McNamara James (Orcid ID: 0000-0001-7625-4507)

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Authors:

James P McNamara, Boise State University, jmcnamar@boisestate.edu

Shawn G Benner, Boise State University, sbenner@boisestate.edu

Michael J Poulos, Boise State University, mikepoulos@boisestate.edu

Jennifer Pierce, Boise State University, jenpierce@boisestate.edu

David Chandler, Syracuse University, dchandle@syr.edu

Patrick Kormos, US Weather Service pkormos@gmail.com

Hans-Peter Marshall, Boise State University, hpmarshall@boisestate.edu

Alejandro Flores, Boise State University, lejoflores@boisestate.edu

Mark Seyfried, USDA Northwest Watershed Research Center, Mark.seyfried@ars.usda.gov

Nancy F Glenn, Boise State University, nancyglenn@boisestate.edu

Pamella Aishlin, Boise State University, pamaishlin@boisestate.edu

Graphical/Visual Abstract and Caption

Catchment form is intimately connected to function in the Dry Creek Experimental Watershed.

Abstract

Fifteen years of cumulative research in the Dry Creek Experimental Watershed in southwest Idaho, USA, has revealed relationships between catchment form and function that would not have been possible through independent short-term projects alone. The impacts of aspect and elevation on incident energy and water, coupled with climate seasonality, has produced tightly connected landform properties and hydrologic processes. North-facing hillslopes have steeper slope angles, thicker soil mantles, finer soil texture, and higher water holding capacities than their south-facing counterparts. This trend is modulated by elevation and vegetation; higher elevation sites, where aspect differences in vegetation are less evident, exhibit less distinct hydrologic properties. The storage of water first as snow, then as soil moisture determines how upland ecosystems survive the seasonal and persistent water stress that happens each year, and sustains streamflow throughout the year. The cumulative body of local knowledge has improved general understanding of catchment science, serves as a resource for conceptual and numerical evaluation of process-based models, and for data-driven hydrologic education.

Introduction

Long-term catchment research is a pillar of scientific hydrology [1, 2]. Knowledge generated from a loosely organized global network of catchment research sites has created a platform upon which paradigms stand and from which they fall, and has advanced our understanding and application of fundamental hydrologic principles. An essential value of long-term sites is that the continuity of data provides a backbone to support short-term campaign-style research: The holistic story of catchment function can be discovered incrementally through short-term studies connected by the long-term record.

This paper describes the operation and scientific contributions of the Dry Creek Experimental Watershed (DCEW) in southwest Idaho, USA (Figure 1). The mission of the DCEW is to provide spatially distributed and temporally continuous hydrometeorological data for researchers and educators in an archetypal semi-arid, snow-dominated montane catchment. Our goals are to discover fundamental concepts about 1) how catchments of this type receive, transmit, and release water, 2) the co-evolution of ecohydrological processes and landscape form, and 3) the interactions between hydrological, geological, and ecological processes.

The DCEW was not established as part of a government agency mission (e.g. the US Department of Agriculture research watersheds), nor is it part of a network funded by long-term grants (e.g. the NSF Critical Zone Observatory network). Rather, the DCEW evolved organically in response to the interests of a small group of researchers dedicated to catchment science. The site began as a hillslope runoff generation project on a typical three-year grant in partnership with the nearby Reynolds Creek Experimental Watershed (RCEW)[3]. As commonly happens at the end of a project, a decision was made to leave dataloggers in place. A stream gauge turned a hillslope study into a catchment study, a series of grants from various federal, state, and local sources turned a collection of instruments into a network, and a long-term site evolved to its present state with approximately 30 stations logging a suite of spatially distributed environmental variables.

Two consistent themes have emerged by discovery and design from DCEW research. First is the intimate connection between catchment form and function as expressed through relationships between aspect, elevation, and water. Aspect moderates the amount of solar radiation that a hillslope receives [4], while elevation relief imposes temperature and precipitation gradients [5, 6]. The combined influences can impose a range of hydroclimatic regimes within a single catchment. Second is the role that storage of water as snow, soil moisture, and groundwater plays in translating climatic seasonality to hydrologic seasonality. Precipitation in the semiarid western US comes primarily in the winter, but ecosystems need water primarily during their growing season. The properties of a catchment that regulate how water is stored and released determine how ecosystems survive the seasonal and persistent water stress that happens each year [7]. In the DCEW, the overlap and continuity of studies within these and other themes over a nearly 20-year period have enabled researchers to test long-standing hydrologic paradigms and new theories in a collective, cumulative approach.

In this paper, we demonstrate how a large body of diverse research campaigns combined with long-term monitoring has led to a set of theses and papers that provide a comprehensive understanding of catchment behavior. Such broad and deep information on the relationships between processes and properties could not have been obtained by short-term projects alone, nor under the limitations that are imposed on mission-oriented sites. Following a description of the setting and monitoring program, we summarize the scientific contributions from the DCEW with an emphasis on the impacts of complex terrain, seasonality, and storage. We then offer some thoughts on the broader impacts of long-term research catchments.

The Setting

The DCEW drains 27 km^2 in the hills adjacent to Boise, Idaho, USA. In the Koppen classification system, the lower portion of the DCEW is classified as a steppe summer dry climate (BSk), and the high elevations are classified as moist, continental climate with dry summers (Dsa).

The DCEW resides in the southwestern margin of the Atlanta lobe of the Idaho batholith, which is composed of mostly-homogenous granodiorite [8]. A relatively thin, coarse-grained soil profile was formed by in-situ weathering of the underlying granite, decomposition of biological material, and deposition of wind-blown loess on lee slopes. In general, soils can be classified as loamy sands and sandy loams [9].

Lower elevations and south-facing slopes tend to support sagebrush-steppe ecosystems, while higher elevations are composed of mixed conifer forest [10]. Mid-elevations show the most diversity with sagebrush-steppe vegetation on south facing slopes and forests on north facing slopes. Riparian vegetation in the lower elevations illustrate stark contrasts to the sparse vegetation on the water-limited hillslopes (Figure 1).

Accessibility to the DCEW is provided via a paved road along the northwest boundary, a seasonal U.S. Forest Service road along the eastern boundary, and a small network of abandoned private logging roads in the northwest portion of the catchment. These abandoned roads are gradually being blockaded by private landowners as part of multiple ongoing conservation efforts. Researchers typically access field sites via a network of privately and publically maintained hiking trails.

