Roaring Fork Observation Network
Annual Report for 2023

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Aspen Global Change Institute
104 Midland Ave., Suite 205
Basalt, CO 81621

Elise Osenga
Aspen Global Change Institute
agci.org/iron

Dear Partners,

For the Roaring Fork Observation Network (iRON), 2023 was a year of community and connection. We welcomed a new research technician, attended workshops and roundtables, helped install soil moisture sensors with other organizations, held conversations with community partners, continued our co-hosted internship, participated in research coordination efforts, and explored possibilities for future collaborations.

As the period of record for the iRON program grows, so too do opportunities for applying its data to real-world questions. Over the past year, much of our focus centered on the Evaluation of Soil Moisture project, a Colorado River District- and Colorado Water Conservation Board-funded exploration into opportunities and challenges for applying *in situ* soil moisture data to projected runoff from spring snowmelt. Results from this study will be shared this October. We have also made some exciting upgrades and additions to our observation stations. We anticipate these changes will add valuable new measurements, support continuity of data collection, and improve ease of access for repairs.

As we celebrate the maturation of this program and the increased public interest in it, we also recognize the energy and resources required for continued research. Throughout 2024, we will be taking time to evaluate the program's achievements and to set goals for future impacts. Funding for long-term research is always a challenge, and we will be exploring creative approaches to help sustain our ongoing work on local climate impacts to water and ecology.

It is remarkable to look back on the progression of the Roaring Fork Observation Network so far. For nearly 12 years, participation and support from partners like you have made the Network possible. This report details just a few highlights and sample data sets from the iRON in the past year—work that took place in concert with many other research endeavors currently active in the Roaring Fork. None of these discoveries, connections, and questions happen in isolation: they are the product of essential collaborative efforts. Whether you donated time, provided land access, shared your expertise, or made financial contributions, **we thank you for your support.**

Sincerely,

Elise Osenga
Community Science Manager
Aspen Global Change Institute

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Data at a Glance

Water balance estimates for the Roaring Fork

As part of our ongoing investigation into the relationship between snowpack, soil moisture, and streamflow for the Roaring Fork region, we estimated the overall water balance in our watershed. The estimate used observed data from the USGS stream gauge at Glenwood Springs (the drainage point for our watershed), recorded trans-basin diversions, estimated in-basin use, and modeled temperature and precipitation data from PRISM[1] to estimate annual water inputs and water losses across our watershed.

