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Bioclimatic and soil moisture monitoring across elevation in a mountain watershed: Opportunities for research and resource management

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Key Points:

- Soil moisture is key to understanding and predicting change in hydrology and ecology amid climate variability and change
- In situ soil moisture and weather monitoring data are now available across an 1800 m elevation span in a mountain watershed
- The network is supported and guided by resource managers and supports both research and resource management goals

Abstract

Soil moisture data are critical to understanding biophysical and societal impacts of climate change. However, soil moisture data availability is limited due to sparse in situ monitoring, particularly in mountain regions. Here we present methods, specifications, and initial results from the interactive Roaring Fork Observation Network (iRON), a soil, weather, and ecological monitoring system in the Southern Rocky Mountains of Colorado. Initiated in 2012, the network is currently comprised of nine stations, distributed in elevation from 1,890 to 3,680 meters, that continually collect and transmit measurements of soil moisture at three depths (5 cm, 20 cm, 50 cm), soil temperature (20 cm), and meteorological conditions. Time-lapse cameras for phenological observations, snow depth sensors, and periodic co-located vegetation surveys complement selected stations. iRON was conceived and designed with the joint purpose of supporting bioclimatic research and resource management objectives in a snow-dominated watershed. In the short term, iRON data can be applied to assessing the impact of temperature and precipitation on seasonal soil moisture conditions and trends. As more data are collected over time, iRON will help improve understanding of climate-driven changes to soil, vegetation, and hydrologic conditions. In presenting this network and its initial data, we hope that the network's elevational gradient will contribute to bioclimatic mountain research, while active collaboration with partners in resource management may provide a model for science-practice interaction in support of long-term monitoring.

Plain Language Summary

As climate change drives shifts in temperature and precipitation, researchers and resource managers can benefit from improved monitoring of soil moisture. Understanding the relationship between soil moisture and other system components is crucial to improving water availability projections and understanding ecosystem responses to climate change. Despite their significance, in-ground soil-moisture measurements are often not available across multiple elevations within a single watershed.

This paper presents a network in the Southern Rocky Mountains intended to help address this data gap and compliment data from other networks. The interactive Roaring Fork Observation Network (iRON) consists of 9 locations across an 1,800 m change in elevation. Each station

measures soil moisture at three depths, soil temperature, air temperature, humidity, and precipitation. Some stations are equipped with cameras or snow depth gauges, and for 8 sites vegetation surveys are conducted. The data are available through a simple data portal.

The network was established with local resource manager support, and one of its guiding purposes is to support management and restoration planning efforts. Because of the network's on-going monitoring across multiple elevations and habitats, iRON will provide researchers and resource managers with access to valuable information about changes in soil conditions in a changing climate.

1 Introduction

Soil moisture dynamics are critical to characterizing regional climate change impacts on hydrology and ecosystems. Although the full extent of soil moisture and climate interactions is a developing area of research (Seneviratne et al., 2010), minimum near-surface soil moisture is projected to decrease in the southwestern United States as climate change continues (Whener et al., 2017). Soil moisture is increasingly understood to be a key driver—and indicator—of regional hydrologic variability and change (Seneviratne et al., 2010), and climate-driven alterations to soil moisture have repercussions for both ecological health (Pecl et al., 2017; Robinson et al., 2008) and human well-being (Lempert & Groves, 2010). Despite the importance of soil moisture in understanding hydrologic systems, limited observational data have hampered both understanding of the relationship between soil moisture and runoff and the ability to develop and validate hydrologic models. Better understanding of soil-moisture dynamics has the potential to advance research and better support resource management in the context of climate change (Seneviratne et al., 2012).

In the southwestern United States, water managers face climate-driven disruptions to water supplies (Barnett et al., 2008) and, simultaneously, challenges to meeting the needs of rapidly growing populations (Dettinger et al., 2015). As future hydrologic conditions will likely depart from historical patterns, models and forecasts of streamflow are becoming increasingly relevant to water management for both near-term, e.g., winter and early season (Pagano, 2010), and long-term planning, e.g., decadal to centennial (Udall & Overpeck, 2017). However, current models of runoff and other hydrologic processes in complex terrains, such as mountain landscapes, often do not represent soil moisture well (Pagano, 2010).

Recent developments in remote sensing of soil moisture, particularly the launch of the Soil Moisture Active Passive satellite in 2015 (Colliander et al., 2017; Entekhabi et al., 2010), provide the opportunity for monitoring and modeling soil moisture across multiple scales (Peng et al., 2017), but the resolution of remotely-sensed soil moisture data is often not fine enough for watershed-scale applications in mountainous regions where topography and soil moisture are heterogeneous, and remotely sensed soil moisture is often limited to shallow depths (Cowley et al., 2017; Dobriyal et al., 2012). There are also a variety of on-the-ground networks across the globe that include soil moisture (International Soil Moisture Network, n.d.) including networks in the southwestern United States, such as NEON, SCAN, and select sites in the SNOTEL program. However, because of the heterogeneity of climate and soil moisture within mountain watersheds, additional data in previously unmonitored watersheds has a potential to be valuable in augmenting existing in situ data and complementing remotely sensed data. With mountains providing the headwaters for millions of water users, it will be increasingly important to monitor soil moisture in the context of understanding water availability (Lempert & Groves, 2010) and improving water forecasts for utility managers (Pagano, 2010).

In addition to water resource management, soil moisture is also pertinent to ecosystem health and ecosystem management in semi-arid climates (Whener et al., 2017). Along with variables like vapor pressure deficit and precipitation, soil moisture is understood to be a key factor in tree survival (Anderegg et al., 2015; Daubenmire, 1968; Worrall et al., 2010) and fire risk (Bourgeau-Chavez et al., 2007; Lavell et al., 2012; Williams et al., 2012).

In light of the importance of soil moisture observations to emerging research and management questions, we report here on the development of an in situ soil, meteorological, and ecological monitoring network in the Southern Rocky Mountains of Colorado that includes soil moisture measurements at 5, 20, and 50 cm depths. This network joins the growing soil moisture research community and contributes a dataset distinguished by its inclusion of in situ observations across multiple elevations in a single watershed. The intention of this network is not only to serve as a monitoring project supporting local research and resource management, but also to augment existing datasets, enabling researchers to answer broader questions about climate impacts on mountain hydrology and ecology. Co-designed with local land managers and other stakeholders, this network seeks to support both scientific research and management needs. The purpose of this article is to describe the context, monitoring set up, specifications, data, and data access for a broad audience of potential data-users.