Land in the DCEW is owned by a patchwork of federal, state, and private holders, and land use has varied. Some new, post-2000, private homes exist along the paved road, but no buildings exist within the catchment itself. Small mining operations were conducted in the catchment beginning in the late 1800's. Mining operations in this region were typically not highly successful ventures, so impacts from those activities have been relatively small. Limited timber harvest operations in upper Dry Creek have occurred as recently as the mid-1990's following the construction of a series of roads, apparently intended for a potential residential development. Timber harvest was limited to areas adjacent to the road network. Limited cattle grazing occurs in the catchment on lease agreements with private landowners, and tended sheep herds pass through the region each spring.**Long-term data collection**

Meteorological measurements are made at five stations spanning elevations from 1151 m to 2114 m (Figure 1). Additionally, a SNOTEL station operated by the US Department of Agriculture exists in the Bogus Basin Ski Resort adjacent to the DCEW. Streamflow is monitored at seven locations ranging from a small ephemeral stream at the Treeline site (TL) draining 1.2 ha to the outlet at Lower Gauge (LG) draining 2690 ha. A v-notch weir and an H-flume are used in streams at the Treeline and Bogus Stream (BG) sites, respectively. All other sites use rating curves developed at natural controls.

Several different approaches to monitor soil moisture have been deployed at various times. The longest operating sites (Treeline (TL) and Lower Weather (LW)) were installed in 1998 and consist of two replicate profiles of Campbell Scientific CS615 dielectric permittivity sensors. These were supplemented at the Treeline site by a network of time domain reflectometry probes spanning the two aspects of the catchment. In 2008 a network of eight stations was installed specifically to evaluate aspect-dependent differences in soil water storage. These stations, henceforth called the aspect-moisture network, are on opposing north and south facing aspects at four elevations. Each station has four pits with four sensors in each pit for a total of 128 sensors (Decagon Devices 5TM, dielectric permittivity sensor). This aspect-moisture network consists of High North (HN), High South (HS), Mid High North (MHN), Mid High South (MHS), Mid Low North (MLN), Mid Low South (MLS), Low North (LN) and Low South (LS) sites (Figure 1).

Most permanent stations are logged with Campbell Scientific dataloggers. Data are delivered to a base station at Boise State University by a 900 MHz line-of-sight telemetry system. Raw near-real time data are stored and made available to the public on a dedicated server at Boise State University. Approximately once a year, routine data are cleaned and corrected, and then published to various repositories. All data are freely available either directly from these sources or upon request. Select data are available through the website earth.boisestate.edu/drycreek/dataaccess. Additionally, the DCEW has served as a testbed for many efforts of the Consortium of Universities for the Advancement of Science (CUAHSI) to provide high-quality data services to the hydrologic community.

Research Contributions: Catchment Properties and Hydrological Processes

A systems approach has guided research in the DCEW. The catchment acts as a processing filter that receives, stores, transmits and releases input signals of mass and energy to conditioned output signals [11]. These short-term hydrologic time-scale processes enacted over longer geological time scales produce catchment properties that in turn affect short-term hydrologic processes. That is, a dynamic feedback system exists between catchment form and function wherein the biophysical properties of a catchment simultaneously impact and are impacted by hydrological processes. For example, Nicotina et al.[12] suggested that the spatial patterns of soil thickness in the DCEW result from long-term interactions between hydrologic forcings, soil production, erosion, and sediment transport, while McNamara et al.[13]

demonstrated that soil water storage, which is regulated in part by soil thickness, impacts the timing and magnitude of runoff generation. The following sections discuss the distinct components of the catchment system in the DCEW including the catchment properties that govern and respond to hydrologic process, and the spatial and temporal variability of the input, internal storage, redistribution, and export of water. Considerable research has been performed worldwide on these topics; however we primarily cite Dry Creek work to demonstrate the value of long-term cumulative research.

Catchment Properties

The orientation of the terrain moderates the intensity and extent of incident solar radiation (Figure 2a), which influences the many processes and feedbacks that control the evolution of catchment form. Accordingly, the DCEW displays distinct aspect-related differences in biophysical properties that fundamentally control the partitioning, storage and release of catchment water.

North-facing hillslopes tend to have steeper slope angles [14] (Figure 2b), thicker soil mantles [15, 16] (Figure 2c), and finer soil texture [17] (Figure 2d) than their south-facing counterparts. Tesfa et al. [15] measured soil thickness at 949 locations throughout the catchment in order to develop statistical models for predicting soil thickness from topographic properties. Aspect is among the best predictors of soil thickness. Smith et al. [16] extended this study by evaluating the 32 soil pits in the aspect-moisture network (Figure 1). Soils are significantly thicker on north facing aspects, but differences diminish with elevation (Figure 2c). Kunkel et al.[18] demonstrated that carbon (C) and nitrogen (N) concentrations in soils are also related to terrain. North facing slopes have approximately 5 times more C and N than adjacent south facing slopes, and both C and N increase with elevation. Geroy et al. [17] confirmed these findings and the findings of Smith et al.[16] in a transect crossing an E-W trending valley. Soils on the north facing aspect are finer grained, have higher organic carbon contents, and have lower bulk densities.

The causes of textural differences between north and south facing slopes is a current topic of research. Stark [19] provided geochemical evidence to suggest that some portion of silt and clay particles in DCEW soils originate from exogenous wind-blown dust. More fine-grained material on north facing slopes could arise from differential deposition related to prevailing wind directions, or from differences in aspect-dependent erosion and weathering processes.

Poulos et al. [20] hypothesized that aspect-related differences in soil properties and slope angles should manifest in changes in catchment form. Indeed, south-facing catchments, on average, have 30% denser drainage networks, are ~5-10° less steep, and are ~40% longer than opposing north-facing slopes. Their explanation is that on south-facing slopes, reduced soil water storage and evapotranspiration at pedon-scales increases subsurface drainage, groundwater flow to channels, and runoff potential. Increased runoff, in conjunction with the reduced cohesion of coarse grained soils, could have increased catchment-scale drainage incision, expansion, and competition, promoting divide migration, land surface gradient reductions, and elongation.

Hydrological Processes: **Water inputs**

The timing and magnitude of water input to the DCEW is the product of regional seasonality, air temperature and precipitation lapse rates, and spatially heterogeneous snowmelt patterns imposed by elevation, aspect and vegetation [13, 21, 22]. The hypsometrically weighted average annual precipitation for the catchment is approximately 630 mm [23], which is consistently similar to what is measured at the mid-elevation Treeline site. The total annual precipitation approximately doubles over the 1100 m elevation range (Figure 3).