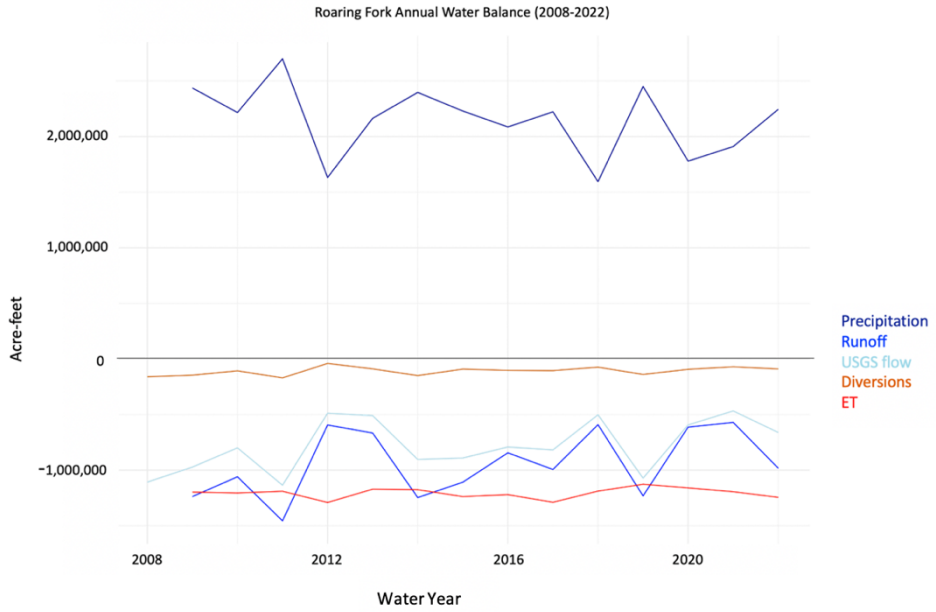


Fig. 1: Annual Water Balance of the Roaring Fork Watershed by water year (October-September). Positive values on the y-axis indicate the estimated amount of water entering the watershed as precipitation (rain + snow). Negative y-axis values represent the volume of water leaving the watershed, as outflow to other watersheds via the Roaring Fork River (USGS flow), runoff to the river (modeled streamflow), diversions (including both trans-basin diversions and in-basin uses), or losses back to the atmosphere via evapotranspiration (modeled ET). Runoff (modeled streamflow) and the sum of diversions and USGS streamflow both present an approach to representing total streamflow in the basin, and these lines are expected to follow a similar pattern across years.

Evapotranspiration (ET): The combined process of liquid water becoming vapor and returning to the atmosphere from both evaporation (loss of water from the land, soils, or bodies of water) and transpiration (loss of water from plants).

The modeled output indicates that, on average, more than half of the water entering the Roaring Fork Watershed as precipitation is lost to evapotranspiration (ET) over the course of a year. Further, the total volume of water lost to evapotranspiration fluctuates much less annually than does total incoming precipitation. This means that in a dry year with little precipitation, the percent of water lost to evapotranspiration accounts for an even larger portion of the total. As the climate continues to warm, evapotranspiration is projected to increase in coming decades, with the potential for noticeable impacts to water supplies if precipitation does not also increase to compensate. Evapotranspiration and soil moisture are closely linked because water can evaporate directly from soils and because soils provide a reservoir from which roots uptake water that is lost during transpiration. As such, soil moisture is an important indicator of climate change impacts.

[1] PRISM is a dataset that generates gridded temperature and precipitation estimates for a region. It is produced by the Northwest Alliance for Computational Science and Engineering, based on measurements from weather stations within each gridded area.

2023 Roaring Fork Soil Moisture

Soil moisture patterns typically follow similar wetting or drying regimes throughout the calendar year. The year begins with little movement in soil moisture, especially in deeper soils, as the ground may be frozen and/or covered by snow. When snow melts in the spring, soils become saturated, and soil moisture may peak for the year. During summer and fall, soil moisture values fluctuate in response to rainstorms and warm drying events. In November and December, soil moisture values become more stable again as soil temperatures near freezing and snow accumulates. However, at lower elevations where snow is not persistent throughout the winter, some soil-wetting events may occur when above-freezing days produce mid-winter snow melt.

For our lowest elevation site at Glenwood Springs (6,200ft elevation), 2023 began as a wetter year than we have typically seen within the period of record (2015-2022). However, as the summer progressed, soils at the 8in depth dried to below average for this site, only rebounding to above average with rainstorms in October. When looking at this year's data, it is important to note that a failure of the 20in sensor in early September led to its replacement with a sensor of the same make toward the end of that month. The 8in sensor was also replaced at this time, and the associated disturbance may have impacted subsequent soil moisture measurements at all depths (a slight drying following the replacement is noticeable). Other impacts to measurements may have been possible in the following weeks, as the soil continued to settle. It is also important to remember that Western Colorado has been in a drought for much of the duration of this station's record.

