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RESEARCH AND OBSERVATORY CATCHMENTS: THE LEGACY AND THE FUTURE

WILEY

A community-supported weather and soil moisture monitoring database of the Roaring Fork catchment of the Colorado River Headwaters

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Abstract
Local community interest in better understanding regional climate change impacts has motivated the establishment of a long-term soil moisture and weather observation network in the Roaring Fork catchment of the Colorado River Headwaters. This catchment-wide suite of 10 stations, installed between 2012 and 2020, collects frequent, fixed-interval data on soil moisture, soil temperature, rain, air temperature, relative humidity, and (at some stations) snow across an elevational gradient from 1800 to 3680 m. In this paper we provide a description of the data this network provides, how data are accessed, and how this community-supported effort has resulted in data that support mountain hydrology research with applications for resource management and climate change adaptation decision making. All data from this network are publicly available.

KEYWORDS
catchment, ecology, hydrology, mountain, observation network, soil moisture

1 | DATA SET NAME: THE INTERACTIVE ROARING FORK OBSERVATION NETWORK DATABASE (IRON DATABASE)

2 | INTRODUCTION AND SITE DESCRIPTION

For headwater communities, understanding hydrologic impacts in a changing climate is paramount for both local water users and downstream communities that rely on mountains for their water supply. Soil moisture forms a critical component of the hydrologic cycle, particularly in streamflow forecasting (Brocca, Ciabatta, Massari, Camici, & Tarpanelli, 2017; Kemppinen, Niittynen, Riihimäki, & Luoto, 2017; Seneviratne et al., 2010), and is increasingly recognized as an influential factor in estimating the impacts of global climate change on regional scales (Seneviratne & Hauser, 2020). As such, the desire to have real-time observations of soil moisture to better understand and forecast streamflow amid a changing climate is increasing (Lukas & Payton, 2020; Bales et al., 2006; Seneviratne et al., 2012), as are pressures on community water supplies (Viviroli, Kummu, Meybeck, Kallio, & Wada, 2020). Yet, adaptation is possible and has been shown to be more effective when there is collaboration between local stakeholders and scientific researchers (Beier, Hansen, Helbrecht, & Behar, 2017; Eden, Megdal, Shamir, Chief, & Lacroix, 2016).

The Roaring Fork Valley is an important headwater catchment of the Colorado River Basin, which serves over 40 million water users. In the Roaring Fork watershed the Aspen Global Change Institute (AGCI) has partnered with local stakeholders to establish a long-term monitoring network: the interactive Roaring Fork Observation Network (iRON) (Osenga, Arnott, Endsley, & Katzenberger, 2019). Through sustained monitoring of soil moisture and other key variables of interest to both research and resource management, the network aims to improve understanding of hydrologic processes and regional climate change impacts.