2 Methods and Context: Introducing the interactive Roaring Fork Observation Network

2.1 Network overview & context

The interactive Roaring Fork Observation Network (iRON) is a series of in situ soil, meteorological, and ecological monitoring stations. iRON is hosted and maintained by the Aspen Global Change Institute (AGCI), a Colorado-based non-profit research organization that works to advance understanding of global change. Its stations are situated across an elevational gradient from 1,890 m (near a confluence with the Colorado River) to 3,680 m (near the Continental divide at Independence Pass) in the Roaring Fork Watershed of the Southern Rocky Mountains of Colorado (Figure 1). The Roaring Fork Watershed has an area of 3,760 km^2 and is a major tributary of the Upper Colorado River Basin. As a headwaters of the Upper Colorado, the Roaring Fork River's flows are critical to meeting present and future water demands of the western states of the Colorado River Compact, as well as the downstream water demands of Mexico. In aggregate, the Colorado River serves around 40 million people (Bureau of Reclamation, 2012). Numerous studies of the Upper Colorado Basin indicate that climate change will reduce streamflow in the coming decades, affecting recharge of the major reservoirs of Powell and Mead and increasing the likelihood of supply shortages (Castle et al., 2014; Dettinger et al., 2015; Udall & Overpeck, 2017; Vano et al., 2013). Abundant concern about climate-related risks to land and water resources, together with the watershed's significance to downstream communities, provides compelling reasons to conduct long-term observations of soil moisture and other environmental variables.

Figure 1 provides a map of the Roaring Fork Watershed, located in the Southern Rocky Mountains of central Colorado. The 3,760 square kilometer Roaring Fork Watershed is part of the larger Colorado River Basin, and Roaring Fork River is an important tributary of the Colorado River. Figure credit: (Katzenberger & Masone, 2009, publisher permission has been granted).

2.2 Network co-design with resource managers

A key feature of the development of iRON has been intensive collaboration with local resource managers to co-design and help sustain the network. Prior to its establishment in 2012, local interest in bioclimatic change in the Roaring Fork Valley was documented through studies that surveyed and interviewed practitioners working to manage and conserve water and land resources (Arnott et al., 2014; Arnott et al., 2015; Aspen Global Change Institute, 2006). This process occurred through multi-stakeholder roundtables focused on water and forestry issues, as well as through targeted interaction with specific land management entities. Local partnerships have ranged from financial support for network establishment and maintenance to identification of opportunities where monitoring stations can support planning, restoration, and evaluation for adaptive management. An example of potential data application includes comparison of changes in evolving bioclimatic conditions with species-specific tolerances to guide restoration decisions. During the establishment of the network, input from management entities was complemented by guidance from the scientific advisory group, acknowledged at the end of this article. The iRON's science advisors provided input on network design and connections between potential research agendas and stakeholder-relevant data applications.

The multi-use approach of iRON is facilitated by a public website which provides the availability to view and access live and archived data (agci.org/iron), including access to an automated data storage platform.

Figure 2. A map of the Roaring Fork Watershed, with iRON stations shown as red stars, SNOTEL stations as blue circles, and snow course sites as yellow triangles. From left to right, the iRON stations are: Glenwood Springs (5), Spring Valley (8), Glassier Ranch (3), Brush Creek (4), Sky Mtn (1), Smuggler Mtn (2), Northstar Aspen Grove (6), Northstar Transition Zone (7), Castle Creek (10) (planned for 2019 installation), and Independence Pass (9).

2.3 Site section, equipment, and data protocols

The primary criteria for iRON station selection has been distribution of monitoring locations across the watershed's elevational spread and main ecozones (Figure 2), including shrublands, montane, and alpine environments with the addition of a sub-alpine site planned for the near future. These ecosystems were subjectively selected because they represent dominant ecosystem types within the watershed and are of particular ecological interest to public land managers. Additional criteria used to determine the research sites were: land use permissions for long-term placement and local management input. For example, two stations were specifically selected to support pre- and post- monitoring of restoration treatments planned by local land managers of a formerly grazed open-space and an impacted riparian meadow.

Each station is equipped with set of dielectric soil moisture sensors, with one sensor at each depth of 5, 20, and 50 cm. Additional equipment includes a soil temperature sensor at 20 cm and additional basic meteorological equipment mounted on a 2 m or 3 m tower (Table 1). Two stations are additionally equipped with a Judd snow depth sensor, and one station includes a time-lapse camera that takes time-stamped photographs every morning and evening. Possible applications of the photographs are still being developed and include: the potential to compare snow depth readings to images that may reveal patchiness in snow persistence and opportunities for identifying phenological events such as flower blooms.

Two stations, Brush Creek and Spring Valley have been equipped with a second set of soil moisture sensors. At Brush Creek, the duplicate set is being used to establish baseline comparisons of a location that will be used as a control and a location that will be replanted during county restoration efforts. In the case of Spring Valley, the second set of soil moisture sensors are located approximately 3 m from the primary set of soil moisture sensors and were included to allow for potential manipulative comparison experiments by local students, as the station is located near to a Colorado Mountain College campus.

A new station at Castle Creek, slated for addition to the network in spring of 2019, will expand on the standard instrumentation of iRON stations to include energy balance measurements, as well snow depth and wind speed and direction. Opportunities for working with relevant data from other networks are also being explored, including the limited LiDAR data (Colorado Geological Survey, n.d.) available for the Roaring Fork Watershed and consideration of data from NRCS SNOTEL sites, particularly the Schofield Pass site-- the only SNOTEL station in the watershed that includes soil moisture (Natural Resource Conservation Service, n.d.).

Table 1. The above table describes instrumentation and general metadata for each of the iRON stations. A “Standard Suite” consists of: 6-watt solar panel; 2 or 3 m grounded metal tripod; Onset tipping bucket rain gauge; Onset relative humidity temperature probe in radiation housing; Onset RX3000 Logger Box; Onset 12 bit soil temperature sensor (at a 20 cm soil depth); Decagon EC-5 dielectric soil moisture probe (5 cm soil depth); Decagon 10-HS dielectric soil

moisture probes (20 and 50 cm soil depths). Note: The Castle Creek station is planned for installation in spring 2019.

Data are collected every 20 minutes at cellular data transmission stations and every hour at one satellite-uplink station. All loggers transmit their data to an online server every 4 to 6 hours. In addition to continuous data collection by the equipment at each site, vegetation surveys are conducted to track species presence and abundance over time. Modified Whitaker Plot surveys (Stohlgren et al., 1995) are conducted at each site on a rotating 3-year basis. Initial Modified Whitaker Plot surveys have already been completed for 8 of the site locations. Additional tree-specific surveys are planned for each site. Routine equipment maintenance is performed annually, with additional site visits as-needed for instrumentation repair. An alarm is set to trigger for potentially false readings from equipment.

