Reynolds Creek Experimental Watershed and Critical Zone Observatory

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The Reynolds Creek Experimental Watershed (RCEW) was established in 1960 as an “outdoor hydrological laboratory” to investigate hydrological processes of interest in the interior northwestern part of the United States. Initial emphasis was on installing and testing instrumentation and data collection and dissemination. The initial instrumentation network sampled the climatic gradient within the 239-km² watershed and focused on specific subwatersheds for intensive instrumentation. This network has expanded and supported ad hoc research and provides a stable platform for the development of long-term programs supporting research and model development in snow hydrology, climate change, water and energy balance, land management, carbon cycling, and critical zone hydrology. Recently, the challenge taken up at the RCEW is to integrate different processes over space for applications to larger areas outside the watershed. The presence of steep local environmental gradients associated with topography in addition to more gradual, elevational gradients requires high-resolution modeling. The snow hydrology program has demonstrated the potential for high-resolution, process-based modeling across large landscapes. The direct linkage of biogeochemical processes with hydrological processes ultimately requires a multidisciplinary approach that has been adopted at the RCEW since inclusion in the Critical Zone Observatory program. We think that coupling of these processes will lead to a better understanding and management of natural resources on the landscape.

Abbreviations: CZO, Critical Zone Observatory; NWRC, Northwest Watershed Research Center; RCEW, Reynolds Creek Experimental Watershed; SIC, soil inorganic carbon; SOC, soil organic carbon.

The Reynolds Creek Experimental Watershed (RCEW), located in southwestern Idaho (Fig. 1), is part of the USDA–ARS network of experimental watersheds established in 1960. It is administered from Boise, ID, where the Northwest Watershed Research Center (NWRC) is located. The watershed was intended as an “outdoor hydrologic laboratory” (Robins et al., 1965) to help understand the basic hydrology of the interior northwestern part of the United States. Similar, sister sites were established for other regions of the United States at the same time. Shortly after initiation in 1960, weirs were built; resource inventories of soils, vegetation, and geology were conducted; and spatial networks of precipitation gauges, meteorological stations, and snow courses were established. Much of the initial work was devoted to developing and testing instrumentation to meet the challenges associated with collecting high-quality, spatially extensive data year-round in a relatively remote mountainous location. This dedication to instrumentation and data collection has been a consistent theme over the years, resulting in high-quality, long-term, and experimental datasets that have been published and made available through a variety of outlets.

A second major theme has been the consistent combination of field research and data collection with process-based modeling. This is a logical extension of the first theme and effectively minimizes the often contentious relationship between “modelers” and field researchers. This combination was expressed early on when the first numerical simulation of hillslope hydrology with field verification was published in 1974 describing hydrology within Reynolds Creek (Stephenson and Freeze, 1974). That study explicitly simulated lateral water movement to a stream channel incorporating field measurements of snowmelt, groundwater, and streamflow. This mating of field data collection and experimentation with modeling has
resulted in numerous publications and the development of important, widely used hydrological models such as iSnobal (Marks et al., 1999, 2002), SHAW (Simultaneous Heat and Water model, Flerchinger et al., 1996a; Flerchinger and Saxton, 1989), and RHEM (Rangeland Hydrology and Erosion Model; Nearing et al., 2011). By providing basic scientific infrastructure and high-quality, long-term data across a range of elevations and hydroclimatic conditions to researchers, the development, testing, and validation of scientific models continues to be an important function of the RCEW “outdoor laboratory.”

An emerging, third theme is the temporal and spatial integration of processes across the landscape. This involves understanding and simulating processes as they interact and are controlled by the variable landscape, and it requires incorporating the critical gradients across that landscape. Previous research was usually directed toward isolating specific conditions within the watershed for detailed study. In its current phase as an observatory, the challenge is to integrate processes spatially across a variable landscape that varies in response to gradients in precipitation, topography, vegetation, and soil and is sensitive to a changing climate. Previous research had also primarily emphasized a single scientific discipline. The new challenge is to explicitly incorporate multiple disciplines. This work builds on successful disciplinary research and utilizes recent developments in computational capabilities and high-resolution remote sensing. It has been facilitated at the RCEW by its recent designation as the Reynolds Creek Critical Zone Observatory (RC CZO), with its infusion of external expertise and scientific diversity, and the demand for operational applications in response to climate change. The exciting potential of this research, which is now beginning to be realized, is that the RCEW/RC CZO (and other observatories) can be used as a stepping stone to implement science within much larger, more socially and economically relevant domains.

**Motivation and Science Questions**

The overall scientific motivation for research at the RCEW is to address the need to spatially and temporally integrate processes across the landscape. The emphasis is on how interactions among geologic, topographic, and climatic gradients across the landscape control hydrologic processes, carbon cycling, soil genesis, and other ecosystem processes over time and climatic variability. Although hydrology continues to be a focus of the observatory, related ecological and biogeochemical processes have been increasingly incorporated into its research themes. This approach considers specific study and measurement sites as providing a sample of the overall landscape to be used for validation and testing of relatively high-resolution spatial models. The intent is to use insights in terms of measurement requirements and modeling approaches determined from this integrated landscape to extrapolate to much larger and less instrumented regions.

This overarching scientific motivation is expressed in a number of interrelated lines of research with separate science questions that have important ecosystem, economic, and social implications. We describe six such questions and the challenges that are part of the current and immediate future research at the RCEW/RC CZO.

