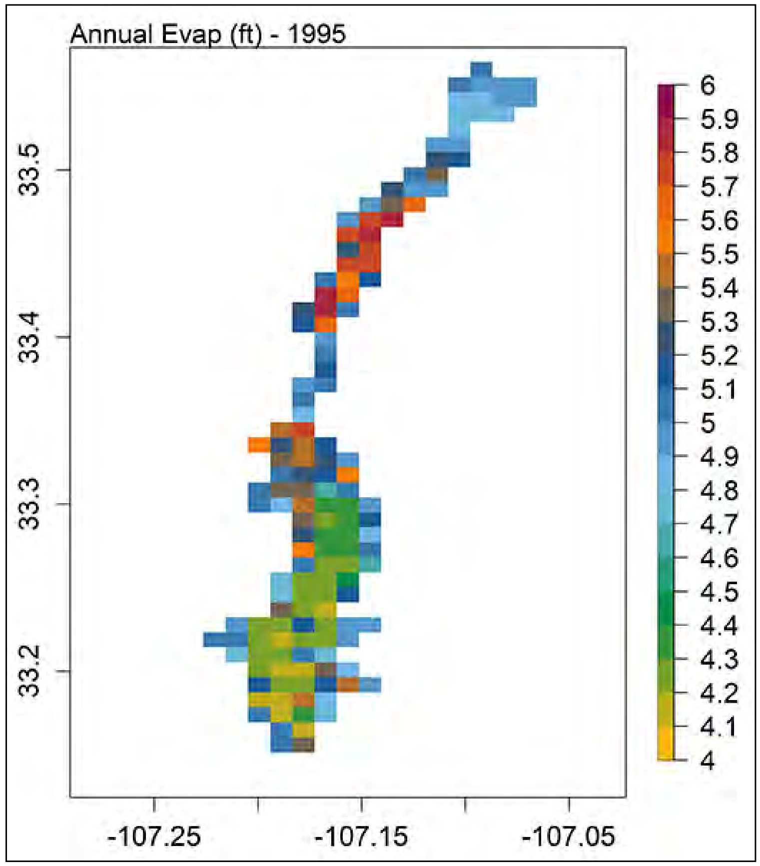
Across much of the Western United States, water is stored in reservoirs to account for the frequent imbalance between water supply (which occurs as spring runoff of accumulated snowpack) and human uses. Water stored in these reservoirs is subject to the continuous process of evaporation, which is typically considered the largest natural sink of water at many reservoirs in the West (Zhao and Gao 2019). Developing and improving estimates of reservoir evaporation may help water managers with short-term water allocation planning, strategic repositioning of available water resources, water delivery estimates (at multiple time scales), and changing water quality conditions (Friedrich et al. 2018).

Many methods exist for estimating evaporation from lakes and reservoirs in which the complexity and cost varies widely. For instance, the Eddy Covariance (EC) approach is considered the gold standard among experts (Moreo et al. 2013), though the method is extremely complex and expensive to initiate and maintain (Friedrich et al. 2018). Conversely, the aerodynamic method, which requires fewer observations, is generally less cost prohibitive and easier to install, maintain, and process. Other approaches include the water budget and energy budget approaches, which require detailed estimates of all sources and sinks of water and energy. Alternative approaches for estimating reservoir evaporation also exist that use various types of gridded datasets, including reanalysis datasets, numerical weather prediction (NWP) model output, remotely sensed variables, among others.



Coupled Weather Research and Forecasting Model estimates of annual evaporation (inches) from Elephant Butte Reservoir, New Mexico, between January 1 and December 31, 1995.

Currently, there are three different reservoir evaporation studies underway by members of the Technical Service Center (TSC) and their associated partners. First, the TSC and team members from the Desert Research Institute (DRI) deployed two floating platforms at Lake Powell in 2018 to estimate evaporation using in-situ over-water observations (figure shown above). The primary methods included the EC and bulk aerodynamic approaches. Project leads are also exploring the use of remotely sensed and gridded weather datasets to develop spatially distributed estimates of evaporation across the lake surface.

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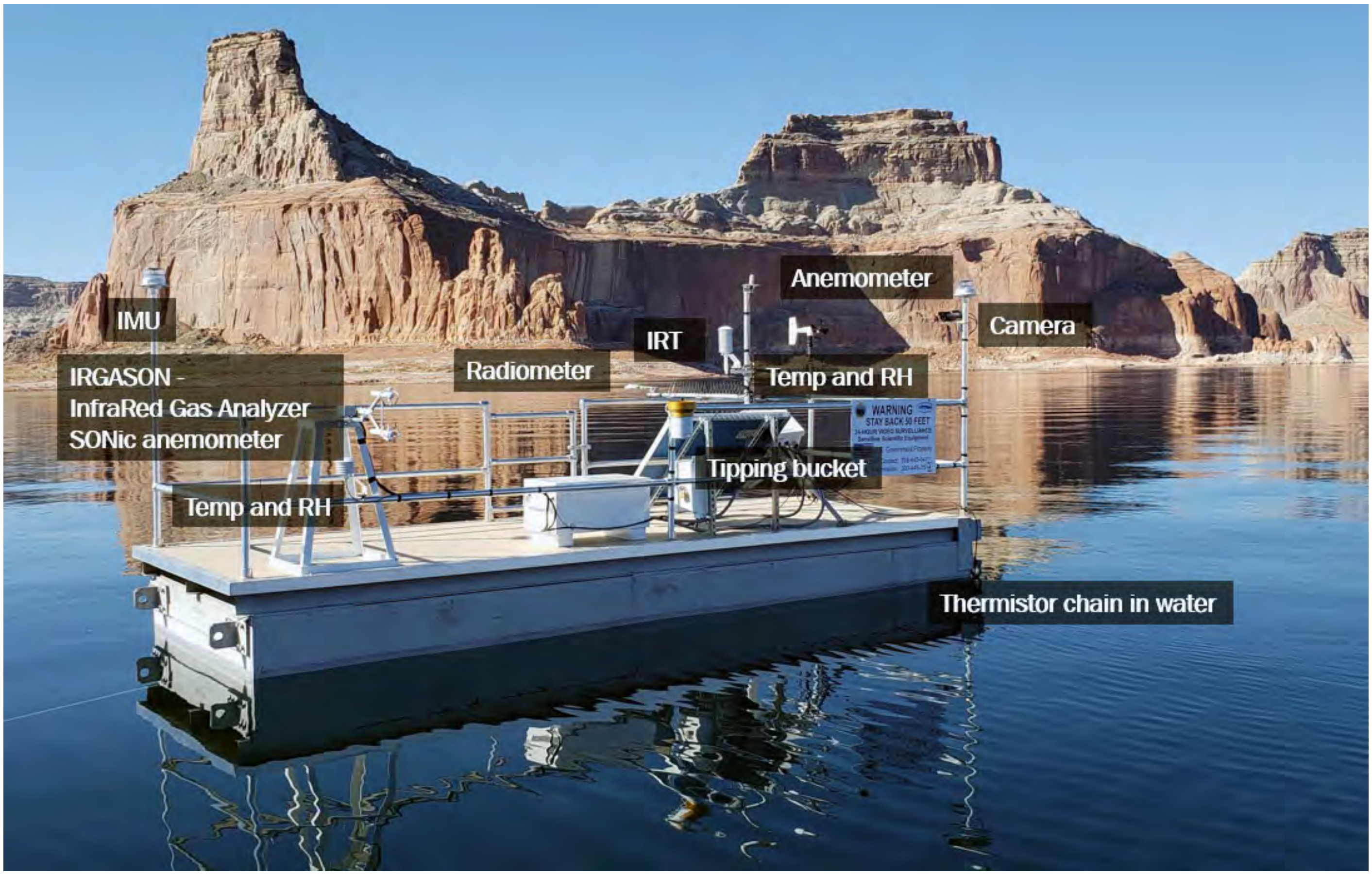

Picture of one of the floating platforms deployed on Lake Powell to support reservoir evaporation estimates from two independent methods, Eddy Covariance and aerodynamic (photo courtesy of D. Broman).

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Second, members of the TSC are exploring historical evaporation across Elephant Butte Reservoir, New Mexico, using the Weather Research and Forecasting Model (an NWP model) coupled to a one-dimensional energy budget lake model. This study is focused on a 2-year period in the mid-1990s when the water levels and surface area of Elephant Butte Reservoir reached record high levels. Figure above shows the annual evaporation estimates across the reservoir during calendar year 1995.