Gravimetric calibrations were carried out for all soil moisture instrumentation: Decagon EC-5 dielectric sensors (for 5 cm readings) and 10HS dielectric sensors (for 20 cm and deeper readings). The EC-5 and 10HS sensors were calibrated in-lab by taking sensor readings of soil moisture after recorded volumes water were mixed into a known volume of soil collected from each site. A regression equation was developed for each depth and station to relate sensor readings to actual soil moisture volumes. Root mean squared error (RMSE) was calculated based on the observed soil moisture volume and soil moisture predicted by the regression equations. RMSE ranged from 0.010 m^3/m^3 (at Northstar Transition Zone, 20-cm depth) to 0.087 m^3/m^3 (Northstar Transition Zone, 50-cm depth) with a median RMSE of 0.027 m^3/m^3. Measurement accuracy at some sites may have been impacted by soil texture and mineral composition. A full table of RSME values by station and soil depth can be found in supporting information materials (Table S2). In the available literature, calibration results for the Decagon sensors were within +/– 0.02 m^3/m^3 to 0.05 m^3/m^3 accuracy of soil moisture for most soil mineral compositions in laboratory settings (Kizito et al., 2008). In-lab calibrations for iRON yielded similar results (Osenga, 2018a).

Other station instrumentation was tested for functionality in-lab but additional, site-specific calibration was not carried out. Manufacturer standards for equipment accuracy can be found in the supporting information materials (Table S1).

2.4 Data management and accessibility

Real-time data are telemetered from iRON stations every 4 hours to Hobolink, a cloud-based system for storing and accessing remote monitoring data, operated by the Onset Computer Corporation. The raw data are then delivered to AGCI's server by secure file transfer protocol (SFTP) and are sorted, stored, flagged, and made available to users through an application programming interface (API). An API is any set of tools and protocols that enable other software to be built; scientific APIs are intended to allow new or existing software to connect to some resource or information, typically through an internet connection.

iRON's API is described and hosted on the iRON Data Board (irondataboard.org). This interface allows for customizable data exports by range of time and variables. Currently, data are available from December 2017 forward on this site, and users can filter by time and station. Data delivery to the server and the server's internal consolidation of new data occur once every 6 hours. The iRON Data Board automatically flags values (using the "valid" field, with values "Y[es]" or "N[o]") that are out of range for a given measurement type. In general, any additional rules can be added, facilitating automated quality assurance and quality checking (QA/QC). These rules, like the soil calibration equations, are applied on top of the raw data, ensuring that raw data are never changed and providing the flexibility for future added value, such as the development of more sophisticated soil calibration.

The iRON Data Board includes a browser-based API that uses URL strings to form requests for data with a standards-based design advantageous for the representation and serialization of geophysical data (Endsley & Billmire, 2010). A small number of assets are hosted by the iRON Data Board, corresponding to endpoints in the browser-based API. Most users will be interested in the "Readings," which are actual measured values for a given station. The "Readings" endpoint accepts a few parameters, such as the "from" and "to" parameters required to specify the date and time range for which observations are requested. The latency, or time delay, between making a data request and the initialization of a download increases with the size of the data request, and API requests for more than 90 days of data across one or more stations will be denied by the server. Therefore, it is recommended to that API requests be made for individual station data by specifying the "station_id" (see Table 1) or a portion of the station name with the "station" parameter. If longer than 90 days of data are needed, exports of archived data through 2018 are available on the iRON Data Board website (irondataboard.org).

Additional functionality has been developed to include the ability to filter for specific variables, such as requests for either calibrated or uncalibrated soil moisture data (calibrated data are the default), the measurement units used (metric or imperial), and the time zone of time stamps. In addition to rich interfaces for accessing iRON data, the iRON Data Board provides internal quality assurance and periodic data backups. Archived public datasets are additionally searchable on Zenodo.org via an ORCID identifier (ORCID 0000-0002-2747-2994).

3 Initial Results & Discussion

Data records for iRON stations currently range from 2.5 – 6.5 years. While the data record is insufficient in length to characterize trends at this time, the existing observations demonstrate the network's potential for long-term research, as well as its near-term utility (Figure 3). Existing data are already being used to characterize wetting and drying events on multiple temporal scales and to provide comparisons across the elevational gradient. The frequency of data collection (every 20 minutes or every hour) allows for observation of soil wetting events on short temporal scales—e.g., tracking penetration of precipitation across 5, 20, and 50 cm soil depths over the course of hours to days. Figure 4a provides an example of how the frequent collection of data reveals dynamic soil responses to rain events. In this example, rain events over the course of the 7-day period totaled 3.2 cm (Figure 4a). Because of the frequency of data collection, it was possible to see the time lag between when this wetting event penetrated to a 5 cm depth and when it penetrated to a 20 cm depth—within the same day. For this event, moisture did not penetrate to a 50 cm depth.

Initial results also show the impact of seasonal events on soil moisture throughout the growing season, particularly highlighting the role snowmelt in early spring as critical in increasing soil moisture prior to late spring and summer drying periods. The Roaring Fork Valley is a snow-dominated watershed, and the significance of the snowpack on soil moisture can be seen in soil moisture response, where all depths (5, 20, and 50 cm) show recharge that brings soil moisture near to saturation in early spring during ground thaw and snowmelt. In this 2013 example, rain events of less than 0.5 cm occurring during the summer season are insufficient to increase soil moisture at a 20 cm depth, and soil moisture at a 50 cm increased only slightly after even the largest summer rain events of 1.5 cm or more in a single day (Figure 4b). Across multiple sites and multiple wetting events, soil moisture at a 5 cm depth was commonly found to be more variable than soil moistures at greater depths

Figure 3. An overview of the existing data record for iRON soil moisture, rain, and air temperature sensors gathered since its establishment, ordered by elevational gradient, from highest at the top to lowest at bottom. On the horizontal axis, each year is labeled on January 1. Because rain is measured by tipping-bucket gage, only growing season rain measurements (May-Oct) are included in this graphic. The Northstar Transition Zone station is located at the same elevation as Northstar Aspen Grove and is omitted for simplicity of presentation.

Figure 4. (a) Soil moisture (at 5, 20, and 50 cm) is shown on the y-axis, while date and time are shown on the x-axis. **(b)** Total daily rain in cm and average daily soil moisture (at 5, 20, and 50 cm) are shown on the y-axis, while dates from February 1, 2013 to Oct 31, 2013 are shown on the x-axis.

The applicability of the network in addressing bioclimatic questions is further augmented by its geographic scale, which spans much of the elevational gradient of the watershed. Observations from iRON provide a basis for tracking and comparing future changes in timing of snowmelt and other hydrologic events at different elevations, such as the date of soil saturation compared between the lowest-elevation and highest-elevation sites (Figure 5).

As timing of snowmelt is anticipated to shift earlier with warming climates (Clow, 2010; Gillan, et al., 2010), data records that observe snow and soil moisture for multiple elevations within a single climatic region may be used to identify elevational differences in intensity of response to regional warming. Specifically, the difference in the timing of the spring melt event across elevations and across years may be directly observed in the data. Additionally, the correspondence between events such as soil saturation and snowmelt indicates a potential to combine iRON data with datasets from outside the network to contribute to hydrologic models and generate improved forecasts of events such as the timing of snowmelt, runoff, and streamflow dynamics (Harpold et al., 2017; Mahanama et al., 2012). Partnerships are currently being developed with researchers working on water models to explore the possibility of using the Roaring Fork Watershed as a case study for applying observational soil moisture data to improve the representation of soil moisture in hydrologic models in mountainous terrain.