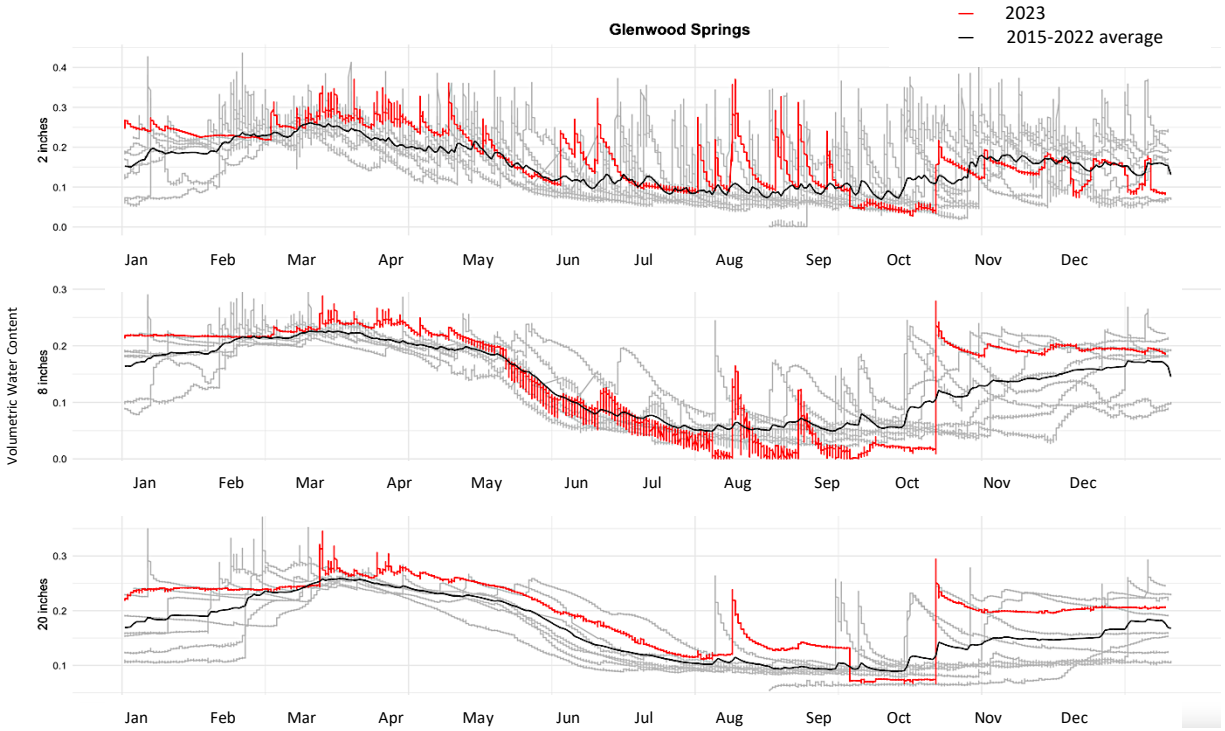


Fig. 2: Glenwood Springs soil moisture values at all depths. The graphs above show soil moisture at 2, 8, and 20in depths across a calendar year. Gray lines show individual years prior to 2023. Red lines show 2023 data, and black lines show an average for the period of record for this station prior to 2023 (2015-2022).

The Sky Mountain site, located in an aspen grove at 8,380ft in elevation, is our network's longest running station (2012-2023). In 2023, soil moisture saturation at an 8in depth peaked around the time that is average for the period of record. Summer soil moisture values were also similar to the average for this station. Few mid-summer rainstorms recharged soil moisture at any depth until October in 2023, whereas data for other individual years (gray lines) show that in some other summers, rainstorms provided soil-wetting events at 2 and 8in depths throughout the season. Entering winter, November soil moisture values at all depths were slightly lower than average for this site. However, it is important to remember that the period of record for this site is only 11 years, and with records of this length, averages may be shifted by a single unusually wet or dry year.