The final project currently underway by members of the TSC and DRI involves developing real-time reservoir evaporation estimates from over 280 Reclamation reservoirs using a single, homogeneous method. The method combines remotely sensed and gridded meteorological datasets with a modified version of the Penman equation to account for reservoir heat storage (Zhao and Gao 2019). A future extension of this project, in conjunction with Texas A&M University and the DRI, is expected to improve the evaporation algorithm and produce real-time forecasts (at multiple time scales) of reservoir evaporation across Reclamation's domain.

In some Reclamation regions, reservoir levels are reaching unprecedented minimums, threatening power generation, water supplies, and environmental flows. The evaporation projects are intended to help water management agencies more accurately quantify water losses at a time when every drop counts.

Future of Western United States Droughts

By Subhrendu Gangopadhyay & Avra Morgan
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The West-Wide Climate and Hydrology Assessment (Bureau of Reclamation [Reclamation 2021a) for the 2021 SECURE Water Act Report (Reclamation 2021b) includes a wide-range of drought analyses across the Western United States. One such drought analysis involved using the Palmer Drought Severity Index, PDSI, to evaluate the future of droughts[1] across the West.[2] Why PDSI? PDSI uses readily accessible temperature and precipitation data in conjunction with a physical water balance model to estimate relative dryness. Also, reconstructions of PDSI from tree rings spanning multiple centuries have been developed and available as a long-term dataset for analysis.

West-wide drought analyses were conducted to understand changes in drought characteristics—duration, severity, and frequencies, in the future (projection period 2006–2099) from a reference historical period, 1473–2005. The future is based on two sets of Coupled Model Intercomparison Project Phase 5 (CMIP5) Global Climate Model (GCM) projections—Representative Concentration Pathway 4.5 (RCP4.5) (a lower emission scenario) and RCP8.5 (a higher emission scenario).

[1] Summer season (June-July-August) averaged PDSI values resulting in a single PDSI value per year was used to define droughts. Droughts were identified using zero-crossover of yearly PDSI values. (i.e., any year for which the PDSI value is ≤ 0 was classified as a drought year).

[2] Spatial resolution of analysis—HUC-8 (U.S. Geological Survey 8-digit Hydrologic Unit Code).

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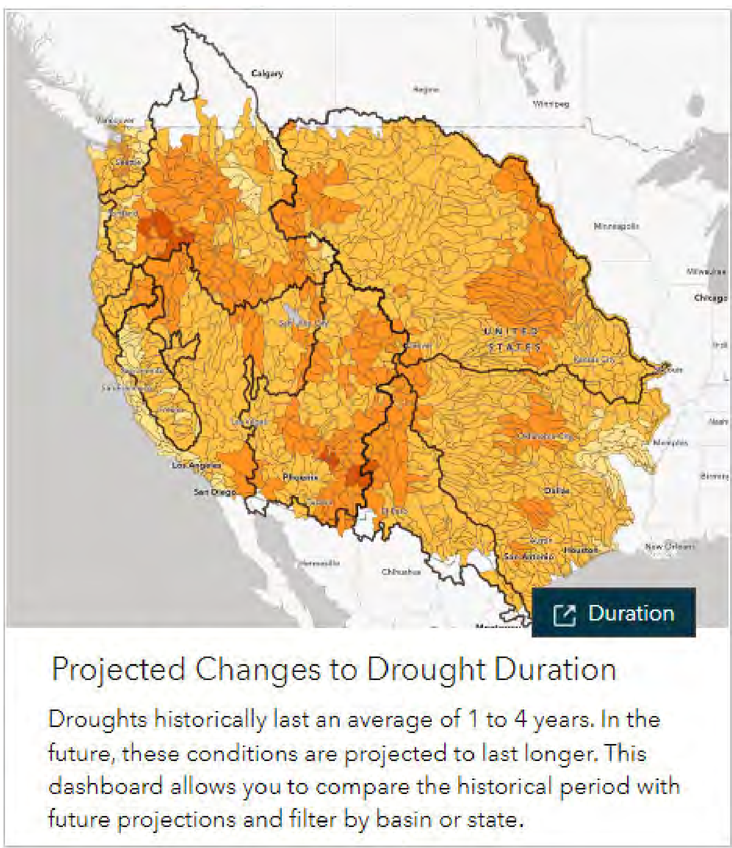

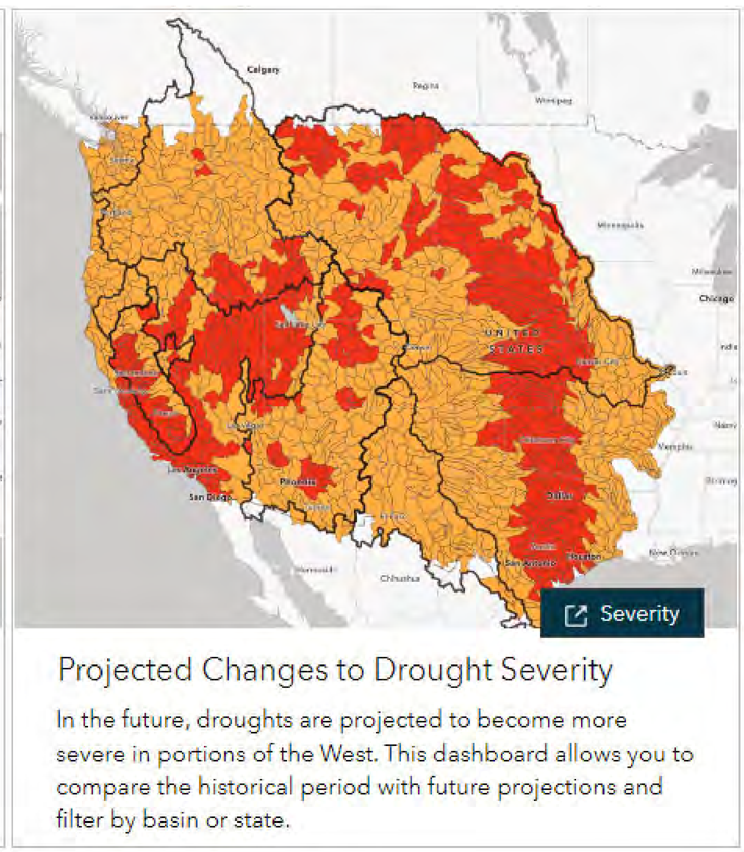

Projected changes in drought duration and severity accessible through the interactive drought dashboard.

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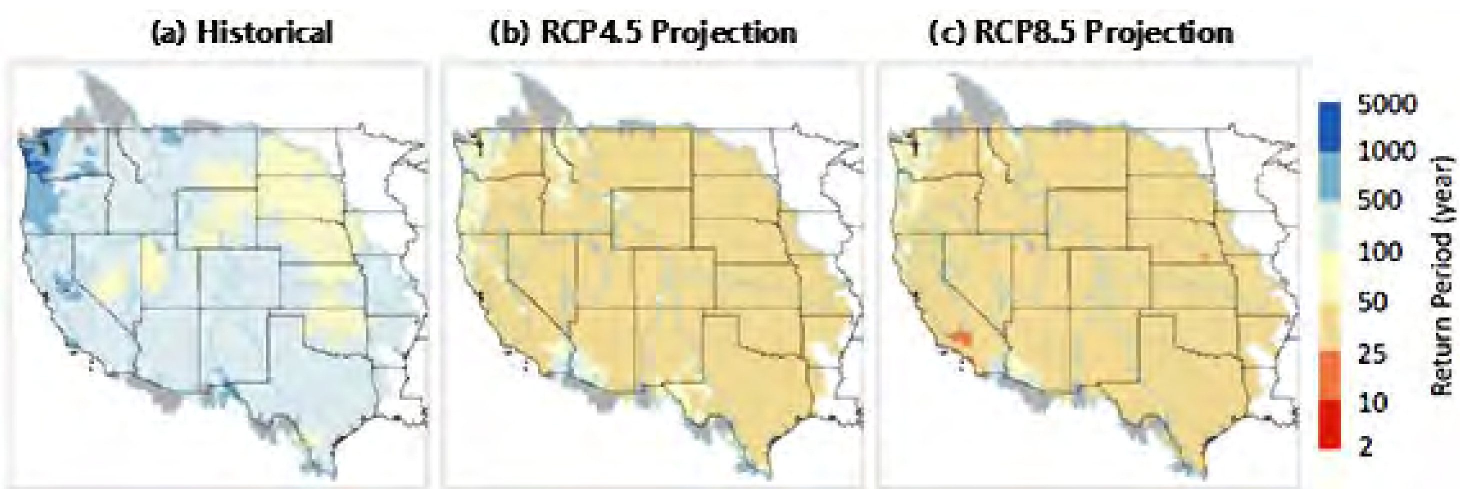
Results for changes in drought duration and severity can be accessed online through the interactive drought dashboard (shown on previous page). In addition to changes in drought duration and severity, the return period of selected drought events was analyzed. Figure below shows the return period of one such drought event (duration of 4 years; severity, PDSI of -2.5) over the historical period and for the two RCP projections. Overall, we found that moderate to severe and extreme droughts (as defined by the selected event here) are projected to occur at an increased frequency (i.e., a reduction in the return period of the events in comparison to what has historically occurred). For example, for the Colorado headwater HUC-8, the return period for this event was estimated to be ≈298 years, but the return period for this same event is projected to be ≈38 years (≈37 years under RCP4.5) (RCP8.5)—an acceleration by a factor of nearly 10. Furthermore, note that the projected return periods for this event are mostly the same under both the projections—RCP4.5 and RCP8.5, suggesting likely reaching water-limited conditions even under the lower emission (RCP4.5) scenario for the West.