Elevation-induced precipitation and temperature gradients put the DCEW in a rain-snow transition zone[21]. A seasonal snowline tends to occur near the mid-elevation Treeline site. Lower elevations receive mostly rain while higher elevations receive mostly snow (Figure 3). The higher precipitation and lower temperatures at high elevations create a persistent annual snowpack that recharges groundwater[24] and sustains streamflow in the dry summer months. Rain-on-snow (ROS) events are possible anytime when snow is on the ground, which complicates efforts to measure and model spatially distributed water input rates [21, 25, 26].

Seasonality of precipitation in the semiarid western US is an important control on catchment hydrologic behavior. In the DCEW, December and March are typically the wettest months, while July and August are the driest (Figure 3). If we begin the water year at August 1, the average centroid of precipitation for all elevations occurs in late January, while the centroid of streamflow occurs in early March. Peak evaporative demand is in August. Storage of water as snow in the higher elevations and as soil moisture throughout the catchment helps bridge the gap between the time of precipitation supply and ecosystem water demand.

Elevation and aspect influence the timing of meltwater delivery to soils through differential accumulation and ablation of snow [22]. Differential accumulation occurs in several ways. First, more precipitation falls as snow at higher elevations due to orographic effects. Second, prevailing southwesterly winds interact with the terrain such that north and east facing slopes tend to be in the lee of storms and receive more snowfall and redistributed snow (e.g. drifts). Third, vegetation intercepts falling snow so that what accumulates on the ground is not uniform. Differential ablation occurs as south and west facing slopes receive more solar radiation, and lower elevations melt earlier in the season due to warmer temperatures. The integrated result of these processes causes the degree of snowpack spatial variability to increase throughout the winter and spring, and highly variable spatial and temporal patterns of snowmelt [21].

Meltwater delivery to soils is further complicated by the properties and processes within a snowpack. For example, it is commonly assumed in hydrologic models that meltwater is delivered vertically to soils. However, in sloped terrain, lateral flow in snow can be significant due to large hydraulic conductivity contrasts between storm layers [27, 28]. Lateral flow in snow can deposit water in advanced downslope positions or even directly into streams without interacting with soil, which reduces travel time through the catchment.

Vegetation complicates the relationship between aspect and snow distribution by intercepting falling snow, shading snow from solar radiation, generating longwave radiation, and reducing wind speeds that drive turbulent energy fluxes. Forested areas in the DCEW tend to accumulate less snow than open areas due to evaporation and sublimation of intercepted snow [22]. However, forested areas retain snow longer due to shading of solar radiation. Because forests tend to occur on north facing aspects, the myriad of processes that forests and topography impose on snow are difficult to distinguish and are currently topics of study.

The interacting processes and properties that affect the point-scale accumulation and ablation of snow create spatially complex snowpack patterns that challenge hydrologic models. For example, hydrologic models are commonly forced by remotely sensed snow cover data at resolutions of tens to hundreds of meters, while snowpack variability occurs at much finer scales with correlation lengths on the order of meters to tens of meters [22]. In an effort to inform satellite-based hydrologic modeling with field-based knowledge about snowpack variability, Homan et al. [29] linked field-derived snow depletion curves (SDC) with fractional snow cover information from the Moderate Resolution Imaging Spectroradiometer (MODIS). An SDC plots modeled snow water equivalent (SWE) in a pixel against the fraction of that pixel that is covered with snow. Once derived for a locale, an SDC can be used to correct satellite-based model estimates of meltwater generation.

Whereas the SDC approach in Homan et al.[29] upscales field-based information to improve satellite snowcover estimates, Walters et al. [30] downscaled satellite-derived snowcover information using landscape properties that are known to control snow distribution. The authors exploited the persistent role of aspect and elevation in controlling hillslope-scale patterns of snow cover to develop a simple algorithm to take as input a MODIS-retrieved fractional snow covered area at 500 m resolution and synthesize 30 m images of snow presence/absence. Through a suite of data denial experiments, they compared synthesized and Landsat-derived snow presence/absence imagery and demonstrated significant predictive skill in their algorithm. These authors found that the optimal downscaling varied seasonally, and the variation in the downscaling could be modeled as a function of potential incoming solar radiation. Unsurprisingly, aspect- and elevation-induced patterns of snow cover are most prominent when and where snow cover is patchy.

Hydrologic Processes: Water Storage and Transmission:

The processes and properties that control the storage and routing of water within a catchment ultimately determine how a catchment transforms rain and snowmelt inputs to outputs as streamflow, deep percolation, and evapotranspiration [31]. Foremost among those controls are the physical properties of soils and their spatial variability, and the impact that those properties have on water holding capacity.

McNamara et al. [13] identified five characteristic soil moisture conditions in a water year: 1) dry, 2) transitional wetting, 3) wet low flux, 4) wet high flux, and 5) transitional drying (Figure 4). During the dry period, the catchment is essentially hydrologically dormant and any precipitation that occurs tends to evapotranspire before significant infiltration occurs. During the transitional wetting period, potential evapotranspiration is reduced due to cooler temperatures and dormant vegetation so that infiltration propagates deeper into the subsurface. The transition from the dry to the wet state occurs rapidly in response to an optimal combination of fall rain and reduced evapotranspiration. Soil moisture content then remains near a wet, stable level determined by field capacity for most of the winter. The lag between when near surface and deeper soils reach that wet stable state can be up to 2 months due to the storage of snow on the surface. Significant runoff generation occurs after the soil profile is wetted to the depth of the soil bedrock interface and connectivity between hillslopes and streams is established [32].

The existence of stable moisture states illustrates an important relationship between soil physical properties and hydrologic thresholds. The wet stable state reflects the field capacity of soils, defined here as the moisture content below which gravitational drainage rates are negligible. Without evapotranspiration, soils will not dry significantly. When the drying season begins and evapotranspiration becomes significant, soil moisture contents decline below that which can be accomplished by drainage alone, until the plant extraction limit is reached. The moisture range between field capacity and plant extraction limit is the effective storage capacity of the soil profile. Above field capacity, soils drain rapidly to streams, deeper soils, or groundwater. Below the plant extraction limit, water is simply unavailable to plants, and declines slowly with vapor diffusion and evaporation.