**Snow Hydrology:** Can we accurately describe the amount, timing, and spatial distribution of water inputs across large mountainous basins by simulating the processes that control snow accumulation and melt? Western reservoirs that provide flood protection and deliver water for irrigated agriculture and power supply are driven by snowmelt. Effective management of this critical resource requires accurate information regarding snow volume and condition in the upstream mountain basins. The challenge is to adapt a snow hydrology model largely developed in a small, highly instrumented subwatershed of the RCEW to the operation of large, sparsely instrumented basins with large economic impact and requires integration of snow accumulation and melt processes across large environmental gradients.

**Climate Change:** How is the climate at the RCEW changing? How does ongoing climate change impact water and vegetative resources in the region? Ongoing global temperature increases have many potential impacts on our natural resources and how they should be managed. These impacts are difficult to predict because temperature affects so many interrelated processes. The RCEW and other similar sites are in a unique position of providing a coherent portrayal of climate change impacts because, in addition to long-term monitoring of air temperature and precipitation, they document associated impacts on snow dynamics, streamflow, and soil climate (soil temperature and water content). The challenge is to develop a process-level understanding of these observations that can...
be extended to the resultant impacts on water supply, forage production, carbon sequestration, and fire hazard throughout the region.

**Land Management, Erosion, and Fire:** What are erosion losses in the interior Pacific Northwest region of the United States and how are those losses affected by vegetation management, grazing, and fire (wild and prescribed). The long-term productivity of the semiarid rangelands of the western United States are dependent on soil resources. With increasing fire frequency and the use of fire as a management tool, it is critical that we develop an understanding of how the landscape recovers from fire and how adverse consequences can be mitigated. The challenge is to understand how the multiple processes associated with fire vary across the landscape at multiple scales and prescribe management adapted for differing conditions.

**Water and Energy Balance:** How is precipitation partitioned among the processes of evaporation, transpiration, overland flow, groundwater recharge, and streamflow? How do these processes, combined with soil temperature, affect biogeochemical processes such as respiration and mineral weathering? The challenge is to measure and spatially distribute soil water and energy dynamics across highly heterogeneous landscapes so that the impacts of those processes can be incorporated in ecohydrological and biogeochemical models.

**Landscape Soil Carbon and Carbon Cycling:** How does carbon cycling vary within the watershed? Can measured and modeled soil environmental variables at the pedon scale (e.g., soil water content, soil depth, soil temperature, net water flux) improve our understanding and prediction of soil C storage, flux, and processes? The terrestrial C budget is poorly quantified in general and yet appears to be a very large sink for atmospheric CO₂. The magnitude and extent of that sink determine, to a large extent, the terrestrial C balance. The challenge is to link C processes to environmental variables so that these processes can be evaluated in a spatially quantitative way across the landscape.

**Critical Zone Hydrology:** Can geophysical data, combined with stream and groundwater chemistry, effectively improve the hydrological models in watersheds where subsurface flow is dominant? [Note that here we distinguish critical zone hydrology from the broader discipline to emphasize belowground (including soil) saturated and unsaturated water and solute processes.] Virtually all water flow from upland sources to stream channels within Reynolds Creek occurs via flow paths multiple meters below the ground surface. This is clearly below the depth of soil instrumentation and characterization. At present, hydrologic models infer subsurface properties only from observed hydrographs. The challenge is to use geophysical and water chemistry data to provide a spatial context to improve hydrological models. This integrates processes of deep percolation and groundwater recharge with surface processes.

Although these research topics are presented as independent, the reality is quite the contrary. They are all intimately connected to the point where significant progress on any requires progress on others. Water and energy balance are directly related to snow dynamics. Carbon uptake is largely controlled by soil water availability (in semiarid regions), which also is an important determinant of fire hazard, while groundwater recharge and streamflow generation are driven by snowmelt and filtered by soil processes. Ultimately, these are all affected by the changing climate. All of these linked processes vary spatially within tens of meters. These overlapping interests point to a fundamental advantage of long-term study sites: they facilitate cross-disciplinary research.

**Catchment Characteristics**

The basic characteristics of the watershed have been previously described in some detail (see Flerchinger et al., 2007; Hanson, 2001; Marks et al., 2007; Seyfried et al., 2001c). Here we describe these briefly with an emphasis on how the characteristics of the watershed promote the process integration we describe as the overarching scientific motivation.

The RCEW is a 239-km² watershed located in the Owyhee Mountains in southwestern Idaho (Fig. 1). Elevations range from 1100 m at the outlet weir to 2245 m at the highest point. Climate varies with elevation, with mean annual air temperature ranging from 8.9°C near the bottom of the watershed and 4.7°C near the top. Mean annual precipitation exhibits a roughly fivefold range, from about 230 mm/yr in the northern low elevations to more than 1100 mm/yr in the southwestern, high elevations. There is a strong east–west gradient of precipitation, with the western slopes receiving approximately twice the precipitation that slopes of the same elevation receive on the eastern side (Fig. 2). Precipitation is dominated by rain at the lower elevations and by snow at the upper elevations. In snow-dominated parts, the spatial distribution of effective precipitation inputs is controlled by local topography because the wind redistributes snow from relatively dry scarp zones into relatively wet drift zones. There is a pronounced annual dry period throughout the watershed in July and August. The entire extent is grazed by cattle. In the lower elevations, there are irrigated fields of hay near the stream. Some occasional logging occurs in the higher elevations.