Figure 5. Elevation (in meters) is shown on the x-axis for each iRON station. Station elevation is plotted against “spring saturation” for the years 2017 and 2018, as defined by the date of peak soil moisture in spring prior to moisture decline. The winter preceding spring of 2017 was a year with near average snowfall in the Roaring Fork Valley, while the winter of 2017-2018 has below average snowpack throughout the basin. Installation of a station within the 3,200m range is planned for future network additions.

Understanding the long-term impacts of climate change for natural resources was a primary motivation for local stakeholders engaged with the initial project development, and ongoing conversations with community partners have been critical to ensuring local relevance of and support for the network. In addition to their near-term utility, data from iRON are also intended to reveal trends over time at longer-term scales (e.g. decadal), including insight into ecological response to climate change. Data from the Modified Whitaker plots have the potential to reveal changes in plant abundance or species type and elevational migration by vegetation over time concurrent with trends revealed in the soil moisture and meteorological data. Improved understanding of the role played by different climatic and hydrologic mechanisms in vegetation invasion or mortality will be important in determining future species ranges and vulnerability to climate change (Allen et al., 2015; CNHP, 2015; Parida & Buermann, 2014), with application opportunities for land managers and other stakeholders. Although identifying species shifts is a multi-decadal undertaking, this project seeks to establish, at the least, baseline ecological records against which future studies may be compared. Initial results from iRON reveal its potential for application in understanding these ecology-climate-soil relationships. Moving forward, establishing partnerships for further application of these data to regional and national scale research will be critical, and it is hoped that such partnerships will aid in securing additional support for this research through federal and local research grants.

4 Conclusion

The interactive Roaring Fork Observation Network can help both researchers and resource managers to better understand the role of soil moisture in mountain watershed ecology and hydrology. As noted by the Intergovernmental Panel on Climate Change (IPCC) and abundant other literature, soil moisture is critically important to Earth systems research, despite scarce in situ monitoring (Mahanama et al., 2012; Seneviratne et al., 2012; Whener et al., 2017). Although satellite-based measurements of surface soil moisture have improved in recent years, challenges remain in measuring variation in soil moisture across complex terrains such as mountain ecosystems (Cowley et al., 2017). Filling gaps in existing soil moisture monitoring networks will improve capacity to model the changing waterscape of mountain regions and allow for more informed ecological and water management decisions regarding mitigation and adaptation to climate change impacts.

Data collected through iRON can support both regionally-focused and more general studies on ecological, climatological, and hydrological response to climate change and variability in mountain areas. In addition, the network also provides a live, simultaneous comparison of weather events across a mountain watershed. Examples of research pursuits that could benefit from the incorporation and use of iRON data include:

- change in vegetation and soil moisture over time, including opportunities to validate and inform models of climate-driven vegetation shifts;
- partitioning of precipitation into the atmosphere, soil reservoirs, and run-off;
- water availability forecasting, with a focus on modeling snowpack-to-streamflow hydrologic dynamics;
- and the relationship between remotely sensed representation of soil moisture and in situ observations across an elevational gradient.

AGCI continues to expand collaboration and encourage researchers working on regional hydrologic or ecologic responses to climate change to join this effort. Additionally, the design of this network as a partnership between local land management, researchers, and an organization spanning the boundary between research and practice may serve as a useful model for supporting the development, maintenance, use, application, and engagement of bioclimatic monitoring elsewhere. We hope the iRON's wide elevational gradient in the Southern Rocky Mountains and its watershed-scale measurements can contribute to a better understanding of the systems that are critical to sustaining mountain communities, including our own.

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Archived data used for this paper's results and figures and supporting metadata can be found at Zenodo.org, under the title "iRON Soil Moisture Calibrated 2013 to 2018," DOI: 10.5281/zenodo.1271667 (Osenga, 2018b). The project API, the iRON Data Board can be found at iRONDataBoard.org.

References

Allen, C. D., Breshears, D. D., & McDowell, N. G. (2015). On underestimation of global vulnerability to tree mortality and forest die-off from hotter drought in the Anthropocene. *Ecosphere*, *6*(8), 1–55. doi:10.1890/ES15-00203.1

Anderegg, W. R. L., Flint, A., Huang, C. Y., Flint, L., Berry, J. A., Davis, F. W., … Field, C. B. (2015). Tree mortality predicted from drought-induced vascular damage. *Nature Geoscience*, *8*(5), 367–371. doi:10.1038/ngeo2400

Barnett, T. P., Pierce, D. W., Hidalgo, H. G., Bonfils, C., Santer, B. D., Das, T., … Dettinger, M. D. (2008). Human-induced changes in the hydrology of the Western United States. *Science*, *319*(5866), 1080–1083. doi:10.1126/science.1152538

Bourgeau-Chavez, L. L., Kasischke, E. S., Riordan, K., Brunzell, S., Nolan, M., Hyer, E., … Ames, S. (2007). Remote monitoring of spatial and temporal surface soil moisture in fire disturbed boreal forest ecosystems with ERS SAR imagery. *International Journal of Remote Sensing*, *28*(10), 2133–2162. doi:10.1080/01431160600976061

Castle, S., Thomas, B., Reager, J., Rodell, M., Swenson, S., & Famiglietti, J. (2014). Groundwater depleation during drought threatens future water security of the Colorado River Basin. *Geophysical Research Letters*, *10*, 5904–5911. doi:10.1002/2014GL061055.Received

Clow, D. W. (2010). Changes in the timing of snowmelt and streamflow in Colorado: A response to recent warming. *Journal of Climate*, *23*(9), 2293–2306. doi:10.1175/2009JCLI2951.1

Colliander, A., Jackson, T. J., Bindlish, R., Chan, S., Das, N., Kim, S. B., … Yueh, S. (2017).