Differences in soil properties between north and south facing slopes produce differences in hydrologic thresholds. The finer texture on north facing slopes (Fig 2d) results in higher water holding capacities. Geroy et al. [17] demonstrated that for any given tension, moisture on the north facing slope is higher than moisture on the south facing slope (Figure 5a). The higher moisture holding capacities on north facing slopes manifest in higher field capacities (Figure 5b). For every depth at every station in the aspect-moisture network, field capacity is greater on the north facing slopes. Accordingly, the wet stable state tends to exist at higher moisture contents on north facing slopes (Figure 6). This enhanced ability to hold water, coupled with the thicker soils, enables north facing slopes to store more water than south facing slopes (Figure 7).

The ability of soils to store water is particularly important in highly seasonal environments where the timing of water supply is not aligned with the ecological water demand. The storage of water first as snow, then as soil moisture allows precipitation that falls in the wet season to be used by vegetation in the dry season. But because of the limited storage capacity of soils, the actual evapotranspiration is markedly lower than potential evapotranspiration. Smith et al. [16] demonstrated that winter precipitation generally exceeds soil storage capacity by 2.5 times. Accordingly, soil moisture profiles at most locations in the catchment tend to reach field capacity in early winter. With soil storage near capacity, additional meltwater makes only a limited contribution to the soil moisture reservoir. Water that is retained by the soil after the snowpack melts is lost to evapotranspiration in as little as 10 days (Figure 4). In contrast, spring precipitation extends moist soil conditions by up to 90 days into the warm season, when ecological water demand is highest (Figure 6). These field observations suggest that changes in spring precipitation may have the greater impact on upland ecosystems in this environment than snow. Furthermore, because soils reach field capacity in early winter, soil moisture availability may be relatively insensitive to transitions from snow to rain.

Water that survives passage through the soil column gets stored in bedrock fractures [33]. No deep monitoring wells exist in the DCEW, although we know from residential wells along the boundary of the catchment that extractable groundwater tends to exist at depths similar to the height above the nearest perennial stream. Isotopic evidence suggests that deep groundwater makes up a significant component of streamflow [34]. That is, annual snowmelt tends to recharge and displace groundwater to streams, rather than flow directly to streams. Tetzlaff et al. [34] used the HBV [35] model coupled with measurements of oxygen and hydrogen isotopes in precipitation and stream water to assess relative residence times in a comparative study of five northern catchments. Dry Creek had the longest relative residence times and the highest annual change in soil water storage of the catchments. The annual change in soil water storage was 289 mm, which closely matches estimates made by Parham [23]. The high soil water storage change occurs because of the extreme drying that occurs in summer in the DCEW, whereas the other sites in the comparison study remain relatively wet. The estimated change in annual deep groundwater storage was only 28 mm. This relatively low groundwater storage change coupled with essentially invariant isotope concentrations in streamwater suggest that groundwater levels remain relatively stable while receiving infiltration and releasing water to streams. Ala-aho et al. [36] confirmed these results and computed a residence time of > 5 years for streamwater in the high elevation Bogus sub-catchment.

Hydrologic Processes: Outputs

Water leaves the DCEW as evapotranspiration, streamflow, and deep recharge to groundwater. Here we present a summary of outputs in the context of the annual water balance written as

$$P-Q-ET-DR = dS$$

where P is precipitation, Q is streamflow, DR is deep recharge, and dS is the change in storage (all units in annual total depths). On an annual timescale we commonly assume that the change in storage equals 0. That is, the catchment returns to similarly dry states each summer regardless of the wetness of winter. Aishlin and McNamara [24], using a chloride mass balance approach, demonstrated that deep recharge at the catchment scale accounts for approximately 14% of annual precipitation. With measurements of streamflow and precipitation, they solved for evapotranspiration as the residual of the steady-state water balance leading to the conclusion that evapotranspiration consumes approximately 65% (449 mm) of total annual precipitation. These water balance numbers vary across sub-catchments depending on the distribution of bedrock fractures. For example, the Treeline sub-catchment loses approximately 34% of annual precipitation to deep recharge. The general magnitude of deep recharge from the Treeline sub-catchment was confirmed by two separate physically-based modeling studies. Kelleners et al. [37] estimated 53% for the same period, and Kormos et al. [38] estimated 34% in a different year. Losses from these higher elevation sub-catchments likely emerge in springs and stream baseflow lower in the catchment.

Whereas Aishlin and McNamara [24] measured deep recharge and then computed evapotranspiration by water balance residual, Parham [23] modeled ET using a distributed Penman-Monteith approach and then computed deep recharge by residual. The two studies agree that deep recharge is important, but Parham [23] estimated that ET accounts for only 46% of precipitation. Although the two studies disagree on the magnitudes of water balance components, both suggest that the annual total ET remains relatively invariant compared to precipitation and streamflow. Parham [23] computed an average annual ET of 326 mm with a standard deviation of 30 mm and coefficient of variation (CV) of 0.09, while precipitation and streamflow had CV's of 0.15 and 0.40, respectively.

The relatively consistent year-to-year annual ET likely reflects the limited soil water storage capacity of the thin soil mantle. This agrees with the concepts reported by Smith et al. [16], who stated that the magnitude of winter precipitation has limited influence on the survival of upland vegetation because the soil can only store what hydraulic properties allow. The catchment enters the drying season with essentially the same amount of water each year. Spring rains that replenish soil water stocks after ET has started can have a more significant impact on summer water availability than snow because they occur when soils are able to store the precipitation.

Parham [23] estimated the spatially distributed average soil water storage capacity to be 147 mm. That the annual evapotranspiration is 326 mm suggest that (a) soils are replenished with spring rains [16], (b) plants get water from other sources including deeper groundwater or (c) riparian zones make a significant contribution to catchment ET. McCutcheon et al. [39] confirmed that deep groundwater is an important source of water for plants, particularly conifers, by analyzing the isotopic composition of plant xylem water, soil water, streamflow, precipitation, and groundwater.

Graham et al.[40] demonstrated that riparian zone vegetation produces significant diurnal fluctuations in streamflow. Based on this observation, Geisler [41] used a "missing streamflow" method to evaluate the hypothesis that riparian transpiration can account for the difference between Parham's estimates of soil water storage capacity and catchment evapotranspiration under the assumption that riparian vegetation transpires at the potential evapotranspiration rate through the summer. In the DCEW, the riparian zone occupies about 8% of the catchment area, but produces about 12% of total catchment ET. Although significant, it is not enough to account for the difference between Parham's estimates of soil water storage capacity and evapotranspiration.