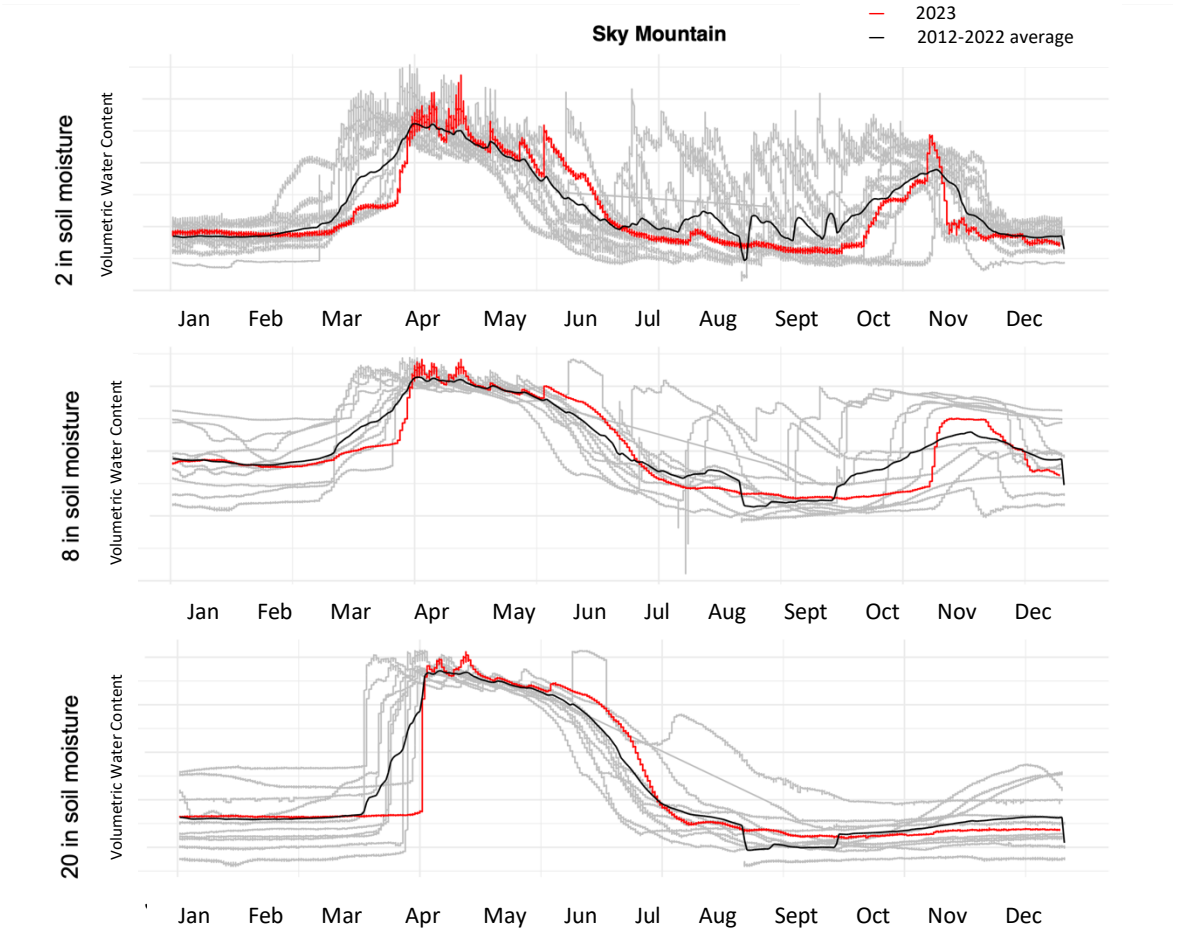


Fig. 3: Sky Mountain soil moisture values at all depths. The graphs above show soil moisture at 2, 8, and 20in depths across a calendar year. Gray lines show individual years prior to 2023. Red lines show 2023 data, and black lines show an average for the period of record for this station prior to 2023 (2012-2022).

2023 Modeled soil moisture for the Upper Colorado River Basin

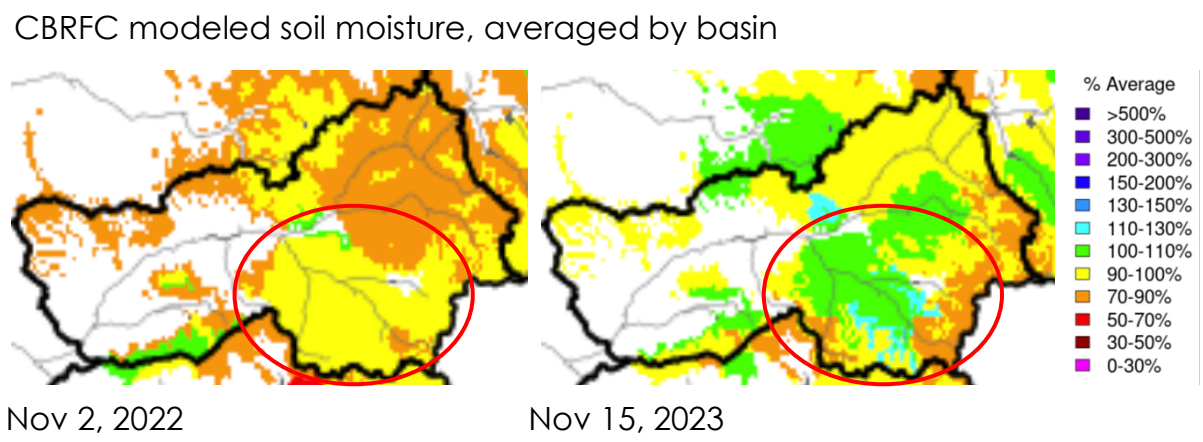


Fig. 4: Gridded average soil moisture for the Upper Colorado River Basin. These maps are taken from the Colorado River Basin Forecast Center: www.crbrf.noaa.gov/rmap/grid800/index_soil.php. Soil moisture values are modeled based on inputs of temperature, precipitation, landscape type, and other variables. Colors indicate current soil wetness as compared to average soil moisture conditions for 1981-2020.