Validation of SMAP surface soil moisture products with core validation sites. *Remote Sensing of Environment*. doi:10.1016/j.rse.2017.01.021

Colorado Geologic Survey. (n.d.). LiDAR in Colorado. Retreived from http://coloradogeologicalsurvey.org/geologic-mapping/lidar/

Colorado Natural Heritage Program [CNHP]. 2015. Climate Change Vulnerability Assessment for, Colorado Bureau of Land Management. K. Decker, L. Grunau, J. Handwerk, and J. Siemers, editors., & Colorado Natural Heritage Program, Colorado State University, Fort Collins, C. (2015). Climate Change Vulnerability in Colorado, (December), alpine 109-114. Retrieved from http://www.cnhp.colostate.edu/download/documents/2015/CCVA_for_Colorado_BLM_final.pdf

Colorado River Basin Water and Demand Study: Executive Summary. (2012). Retrieved from https://www.usbr.gov/watersmart//bsp/docs/finalreport/ColoradoRiver/CRBS_Executive_Summary_FINAL.pdf

Cowley, G. S., Niemann, J. D., Green, T. R., Seyfried, M. S., Jones, A. S., & Grazaitis, P. J. (2017). Impacts of precipitation and potential evapotranspiration patterns on downscaling soil moisture in regions with large topographic relief. *Water Resources Research*, *53*(2), 1553–1574. doi:10.1002/2016WR019907

Daubenmire, R. F. (1968). Soil moisture in relation to vegetation distribution in the mountains of Northern Idaho. *Ecology*, *49*(3). doi:10.2307/1934109

Dettinger, M. D., Udall, B., & Georgakakos, A. (2015). Western water and climate change. *Ecological Applications*, *25*(1), 2069–2093. doi:10.1890/15-0938.1

Dobriyal, P., Qureshi, A., Badola, R., & Hussain, S. A. (2012). A review of the methods available for estimating soil moisture and its implications for water resource management. *Journal of Hydrology*, *458–459*(January 2018), 110–117. doi:10.1016/j.jhydrol.2012.06.021

Endsley, K. A., & Billmire, M. G. (2010). Distributed visualizations of gridded geophysical data: the Carbon Data Explorer, version 0.2.3. *Geoscientific Model Development*, *9*, 383–392. doi:10.5194/gmd-9-383-2016

Entekhabi, D., Njoku, E. G., O'Neill, P. E., Kellogg, K. H., Crow, W. T., Edelstein, W. N., … Van Zyl, J. (2010). The Soil Moisture Active Passive (SMAP) Mission. *Proceedings of the IEEE*, *98*(5).

Gillan, B. J., Harper, J. T., & Moore, J. N. (2010). Timing of present and future snowmelt from high elevations in northwest Montana. *Water Resources Research*, *46*(1), 1–13. doi:10.1029/2009WR007861

Harpold, A. A., Sutcliffe, K., Clayton, J., Goodbody, A., & Vazquez, S. (2017). Does Including Soil Moisture Observations Improve Operational Streamflow Forecasts in Snow-Dominated Watersheds? *Journal of the American Water Resources Association*, *53*(1), 179–196. doi:10.1111/1752-1688.12490

International Soil Moisture Network. (n.d.). Retreived from https://ismn.geo.tuwien.ac.at/

Katzenberger, J., & Masone, M. (2009). Colorado’s Roaring Fork River: Incorporating climate change projections into watershed management. *Mountain Research Initiative News*.

Kizito, F., Campbell, C. S., Campbell, G. S., Cobos, D. R., Teare, B. L., Carter, B., & Hopmans, J. W. (2008). Frequency, electrical conductivity and temperature analysis of a low-cost capacitance soil moisture sensor. *Journal of Hydrology*, *352*(3–4), 367–378. doi:10.1016/j.jhydrol.2008.01.021

Lavell, A., Oppenheimer, M., Diop, C., Hess, J., Lempert, R., Li, J., … Myeong, S. (2012). *Disaster risk, exposure, vulnerability, and resilience. In: Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation.* Cambridge, UK and New York, NY, USA.

Lempert, R. J., & Groves, D. G. (2010). Identifying and evaluating robust adaptive policy responses to climate change for water management agencies in the American west. *Technological Forecasting and Social Change*, *77*(6), 960–974. doi:10.1016/j.techfore.2010.04.007

Mahanama, S., Livneh, B., Koster, R., Lettenmaier, D., & Reichle, R. (2012). Soil moisture, snow, and seasonal streamflow forecasts in the United States. *Journal of Hydrometeorology*, *13*(1), 189–203. doi:10.1175/JMH-D-11-046.1

Osenga, E. C. (2018a). iRON Methods Used for Calibration of Decagon 10HS, EC5 Soil Moisture Probes (Version 1). Zenodo. Retreived from https://doi.org/10.5281/zenodo.1294073

Osenga, E. C. (2018b). iRON Soil Moisture Calibrated 2013 to 2018 (Version V1). Data set. Zenodo. Retreived from https://doi.org/10.5281/zenodo.1271667

Pagano, T. C. (2010). Soils, snow and streamflow. *Nature Geoscience*, *3*(9), 591–592. doi:10.1038/ngeo948

Parida, B. R., & Buermann, W. (2014). Increasing summer drying in North American ecosystems in response to longer non-frozen periods. *Geophysical Research Letters*, *41*, 5476–5483. doi:10.1002/2014GL060495

Pecl, G. T., Araújo, M. B., Bell, J. D., Blanchard, J., Bonebrake, T. C., Chen, I. C., … Williams, S. E. (2017). Biodiversity redistribution under climate change: Impacts on ecosystems and human well-being. *Science*, *355*(6332). doi:10.1126/science.aai9214

Peng, J., Loew, A., Merlin, O., & Verhoest, N. E. C. (2017). A review of spatial downscaling of satellite remotely sensed soil moisture. *Reviews of Geophysics*, *55*(2), 341–366. doi:10.1002/2016RG000543

Robinson, D. A., Campbell, C. S., Hopmans, J. W., Hornbuckle, B. K., Jones, S. B., Knight, R., … Wendroth, O. (2008). Soil Moisture Measurement for Ecological and Hydrological Watershed-Scale Observatories: A Review. *Vadose Zone Journal*, *7*(1), 358. doi:10.2136/vzj2007.0143

Seneviratne, S. I., Corti, T., Davin, E. L., Hirschi, M., Jaeger, E. B., Lehner, I., … Teuling, A. J. (2010). Investigating soil moisture–climate interactions in a changing climate: A review. *Earth-Science Reviews*, *99*(3–4), 125–161. doi:10.1016/j.earscirev.2010.02.004

Seneviratne, S. I., Nicholls, N., Easterling, D. R., Goodess, C. M., Kanae, S., Kossin, J., … Zhang, X. (2012). Changes in climate extremes and their impacts on the natural physical environment. *In: Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation* [Field, C.B., V. Barros, T.F. Stocker, D. Qin, D.J. Dokken, K.L. Ebi, M.D. Mastrandrea, K.J. Mach, G.-K. Plattner, S.K. Allen, M. Tignor, and P.M. Midgley (eds.)]. A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change (IPCC). Cambridge University Press, Cambridge, UK, and New York, NY, USA, pp. 109-230

Service, N. R. C. (n.d.). Snow Telemetry (SNOTEL) and Snow Course Data and Products. Retreived from www.wcc.nrcs.usda.gov/snow

Stohlgren, T. J., Falkner, M. B., & Schell, L. D. (1995). A Modified-Whittaker nested vegetation sampling method. *Vegetatio*, *117*(2), 112–121.