The Owyhee Mountains and the RCEW are underlain by granite of the Idaho Batholith, which is prominent to the north. The Snake River Plain, a rift feature that bounds the northern end of the Owyhees, cuts across the batholith. Although bearing some similarities to the Basin and Range Province, the Owyhees are not usually considered to be part of that nearby province (Norman, 1987). The surficial geology (Fig. 3) is a complex mixture of exposed granite, basalt, mixed volcanics (mostly rhyolite), and alluvial stream and lakebed sediments (McIntyre, 1972). There is a large granitic exposure on the western side of the watershed, while basalts dominate the eastern side. To the northwest, a range of different volcanic deposits dominate. Terraced alluvial deposits cover most of the valley bottom. Upland soils are derived from a combination of loess and the weathered bedrock, presented in Fig. 3 in groupings of roughly associated soil series. In the lower elevations, soils are derived from alluvial and lakebed sediments. Soil textures in the RCEW span a very wide range, from loamy sands to silt loam to clay; pH ranges from 6 to >9, with some saline soils. Most relevant at present, there is a highly variable distribution of soil C, with organic C dominating in the higher elevations and inorganic C dominating in the lower elevations.
Plant communities in the RCEW are typical of much of the Great Basin floristic area. At lower elevations, the vegetation is dominated by semiarid shrubs such as Wyoming big sagebrush \((Artemisia tridentata\) Nutt. ssp. \(wyomingensis\) Beetle & Young) and greasewood \((Sarcobatus\) Nees) (Fig. 3). At higher elevations, mountain big sagebrush \([Artemisia tridentata\) Nutt. ssp. \(vaseyana\) (Rydb.) Beetle], Douglas-fir \([Pseudotsuga menziesii\) (Mirb.) Franco], and aspen \([Populus\) spp.] dominate with associated grasses and forbs. The irrigated fields are planted with hay for cattle. The vegetative composition has been changing in the past 30 yr, with a dramatic increase in juniper \((Juniperus\) spp.) cover, primarily in the intermediate elevations, and annual grasses and forbs in the northern, fire-affected part of the watershed.

The net effect of these climatic, topographic, and geological gradients is a complex soil–vegetation mosaic that reflects strong hydrologic gradients in terms of water supply on site and streamflow generation. Gradients are generated both with elevation and within elevation by local topography. Both of these gradients affect hydrological processes, soil formation, and vegetation productivity.

**Basic Long-Term Observations**

The general characteristics and much of the long-term scientific infrastructure has been previously described in a number of publications (Flerchinger et al., 2007; Hanson, 2001; Marks, 2001, 2007; Pierson et al., 2001; Seyfried et al., 2001a, 2001b, 2001c, 2001d; Slaughter et al., 2001). Briefly, the RCEW is heavily instrumented in terms of precipitation sites (29), meteorological stations (32), stream discharge and sediment (11), soil water and temperature (46), eddy covariance (4), and snow courses (7). Almost all data are telemetered to the NWRC in Boise daily. These numbers and measurements have changed with time, but the basic core dataset has remained fairly constant, as illustrated in Table 1. These stations are not randomly distributed (Fig. 4) but are more dense where the elevation and climatic gradient is steepest and in specific subwatersheds that were selected for more intensive instrumentation in recognition of the differing “hydrologies” within the RCEW (Seyfried and Wilcox, 1995).

Funding for instrumentation, maintenance of the network, and data quality control has been almost entirely from the base funding of the NWRC in Boise and not the result of individual research projects. This consistent funding source is an important reason why this long-term approach is possible.

Since the publication of the studies listed above, there have been some significant additions to the long-term network to support new research. Although these more recent additions are relatively new, they are intended to be retained as long-term sites. These are described in more detail below.
Johnston Draw and Murphy Creek

Data collection within Johnston Draw was initiated for several focused studies. The 1.8-km² subwatershed has an elevation gradient of more than 300 m (1497–1869 m asl), which brackets the rain–snow transition elevation for most winter storms (Fig. 4). It contrasts with other subwatersheds in the basin in that it is almost entirely underlain by granite, as opposed to basalt or other volcanics. A weir was constructed in Johnston Draw, and stream discharge and sediment monitoring started in 2003. The subwatershed has been heavily instrumented with partial meteorological stations installed at 50-m elevation increments to evaluate the rain–snow transition elevation. Precipitation and full meteorological stations are located near the highest and lowest elevations. In addition, three paired microclimate stations were installed on opposing north- and south-facing slopes (Godsey et al., 2018). Johnston Draw has been the location of studies on: the rain–snow transition (Marks et al., 2013; Winstral et al., 2013), soil depth and topography (Patton et al., 2013a), carbon distribution (Patton et al., 2018b), and slope and aspect effects on soil climate.

A weir within the Murphy Creek subwatershed was initially installed in 1967 but, for various reasons, was discontinued in 1977. It was re-instrumented in 2015 along with ancillary observations (meteorological stations, erosion monitoring with silt fences, and vegetation monitoring) in response to a wildfire that consumed the entire Murphy Creek subwatershed as well as about 25% of the RCEW. The subwatershed is 1.24 km² in extent, with elevation ranging from 1388 m asl at the outlet to 1823 m at the highest point. The broad range of conditions in Murphy Creek offers the potential to assess fire impacts and wildfire. Currently, analysis of erosion rates and vegetation regrowth are underway.

Environmental Gradient of Energy, Carbon, and Water Balance

As part of the Critical Zone Observatories (CZO) project, four study areas (CORE stations at Nancy Gulch, Lower Sheep, Upper Sheep, and Reynolds Mountain East) located along an environmental gradient (low to high elevation) dedicated to measuring C, energy, and water balance were established in 2014 (Fig. 4). The
purpose of these sites is to provide detailed, comprehensive process data describing C, water, and energy fluxes across the primary environmental gradient to inform or test process-based spatial simulation models. They are located within previously instrumented subwatersheds where long-term meteorological, precipitation, snow depth, discharge, soil water content, and soil temperature information are monitored.

