Title:

A Community-Engaged Weather and Soil Moisture Monitoring Network in the Roaring Fork Catchment of the Colorado River Headwaters

Abstract:

Local community and research interest to better understand regional climate change impacts has led to 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 collects frequent and continuous data on soil moisture, soil temperature, rain, air temperature, relative humidity, and (at some stations) snow across an elevational gradient from 1,800m to 3,680m in elevation. We demonstrate how this effort can support research on mountain hydrology with applications for resource management and climate change adaptation decision making. We also share perspectives on the value and opportunities a community science approach can bring to catchment studies moving forward. All data from this project are publicly available.

Key Words: soil moisture; observation network; hydrology; ecology; mountain; catchment

Main Text:

1. Introduction and Site Description

For headwaters 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. In the Roaring Fork Valley, an important headwater catchment of the Colorado River Basin, which serves over 40 million water users, 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 continuous monitoring of soil moisture and other key variables of interest to both research and resource management, the program aims to improve understanding of hydrologic processes and regional climate change impacts.

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 initial 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 catchment's elevational gradient (Fig. 1). The Roaring Fork catchment has an area of 3,760km^2 and is located in the Colorado Rocky Mountains (39.35º, -107.07º). Headwaters 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 a snowpack-dominated hydrology and ecosystems that range in elevation from 1,800m to over

4,200m, 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 (Fig. 1, Table 1). This community-driven and community-supported effort also offers a case-study of engaging local partners in the design, installation, and operation of a long-term research network.

2. Instrumentation

Network data are collected every 20 to 60 minutes via an automated logging system (Fig. 2). Data are transmitted to online databases daily via cellular or satellite connections. A basic suite of equipment is consistent across most stations in the network and includes an Onset RX 3000 cellular logger, Onset tipping bucket rain gauge, Onset temperature/relative humidity sensor, Onset 12-bit soil temperature sensor (20cm depth), Decagon EC-5 dielectric probe (5cm), and a Decagon 10-HS dielectric probe (20cm, 50cm). Variations on this basic suite can be found in Table 1. All soil moisture sensors have been gravimetrically calibrated by soil type, using site-specific instrumentation and soil samples collected from the station location (Osenga, 2018).

3. Data Access

All data collected by iRON stations are managed by AGCI. AGCI retains full ownership of the network's soil moisture and weather data. Soil sample analysis was conducted by Colorado State University's Soil, Water, and Plant Testing Laboratory, and vegetation surveys were done with assistance from the Colorado Natural Heritage Program (CNHP) and Western Ecological

Resource, Inc. Survey data collected by CNHP are owned by AGCI, and data from Western Ecological Resource, Inc. are jointly owned with AGCI.

Data from iRON stations are available through the CUAHSI Hydrologic Information System (https://hiscentral.cuahsi.org/pub_network.aspx?n=5668) (AGCI, 2020). For each station, data are available from the date the station went online after installation through August 2020, with occasional gaps in instances of equipment failure. Data from the network are also widely shared via the National Soil Moisture Network (nationalsoilmoisture.com) and the International Soil Moisture Network (https://ismn.geo.tuwien.ac.at/). A full record of data availability dates, data flags, and metadata is available online (Osenga, 2020).

4. Network Applications and Importance

The iRON network seeks to improve understanding of mountain ecosystems and hydrology in the context of a changing climate. For the surrounding region, network data already provide important context to decision makers in the Roaring Fork Valley on real-time conditions (see https://www.agci.org/iron/stations). As the data record grows over time, we anticipate more extensive local resource management applications. For example, a drinking water utility that has helped financially support network expansion and long-term maintenance intends to use these data to better track relationships between streamflow and snowpack. Additionally, 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 local awareness about the local impacts of climate change.

The data have also been employed in support of other soil moisture analysis efforts regionally and globally. As the record becomes longer, the datasets will have increasing value to research on regional climate change impacts in the Colorado River basin and in mountain headwaters globally. The most recent report on the science of the Colorado River Basin specifically calls out the need for real-time observations of soil moisture and other hydrologic variables to better understand and forecast Colorado River flows (Lukas & Payton, 2020), an outlook that is also reflected more broadly in considering data gaps in other mountain hydrologic systems (Bales et al., 2006; Seneviratne et al., 2012).

Soil moisture forms a critical component of the hydrologic cycle, particularly in streamflow forecasting (Brocca, Ciabatta, Massari, Camici, & Tarpanelli, 2017) (Brocca, Ciabatta, Massari, Camici, & Tarpanelli, 2017; Kemppinen, Niittynen, Riihimäki, & Luoto, 2017; Seneviratne et al., 2010). Furthermore, soil moisture is increasingly recognized as an influential factor in estimating the impacts of global climate change on regional scales (Seneviratne & Hauser, 2020). However, in-situ soil moisture datasets are often sparse or under-reported (Quiring et al., 2016). In this context, the iRON provides a dataset with the potential to advance understanding of mountain hydrologic cycles in multiple capacities--for example, ground-truthing remotely sensed or derived soil moisture data, improving outputs of hydrologic models (regionally), and clarifying land-atmosphere interactions through the lens of soil moisture.