Joint return period for drought with a duration of ≥ 4 years and severity (Palmer Drought Severity Index) of ≤ -2.5—(a) historical period (1473–2005); (b) Representative Concentration Pathway 4.5 (RCP4.5) projection period (2006–2099); and (c) RCP8.5 projection period (2006–2099).

The Colorado River Basin's Worst Known Megadrought was Around 1,800 Years Ago

By Subhrendu Gangopadhyay; with partners, University of Arizona & U.S. Geological Survey
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The Colorado River drought1 we currently are experiencing is severe in the context of the 116–year gauge record (1906–2021), but how severe is it in a long-term context?

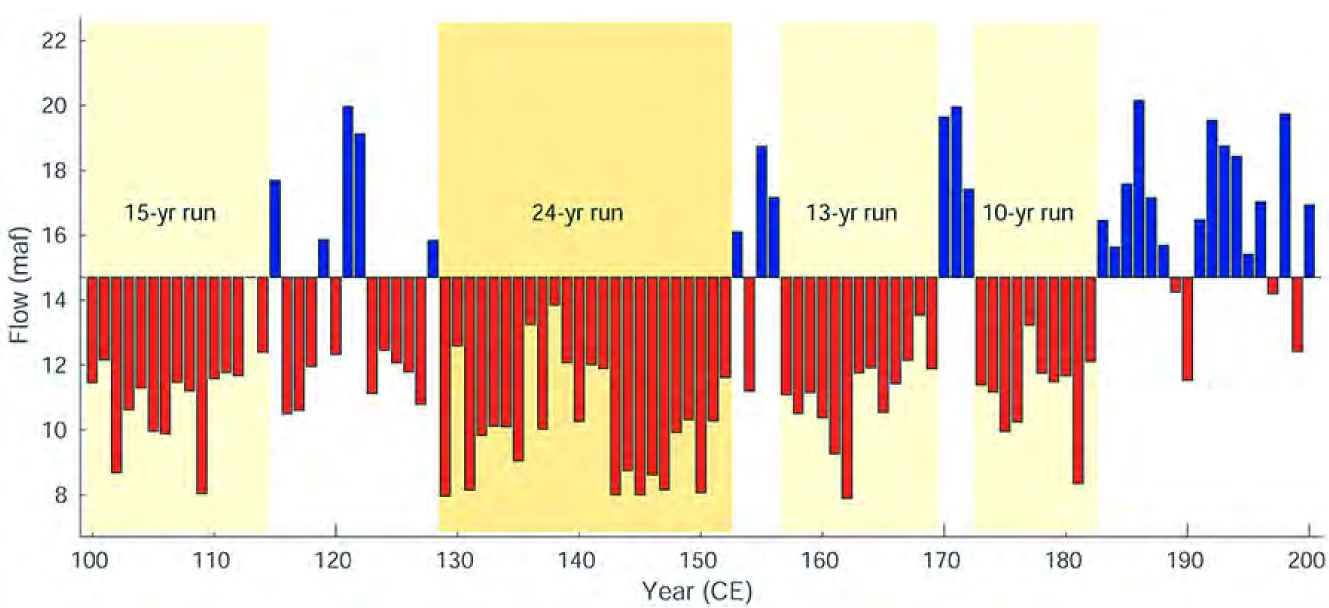
A new tree ring-based streamflow reconstruction starting in 1 CE (Common Era) was recently developed for the Colorado River at the Lees Ferry, Arizona, gauge. Development of this new reconstruction spanning the last two millennia and research using these data was published in Geophysical Research Letters (Gangopadhyay et al. 2022). The research found that the ongoing 22-year period (2000–2021) of low Colorado River streamflow is a rare event, but it is not the most severe drought in the past 2,000 years.

The worst megadrought in the Colorado River Basin was found to be around 1,800 years ago in the second century. The figure belows shows droughts in the second century with multiple runs of 10 or more years below the 1906–2021 mean observed annual streamflow at Lees Ferry (14.7 million acre-feet (maf). The 24-year run of consecutive years with below-average streamflow (14.7 maf) is a defining feature of this second century drought.

Within the exceptional 24-year run, the lowest 22-year average flow ending in 150 CE was estimated to be about 10 maf, just 68 percent of the 1906–2021 observed Lees Ferry streamflow mean. In comparison, the current 22-year drought (2000–2021) observed streamflow average was about 12.3 maf—84 percent of the 1906–2021 observed mean.

These results show that the range of natural hydroclimate variability in the Colorado River is broader than previously recognized, setting a new bar for a worst-case scenario from natural variability alone. These findings can provide water managers with an increased understanding of the range of flow variability in the Colorado River and can help them plan for persistent and severe droughts in the Colorado River Basin.

[1] Drought here is defined as below-average flows broken by no more than 1 year of above-average streamflow.



Droughts in the second century showing multiple runs of 10 or more years below the 1906–2021 observed Lees Ferry, Arizona, streamflow mean of 14.7 million acre-feet.

Addressing Drought Portal

By Lindsay Bearup
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The Addressing Drought Portal is an interactive platform that highlights the Bureau of Reclamation’s efforts and investments to monitor, manage, and develop solutions for drought across the West, past, present, and future. In addition to collaborations and actions being taken to address drought, the portal provides visualizations of current drought conditions and the conditions driving it. The portal also connects to more drought-related climate change analysis from the 2021 SECURE Water Act Report (Bureau of Reclamation 2021).

Visit the web portal to view real-time information and interactive resources!

Addressing Drought Portal Landing Page.

Managing through Drought

Combining Physically Based Snow Modeling and Remote Sensing at High Spatial Resolution to Improve Snowmelt Runoff Forecast in Colorado

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S&T Project page: www.usbr.gov/research/projects/detail.cfm?id=21041

As managers of the Colorado Big Thompson Project, the Bureau of Reclamation's Eastern Colorado Area Office (ECAO) and Northern Colorado Water Conservancy District (Northern) operate the project reservoirs in the Big Thompson River and Upper Colorado River basins in Colorado. Streamflow forecasting in these basins is crucial for daily reservoir operations and seasonal and long-term system planning to meet project objectives of delivering water and generating hydropower, particularly during a drought.

The spring and early summer runoff from these basins is typically dominated by snowmelt. Currently, the ECAO and Northern rely on coarse spatial resolution (1 kilometer) of snow water equivalent (SWE) from the SNow Data Assimilation System (SNODAS) and in-situ SWE observations at limited locations below the tree line as predictors for short-term and seasonal runoff forecasts. These datasets tend to underestimate SWE, particularly in the late spring and early summer months when the remaining snowpack in the basins is distributed across a matrix of deep snow patches interspersed with snow-free ground across the high elevation alpine zones. With the objective of improving basin-wide SWE estimates and runoff forecast, the U.S. Geological Survey (USGS), ECAO, and Northern are implementing an integrated remote sensing and physically based modeling approach to simulate daily 30-meter resolution SWE in near-real time (3–4-day latency) for the Big Thompson River basin upstream of Lake Estes and the Upper Colorado River basins upstream of Willow Creek Reservoir, Lake Granby, Grand Lake, and Shadow Mountain Reservoir.