Uncertainty in Parham's estimates of actual evapotranspiration may be related to inaccurate estimates of growing season length. Poulos et al. (in review) compared nine years of soil moisture and temperature data from the paired aspect sites established by Smith et al. [16] , with remotely sensed observations of vegetation productivity, to assess how the physical controls of growth (e.g. cold temperatures and dry soils) affect growing season timing and productivity. The active growth begins shortly after snow melt when temperatures rise, while growth declines when soil water stress begins, and ends when plants cannot extract residual moisture (i.e. the plant extraction limit). Growing season timing varies with elevation and aspect, occurring earlier at lower elevations and on southern aspects, but also ending earlier than higher elevations and northern aspects. Despite these timing differences, there is no discernable different in the duration of the growing season with elevation or aspect. While growing season lengths are similar, higher elevation and north facing sites are more productive, with twice the MODIS-derived net primary production (40 kg C m^{-2}) found at lower elevations (20 kg C m^{-2}). This increased productivity at higher elevations and on northern aspects may be explained by a number of factors including: (a) increased water availability (thicker soils provide larger storage capacity), (b) alignment of water availability with the peak in insolation, producing more increased growing intensity, and (c) reduced duration of the water stress period associated with the summer dry season.

Annual streamflow patterns reflect the seasonality of precipitation and snowmelt. The centroid of the annual hydrograph lags the centroid of annual precipitation by 25 to 50 days due to the storage and melt of snow (Figure 3). As discussed above, however, streamflow is primarily composed of water that has been stored in deep groundwater. The groundwater reservoir sustains flow in Dry Creek through most summers, although in some dry years the creek can cease flowing, and drying of the streambed advances upstream towards perennial springs.

While the size of the snowpack reservoir may not not strongly influence upland vegetation productivity, it does strongly control streamflow and the associated riparian ecosystem. Graham et al. (in review) demonstrated that the magnitude of peak snow water equivalent is the dominant control on the magnitude of the 7-day low streamflow. The timing of the 7-day low flow, however, is not well correlated to any metric of the snowpack, but is closely related to summer temperature and the onset of cool fall conditions.

Fieldwork leads to improved models

A rallying call of experimental hydrologists worldwide is that long-term field observations are essential to develop conceptual understanding of how water moves through catchments, and that improved conceptual understanding will lead to improved hydrologic models [42]. Further, dialogue between modelers and experimentalists is essential to ensure that knowledge is properly encoded into predictive models [43], and to help guide experiments that are relevant to improving predictive capabilities. In the DCEW, our work demonstrates that improved understanding of hydrologic processes and properties has indeed led to improved hydrologic models. Kelleners et al., [37, 44] developed a physically-based snowmelt and runoff generation model that emphasizes the role of bedrock infiltration based on the work of Aishlin et al. [24]. Kormos et al. [21] developed a spatially distributed water input model based on knowledge gained from the empirical work of Williams et al. [45] and McNamara et al. [31] that highlighted the important role that storage plays in moderating runoff generation. Early thesis work on isotopic fraction of meltwater [46] went unpublished because our observations did not agree with current literature until Ala-aho et al.[47] used our work to develop a new meltwater generation model. That work then informed a new physically based catchment model that is able to simultaneously explain the runoff generation dynamics as well as the residence times of streamwater in the snowmelt-driven Bogus sub-catchment[36]. Burnop [48] incorporated the snow depletion curve work of Homan et al. [29] into the Sacramento Runoff Model operated by the US National Weather Service to produce improved simulations of snowmelt-driven streamflow. Stratton et al. [26] could not calibrate the SWAT model until allowances were made for known rain-on-snow events. We contend that these and other improvements in hydrologic modeling were made possible by integrating the cumulative knowledge and institutional memory that comprise the core benefit of long-term catchment research sites. Additionally, the wealth of data in the DCEW benefits research to evaluate remote sensing products[29, 30, 49, 50], and instrumentation development[51-53].

Broader impacts: The DCEW Sense of Place

The DCEW has served as a place for field scientists to accumulate knowledge about the properties and processes that govern catchment function, and has provided opportunities to develop and test predictive models. Additionally, the long-term record and network of hydrologic infrastructure has been valuable for instrumentation and method development [51, 52, 54, 55]

Whether the DCEW remains a relevant place in the lexicon of hydrologic research is up to future generations of researchers. Regardless, we feel that the DCEW has been a tremendous value in several additional ways. First, the DCEW serves as a model for integrating long-term research sites into hydrologic education. The DCEW has been a foundation of the Hydrologic Science program at Boise State University, and serves as a model for data-driven hydrologic education. Data from the publications and long-term records scaffold and enrich a suite of exercises that are used throughout the hydrologic science curriculum (earth.boisestate.edu/drycreek/education). At the time of this writing approximately forty-five theses and dissertations have been completed in the DCEW. Of those, forty were MS theses. Clearly, a focus of the DCEW has been training MS students to enter the workforce.

Second, the DCEW has been part of a significant international movement to sustain the rich history of experimental catchments. Participating in this movement is challenging for backyard catchments without a permanent budget. Academic institutions often have limited capacity to provide baseline support needed to maintain long-term research catchments. Dataloggers must be downloaded, power sources maintained, instruments calibrated and repaired, databases updated and a suite of other tasks must be accomplished even when grants lapse. We advise that it is not possible to sustain a research catchment without long-term institutional support. The DCEW has been fortunate to receive permanent funding for a technician to maintain instruments and a database through seed funding by NSF EPSCoR program and long-term funding by Boise State University.

Third, the DCEW has, in a small way, helped stem the decline of fieldwork in hydrology. Burt and McDonnell [56] noted that roughly 10% of articles currently published in a leading hydrology journal are field-based. Vidon [57] argued that without a field-based hydrologic education, model development will be hampered; innovative models integrate empirical and theoretical insight. Both commentaries urge the academic community to promote field-based research as core training for students in the hydrologic sciences. We have taken this message to heart.

The DCEW research and education activities have created a sense of place for our hydrologic community. Sense of place is a geographic term that refers to a felt value regarding the relationships between people and spatial settings[58]; by endowing this space with value, space becomes place[59, 60]. Researchers working in DCEW have brought meaning to this place by living and learning in it. This sense of place is a core characteristic of all great long-term hydrologic field sites where generations of researchers pass through, each enriched by, and building on, the cumulative knowledge of those who came before.