Each site is anchored by eddy covariance instrumentation to obtain net fluxes. To better understand and quantify the components of those fluxes, which will vary spatially across these study areas, we are now monitoring sap flux, soil respiration, soil CO₂ concentration with depth, and soil O₂ concentration. Detailed vegetation monitoring, including net aboveground productivity, plant diversity, litter production, ground cover, and leaf area index by species are also measured using a combination of intensive on-the-ground sampling, terrestrial lidar, and unmanned aerial vehicle imagery. This work is conducted in coordination with remote sensing research to provide a basis for extrapolating the results to much larger areas (e.g., Mitchell et al., 2015; Olsoy et al., 2016; Li et al., 2017; Anderson et al., 2018). In addition, complementary studies of soil crust function and microbial sensitivity to temperature have been undertaken (Blay et al., 2017; Schwabedissen et al., 2017).

### Stream Water Chemistry

Also as part of the CZO project, monitoring of stream water chemistry is now part of the long-term data collection effort. Emphasis is on sampling at four weirs, with supplementary data

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<table>
<thead>
<tr>
<th>Parameter</th>
<th>Measured value†</th>
<th>No. of stations</th>
<th>Years of record</th>
<th>Data interval</th>
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<td>snow depth</td>
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<td>15 min</td>
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<td>wind speed and direction</td>
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<td>production, LAI, and cover</td>
<td>3</td>
<td>2009–2017</td>
<td>semiannually</td>
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</table>

† SWE, snow water equivalent; $T_{\text{max}}$ and $T_{\text{min}}$, maximum and minimum temperature; LAI, leaf area index; $H$, sensible heat; $R_{n}$, net radiation.
‡ bp, breakpoint.
collection of groundwater. Measurements include electrical conductivity, temperature, pH, dissolved organic matter, anions, nutrients, and cations. These measurements serve the larger study to understand C and nutrient fluxes and subsurface lateral flow paths.

**Long-Term Research Programs**

Over the years numerous measurement campaigns have been directed toward specific projects. In addition, there have been many “side” studies evaluating instrumentation or alternative model applications. These studies are often facilitated by the extant scientific infrastructure but may be only peripherally related to the long-term research program. What follows is a brief description of long-term programs directed toward the science questions listed above along with some illustration of how they are working toward the larger scientific integration motivation. Each program described has a somewhat different history with some less “mature” than others. In all cases, the observatory plays a critical role.

**Snow Hydrology**

This program is the most mature and serves to illustrate how observatories can provide the stable environment for progressive model development over time and how that can be used outside the observatory boundaries for operational applications. The snow program is also the most completely integrated into the spatial measurement domain. Snow monitoring was initiated at the very start of the RCEW project, as the importance of snow in the overall hydrologic cycle was recognized from the outset. In the early years, snow courses were established, the snow pillow, now used throughout the United States, was developed (Johnson and Marks, 2004; Marks et al., 2002), and methods for estimating wind-affected precipitation were established (Hanson et al., 1979; Rawls et al., 1975). It was quickly discovered that the amount of snow falling was only part of the knowledge required to understand snow accumulation and melt dynamics. Detailed snow surveys (30-m grid) within two subwatersheds were conducted starting in the 1980s (Winstral and Marks, 2014). Modeling began in earnest in the late 1990s when the energy-balance-based iSnobal (Marks et al., 1999, 1992) model...
was applied to the previously established Reynolds Mountain East subwatershed (Marks et al., 2002). The general approach was to measure and evaluate the processes controlling snow accumulation and melt at the spatial scale required to effectively capture the effects of those processes, starting with precipitation, incoming solar radiation, and air temperature. Over the years, processes of wind redistribution (Winstral and Marks, 2002; Winstral et al., 2013), vegetation interactions (Hardy et al., 2004; Link et al., 2004; Sicart et al., 2004), longwave radiation (Marks and Dozier, 1979), and the rain–snow transition elevation (Marks et al., 1998, 2001, 2013) were progressively added, tested, and verified. Each year, as conditions varied (wet, dry, warm, cool, etc.), effectively became another small test of the model. Eventually, it was shown that a process-based, high-resolution (10-m) snow model could accurately simulate snow accumulation and melt dynamics in a well-instrumented catchment (Kormos et al., 2014, 2017; Marks et al., 2002) and that, when coupled to a hydrology model, it could accurately track streamflow across a small catchment in the RCEW (Kumar et al., 2013) or a much larger basin (Garen and Marks, 2005). While this was a great achievement, it was widely regarded as too complicated an approach for large-scale management of water resources on an operational basis.

The next generation model development is now underway to accomplish just that. The foundation for the approach is a verified model based on physical processes and hence, in principle, transferable across scales and locations. Application requires considerable computational resources in terms of CPU and storage because near-real-time energy balance is calculated at a high spatial resolution (50 m) every hour across domains of thousands of square kilometers. Recent hardware advances have largely solved this problem. The challenge is more to develop utilities that effectively use that hardware. For example, non-static forcing data (temperature, radiation, humidity, precipitation, phase) need to be distributed from limited measurements across the modeling domain. An example of this is a dataset developed as part of the CZO project that uses approaches developed by Susong et al. (1999) and includes 31 yr of hourly forcing data at a 10-m spatial resolution (Kormos et al., 2018). Figure 2 was created with those data. They will facilitate model development and testing at a variety of spatial and temporal scales.

The Spatial Model for Resources Framework (SMRF) utility (Havens et al., 2017) was developed to automate those forcing data generation procedures, ensuring consistency in model setup and making it possible to apply the suite of modeling tools easily across any area, independent of data availability. This has been combined with other utilities to form a coherent snow and water supply simulation and forecasting system that is modular and flexible. Reports are currently provided biweekly on snow volume and conditions for the 7000-km² Boise River basin to the water managers in Idaho.