TABLE 1 Station metadata and equipment summary

Site ID	Station name (decimal Lat., long)	Start	Elevation	Ecozone (MWP years)	Equipment[a]	Transmission frequency	Sampling frequency	Community partners
1	Sky Mountain (39.22, −106.91)	Aug 21 2012	2550 m	Montane (2016, 2019)	Basic suite, which includes: Onset Hobo Logger, Decagon EC5 soil moisture (5 cm depth), Decagon 10HS soil moisture (20, 50 cm depth), 12 bit temp sensor (20 cm), Onset temp/rh sensor, Onset tipping bucket rain gauge	Cellular/4 hr	20 min	Pitkin County Open Space & Trails (OST); Healthy Rivers; Colorado Natural Heritage Program
2	Smuggler Mountain (39.20, −106.80)	June 5 2013	2759 m	Montane (2017, 2020)	Basic suite	Cellular/4 hr	20 min	Pitkin County OST; Aspen Center for Environmental Studies
3	Glassier Ranch (39.37, −107.09)	July 30 2014	1970 m	Riparian	Basic suite +10HS Decagon soil moisture sensor (100 cm)	Cellular/4 hr	20 min	Pitkin County OST; Basalt High School
4	Brush Creek (39.23, −106.90)	Oct 7 2014	2370 m	Montane (2017)	Basic suite	Cellular/4 hr	20 min	Pitkin County OST
5	Glenwood Springs (39.54, −107.34)	Aug 21 2015	1890 m	Shrublands (2017, 2020)	Basic suite	Cellular/4 hr	20 min	City of Glenwood Springs; Colorado Mountain College
6	Northstar Aspen Grove (39.17, −106.79)	Sept 11 2015	2450 m	Montane (2017)	Basic suite	Cellular/4 hr	20 min	Pitkin OST; Healthy Rivers
7	Northstar Transition Zone (39.17, −106.79)	Oct 1 2015	2450 m	Riparian (2017)	Judd snow depth sensor, Decagon EC 5 soil moisture (5 cm), Decagon 10HS soil moisture (0, 50 cm), 12 bit soil temp (20 cm)	Cellular/4 hr	20 min	Pitkin OST
8	Spring Valley (39.47, −107.22)	June 8 2016	2160 m	Shrublands (2016, 2017, 2020)	Basic suite + additional Decagon EC 5 soil moisture (5 cm), Decagon 10HS soil moisture (20, 50 cm), 12 bit soil temp (20 cm)	Cellular/4 hr	20 min	Aspen Community Foundation; Private Landowner; Colorado Mountain College, CNHP; John Denver Aspenglow Fund
9	Independence Pass (39.10, −106.57)	Aug 25 2016	3680 m	Alpine (2016, 2019)	Basic suite + Davis wind speed/ direction, Judd snow depth	Satellite/1.5 hr	60 min	Independence Pass Foundation; Pitkin County OST; John Denver Aspenglow Fund; Aspen Field Biology Laboratory
10	Castle Creek (39.00, −106.79)	June 24 2020	3505 m	Sub-alpine	Stevens logger box, Stevens Hydraprobe II- soil moisture and soil temperature (5, 20, 50 cm), Campbell snow depth, RM Young wind speed/direction, Apogee up/down pyranometer; Met One rain gauge; Stevens Smart BHT temp/rh sensor	Satellite/1 hr	60 min	City of Aspen; Pitkin County Public Works

Note: Partners include a variety of participatory roles with the iRON, such as funder, internship participant, land permitter, education/outreach participant, etc. Partners are listed with the station most closely related to their activities but are often also involved with the network as a whole.

[a]The 'basic suite' of instrumentations is listed in full in Row 1 of the 'Equipment' column. Further detail about equipment model and manufacture is provided in the section titled 'Data Acquisition'.

The iRON is inspired, guided, and sustained by local community partnerships. Partners have been critical to this program since its establishment in a variety of ways: providing financial support, professional expertise, land use permissions, opportunities for education and outreach, internship participation, and more. Since the first station installation in 2012, the network has grown to include 10 stations that log and transmit recurrent observations of weather and soil moisture conditions across the elevational gradient, with the most recent station coming online in 2020 (Table 1). The intent of the network is to continue collecting data from its current stations in perpetuity; no plans to expand are currently underway. Station sites were selected according to criteria of: (a) representing an elevation gradient, (b) representing multiple ecosystems across this elevation gradient, (c) addressing a community interest—be that tracking conditions for species (e.g., *Populous tremuloides)*, monitoring soil and ecological response to restoration activities, or water management planning, and (d) long-term land-use permissions through partnership with public entities or individuals.

The Roaring Fork catchment has an area of 3760 km^2 and is located in the Colorado Rocky Mountains. Mountain headwater regions like the Roaring Fork contribute around 85% of annual runoff to the Colorado River, with the Roaring Fork River providing approximately 5% of total flows (Department of the Interior, 2012; Lukas & Payton, 2020). This high elevation catchment has snowpack-dominated hydrology and ecosystems that range in elevation from 1800 to over 4200 m, comprising sagebrush meadows and pinyon-juniper stands to Gambel oak, aspen, and mixed conifer forests. By design, the network spans all major ecozones of the catchment, providing a unique capacity to advance understanding of hydrologic processes in mountain headwaters (Figure 1). This community-engaged and community-supported effort also offers a case-study of collaboration with local partners in the design, installation, and operation of a long-term research network. Further information about the network and site locations can be found at https://agci.org/iron/about.