The modeling tool, SnowModel, is a physically based spatially distributed snow evolution modeling system that accounts for important snow processes in the alpine areas such as wind redistribution, sublimation, canopy interception, and shading. The SnowModel was set up with a 30-meter spatial resolution and forced with meteorological data from the National Land Data Assimilation System (NLDAS-2) from 2000 to 2020. Automatic model calibration was performed using a Latin Hypercube Sampling method. Historical model simulations were constrained by assimilation of daily SWE time series from SNOTEL sites. Model parameters were further refined using manual calibration informed by historical Landsat snow persistent layers and Landsat-based Snow-Covered Area (SCA) time series.

The high spatial resolution of the Landsat snow cover product consistently captures the patchy alpine snow cover that is critical for late spring and early summer runoff in Colorado. The primary limitation of this SCA product is the lengthy interval between cloud-free image acquisitions (8–16 days or more). To overcome this limitation, Landsat Fractional SCA product data will be

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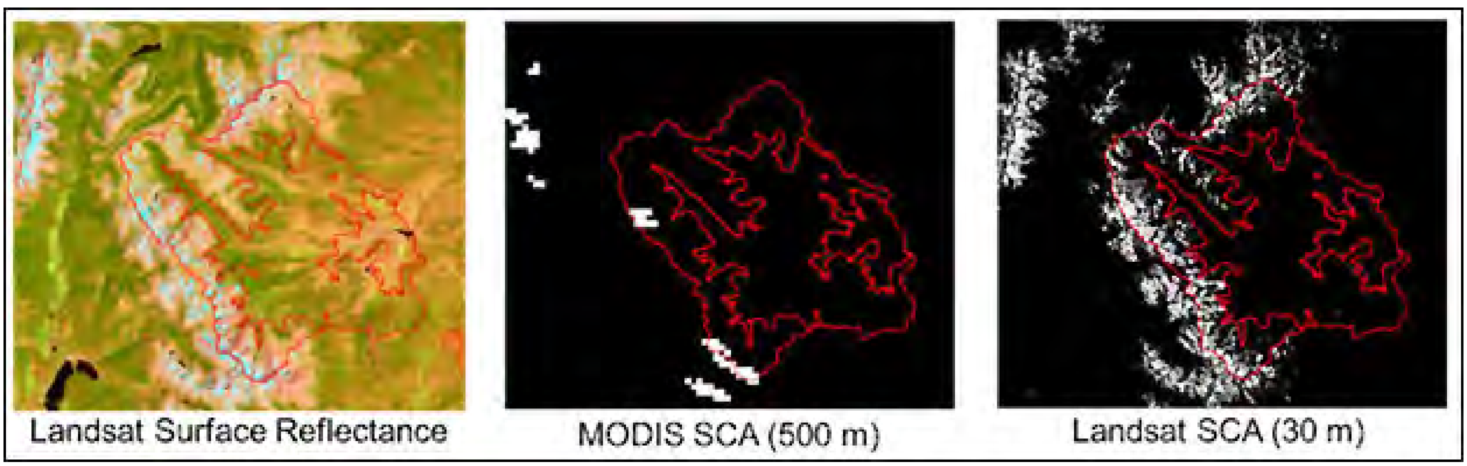
combined with Sentinel 2 data to provide a time series of remotely sensed SCA at 30-meter spatial resolution and 3–4-day temporal resolution.

Figure below shows a comparison of SCA products in the Big Thompson River basin from MODIS and Landsat satellites on July 4, 2003. MODIS is a data source for SNODAS; Landsat can capture snow in places where MODIS cannot.

This project will be completed by September 2023. Remaining project tasks include the development of a precipitation correction grid based on comparison of modeled SCA and Landsat SCA. This correction grid will be used in the real-time implementation of the modeling tool to adjust biases identified in the NLDAS-2 precipitation forcing during model calibration. Another ongoing task is the development of a machine learning approach to simulate Landsat-derived fractional SCA from Sentinel 2 surface reflectance data to minimize potential biases between Landsat and Sentinel-2 datasets. Finally, the snow and remote sensing tools will be coupled as a single tool to provide weekly basin-wide SWE updates forced by bias-adjusted NLDAS-2 meteorological data, snow data from SNOpack Telemetry (SNOTEL) sites, and recently acquired SCA imagery.

The ECAO and Northern will incorporate the historical bias-adjusted SWE time series from model calibration in their statistical water supply forecast models and evaluate if seasonal forecast accuracy is improved. In addition, the weekly basin-wide SWE updates for the Big Thompson River basin will be used to guide the states of the snow model implemented within ECAO's streamflow forecast system, which provides short-term inflow forecasts to Lake Estes.



Snow-covered area in the Big Thompson River Basin, Colorado, on July 4, 2003.

Machine Learning for Streamflow Forecasting: Exploring the Use of Temperature to Understand Recent Drought and Project Future Conditions in the Colorado River Basin

By David Woodson & Rebecca Smith; with partners, National Center for Atmospheric Research & University of Colorado
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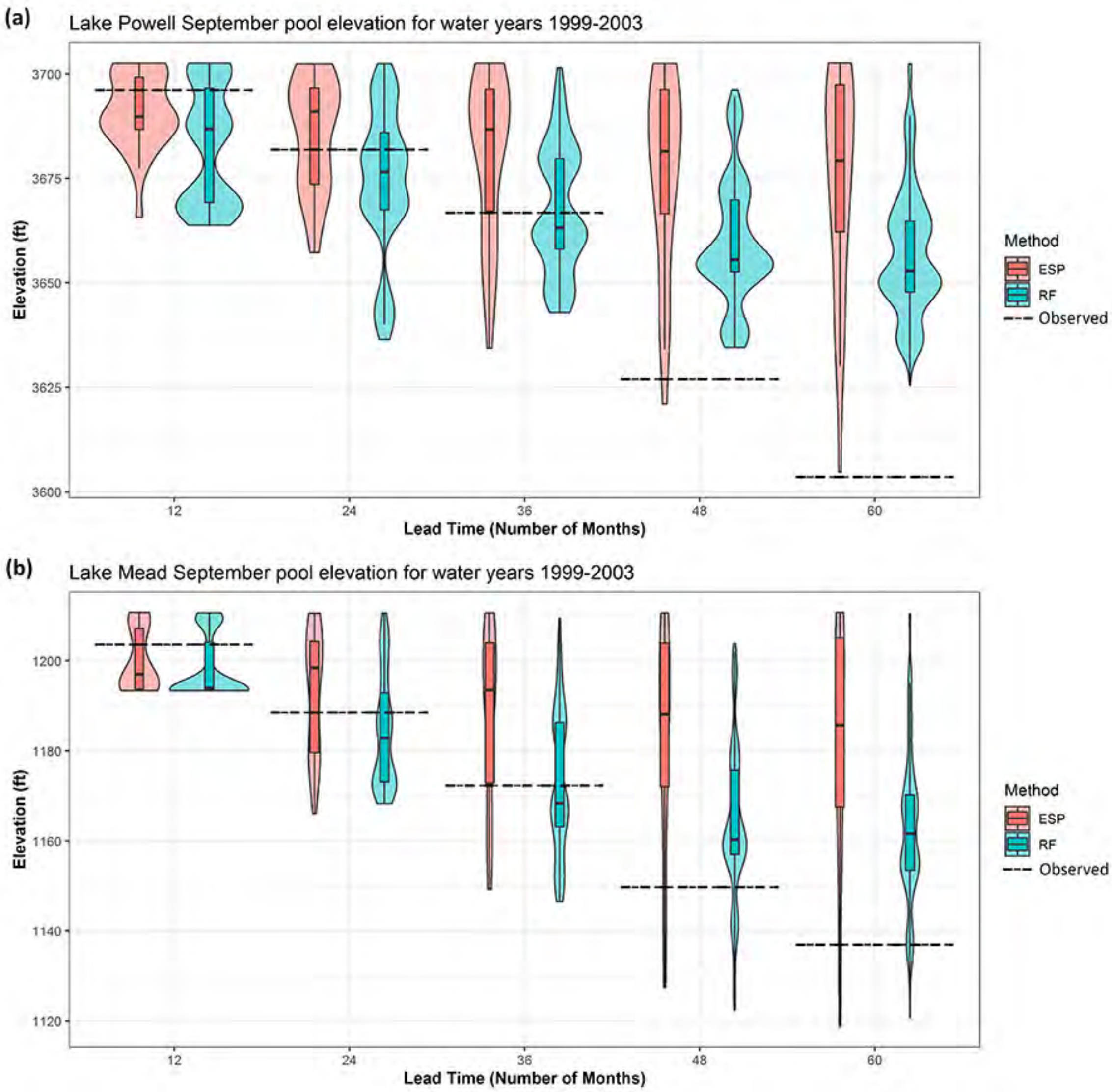
The Colorado River Basin (CRB) is a critical resource for over 40 million people in the Southwestern United States and Northern Mexico but exhibits highly variable streamflow year to year and is susceptible to multiyear and even multidecadal droughts. In river basins with storage capacities that can hold multiple years' worth of average flow, like the CRB, flow projections past a 12-month lead time are important for planning. as they can potentially be used to inform current year operations. While many good forecasts for Colorado River flow exist at seasonal time scales, projections beyond 1 year into the future perform little better than simply using a long-term average. Improving so-called "decadal" projections, or forecasts spanning 2 to 10 years into the future, can help water managers better plan under increasing pressures from population growth and climate change.