Another critical part of the snow model implementation has been the integration of high-resolution (lidar) snow depth data in collaboration with the NASA Jet Propulsion Laboratory Airborne Snow Observatory, who provide airborne lidar snow depth measurements at roughly 2-wk intervals (Painter et al., 2016). For example, in the Tuolumne River basin in California (1200 km²), the snow modeling system is initiated on 1 October, run forward to the first lidar overflight, stopped and updated with lidar-measured snow depths, and then run until the next lidar overflight. This is repeated to the end of the year and is illustrated in Fig. 5 (Hedrick et al., 2018), where the initial model simulation results in a fairly smooth snow cover but the update redistributes the snow to a more realistic drift and scour distribution. The first update (e.g., 2014 in Fig. 5) results in the greatest change, while later updates (e.g., 2015 in Fig. 5) indicate much smaller differences. It is evident that simulated snow volume is generally representative of basin storage, but snow distribution (patterns of drift and scour locations) is not well represented until it is integrated with spatial measurements of depth from the lidar overflight. Once the distribution has been defined by lidar, even issues of limited precipitation and meteorological data for this remote alpine basin can be corrected.

Climate Change

Climate change was not regarded as a research topic when the project was initiated in 1960 because climate stationarity was widely assumed then. Our investigations into climate change have been essentially opportunistic in that existing data collected for other purposes happened to be useful. An examination of 45 yr of RCEW data (Nayak et al., 2010) indicates that: (i) temperatures increased at all elevations (upper, middle, and lower parts of the RCEW), (ii) daily minimum temperatures increased more than daily maximums, (iii) the proportion of precipitation falling as snow has declined, (iv) peak streamflow is earlier in the year, and (v) total precipitation and streamflow show no trend. One very important implication of these results is that the rain–snow transition elevation has increased, so that a smaller portion of the watershed is dominated by winter snow (Fig. 6). Interestingly, no trends in soil water content were observed during a somewhat shorter (30-yr) period (Seyfried et al., 2011).

This kind of analysis is notable in that it provides a coherent picture, from precipitation to snowmelt to water uptake and storage to streamflow, across a broad environmental gradient of an entire watershed. It opens the opportunity to investigate more fully the impacts of climate change on ecohydrologic and biogeochemical processes. This work has only begun at the RCEW, with a recent investigation into the viability of snow-drift-dependent aspen groves (Soderquist et al., 2018). Investigation of deep weathering in the critical zone at different elevations indicates, tentatively, that the ongoing migration of the rain–snow transition elevation may be impacting granite weathering (Nielsen, 2017).

Land Management, Erosion, and Fire

Among the first charges for the newly established RCEW was to determine rangeland erosion rates and the impacts of management. Along with the first vegetation map of the area, a series of Universal Soil Loss Equation erosion plots were established and measurement of sediment discharge was initiated. In the 1970s, grazing exclosures were established in different subwatersheds to assess the impacts of cattle grazing on vegetation. Erosion research at the RCEW (Pierson et al., 2015; Al-Hamdan et al., 2012, 2017)
has substantially contributed to the further development of the Rangeland Hydrology and Erosion Model. Recent studies evaluating the impact of grazing on biological soil crusts show no significant influence of grazing on soil biological crust activity as measured by nitrogenase activity (Schwabedissen et al., 2017) and microbial composition (Blay et al., 2017), with the exception of lower elevation sites where legacies of fire may mask these treatment effects.

Indeed, fire has become an important part of this research due to the impact fire is having on native vegetation, leading to a conversion of native sagebrush ecosystems to exotic annual grasses in low-elevation areas and for the potential use of fire to control expanding juniper at higher elevations. Most fire research takes place post-fire, with no opportunity to document pre-fire conditions, thus making it difficult to determine the changes caused by fire. As a long-term observatory, it has been possible to schedule prescribed fires in which pre-fire conditions are well documented. Since 2002 there have been three prescribed, research fires within the RCEW leading to insights into erodibility. This research, combined with data from other sites and studies, has resulted in generalized appreciation for the effects of fire on the erosion hazard over time (Clark et al., 2016, 2018; Williams et al., 2016, 2018). In general, results indicate that rangeland sites are highly susceptible to erosion, with its attendant loss of C and nutrients, immediately following fire, but that the system “heals” rapidly, substantially improving after 1 yr (Fig. 7).

The integrative work has begun with a determination of water and C uptake response to prescribed fire. Results show rapid
recovery of vegetation, water uptake, and productivity following prescribed fire (Fellows et al., 2018; Flerchinger et al., 2016). In Fig. 8, we show that gross ecosystem production (GEP) increased following prescribed fire, with the exception of the year immediately after the fire (Fellows et al., 2018).

Water and Energy Balance

Precipitation gauges and weirs installed in the initial years of the RCEW are important in closing the water balance, but they tell only a small part of the story. In snow-dominated, semiarid regions, evapotranspiration often consumes >90% of the water balance, and nearly all of the streamflow passes through the soil, reaching the stream via subsurface flow. Advances in energy balance monitoring, soil water monitoring, and geological mapping have contributed significantly toward understanding and quantifying catchment-level water and energy balances.

Soil water content and storage is a critical part of the water balance affecting streamflow generation, evapotranspiration, and plant growth and productivity. Measurement of soil water was a priority very early in the project. By the late 1970s, a network of neutron probe monitoring locations was established in conjunction with established, instrumented subwatersheds, and a biweekly measurement regime has been maintained since that time, resulting in an unusually long, >40 yr, record (Seyfried et al., 2001d). Soil temperature measurements at five stations started in the late 1980s. With the development and testing of relatively new electronic instrumentation (e.g., Seyfried et al., 2005), monitoring has expanded to >40 locations. These data have provided a rigorous basis for evaluating the Soil Ecohydrology Model and evaluating soil water trends with time (Seyfried et al., 2009; Finzel et al., 2016).