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Figure Captions

Figure 1. The Dry Creek Experimental Watershed in southwest Idaho, USA. a) Map indicating major instrumentation locations. Photographs illustrating general terrain features at b) high, c) mid, and d) low elevations.

Figure 2. Aspect-dependent differences in a) insolation*, b) slope**, c) soil thickness*, and d) texture*.
*Data from the aspect-moisture network (Figure 1) described in Smith et al.[16]
**Modified from Poulos et al.[20]

Figure 3. Average monthly values (2012-2016) of precipitation at a) Bogus Ridge (2114 m), b) Treeline (1610 m), and c) Lower Weather (1036 m) meteorological stations, and d) streamflow at Lower Gauge outlet.

Figure 4. A hydrologic year in the DCEW illustrating a) precipitation at the Treeline site (TL), b) soil moisture in a pit at the Treeline site (TL), and c) streamflow measured at the Treeline site (TL) and Lower Gauge (LG). Crosscutting dashed lines separate moisture periods as 1) dry, 2) transitional wet, 3) wet low flux, 4) wet high flux, and 5) transitional dry.

Figure 5. Aspect-dependent differences in hydrologic thresholds. a) Moisture release curves from 32 soil cores collected from a transect across north (n=16) and south (n=16) facing slopes Geroy at al.[17]. Points and error bars are means and standard deviations, respectively, of volumetric moisture contents for all samples at prescribed tensions in multistep outflow tests. b) Field capacities determined by methods described by Chandler et al.[54] for the aspect-moisture network (Figure 1). Points and error bars are the means and standard deviations, respectively, of samples from four depths in four pits at four elevations (n=64).

Figure 6. Soil moisture time series for north (blue) and south (red) facing sites in the aspect-moisture network. a) High North (HN) and High South (HS), b) Mid High North (MHN) and Mid High South (MHS), c) Mid Low North (MLN) and Mid Low South (MLS), and d) Low North (LN) and Low South (LS) sites. Solid lines and error bars are the means and standard deviations of all sites and depths at a station. Gaps indicate missing data due to instrument failure.

Figure 7. Soil column water storage at the aspect-moisture stations for the 2008-2009 water year. Symbols and error bars indicate the annual means and standard deviations for the entire year for each site.

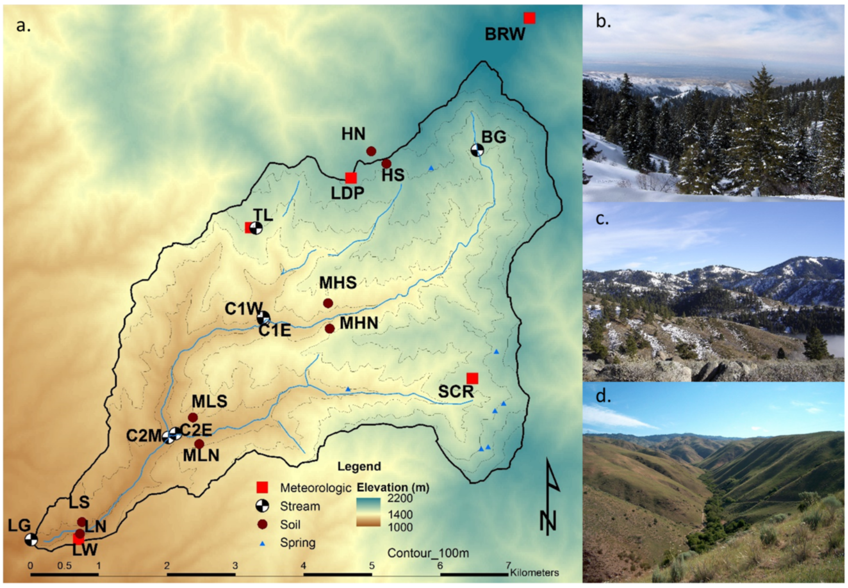

a.
BRW
HN
BG
HS
LDP
TL
MHS
C1W
C1E
MHN
SCR
MLS
C2M
C2E
MLN
LS
LG
LN
LW
Legend
Meteorologic
Stream
Soil
Spring
Elevation (m)
2200
1400
1000
Contour_100m
0 0.5 1 2 3 4 5 6 7
Kilometers
b.
c.
d.