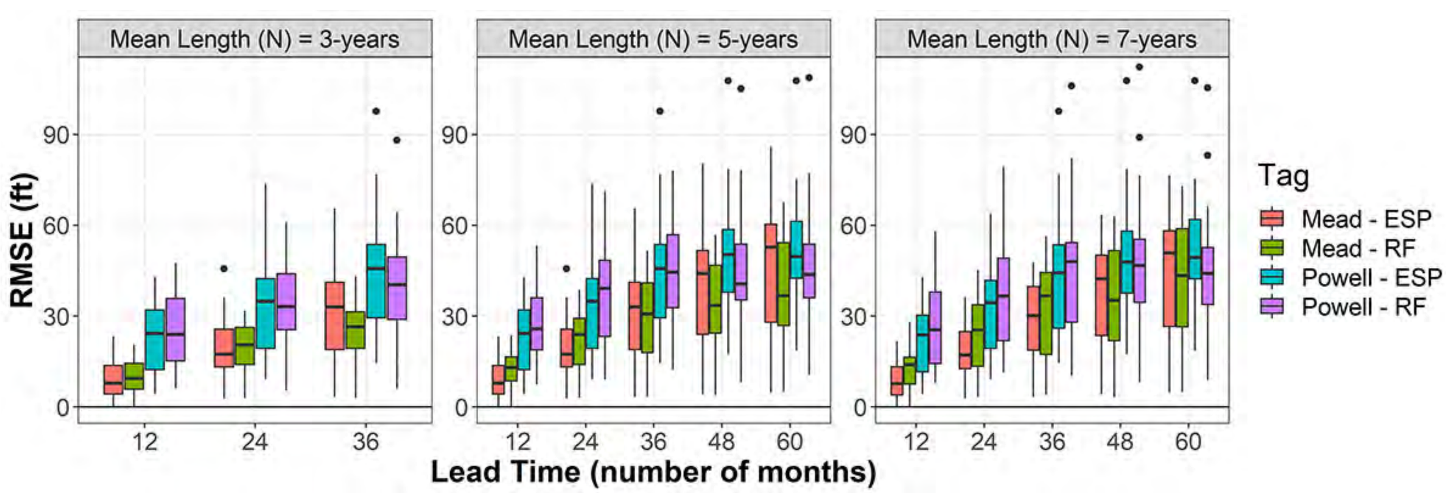
We investigate whether the skill found in climate model-based temperature projections can be transferred to decadal streamflow forecasts in the CRB. This critical need, combined with the knowledge that (a) global climate models have good skill and agreement in projecting decadal temperatures and (b) the documented sensitivity of CRB flows to temperature, motivates the present study with this research question—Can the skill in decadal temperature projections be translated to operationally skillful flow projections and, consequently, water resources management?

We used temperature projections from the Community Earth System Model-Decadal Prediction Large Ensemble (CESM-DPLE) along with past basin runoff efficiency as covariates in a Random Forest (RF) machine learning model to project ensembles of multiyear mean flow at the key aggregate gauge of Lees Ferry, Arizona. The projections were disaggregated to monthly and subbasin scales to drive the Colorado River Mid-term Modeling System (CRMMS) to generate ensembles of water management variables. Of key interest were pool elevations at Lakes Mead and Powell, the two largest U.S. reservoirs that are critical for water resources management in the basin (top figure, next page).

When used as hydrologic flow forcings in the CRMMS operational simulation model of the CRB, RF projections generally outperformed extended streamflow prediction (ESP) in predicting pool elevations at Lakes Powell and Mead for lead times of 36 months or greater. The RF forecasts were found to reduce the hindcast median root mean square error by up to 20 and 30 percent at lead times of 48 and 60 months, respectively, relative to projections generated from ESP (bottom figure, next page). Future work might involve investigating methods to improve the skill of the RF approach and the covariates used. Of particular importance is improving the skill for precipitation and pre-1980 temperature simulations upon which the performance of any derivative flow projection is heavily dependent. Additionally, the model training dataset might be further expanded through inclusion of paleo-reconstructed flow and overlapping simulated hydroclimate data.



Colorado River Mid-term Modeling System – simulated end of water year (EOWY) pool elevation at Lake Powell (a) and Lake Mead (b) from extended streamflow prediction and 5-year mean Random Forest flow forecasts as well as a historical simulation. Hindcast covers water years 2000–2004 (October 1999 to September 2004). x-axis values delineate lead times for each EOWY. Historical EOWY pool elevations are indicated by horizontal black-dashed lines.



End of water year ensemble root mean square error calculated on Colorado River Mid-term Modeling System – simulated pool elevation at Lakes Powell and Mead for running hindcasts (1982–2017) disaggregated from 3-, 5-, and 7-year mean flow projections as well as extended streamflow prediction. Historic simulations forced by historical unregulated flows were considered the observed value in error calculations.

Evaluating Water Temperature Modeling and Prediction in the Sacramento River Basin

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S&T Project page: www.usbr.gov/research/projects/detail.cfm?id=22050

The Bureau of Reclamation's Central Valley Operations Office is partnering with the National Center for Atmospheric Research (NCAR) to investigate improving water temperature predictions in the Sacramento River, downstream from Shasta and Keswick Dams, where winter run Chinook salmon spawn. Drought, low carryover storage, warming conditions, and wildland fire smoke cover conditions exacerbate the ability to produce dependable operational outlooks to target downstream temperatures 6 to 8 months into the future. Due to the long lead time for meteorological forecasts, NCAR will leverage Seasonal to Sub-seasonal (S2S) and Gridded Meteorological Ensemble Tool (GMET) forecasting techniques and test prediction capabilities. New meteorologic inputs aim to improve stream temperature projections.

Temperature control device at Shasta Dam.