5. Broader implications of community engagement

Communities throughout the world face increasing pressures on their water supplies. Water demand is rising as populations grow (Viviroli, Kummu, Meybeck, Kallio, & Wada, 2020). At the same time, snow- and glacier-fed water supplies, which provide water to over one-sixth of the global population, are vulnerable to decline with climate change(Barnett, Adam, & Lettenmaier, 2005). Adaptation will not be easy, but it has been shown to be more effective when there is well-coordinated collaboration between local stakeholders and scientific researchers (Beier, Hansen, Helbrecht, & Behar, 2017; Eden, Megdal, Shamir, Chief, & Lacroix, 2016).

The community-engaged foundation of the iRON provides an opportunity to better understand how improved observations and local community participation can help facilitate adaptation, which is increasingly needed within mountain catchments. As such, the overarching goal of this network is to help a diverse group of stakeholders, including water and land managers, local residents, and scientific researchers, better understand the relationship between warming air temperatures and the hydrology and ecology that support natural and human communities. Accordingly, many applications of iRON research go beyond peer-reviewed papers to provide locally relevant data and analysis to the community of the Roaring Fork catchment. Reports written to be accessible to a broad audience are shared with stakeholders annually. Data visualizations have been used to inform local reporting on climate change issues, and presentations using iRON data have been used to ground community discussions around planning for future changes.

The network has further engaged the community through educational opportunities. Each summer, a paid internship is provided to a student in the Sustainability Studies program at Colorado Mountain College, and local college and high school students periodically visit network sites on class field trips.

Collectively, these engagements are critical to the longevity and relevance of the network. They create greater buy-in to science-driven decision making while also improving understanding of changing local conditions and how these are connected to global change.

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Tables:

Station ID	Station Name	Data Start	Elevation	Ecozone	Equipment	Transmission/ Frequency	Data Collection Frequency	Community Partners†
1	Sky Mountain	2012	2,550m	Montane	Basic suite	Cellular/ 4 hours	20 minutes	Pitkin County Open Space & Trails; Healthy Rivers; Colorado Natural Heritage Program
2	Smuggler Mountain	2013	2,759m	Montane	Basic suite	Cellular/ 4 hours	20 minutes	Pitkin County OST; Aspen Center for Environmental Studies
3	Glassier Ranch	2014	1,970m	Riparian	Basic suite + 100cm soil moisture	Cellular/ 4 hours	20 minutes	Pitkin County OST; Basalt High School
4	Brush Creek	2014	2,370m	Montane	Basic suite+ additional soil sensors (soil moisture-5, 20, 50cm; soil temp 20cm)	Cellular/ 4 hours	20 minutes	Pitkin County OST
5	Glenwood Springs	2015	1,890m	Shrublands	Basic suite	Cellular/ 4 hours	20 minutes	City of Glenwood Springs; Colorado Mountain College
6	Northstar Aspen Grove	2015	2,450m	Montane	Basic suite	Cellular/ 4 hours	20 minutes	Pitkin OST; Healthy Rivers
7	Northstar Transition Zone	2015	2,450m	Riparian	Judd snow depth sensor, soil moisture (5, 20, 50cm), soil temp (20cm)	Cellular/ 4 hours	20 minutes	Pitkin OST
8	Spring Valley	2016	2,160m	Shrublands	Basic suite + additional soil sensors (soil moisture-5, 20, 50cm; soil temp 20cm)	Cellular/ 4 hours	20 minutes	Aspen Community Foundation; Private Land owner; Colorado Mountain College, CNHP; John Denver Aspenglow Fund
9	Independence Pass	2016	3,680m	Alpine	Basic suite + Davis wind speed/direction; Judd snow depth	Satellite/ 1.5 hours	120 minutes	Independence Pass Foundation; Pitkin County OST; John Denver Aspenglow Fund; Aspen Field Biology Laboratory
10	Castle Creek	2020	3,505m	Sub-alpine	Stevens logger box, Stevens Hydraprobe II (5, 20, 50cm), Campbell snow depth, RM Young wind speed/direction, Apogee up/down pyranometer; Stevens rain gauge	Satellite/ 1 hour	60 minutes	City of Aspen; Pitkin County Public Works

†Community 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.

Figure Legends:

Caption Table 1: Table 1. Equipment type and site metadata by station. †Community 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.

Caption Figure 1: Fig. 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, 2018.