Each year, the Colorado River Basin Forecast Center (CBRFC) releases a map showing modeled soil moisture for the Colorado River, averaged by region. These maps, representing early-November soil moisture conditions, are intended to be representative of soil moisture conditions throughout the winter and at the onset of snowmelt in the spring. Recent data analysis by the CBRFC indicates that soil moisture conditions prior to snowmelt may impact the percent of runoff from snowmelt that becomes streamflow[2], making these fall soil moisture values of interest when considering potential runoff conditions for the coming spring.

The CBRFC modeled soil moisture data showed wetter soil moisture values for November 2023 than November 2022 for most regions in the Roaring Fork Watershed, although some higher elevation areas at the edges of the watershed were drier in 2023 than 2022. While November conditions for this water year seem to be promisingly wetter than in many recent years, multiple areas remain below 100% of average soil moisture both within the Roaring Fork and, especially, in areas of the Upper Colorado River Basin outside the Roaring Fork.

Using multiple approaches to measure soil moisture (such as *in situ* measurements, like the iRON, and modeled measurements, like the CBRFC) helps to provide a more nuanced picture of conditions in our watershed. Modeled data give a broad overview of watershed conditions that cannot be gathered from individual station measurements since soil moisture varies widely from location to location. Meanwhile, *in situ* measurements, like those from AGCI's iRON stations, provide a nuanced view of what is happening in the soil at specific locations across years, timing of events such as saturation and thaw, and a breakdown of soil moisture behavior across multiple depths.

Over the past year, AGCI and the CBRFC have been in conversation about our respective datasets. We are currently working to share our data with the CRBFC in the hopes of improving understanding of how *in situ* data fit into the bigger picture of water cycles in snowpack-driven mountain systems like the Roaring Fork Watershed.

[2] Introduction to CBRFC Soil Moisture Data: cbrfc.noaa.gov/wsup/doc/CBRFCsoilmoisture_online_documentation.pdf

Station Upgrades

Changes at Castle Creek

Two exciting upgrades took place on the Castle Creek station in 2023. After repeated issues with the old logger system in 2022, we decided to upgrade to a Campbell CR1000X, a common system within the field research community. Learning the code for a new system and adjusting that system to match our particular array of sensors took some time, but with advice from partners and repeat site visits, we were able to get the station online before winter closed the road above Ashcroft. So far, the system has been operating smoothly, and we have high hopes of more reliable data collection at this site going forward.

Elise Osenga (AGCI) prepares the ground to install a snow pillow at Castle Creek (above). Image Credit: Asa DeHaan.

The installed snow pillow and Castle Creek station viewed from upslope (below). Image Credit: Asa DeHaan.

A new logger wasn't the only exciting addition to the Castle Creek station in 2023. Following the completion of a project at Rocky Mountain Biological Lab, our partners at the University of Washington donated a fluidless snow pillow to AGCI. Snow pillows measure snow water equivalent (SWE) or the amount of water contained in the snowpack. Traditionally, these devices are large, weather-resistant sacs filled with antifreeze fluid. Traditional pillows, used by SNOTEL sites and others, tend to yield good data, but they are challenging to maintain, and the antifreeze can attract bears during low-food springs. The fluidless pillows are made metal and weigh the snow by operating much like a large bathroom scale. This technology is fairly new, however, and researchers in the snow community are interested to see how well the sensors hold up and how accurately they measure SWE. We and the National Resource Conservation Service (NRCS) hope that data from the snow pillow at our Castle Creek station will provide an interesting comparison to a traditional snow pillow NRCS plans to install next year in another, nearby catchment within the Castle Creek area.

In another exciting opportunity for data comparison, billy barr (who prefers his name in lowercase), famous for his longtime snow record collections in Gothic, Colorado, also received two fluidless snow pillows this past year. Gothic is just on the other side of the mountains from Castle Creek, only 11 miles as the crow flies. AGCI staff and billy are looking forward to seeing how our respective observations measure up!