Udall, B., & Overpeck, J. (2017). The twenty-first century Colorado River hot drought and implications for the future. *Water Resources Research*, *53*(3), 2404–2418. doi:10.1002/2016WR019638

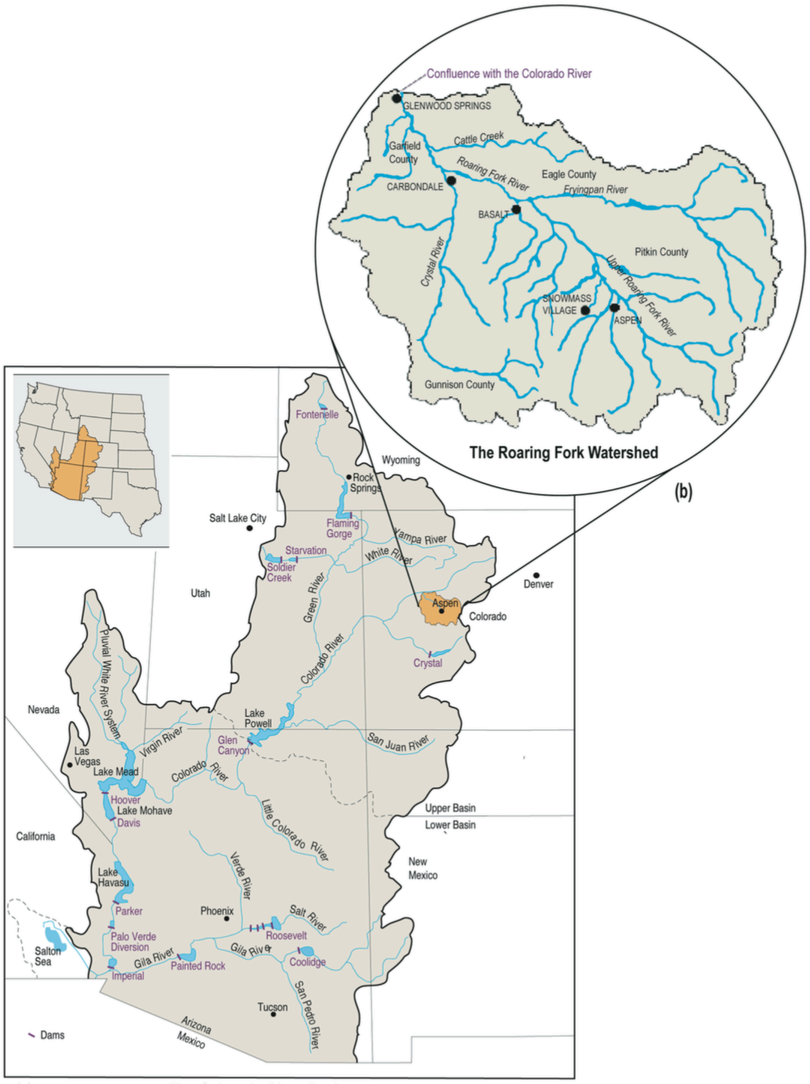
Vano, J. A., Udall, B., Cayan, D. R., Overpeck, J. T., Brekke, L. D., Das, T., … Lettenmaier, D. P. (2013). Understanding Uncertainties in Future Colorado River Streamflow. *Bulletin of the American Meteorological Society*, *95*(1), 59–78. doi:10.1175/BAMS-D-12-00228.1

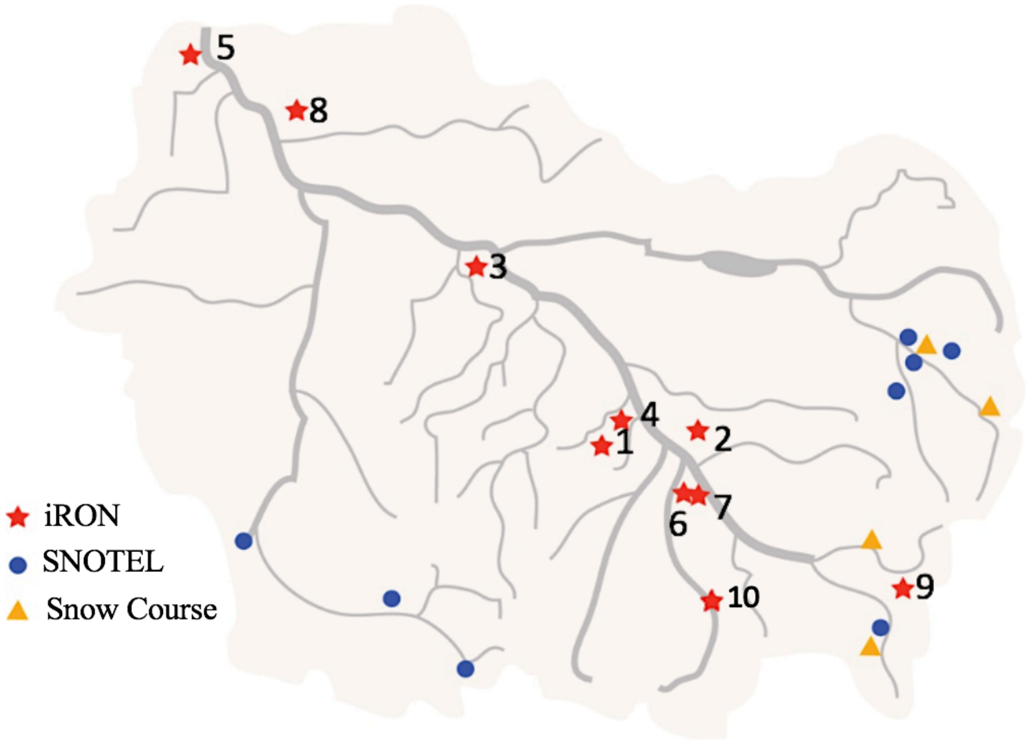
Whener, M. F., Arnold, J. R., Knutson, T., Kunkel, K. E., & LeGrande, A. N. (2017). *Droughts, floods, and wildfires. In Climate Science Special Report: Fourth National Climate Assessment, Volume I*. Washington, D.C. doi:10.7930/J0J8BNN

Williams, A.P., Allen, C. D., Macalady, A. K., Griffin, D., Woodhouse, C. A., Meko, D. M., … McDowell, N. G. (2012). Temperature as a potent driver of regional forest drought stress and tree mortality. *Nature Climate Change*, *3*(3), 292–297. doi:10.1038/nclimate1693