Technical Responses to Drought

Optimizing Hydraulic Turbine Operating Zones Through Cavitation Monitoring and Air Injection

By John Germann
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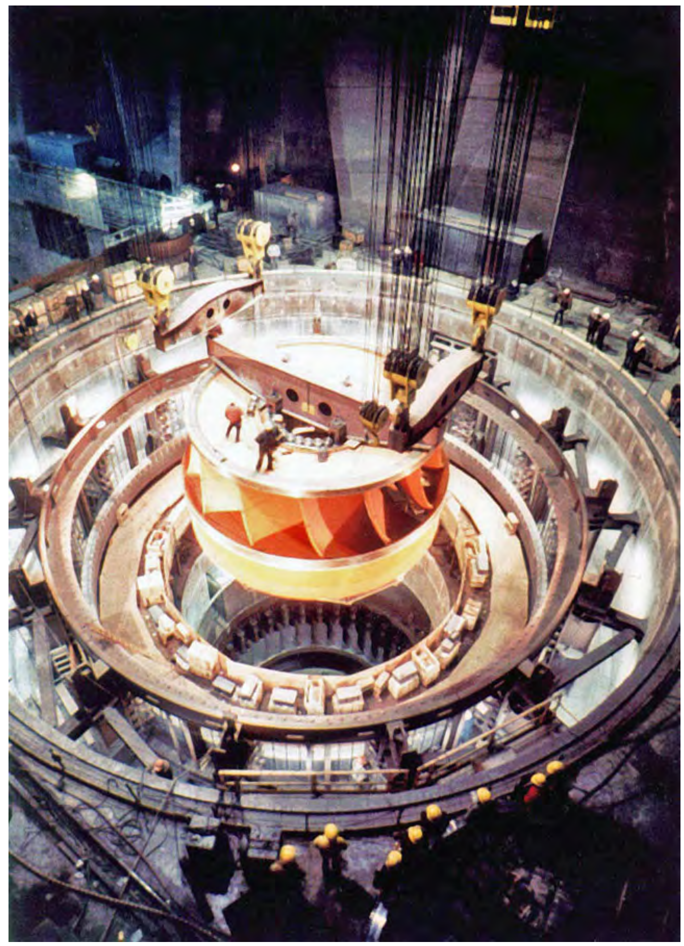
S&T Project page: www.usbr.gov/research/projects/detail.cfm?id=21104



Grand Coulee Powerplant on the Columbia River, Washington.

Water levels at Bureau of Reclamation (Reclamation) reservoirs affected by ongoing drought are historically low. Dropping water levels will affect the ability of those reservoirs with hydroelectric powerplants to produce power. It is difficult to exactly predict what the adverse characteristics of operating generators at these extreme low water levels will look like since most of the turbines at these reservoirs have never operated under this condition before. In addition to the threat of dropping below power pool, operating under off-design conditions results in dynamic hydraulic phenomena that can produce undesired and damaging effects such as turbine runner cavitation induced erosion, excessive pressure pulsations, and high vibration.

Cavitation is a well-known destructive hydraulic phenomenon in which localized areas of static pressure fall below vapor pressure. Across the hydropower industry, cavitation and operating in rough zones is a costly and complex problem.

Reclamation and GE Renewable Energy (GE) are currently performing research at Grand Coulee, Washington, to study and improve on suitable techniques to detect and map turbine cavitation, including runner erosion and its intensity and fluctuating pressure-induced rough operations, with the goal of quantifying this damage so operational ranges where these conditions occur can be avoided. In 2017, Reclamation entered a cooperative research project with GE and the Bonneville Power Administration for cavitation testing and monitoring as well as air injection testing using generator Unit G24 at Reclamation's Grand Coulee hydroelectric complex. Grand Coulee Unit G24 is an 805-megawatt hydroelectric generator, one of the largest hydroelectric machines in the world. This unit provides a unique test platform for conducting effective real-time research on cavitation.

Initial tests conducted identified and mapped areas of inter-blade vortex cavitation, inlet suction cavitation, the hydraulic-induced turbine rough zone, and a particular operational area where damaging strong pressure surges were occurring within the turbine. Researchers found that these surges could be effectively mitigated through air injection.

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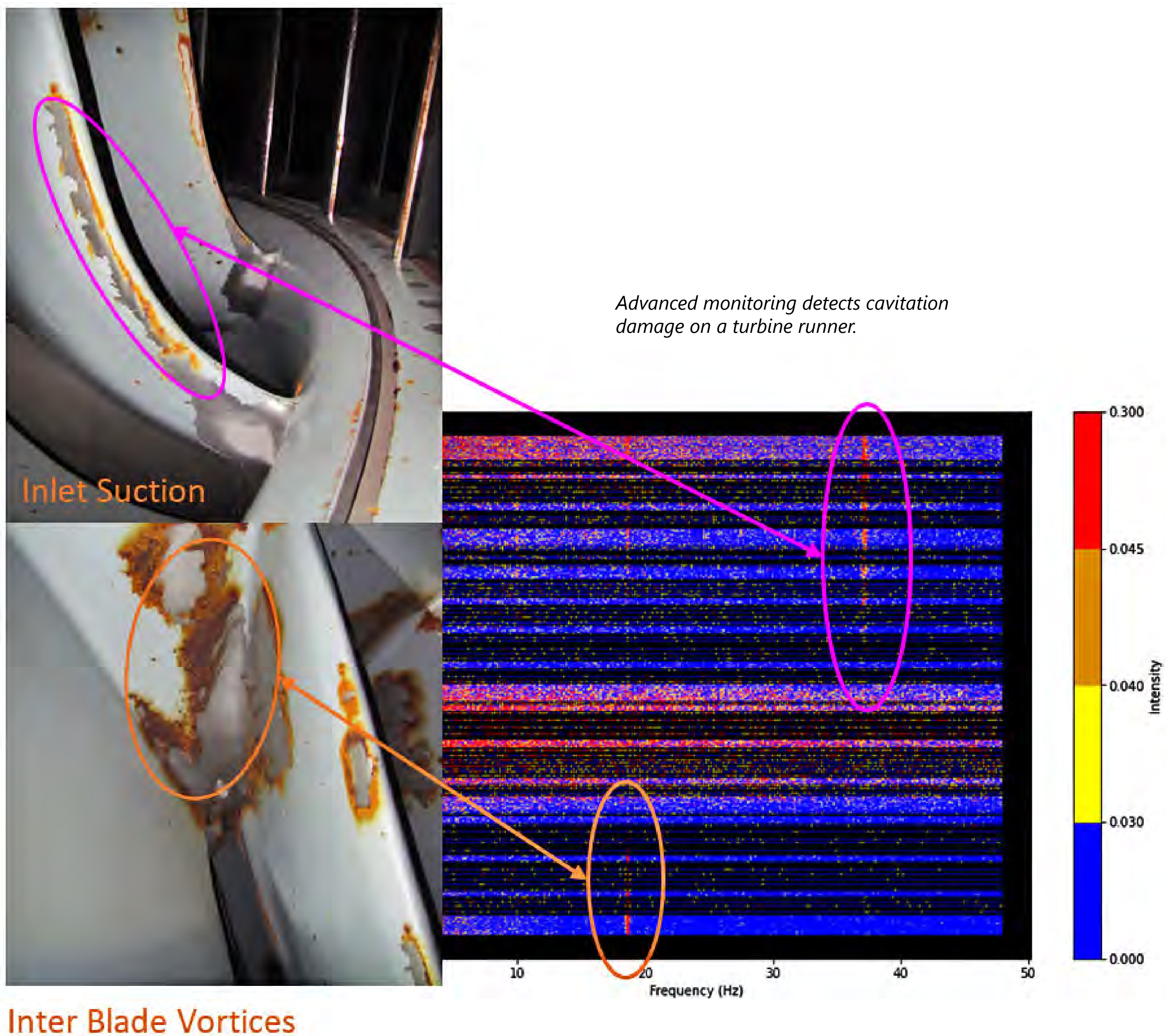
Over the past few years, this successful research study culminated with the installation of separately designed Reclamation and GE cavitation monitors on Unit G24. These monitors have the ability to accurately detect, map, and trend cavitation activity occurring on the turbine runner, with the ultimate product of advanced cavitation monitors that accurately translate sensor activity to cavitation erosion rates and the mapping of optimized operating zones.

Benefits from this unique collaborative effort and the methods and techniques used in testing and monitoring for cavitation and other adverse hydraulic activity will directly translate to a better understanding of how to operate Reclamation generators within low reservoir elevations, and how to avoid damaging these units, particularly in times of ongoing drought.



Advanced monitoring detects cavitation damage on a turbine runner.