Expanding soil moisture and snow depth measurements

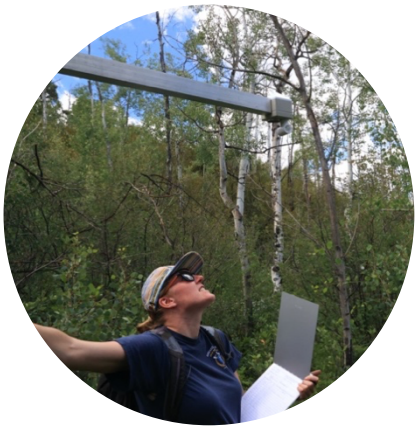
Todd Caldwell of the USGS inserts a di-electric soil moisture probe into the soil. These point-based sensors are used for comparison against the landscape-averaged CRNS measurements (top). Image Credit: Elise Osenga.

AGCI and USGS staff build a CRNS station at Spring Valley. Left to right: Asa DeHaan (AGCI), Tyler Lampard (USGS), Todd Caldwell (USGS), Gwen Davies (USGS) (bottom). Image Credit: Elise Osenga.

Castle Creek wasn't the only station in the Roaring Fork Valley to update its sensor suite this past year. In 2022, the USGS selected the Roaring Fork Watershed as one of its test sites for intensive watershed measurements, including installation of cosmic ray neutron sensors (CRNS), an emerging technology being deployed around the US as part of the Next Generation Water Observing System (NGWOS) program. CRNS sensors measure average soil moisture over hundreds of acres, but they have not yet been widely tested in mountain settings. Over the summer of 2023, the USGS installed 15 stations that included CRNS technology across the Roaring Fork. AGCI has been a partner since the USGS began considering the Roaring Fork as a location, and we were invited to participate alongside USGS staff as they installed sites in our watershed. We helped with installations at three sites, including two co-located with iRON stations: Spring Valley and Northstar Aspen Grove. Both our organizations are excited to begin comparing the data from our respective measurement approaches and sharing what we learn with the Roaring Fork community.

Other measurement advancements AGCI participated in this summer included new sensor additions via our *Evaluating Soil Moisture* project. This project is investigating the relationship between snowpack, soil moisture, and streamflow, and is funded by the Colorado River District (CRD) and Colorado Water Conservation Board (CWCB).

In addition to supporting data analysis and community engagement, the project provides funds to expand the number of locations measuring both snow and soil moisture congruently. Funding from this project allowed AGCI to add snow depth sensors to five additional iRON stations: Smuggler Mountain (2023), Sky Mountain (2023), Brush Creek (2023), Spring Valley (2022), and Glenwood Springs (2022). (Three existing iRON sites are already equipped with snow depth sensors: Castle Creek, Independence Pass, and Northstar Aspen Grove.) We look forward to seeing how each of the new snow sensors performs over the coming year. For this first winter of snow depth measurements, we will be tracking to see if the data collected are reasonable and reliable, and we may alter sensor placement or measurement approach next summer accordingly. These installations are exciting both as an opportunity to track snow and soil moisture at shared sites and because they add snow depth measurements at lower elevations than were previously available in the watershed (Glenwood Springs, 6,200ft, and Spring Valley, 7,100ft).



Tanya Petach (AGCI) checks a newly installed snow depth sensor at Sky Mtn. Image Credit: Emilio Mateo.

Additionally, AGCI worked with NRCS, CBRFC, and CRD to identify two appropriate SNOTEL sites for sensor additions within the catchment for Ruedi Reservoir, a critical local water resource. Kiln and Chapman were selected as the most suitable SNOTEL sites, and AGCI joined the NRCS to help install the di-electric soil moisture sensors they provided at 2, 8, 20, and 40in depths.

Soil moisture sensors inserted at 2, 8, and 20in in the pit at the Chapman SNOTEL site. The rocky soil profile is visible, as is the water table appearing at ~38in down. Image Credit: Asa DeHaan.