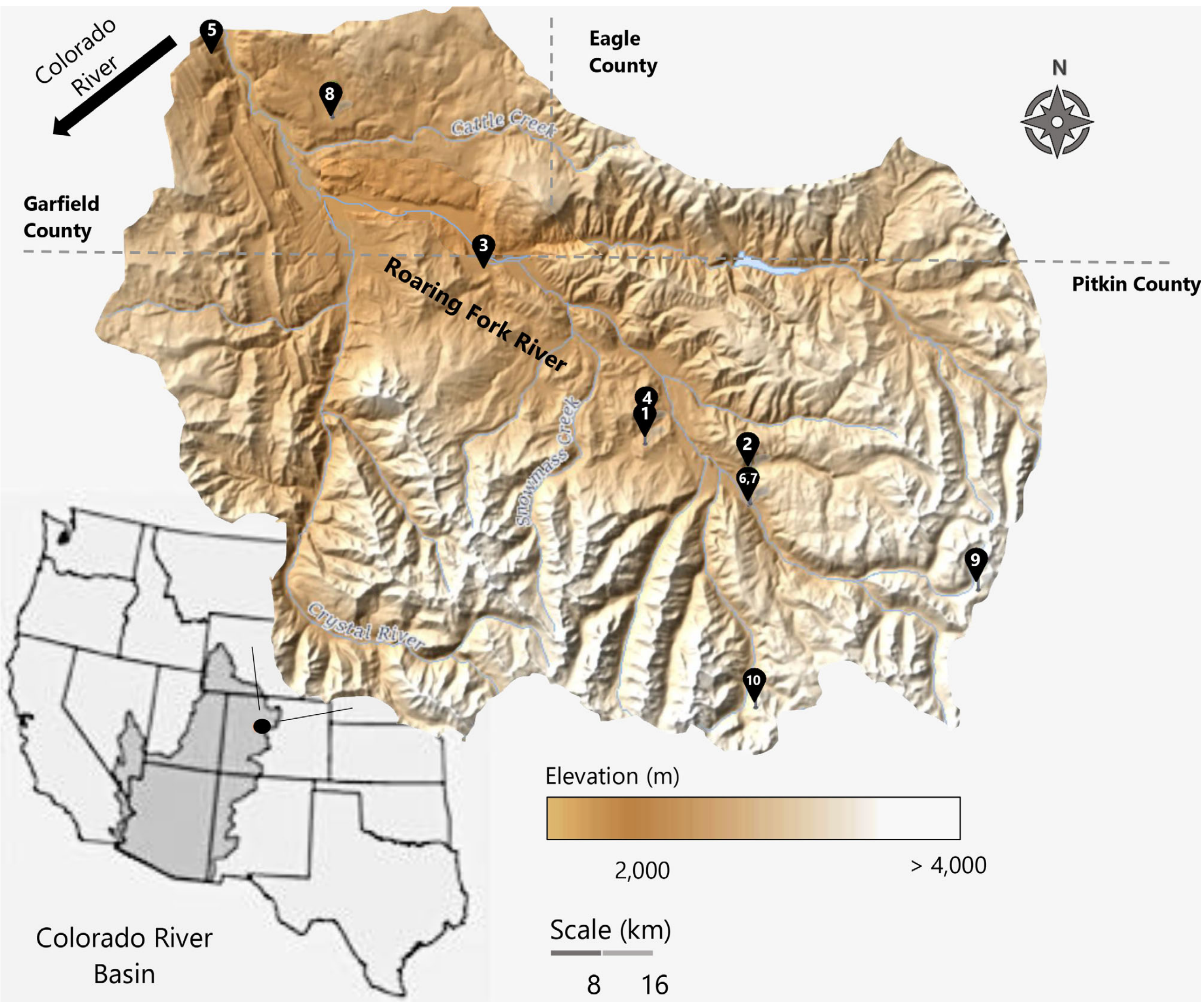

FIGURE 1 An elevational map of the Roaring Fork catchment with iRON stations identified by station ID number. Numbers correspond to the 'Station ID' column in Table 1. Base map modified from Osenga et al., 2019

3 | DATA ACQUISITION

Network data are collected every 20 to 60 min via an automated Onset Hobo RX3000, Stevens Water, or Datagarrison logging system (Table 1). Data collection frequency is consistent across all instruments at a single site. Data are transmitted to online Hobolink, Stevens Water, or Datagarrison databases, respectively, several times a day via cellular or satellite connections. From these collection databases, data are then exported either manually or via automation for storage and quality control (see 'Section 3: Data Availability'). Data are reported in the same frequency at which they are collected, although not all public datasets are updated daily.