Investigating the Potential of Cloud Seeding to Enhance Precipitation in the East River Basin of Colorado

By Lindsay Bearup & Sarah Tessendorf; with partner, National Center for Atmospheric Research
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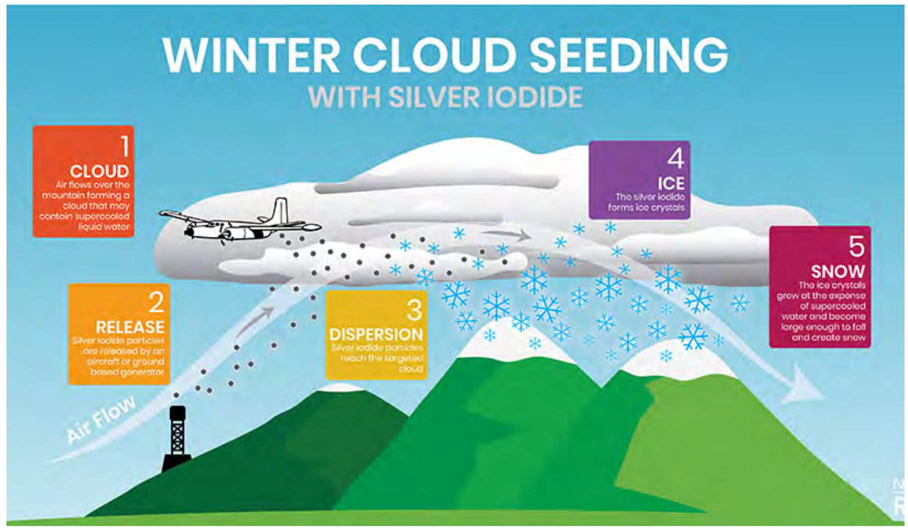
S&T Project page: www.usbr.gov/research/projects/detail.cfm?id=22068

Cloud seeding is a type of weather modification that aims to increase precipitation and subsequent streamflow. Cloud seeding programs are typically designed to increase precipitation on a targeted mountain barrier to enhance water supplies in a local basin. The Upper Colorado River Basin Drought Contingency Plan identifies system augmentation through cloud seeding as a method to increase Lake Powell inflows, which is especially critical given the prolonged drought and unprecedented low water levels in the reservoir.



Conceptual model of the physical processes in cloud seeding.

Despite significant advances in monitoring and modeling, some important questions remain related to quantifying the effectiveness and optimization of cloud seeding technology for specific locations. In partnership with scientists at the National Center for Atmospheric Research (NCAR), Bureau of Reclamation S&T Project 22068 will address the overarching question "What is the potential impact of cloud seeding on precipitation in the East River Basin in Colorado?"

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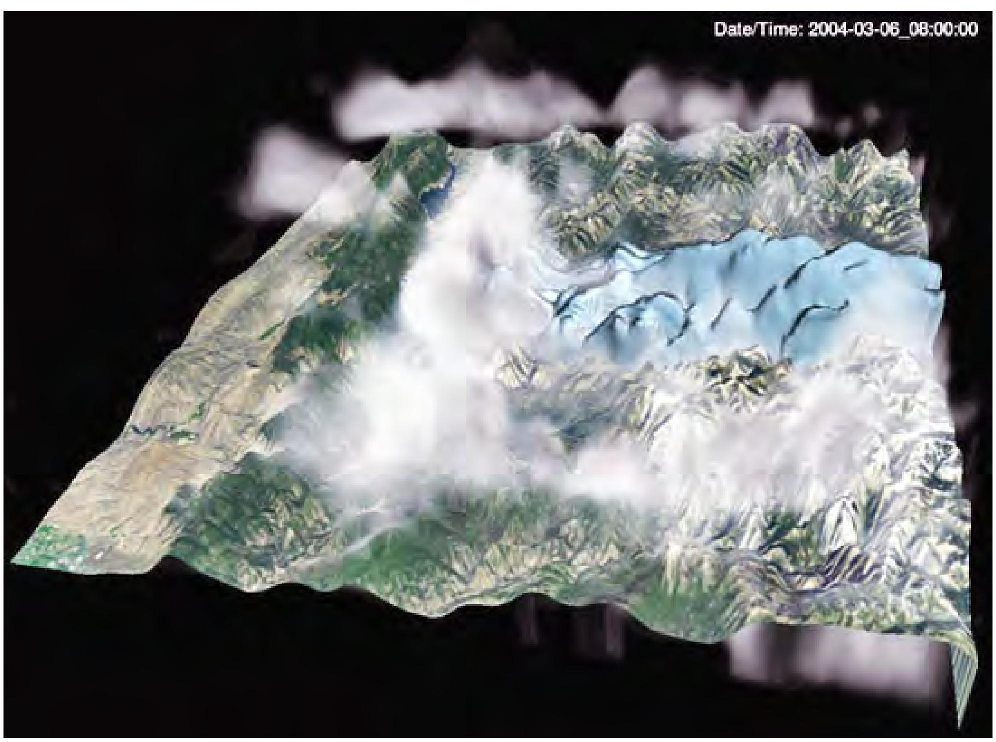

Three-dimensional rendition of the silver iodide dispersion (cyan) among a cloud field (white) over complex terrain (Xue et al. 2017).

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This question will be addressed using state-of-the-art modeling tools developed by NCAR partners using the Weather Research and Forecasting (WRF) model with a module for the direct simulation of silver iodide cloud seeding (WRF-Wxmod). This project also engages local representatives, including water districts who operate local cloud seeding programs, and researchers that will provide extensive data from ongoing projects in the region. Using these modeling tools, coupled with observations, this recently funded project will identify the characteristics and frequency of local storms suitable for cloud seeding in the East River Basin, under both current and future atmospheric conditions, and quantify the potential enhancement of seasonal precipitation volumes. By guiding existing operational programs and optimizing these networks going forward based upon state-of-the-art technologies, this applied research will provide valuable information for the Bureau of Reclamation and its partners in the Upper Colorado Basin regarding how and when cloud seeding could be conducted so resources are used as effectively as possible.

Water Treatment Technologies to Reduce Drought Impacts

By Andrew Tiffenbach & Lindsay Bearup
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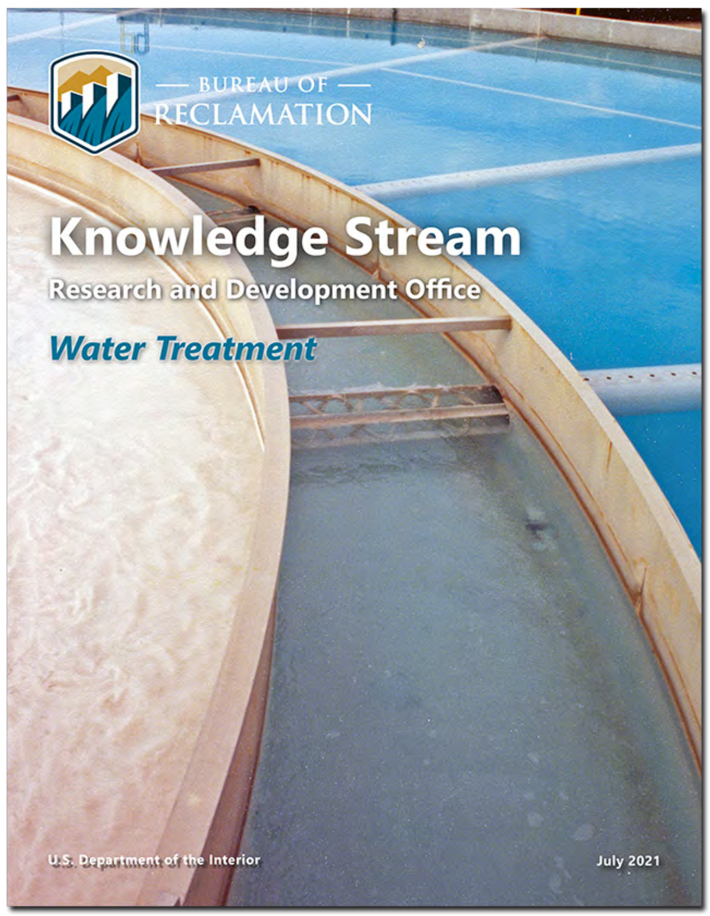
Water treatment technologies provide an opportunity to diversify water supplies and help meet demands in times of drought. Technologies include desalination and advanced treatment of impaired waters, including but not limited to, seawater, inland brackish groundwater, municipal wastewater, and produced waters from oil and gas extraction activities. The Bureau of Reclamation-funded research into these topics also spans a variety of programs such as external research from the Desalination and Water Purification Research Program, Science and Technology projects, prize competitions, and research activities at Bureau of Reclamation facilities such as the Brackish Groundwater National Desalination Research Facility. To learn more about these exciting innovations in water treatment, check out the recent Knowledge Stream on water treatment, www.usbr.gov/research/docs/ks/kswattreat.pdf.