Energy balance measurements were conducted in the 1990s with Bowen ratio instrumentation (Flerchinger et al., 1996b; Wight et al., 1993). Eddy covariance, first over snow (Reba et al., 2009), then including summer conditions (Flerchinger et al., 2010), followed in the early 2000s. These field observations, combined with process-based modeling, contributed to advancements and validation in snowmelt modeling with isNoBal (Reba et al., 2012, 2014) and surface energy and water balance modeling within a multilayer canopy model using the SHAW model (Flerchinger et al., 1996a; Flerchinger and Seyfried, 2014).

The first extensions to larger scales involved water and energy balance research in the subwatersheds. Thus, energy balance and soil water monitoring, combined with meteorological and streamflow measurements, have contributed to quantifying hydrologic processes within the RCEW, enabling accurate, multiyear water balance closure for multiple years (Flerchinger et al., 1998, 2010; Flerchinger and Cooley, 2000; Chauvin et al., 2011; Flerchinger and Seyfried, 2014). Additionally, pre- and post-fire monitoring of energy, water, and C balances and soil water has led to assessment of the hydrologic and vegetation response and recovery to

Fig. 6. With rising temperatures, the rain–snow transition elevation is also rising. In the history of the Reynolds Creek Experimental Watershed (RCEW), the watershed has transformed from about 40% of the land surface dominated by snow to about 5%.
prescribed fires (Seyfried and Wilcox, 2006; Flerchinger et al., 2016; Fellows et al., 2018).

We are extending research to the entire RCEW, evaluating two of the primary environmental gradients, those associated with elevation and those with local topography. Using long-term data, soil water storage along the elevation gradient has been described in terms of the interannual variability in the amount of soil water stored and the timing of maximum storage (Fig. 9) (Seyfried et al., 2011). On average, maximum soil water storage at the lowest site (Flats, 1190 m) peaks in late February with about 5 cm of water, while at the highest site (Reynolds Mountain East, 2185 m), it peaks in mid-April with about 16 cm of water. Interannual variability of soil water is very low at all elevations by the end of the very dry summer months.

Investigation into topographic effects is also underway. As an example, soil temperature measurements using fiber optic cable has shown that local gradients on the order of 200 m can be as strong as the entire elevational gradient (Fig. 10) (Seyfried et al., 2016). Note that temperature is nearly uniform on both slopes (north-facing and south facing) during the snow-covered winter but differs by >8°C in the summer. In fact, the mean annual soil temperature difference between the two slopes is about the same as the difference between the top and bottom of the watershed (1000-m elevation difference) on nearly level topography. These findings support the conclusion from snow modeling that high resolution is critical for understanding soil processes. This is further supported by an analysis of the energy balance and SHAW modeling indicating that evapotranspiration from adjacent areas characterized by differing soils and snow regime vary dramatically both in terms of the amount and timing of transpiration.

### Landscape Soil Carbon Cycling

Little attention was paid to soil C or to C cycling during the first 50 yr of the project. With increasing CO$_2$ concentrations in the atmosphere worldwide, quantification of the cycling and sequestration of C on the landscape have become vital but poorly quantified topics. The amount of soil C is a reflection of the long-term C cycling. Not surprisingly, the amount of soil C in RCEW soils is highly variable. For example, at one high-elevation site under aspen and affected by snow drifting, the depth-weighted average (to 150 cm) soil organic C (SOC) content is 20.3 g/kg C with no measureable soil inorganic C (SIC). (Soil pH is about 6.3 at all depths). This contrasts with a depth-weighted average SOC content of 5.0 g/kg C at a low-elevation, much drier site dominated by sagebrush. At this site, however, 39.8 g/kg C of SIC was measured, indicating that considerably more total soil C may be stored at such low-elevation locations. Preliminary data indicate that SIC is not found where the mean annual precipitation is >500 mm/yr due to leaching of carbonates. Thus, there are strong gradients of soil C amount and form within the RCEW, reflecting a host of processes related to plant productivity and biogeochemical reactions in the soil and driven by the climate. This “flipping” of the predominant soil form with elevation, or more precisely, with soil environment, is evident in the detailed, watershed-specific soil survey reported nearly four decades ago by Stephenson, (1977).
Since its inception in 2013, the RC CZO has been directed toward the overarching hypothesis that soil environmental variables (e.g., soil water content, soil temperature, net water flux) measured and modeled at the pedon and watershed scales will improve our understanding and prediction of soil C storage, flux, and processes. The ultimate objective is to develop a spatially integrated understanding of C fluxes in the watershed that is transferrable to the wider terrestrial ecosystem. The primary objectives are to: (i) create a landscape-scale distributed soil C and environmental dataset that can inform our understanding of the processes controlling soil C fate from the plot to the watershed scale; (ii) develop an integrated, watershed-scale instrumentation and monitoring network focused on soil C dynamics that is of value across hydrologic, ecologic, and geologic disciplines; and (iii) develop an integrated modeling framework that can promote the evaluation of conceptual models of soil C behavior and associated interactions with climate, ecology, and landscape that can inform upscaling mechanistic understanding to climate models.