The exact instrumentation associated with each station can be found in Table 1. Most stations have a basic suite of equipment that is consistent throughout the network and includes the following, with manufacturer-provided measurement accuracy in brackets: Onset RX 3000 Hobo cellular logger, Onset 6 watt solar panel, Onset S-RGA-M002 tipping bucket rain gauge [± 2% 25–500 mm/hr, ± 1 tip from 1–25 mm/hr], Onset S-THB-M002 12-bit temperature/relative humidity sensor [± 0.21°C from 0 to 50°C, ± 2.5% from 10 to 90%] with RS3 radiation shield, Onset S-TMB-M002 12-bit soil temperature sensor at a 20 cm depth [±0.2°C from 0 to 50°C], Decagon EC-5 dielectric smart sensor S-SMC-M005 at 5 cm [±0.020 m^3/m^3 with soil specific calibration], and Decagon 10-HS dielectric smart sensors S-SMD-M005 at 20 and 50 cm) [±0.020 m^3/m^3 with soil specific calibration]. Some stations are additionally or alternatively equipped with the following instrumentation: Datagarrison satellite logger, Stevens Water satellite logger V 2.0, Judd 5v analog snow depth sensor [± 1 cm or 0.4% distance to target], Campbell ST50A sonic distance sensor (snow depth) [± 1 cm or 0.4% of distance to target], Stevens digital hydra probe II [± 0.01 WFV for most soils], Davis S-WCFM003 anemometer [±1.1 m/s (±2 mph) or ±5% of reading, whichever is greater; ±7°C], RM Young 05103L anemometer [± 0.3 m/s (0.6 mph) or 1% of reading, ± 3°C], Apogee up/down facing pyranometer SN-500-SS [±5%], Stevens Smart BHT temperature and relative humidity sensor with radiation shield [±0.1°C from -20°C to +70°C, ±3% for 0 to 80% and ±5% for 80% to 100%], or Met One model 380 tipping bucket rain gauge [± 2% at 25–500 mm/hr, ± 1 tip from 1–25 mm/hr]. Equipment is manufactured in the following locations: Judd sensors—Salt Lake City, UT; all Onset sensors—Bourne, MA; Davis wind sensors—Hayward, CA; RM Young sensors—Traverse City, MI; all Stevens sensors and products—Portland, OR; Apogee sensors—Logan, UT; Campbell sensors—Logan, UT.

Soil moisture values are recorded using dielectric probes, inserted horizontally into the soil during installation. All soil moisture sensors have been gravimetrically calibrated by soil type prior to installation, using site-specific instrumentation and a gallon volume of soil sampled from near the respective station location. All calibration equations and a complete description of calibration methods are accessible through https://agci.org/iron/datafeed (Osenga, 2020a; Osenga, 2018).

Each site is visited at least once annually to perform routine maintenance and field repairs are carried out as needed throughout the year.

To better understand the relationship between vegetation survival, migration, and abundance relative to changes in soil moisture and climate, Modified Whitaker Plot (MWP) vegetation surveys were carried out at eight stations in 2016 to 2017 to assess general vegetation species and abundance. The MWP surveys will be repeated every 3 to 4 years and were done accordingly at several sites in 2019 and 2020 (column 5 of Table 1). MWP surveys were not carried out at the Glassier Ranch site or the Castle Creek site. Vegetation surveys may be added to these sites in the future.

4 | DATA AVAILABILITY

All data collected by iRON stations are managed by AGCI. Fixed-interval data from iRON stations are currently available to users through four types of online systems, each of which serves a specific purpose: (a) the iRON Data Board, an application programming interface (API) that provides near-real time data, (b) a dataset posted to the CUAHSI Hydrologic Information System, an annually archived set of hydrologic values, (c) a complete dataset posted to the International Soil Moisture Network (ISMN), also updated annually, and (d) vegetation survey data, updated periodically as surveys are complete.