Figure_1.tif

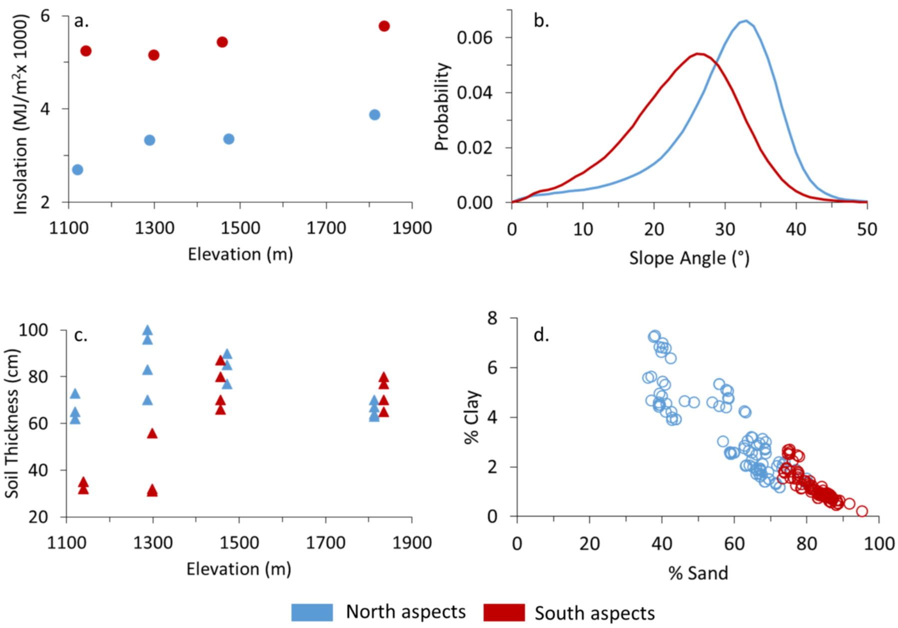
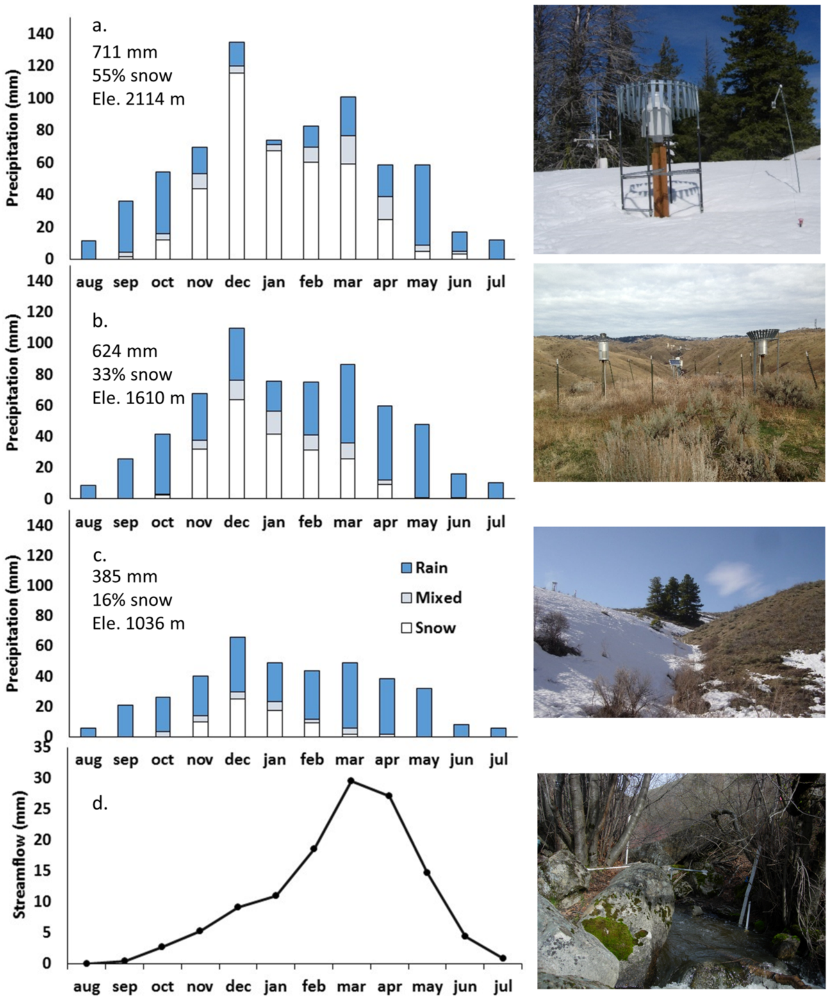
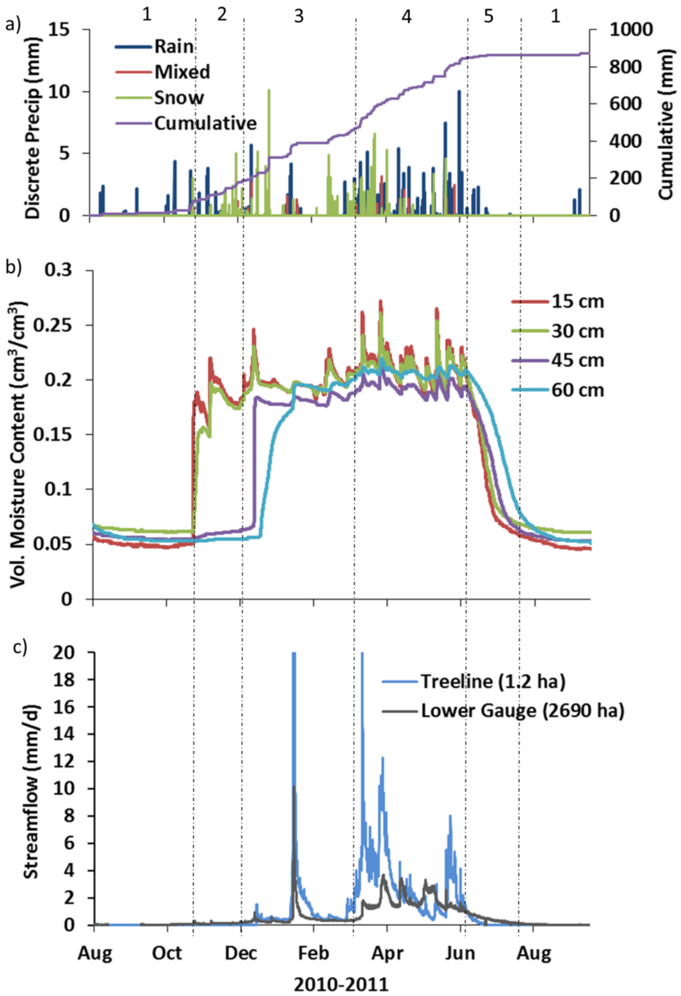

a.
Insolation (MJ/m²x 1000)
6
4
2
1100
1300
1500
1700
1900
Elevation (m)
b.
Probability
0.06
0.04
0.02
0.00
0
10
20
30
40
50
Slope Angle (°)
c.
Soil Thickness (cm)
100
80
60
40
20
1100
1300
1500
1700
1900
Elevation (m)
d.
% Clay
8
6
4
2
0
0
20
40
60
80
100
% Sand
North aspects
South aspects

Figure_2.tif



a.
711 mm
55% snow
Ele. 2114 m
b.
624 mm
33% snow
Ele. 1610 m
c.
385 mm
16% snow
Ele. 1036 m
Rain
Mixed
Snow
d.
Precipitation (mm)
Streamflow (mm)
aug sep oct nov dec jan feb mar apr may jun jul

Figure_3.tif



a)
1
2
3
4
5
1
Discrete Precip (mm)
15
10
5
0
Rain
Mixed
Snow
Cumulative
Cumulative (mm)
1000
800
600
400
200
0
b)
Vol. Moisture Content (cm³/cm³)
0.3
0.25
0.2
0.15
0.1
0.05
0
15 cm
30 cm
45 cm
60 cm
c)
Streamflow (mm/d)
20
18
16
14
12
10
8
6
4
2
0
Treeline (1.2 ha)
Lower Gauge (2690 ha)
Aug
Oct
Dec
Feb
Apr
Jun
Aug
2010-2011