For the first objective, soil C distribution, both organic and inorganic, generally to a depth of 1 m has been measured using data from more than 300 soil pits. At present, these data are being distributed across the landscape using more easily measured, strongly correlated parameters. Patton et al. (2018a) found that soil depth, a key determinant of total soil C, can be effectively predicted from watershed-scale surficial slope curvature data derived from high-resolution (e.g., 3-m) topographic information in a wide range of watersheds. In the Johnston Draw subwatershed, for example, we have found that surficial curvature, determined with high-resolution airborne lidar, can be used to spatially distribute SOC and soil depth (Fig. 11) (Patton et al., 2018b). Aspect is an additional local control, with SOC concentrations about twice those of adjacent south-facing slopes. On a larger, RCEW-wide scale, lidar (for aboveground biomass), in conjunction with hyperspectral and climatic data, has been found to correlate strongly with SOC (Will, 2017). Similar efforts are underway for SIC (Stanbery et al., 2017). Ultimately, these maps will be constructed from process-based C models.

The basic monitoring associated with the C environmental gradient was described above. The intention is evaluate the fluxes, such as respiration, in the context of net ecosystem exchange and how it is affected by variable climate and soil conditions. In addition, detailed monitoring of vegetative productivity, phenology, and forage production are included to inform models about rangeland productivity for livestock production. It is intended that they provide the information required to inform process-based models along the environmental gradient that can then be applied throughout the RCEW and, eventually, the region in general. Basic data to date indicate that the entire watershed is probably a C sink in most years, although the lower elevations may be almost neutral (Fig. 12). Relationships between water and C uptake are currently under investigation.

These data provide considerable insights on their own, but the intent is to use this combination of process-level information, spatial patterns, and landscape-scale controls to test and develop C models that describe soil C dynamics across the landscape. The data required for this are now coming together, and model forcing data have been published to facilitate model testing. Testing of the ecosystem model BIOME BGC is currently underway.
Critical Zone Hydrology

There was considerable interest early in the project in groundwater resources, and it was understood that streamflow generated from lateral flow occurs mostly via groundwater. A number of observation wells were drilled, limited chemical analysis performed, and some early geophysical surveys conducted. For various reasons, that work received little attention until the recent participation in the CZO. In the meantime, hydrologic models have advanced tremendously both structurally, incorporating belowground “bedrock” flow, and computationally, so that capabilities have increased by several orders of magnitude. Models, such as iSnobal, can now be applied to relatively large areas. The present limitation is the parameterization of those models. Very little is known, even on a qualitative level, about how water moves laterally to channels through underlying geologic material, which remain, effectively, a “black box.” It is safe to say, however, that homogenous conditions generally do not prevail. Recent developments in near-surface geophysics offer the potential to better inform these models. In particular, catchment-scale geophysical transects offer information about the distribution of subsurface porosity (Holbrook et al., 2014) and suggest that porosity may be controlled by several processes, including frost cracking (Befus et al., 2011), hydrological drainage of bedrock (Rempe and Dietrich, 2014), and topographic and tectonic stress (St. Clair et al., 2015). Such geophysical transects, typically on the order of a few hundred meters long and consisting of seismic refraction and/or electrical resistivity data, can provide important information at the catchment scale. However, in a watershed the size of Reynolds Creek, it is impractical to collect enough refraction and resistivity data to map the entire watershed and difficult to achieve the depth of penetration necessary to characterize the likely flow paths.

As part of the RC CZO project, therefore, we have collected geophysical data across multiple scales, from meters to tens of kilometers, to characterize possible subsurface flow paths. The centerpiece of this effort is a large-scale electromagnetic survey flown in 2016—the only one of its kind to date in a CZO (Fig. 13). These data were acquired using the SkyTEM time-domain electromagnetic instrument (SkyTEM, 2017), a large instrument flown by a helicopter that transmits an electromagnetic field into the subsurface and records a secondary field generated by eddy currents in subsurface conductors. The resulting profiles can be collected rapidly and provide images of subsurface electrical resistivity that typically extend 300 to 500 m into the subsurface. Our survey acquired 834 line-kilometers of data covering an area of $\geq 100$ km$^2$ at a line spacing of 150 m—a substantial fraction of the watershed. The results show several electrical conductors that may represent deep aquifers.
or hydrological flow paths (Fig. 13C). These large-scale surveys can be combined with higher resolution, local geophysical transects that show the distribution of shallower weathering and aquifers (Fig. 13B). Such detailed transects (seismic refraction and electrical resistivity) have been conducted in or near three of the long-term subwatersheds. At Reynolds Mountain, where the surficial hydrology has been intensively studied, these surveys suggest flow paths that are consistent with known water sources and springs (Radke, 2018). The RC CZO thus represents a primary locale for collecting multiscale geophysical observations to address critical zone and hydrological questions (Robinson et al., 2008; Parsekian et al., 2015).

We are currently planning to drill observation wells to verify the efficacy of these flow paths and “ground truth” the geophysical data. In addition, we are measuring water chemistry in streams and groundwater, with the idea that this chemistry must reflect the flow paths through which it has traveled. Finally, we are conducting preliminary modeling exercises that utilize more specific flow path information to improve and constrain subsurface parametrizations. This work has a long way to go, but we expect to be fruitful in the context of long-term research. Much as snow modeling at a large scale seemed impossible 20 yr ago but is being witnessed today, this may prove to be the exciting frontier of the future.

**Data Availability**

The NWRC has a long history of not only collecting high-quality data but also making it publically available. In 2001, a series of data reports were published describing the primary data collected up to 1996 and pointing to an ftp site where quality-controlled data from the 1960s can be retrieved (Hanson, 2001; Hanson et al., 2001; Marks, 2001; Marks et al., 2001; Pierson et al., 2001; Seyfried et al., 2001a, 2001b, 2001c, 2001d; Slaughter et al., 2001). This policy has continued to the present. Since then, a series of modeling data sets have been published, with appropriate
digital object identifiers (DOI’s), in which missing forcing data have been gap filled using local knowledge of the climate and correlations with other stations (Enslin et al., 2016; Godsey et al., 2018; Kormos et al., 2013, 2018; Reba et al., 2011; Winstral and Marks, 2014). In addition, all CZO student research data are being published through either the Ag Data Commons at the National Agricultural Library or ScholarWorks at Boise State University. At present, there are nine such publications in ScholarWorks, including the 31-yr model forcing parameter dataset described above.