Cover of the recent Knowledge Stream on water treatment.

Science & Technology Prize Competitions Recap

Snowcast Showdown

By Lindsay Bearup
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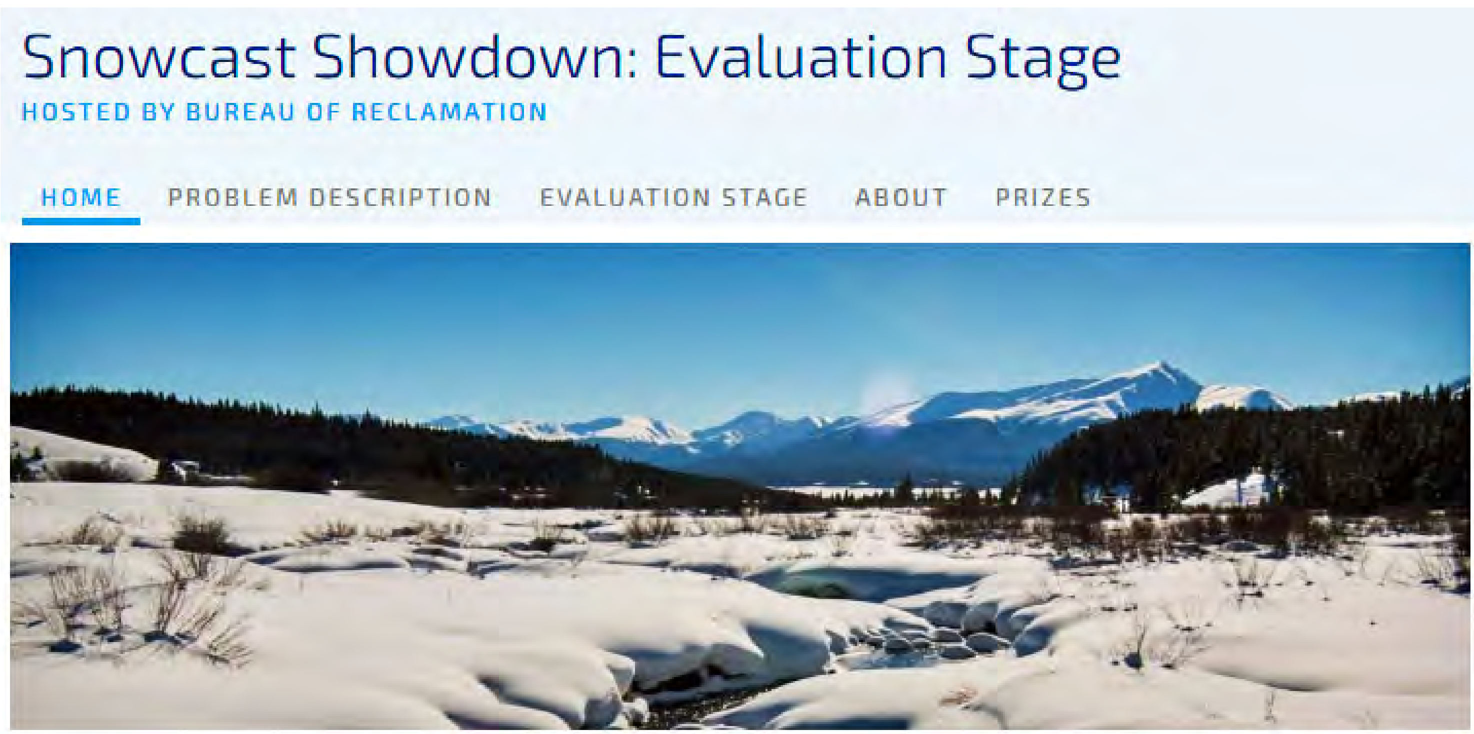
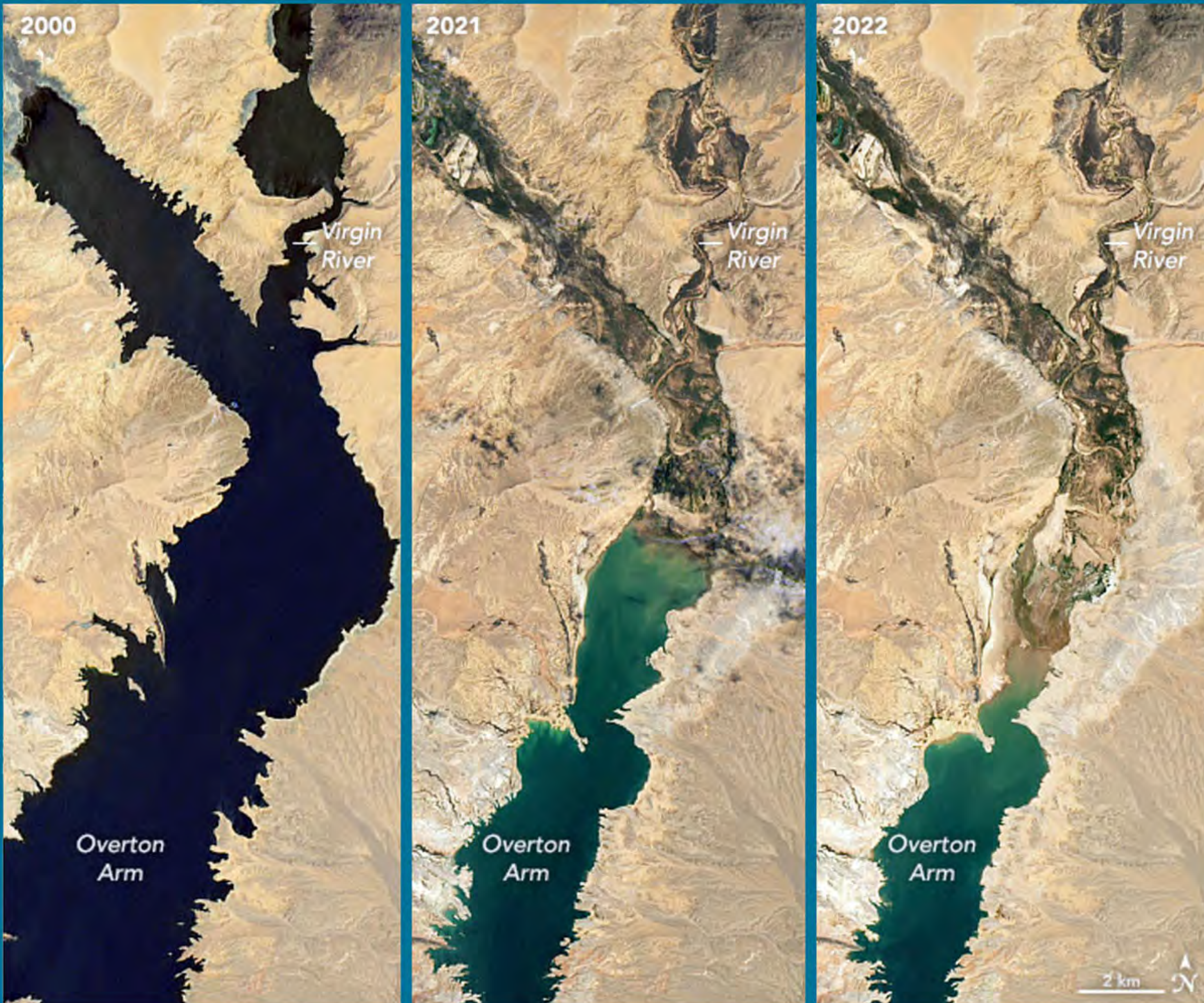
www.usbr.gov/research/challenges/



The Snowcast Showdown prize competition launched in the winter of water year 2022. Solvers were challenged to generate estimates of snow water equivalent at 1-kilometer resolution across the Western United States in near real-time. Solutions typically relied on ground-based and remote datasets that were available for weekly submissions. Prizes will be awarded to solvers for the overall accuracy of predictions as well as for the best regional solutions or write-up indicating the solutions are robust and interpretable. Over 300 teams participated in the evaluation phase of the challenge, submitting nearly 800 entries. Winners were announced on August 31, read the full press release here!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