A new tower for Independence Pass

Situated near the top of Independence Pass at 12,080ft in elevation, the Independence Pass station provides information about above-treeline conditions—an important but undermeasured elevation band when it comes to tracking snow in Colorado. To account for the deep snows that accumulate on the Pass in winter, our station tripod needed to be over 12 feet tall. While this height effectively kept our logger box above the snow, it made accessing the logger and some sensors on the tripod challenging, as it required a tall ladder. To improve our ability to access sensors on this station for maintenance and repairs, we decided to replace the old tripod with an Eiffel Tower-shaped structure that can be climbed and harnessed into. In September of 2023, with help from a visiting USGS guest, Noah Hoffman, we installed the new tower successfully. No cement was used in this delicate ecosystem. Instead, we secured the new tower with a buried baseplate and guy wires. The new tower makes working on this station both safer and easier.

The new tower at Independence Pass. Image Credit: Elise Osenga

Partnerships

Learning from you

Central to the *Evaluating Soil Moisture* project is community engagement—not only sharing results from our data analysis, but also making certain these analyses are informed by active conversations with the community about their water data knowledge, interests, and needs. Over the course of 2023, we attended local water roundtables and events and held one-on-one conversations with stakeholders in the Roaring Fork. We connected with individuals from the land management, water management, conservation, education, agricultural, and recreation communities. We appreciate learning from these varied perspectives, and we continue to weave information from these conversations into our related work.

If you have not yet had a conversation with us about the role of water data in your work and would like to, please reach out to us. We would be happy to set up a time to talk!

Partnerships across watersheds

The Roaring Fork Observation Network (iRON) community doesn't end at the boundaries of our watershed. By working in collaboration with a variety of relevant groups across other mountain regions, particularly in the Mountain West, we can develop a more complex and complete understanding of the ecology and hydrology of our areas than any of us would have alone.

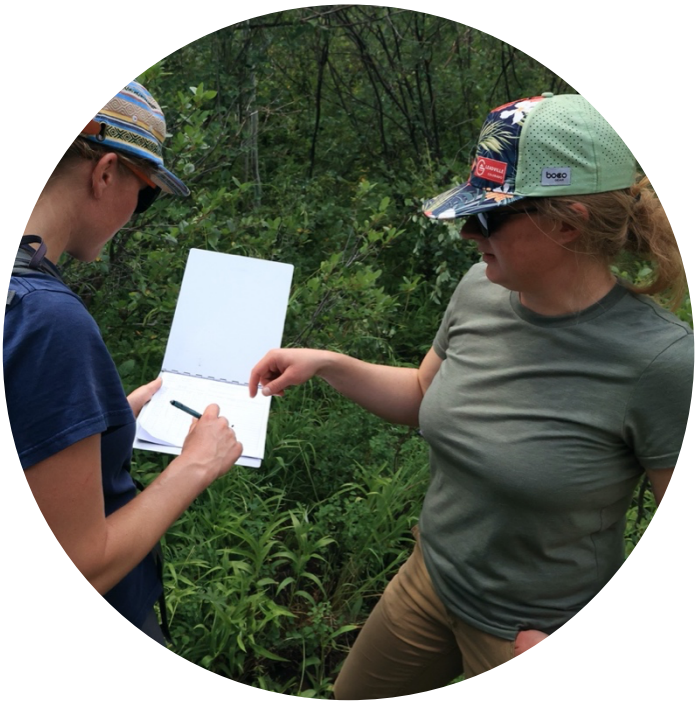
Over the past year, we've formed some exciting new connections in the scientific community, including: meeting others working on soil moisture at the National Soil Moisture Conference, speaking with researchers at the American Geophysical Union Fall Meeting, joining virtual conversations around data quality and control with the National Collaborative Soil Moisture Monitoring Network, and participating in a nascent effort out of Colorado State University to coordinate among soil moisture programs across Colorado.

Asa DeHaan (AGCI) (right) shares initial findings from iRON data at the American Geophysical Union 2023 Fall Meeting. Image Credit: James Arnott.

Continuing the iRON internship program

In 2023, we continued working with the Center for Western Weather and Water Extremes (CW3E), the Yampa Basin Sustainability Council (YVSC), and Colorado Mountain College (CMC), coordinating on their growing soil moisture observation network in the Yampa Watershed, as well as on our partnered internship program.