Figure_4.tif

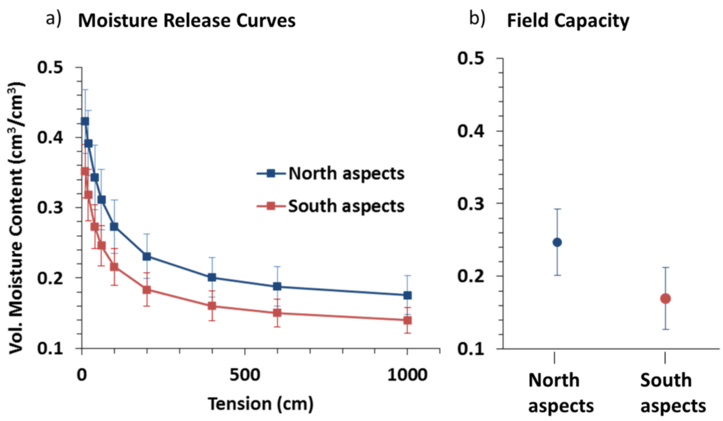
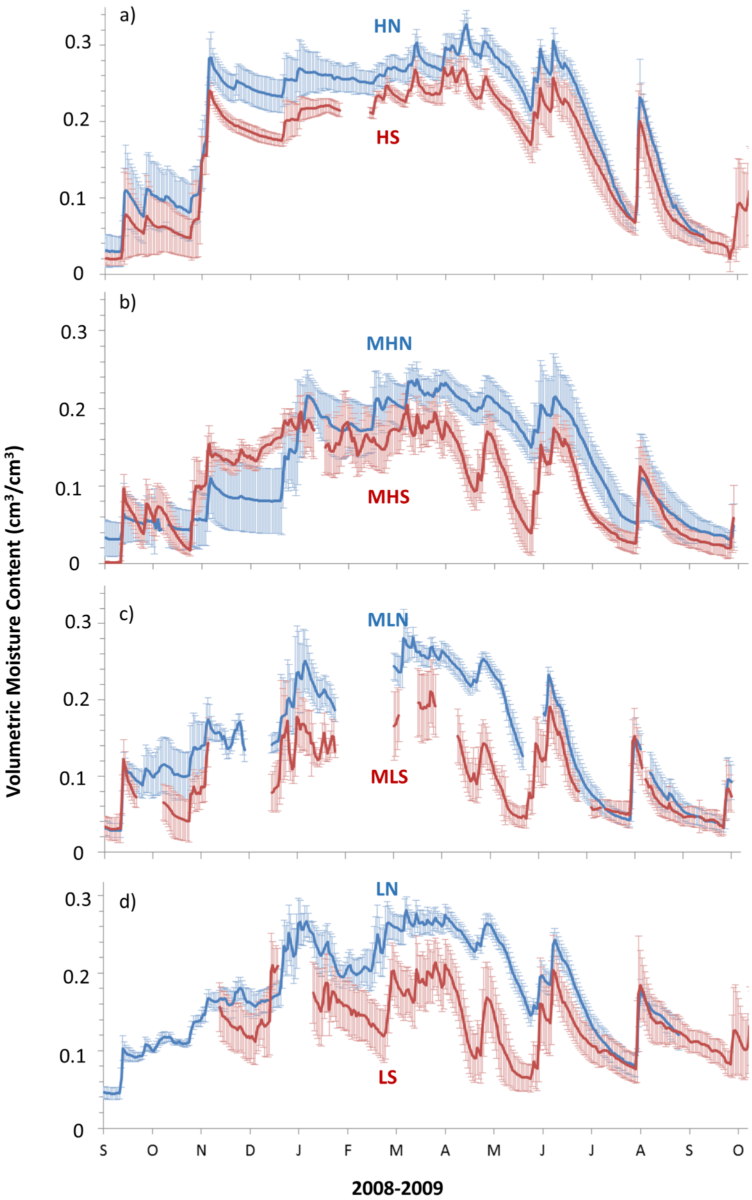

a) Moisture Release Curves
Vol. Moisture Content (cm³/cm³)
0.5
0.4
0.3
0.2
0.1
0
500
1000
Tension (cm)
North aspects
South aspects
b) Field Capacity
0.5
0.4
0.3
0.2
0.1
North aspects
South aspects

Figure_5.tif



a)
HN
HS
b)
MHN
MHS
c)
MLN
MLS
d)
LN
LS
0.3
0.2
0.1
0
Volumetric Moisture Content (cm³/cm³)
S O N D J F M A M J J A S O
2008-2009

Figure_6.tif

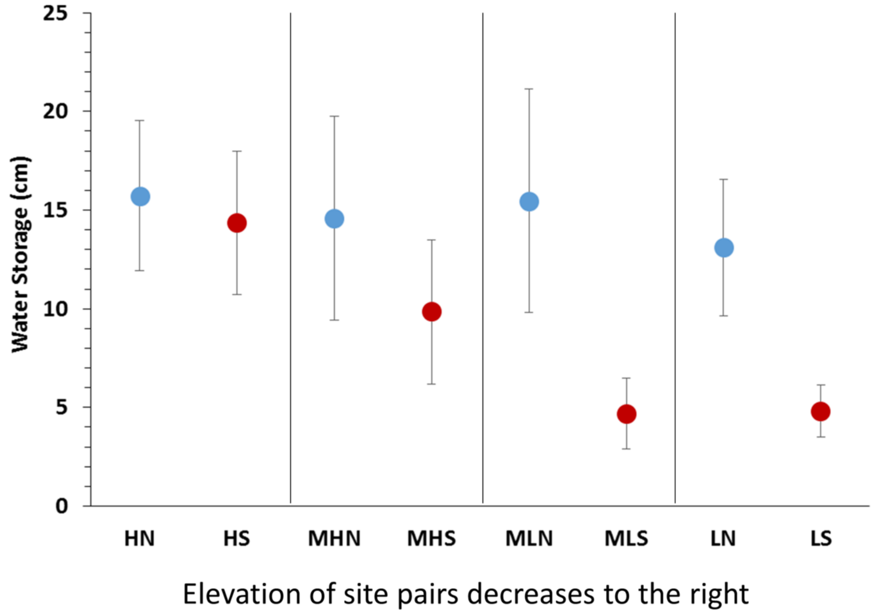

25
20
15
10
5
0
Water Storage (cm)
HN
HS
MHN
MHS
MLN
MLS
LN
LS
Elevation of site pairs decreases to the right

Figure_7.tif

graphical abstract.tif