1. iRON Data Board (http://irondataboard.org): Data from the eight iRON stations with Onset loggers are collected and shared through an automated API, the iRON Data Board, that is updated several times each day (http://irondataboard.org). Work is currently underway to automate data collection to this same API from the remaining two satellite-based iRON stations. Data found on the iRON Data Board are flagged for values outside of expected ranges and soil specific calibrations have been added to soil moisture values. However, iRON Data Board data sets have not undergone manual quality assurance for other potential errors or sensor sensitivities (e.g., tipping bucket rain gauges are unreliable in reporting precipitation values when temperatures are near or below freezing).
2. The CUAHSI Hydrologic Information System (DOI: http//dx.doi.org/10.4211/his-5644-agci-irondataset): A full record that has been quality controlled is available through the CUAHSI Hydrologic Information System (DOI: http//dx.doi.org/10.4211/his-5644-agci-irondataset) (AGCI, 2020). On CUAHSI, data are available for each station from start date of data collection (Table 1) through August of 2020, with occasional gaps in instances of equipment failure. These datasets are scheduled to be updated on an annual basis. Data provided on CUAHSI have undergone manual quality control, and soil-specific calibrations have been applied to soil moisture values. The CUAHSI web page also provides links to site metadata, calibration information, and data flags (Osenga, 2020b).
3. International Soil Moisture Network (ISMN) (https://ismn.earth/en/): Data that have been cleaned and calibrated are also shared via the International Soil Moisture Network (ISMN). AGCI sends

IMSN updated data sets annually that include the full previous calendar year. ISMN datasets are publicly available at https://ismn.earth/en/. Data from the network are also automatically uploaded by the National Soil Moisture Network (NSMN) in real time to be incorporated into the NSMN database (nationalsoilmoisture.com). Stations included on the NSMN soil moisture directory map are incorporated into their products and iRON data not available for direct download.

4. Data from Modified Whitaker Plot surveys at iRON sites can be found on Zenodo.org (DOI: https://zenodo.org/record/1252401#.YCwaSndKjlw) or accessed via a link on https://agci.org/iron/datafeed.

AGCI retains full ownership of iRON soil moisture and weather data. Soil sample analysis was conducted by the Soil, Water, and Plant Testing Laboratory of Colorado State University, and vegetation surveys were done with assistance from the Colorado Natural Heritage Program (CNHP) and Western Ecological Resource, Inc. MWP survey data collected by CNHP are owned by AGCI but openly shared with CNHP and publicly. Data from Western Ecological Resource, Inc. are jointly owned with AGCI. No embargoes are placed on use of data, although AGCI does not recommend use of raw data.

5 | FUNDING

Funding over the course of the iRON program has come from AGCI and a combination of local governments and organizations. Current program funders are: Pitkin County Open Space and Trails, City of Aspen Water Department, the Aspen Community Foundation, and the Independence Pass Foundation. Previous funders include: Alpine Bank, Aspen Field Biology Laboratory, John Denver Aspenglow Foundation, New Belgium Brewing Company, the Environment Foundation, and Pitkin County Healthy Rivers and Streams. Non-financial contributions to the project such as land leases, in-kind donation of time, or educational partnerships have been provided by: City of Glenwood Springs, Colorado Mountain College, Colorado Natural Heritage Program, and engaged community members.

6 | DATA APPLICATIONS

Early and ongoing conversations with community partners are a foundational component of the iRON Database. Not only do they provide important resources via dollars and expertise, they provide opportunities to understand how community input can better promote data usability and how improved accessibility to observations can best facilitate the climate adaptation increasingly needed within mountain catchments. The partnership model, including shared efforts to support the work, has enabled the network to more effectively reach its goal of helping a diverse group of stakeholders, including water and land managers, local residents, and researchers, better understand the relationship between warming air temperatures, changing precipitation, and the hydrology and ecology that support natural and human communities.

The network already provides important context to decision makers in the Roaring Fork Valley on real-time conditions, e.g., avalanche risk, pre-winter soil moisture values. As the data record grows over time, more extensive local resource management applications are anticipated. For example, City of Aspen's water utility, which has helped financially support network expansion and long-term maintenance, intends to use these data to better track relationships between streamflow and snowpack. Additionally, Pitkin County, a local land management entity, expects to incorporate data into restoration planning by using it to track evolving habitat suitability for plants and trees across different ecozones. These and other partners also see opportunities for raising awareness about the local impacts of climate change.

As the iRON data records become longer, we anticipate this database will have increasing value to research on regional climate change impacts in the Colorado River basin and in mountain headwaters globally.

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