Hannah Harbert of the Leadville CMC campus joined AGCI as our CW3E intern for the summer. Hannah contributed to the iRON project by conducting sensor comparisons, creating a protocol for soil moisture sampling across elevational gradients, mapping handheld data collected over the course of the summer, and participating in shared learning experiences with the rest of the CW3E cohort (virtually) and AGCI's high school intern, Henry Hurd (in person). At the end of the summer, YVSC's CW3E intern, Abbey Ertzbischoff, made a short visit to the Roaring Fork Valley so she and Hannah could share field experiences and swap tips for their respective projects.



Tanya Petach (AGCI) and Hannah Harbert (CW3E/AGCI Intern) discuss the soil moisture transect protocol at the Sky Mountain site. Image Credit: Emilio Mateo

AGCI's other summer 2023 intern was Aspen High School student Henry Hurd. Henry worked with his AGCI mentors to carry out some basic data analysis, comparing soil moisture values across different time periods in November—the month typically used to determine soil moisture values as mountain regions head into winter. Henry also helped with field work and participated in shared discussions with Hannah.

"I learned so much and am more enthusiastic about AGCI's work than ever!"

~ Henry Hurd, 2023 Summer Intern

Every summer, our interns expand and enrich our perspectives with their own approaches to the work and to AGCI. Meanwhile, we're able to offer them valuable real-world experience with field work and an introduction to what careers in science can look like outside of academia. These internships continue to be a highlight of the iRON program!

Henry Hurd taking handheld soil moisture measurements at the Independence Pass station, July 2023. Image Credit: Elise Osenga.

Looking to 2024

The Evaluating Soil Moisture project

The *Evaluating Soil Moisture project* will wrap up in fall of 2024, and much of the iRON program's work this year is committed to carrying out associated tasks. Interesting findings are already emerging from our initial exploration into the relationship between iRON sensor data, snowpack, and streamflow. Meanwhile, our conversations with community members have underscored the need for clearer information about soil moisture data, collection methods, and which applications of the data are viable (or not). As the project concludes, we will share a Guidebook for Stakeholders that outlines our findings and what they mean for the Roaring Fork and in relation to climate change. We also plan to host a public event to present these findings to the community, followed by a Q & A and a mixer with interactive tables for conversation with AGCI staff and other community members.

Other priorities for the coming year include: continuing to clean and quality control our data archive, moving forward on making our data more easily accessible, continuing our partnered internship through CW3E, maintaining stations and equipment to the best of our ability, and learning alongside our vibrant local community.

A view of the back side of the Maroon Bells from the Castle Creek site. Image Credit: Elise Osenga.

What's next for the program

As we move into the 12th year for the Roaring Fork Observation Network (iRON), we continue to think creatively about potential future pathways for the program. As is common in long-term research, funding general maintenance and operations continues to be a challenge, especially as costs rise over time. Both to maintain existing operations and to leverage partnership and learning opportunities as they arise, securing new funding is a high priority for the program going forward. To this end, we are applying for federal, local, and private grants and also considering how new research partnerships that look beyond soil moisture can help bolster program support. We are excited to see where these opportunities lead us, both in terms of new approaches to mountain eco-hydrology research and in terms of new collaborations and lenses through which to view this watershed. If you have ideas for how to sustain this work, we welcome your thoughts and continued partnership.

"We must begin thinking like a river if we are to leave a legacy of beauty and life for future generations."

~ David R. Brower

After nearly 12 years working on this program, each year still brings new achievements, unexpected insights, and fulfilling interactions. It is a pleasure to be able to explore and appreciate the Roaring Fork Watershed alongside each one of you. Without your encouragement, knowledge, and participation, this journey into the workings small and large of this incredible place could not happen.

Thank you for helping make this project possible.

2022 Project Partners*

Aspen Valley Land Trust
City of Aspen
City of Glenwood Springs
Colorado Avalanche Information Center
Colorado Mountain College
Colorado Natural Heritage Program
Colorado River District
Colorado Water Conservation Board
Denver Foundation
Independence Pass Foundation
Pitkin County Open Space and Trails
Pitkin County Public Works
Private citizens with soils and ecology expertise
Roaring Fork Conservancy
Scripps Institution of Oceanography, UCSD
U.S. Geological Survey
Yampa Valley Sustainability Council

** Community Partners engaged with the iRON as funders, intern mentorship, land permitters, education/outreach participants, or through commitment of time or expertise*