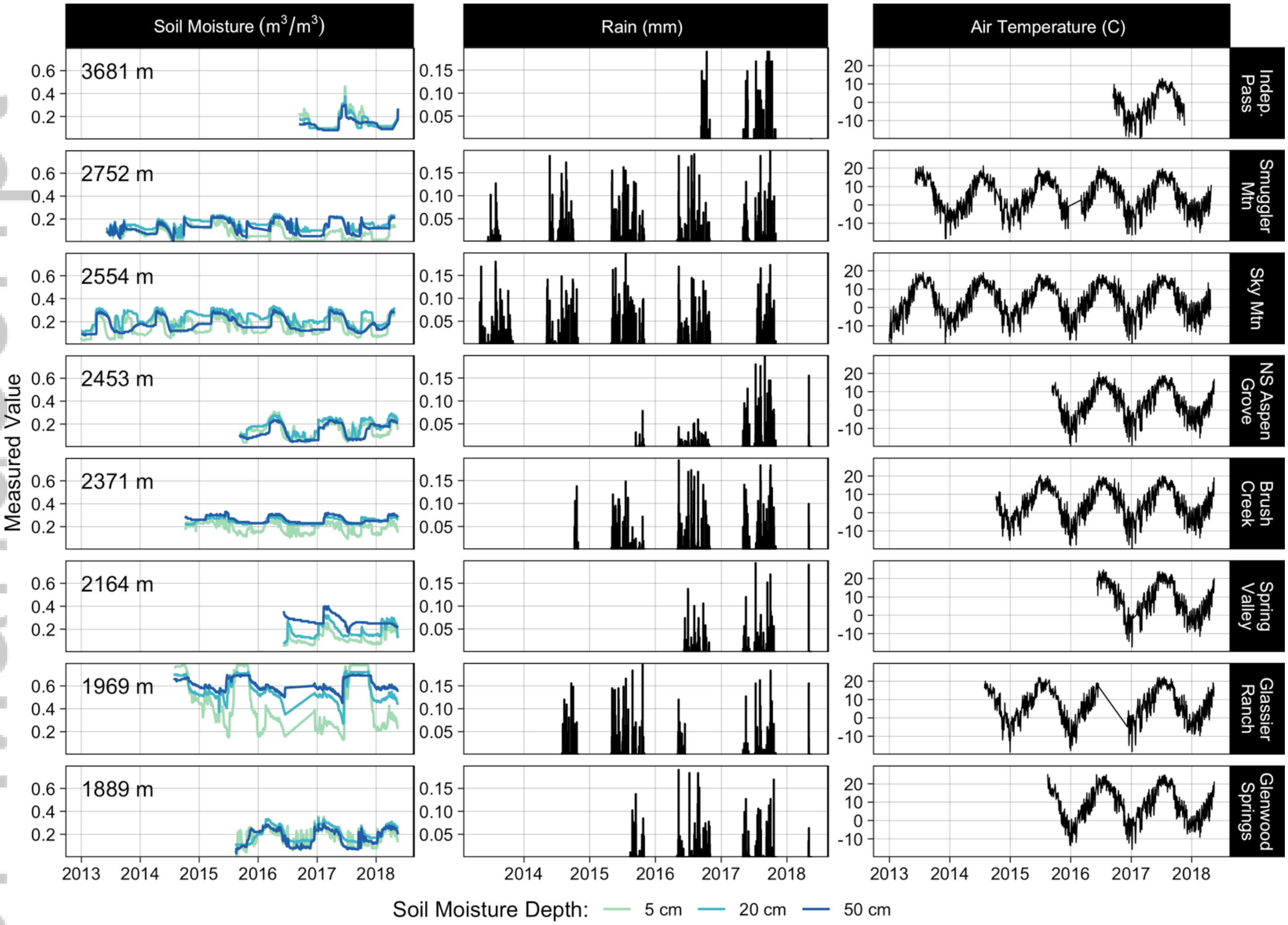
Worrall, J. J., Marchetti, S. B., Egeland, L., Mask, R. A., Eager, T., & Howell, B. (2010). Effects and etiology of sudden aspen decline in southwestern Colorado, USA. *Forest Ecology and*

Management, *260*(5), 638–648. doi:10.1016/j.foreco.2010.05.020

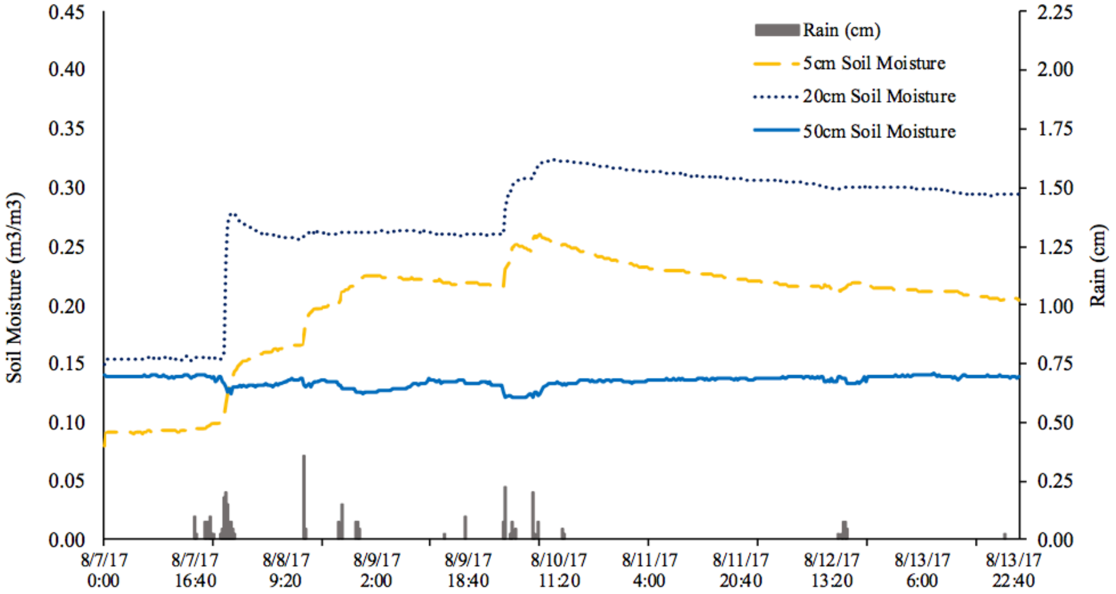

Confluence with the Colorado River
GLENWOOD SPRINGS
Cattle Creek
Garfield County
Roaring Fork River
Eagle County
CARBONDALE
Fryingpan River
BASALT
Crystal River
Pitkin County
Upper Roaring Fork River
SNOWMASS VILLAGE
ASPEN
Gunnison County
The Roaring Fork Watershed
(b)
Fontenelle
Wyoming
Rock Springs
Salt Lake City
Flaming Gorge
Vampa River
Starvation
Soldier Creek
White River
Denver
Utah
Green River
Aspen
Colorado
Crystal
Colorado River
Pluvial White River System
Nevada
Lake Powell
Virgin River
Glen Canyon
San Juan River
Las Vegas
Lake Mead
Colorado River
Hoover
Lake Mohave
Davis
Upper Basin
Lower Basin
California
Little Colorado River
New Mexico
Verde River
Lake Havasu
Parker
Phoenix
Salt River
Palo Verde Diversion
Roosevelt
Salton Sea
Gila River
Gila River
Coolidge
Imperial
Painted Rock
Tucson
San Pedro River
Dams
Arizona
Mexico