**Observatory Networks**

There has been a trend in recent years toward the development of observatory networks. These networks have the potential to expand the scope of influence of any specific observatory by extending the environmental gradient well beyond that of any individual observatory through cross-site research. In addition, individual sites benefit from shared resources. The RC CZO has benefitted from this association in that geophysical and remote sensing data acquisition has been greatly facilitated. We are also actively participating in cross-site hydrologic research. Other networks relevant to the RCEW include: the Long-Term Agroecosystem Research (LTAR) Network, NASA’s Soil Moisture Active and Passive (SMAP), and the Detritus Input Removal and Transfer (DIRT) network.

The LTAR was established to build the knowledge required for sustainable intensification of agriculture, increasing yields from the current agricultural land base while minimizing or reversing agriculture’s adverse environmental impacts. As part of the NWRC, the RCEW has recently become a funded partner in the network. In the Intermountain West, much of the emphasis is on the sustainability and productivity of rangelands similar to those in the RCEW. Soil fertility, soil organic matter, and soil erosion, combined with the soil water balance, are clearly keys to understanding sustainability in these unfertilized systems. For this reason, the contributions of ongoing CZO and other RCEW projects are foundational. We expect to build on this work to evaluate grazing management, better quantify forage production, and assess the impacts of vegetation conversion to evaluate the long-term productivity of Great Basin landscapes.

As part of the SMAP validation network, we have greatly expanded soil water instrumentation to get a much better understanding of how soil water varies across the landscape. These data have contributed to a host of publications analyzing sampling strategies for ground truthing satellite data and interpretation of the SMAP soil water production (e.g., Nearing et al., 2017; Reichle et al., 2017; Colliander et al., 2018).

The DIRT project is long-term in nature (Crow et al., 2009) and the Reynolds Creek location is only recently established. There is great potential for this study to further inform soil C research on the watershed while contributing valuable data to the larger, international study.

**Perspectives for Future Observatory Research**

Observatories such as the RCEW occupy an important niche in the overall natural science research environment due to the combination of longevity and relatively large scale. Longevity informs research both in terms of trends and context and provides a stable platform for research. The relatively large scale can provide critical environmental gradients, which must be incorporated into larger scale extensions of results obtained from the
Local Topography Matters

The impacts of climate on ecohydrologic and biogeochemical processes are well documented and incorporated in models. In mountainous terrain, this generally translates into discretization in terms of elevation bands. Research at the RCEW (and other locations) is showing that gradients on the scale of tens of meters can have impacts of similar magnitude to large (hundreds of meters) of elevation change. Examples from Reynolds Creek include snow deposition, groundwater recharge, aboveground biomass, soil water and C uptake, soil C content, soil temperature, and soil depth. Furthermore, these gradients can be measured with relatively new, high-resolution instrumentation such as lidar, geophysics, and fiber optic temperature sensing. The implications for future research and modeling are that this small-scale, “subgrid” variability must be incorporated into larger scale models and that the tools for describing this variability are increasingly available. The observatories often provide an excellent platform for this research.
important implications for future scientific research as well as practical management of natural resources.

**Carbon Cycling in Semiarid Landscapes May Play an Important Global Role**

Though often overlooked due to relatively low productivity, the amounts of C stored in semiarid soils, when integrated over depth and when inorganic C is considered, is considerable. At present, net C uptake occurs throughout the watershed. In addition, it appears that recoveries from major perturbations, such a fire, are quite rapid. These resources are further enhanced when the relatively high productivity “hotspots” in the landscape are considered. Looking to the future, we think that major advancements will occur as we integrate hydrological and biogeochemical processes across the landscape.

**Climate Change and Coherence**

The ability to document climate change impacts is an unexpected benefit of the long-term data collected at the RCEW. The original intention was to properly quantify hydrologic parameters assumed to be stationary, but instead the data indicate a non-stationary climate. In addition, there is added value in a spatially integrated system of measurements that incorporates key environmental variables because it shows directly how various processes are linked and because it provides data for a spatially integrated hydrologic analysis of climate change impacts. Looking ahead, we intend that this information, when linked to biogeochemical processes, will expand our understanding of climate change impacts. There could hardly be a more important challenge for our time.

**Multidisciplinary Approaches Hold Extra Value**

The addition of CZO research to the RCEW has revealed a wealth of cross-discipline connections related to hydrology, stream chemistry, geology, and C dynamics. It is unlikely that any institution could staff the variable expertise that becomes available when resources are provided to outside researchers. Multiple disciplines foster cross-disciplinary research, which, in the long run, is essential. We should be aware that Nature does not recognize the disciplines we have constructed.

**Long-Term Funding Continuity Is Critical**

Funding for most grants comes and goes. Principle investigators come and go. Specific projects come and go. It is extremely helpful to have consistent staff with long-term support, such as provide by the USDA-ARS in our case, to maintain high-level scientific infrastructure over time. This includes support of instrumentation, maintenance, and scientific personnel. The latter is often overlooked but critical. In the long run, data quality will not be maintained without scientific interest. Given this, the coming and going of projects and scientists can be effectively supported and the rather large investment in scientific infrastructure at observatories can pay off.

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