5
8
3
4
1
2
6
7
10
9
★ iRON
● SNOTEL
▲ Snow Course

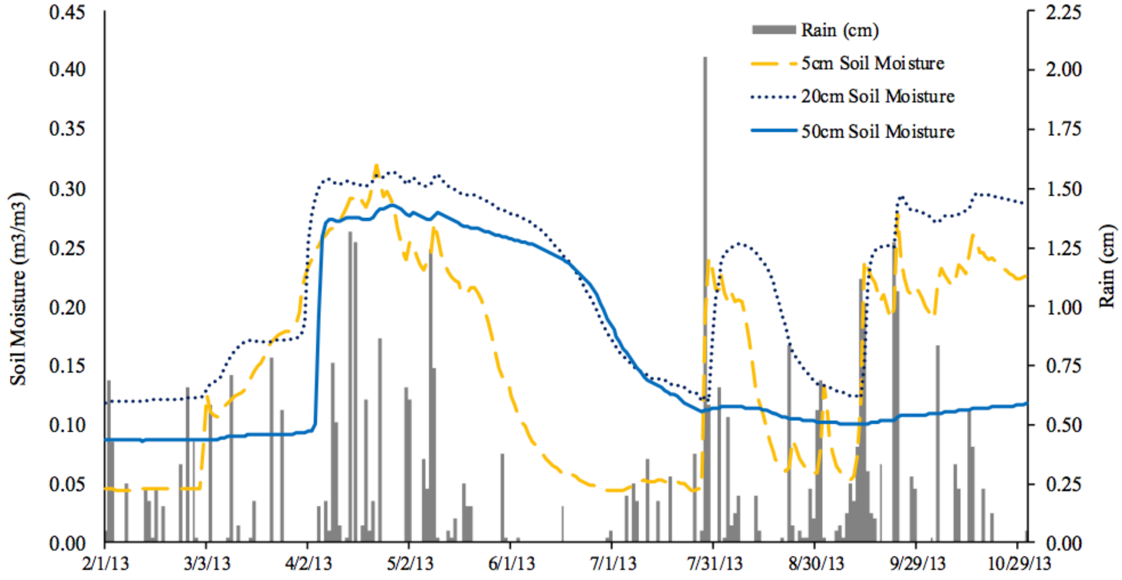
-

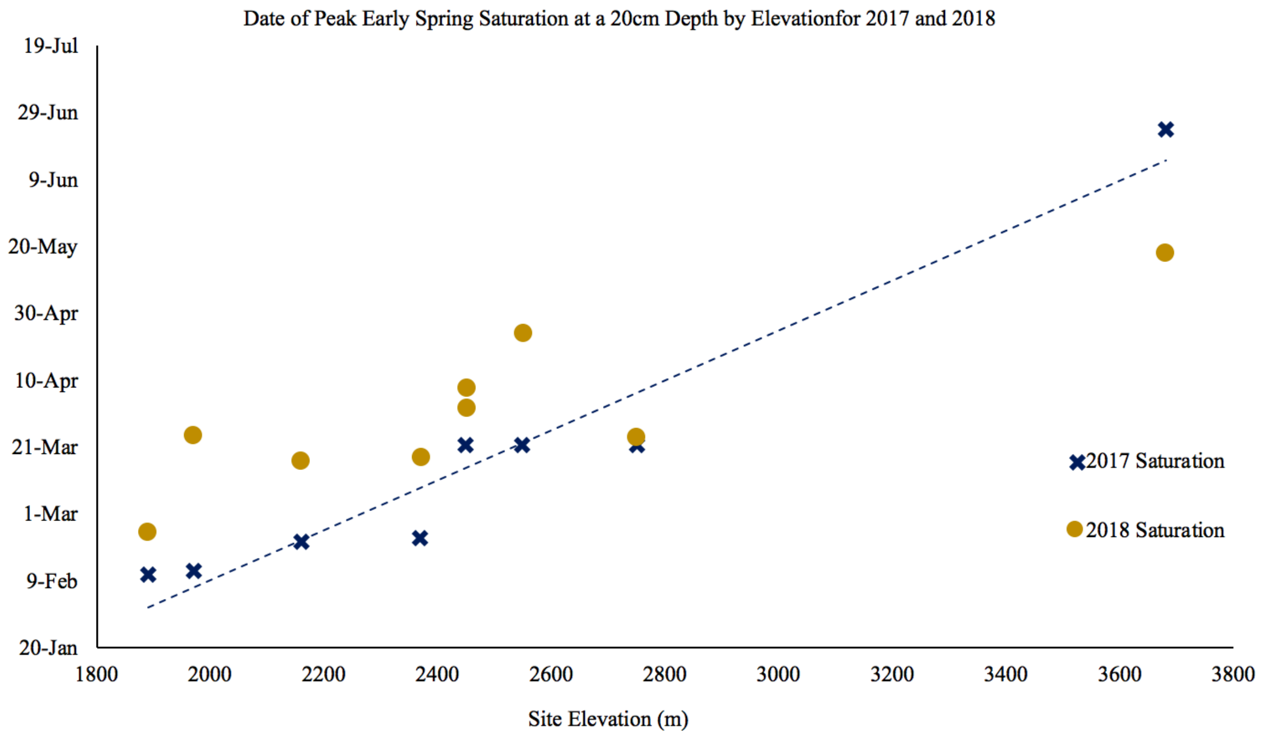

Soil Moisture (m³/m³)
Rain (mm)
Air Temperature (C)
Measured Value
3681 m
2752 m
2554 m
2453 m
2371 m
2164 m
1969 m
1889 m
0.6
0.4
0.2
0.15
0.10
0.05
20
10
0
-10
Indep. Pass
Smuggler Mtn
Sky Mtn
NS Aspen Grove
Brush Creek
Spring Valley
Glassier Ranch
Glenwood Springs
2013
2014
2015
2016
2017
2018
Soil Moisture Depth:
5 cm
20 cm
50 cm

4a. Northstar Aspens (Clay Loam): Soil Moisture at 5, 20, & 50cm and Rain
August 7th to August 13th, 2017



4b. Sky Mountain (Loam): Soil Moisture at 5, 20, & 50cm and Rain
Feb 1 to Oct 31, 2013




Date of Peak Early Spring Saturation at a 20cm Depth by Elevationfor 2017 and 2018
19-Jul
29-Jun
9-Jun
20-May
30-Apr
10-Apr
21-Mar
1-Mar
9-Feb
20-Jan
1800
2000
2200
2400
2600
2800
3000
3200
3400
3600
3800
Site Elevation (m)
2017 Saturation
2018 Saturation