First Annual Report for NSF EAR-0724958 entitled "Transformative Behavior of Water, Energy and Carbon in the Critical Zone: An Observatory to Quantify Linkages among Ecohydrology, Biogeochemistry, and Landscape Evolution" (The JRB-SCM CZO).

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1. Major Research and Education Activities

Project funding was initiated in September 2009. The CZO team, initially comprising 12 faculty from five departments at the University of Arizona began meeting biweekly to discuss research and education strategies to initiate the CZO. The revised version of the proposal funded by NSF required establishment of two observatory locations (Jemez River Basin [JRB] NM and Santa Catalina Mountains [SCM] AZ). The inclusion of SCM significantly expanded the climatic and lithologic space explored by the CZO and necessitated the refinement of project hypotheses by thematic area.

Figure 1. Four cross-cutting science themes of the

We are using the parameter of *effective energy and mass transfer* (EEMT, MJ m^{-2} y^{-1}) to quantify climatic forcings that shape the co-evolution of vegetation, soils and landscapes across the CZO, and to assess how this co-evolution is reflected in real-time measurements of hydrologic dynamics (Rasmussen et al., 2010a). The calculation of EEMT across the JRB and SCM CZO surfaces is being accomplished using PRISM data on precipitation and temperature, along with a 10 m DEM and the MODerate-resolution Imaging Spectroradiometer (MODIS) BRDF/Albedo Product data (MCD43A3). Calculating EEMT in this way permits the inclusion of aspect-dependent radiation inputs that, among other things, impact the difference between precipitation and evapotranspiration (i.e., effective precipitation). These data are being used to identify sites for various field campaigns across a wide EEMT gradient and also to locate potential zero order basin sites for installation of instrumentation. Since EEMT trends with elevation, evaluating process coupling along an EEMT gradient is being accomplished in the JRB-SCM CZO by locating intensively-instrumented zero order basin (zobs) across a range of elevations on constant lithologies (granite and schist in SCM, rhyolite in JRB). In the SCM, instrumented zero order basins (zobs) have been located and instrumented – or are being instrumented – at low (ca. 1100 m) intermediate (ca. 2100 m) and high (ca. 2400 m) elevations, partly through earlier State of Arizona funding to Peter Troch and Jon Chorover. In the JRB, a high elevation zob has been located (ca. 3000 m) and is in the early stages of instrumentation. Location of mid and low elevation sites at the JRB is in process.

The JRB-SCM CZO seeks to quantify fluxes of energy, water, and carbon in the Critical Zone in order to better predict CZ evolution and structure. Our CZO is organized around four, cross-cutting scientific "themes" that we assert will facilitate the establishment of physical, chemical and biological process coupling:
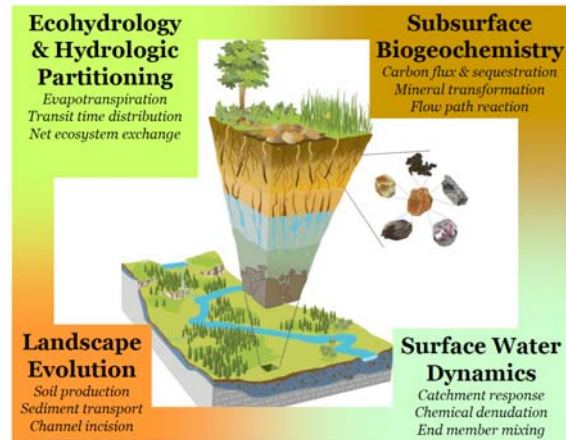
1. Ecohydrology and Hydrologic Partitioning (EHP)
2. Subsurface Biogeochemistry (SSB)
3. Surface Water Dynamics (SWD)
4. Landscape Evolution (LSE)

1.1 Ecohydrology and Hydrologic Partitioning Theme
The EHP group worked closely with the other thematic groups (LSE, SWD, SSB), via weekly meetings, to develop the following **three hypotheses** to be addressed as part of our CZO efforts:

Energy: Hydrologic partitioning is uniquely related to effective energy;
Water: Vegetation controls pedon-scale water transit time; geomorphology controls catchment-scale water transit time;
Carbon: Hydrologic partitioning and water transit time control DOC and DIC input to subsurface.

EHP research efforts are focused on **two overarching questions** that guide installations and observations.
(i) *How do **ongoing changes in vegetation (death, phenology, seasonality)** affect hydrologic partitioning and the resultant transfer of water and carbon to subsurface and streamflow?*
(ii) *How does variability in **vegetation structure** reflect (control) patterns in **hydrologic partitioning** over the last 1 – 100 yrs?*

The first question will be largely addressed in instrumented zero order basins (ZOBs) with measurements co-located with observations from other themes. Addressing the second question will rely primarily on distributed observations. This latter research is closely related to work in the zero order basins and is required to scale sub-catchment and catchment-scale observations to larger areas. Distributed observations also take advantage of ongoing related work in the region.

To address these issues, the EHP group conducted multiple field observation and instrumentation campaigns in coordination with other research themes. These efforts include:
o Distributed snow survey in the JRB designed to provide ground truth data for winter LIDAR flights;
o Installation of phenocams that capture vegetation and climate dynamics at both JRB and SCM to track how changes in phenology affect exchanges/ fluxes of water and carbon, and how distributed phenology measurements can be used to scale fluxes from towers to catchments/ landscapes/ ecosystems;
o Continued operation of flux towers in both SCM and JRB through transfer from SAHRA to CZO;
o Distributed vegetation surveys to ground truth summer LIDAR flights for vegetation structure and land surface DEM;
o Describing the patterns in (and causes of) forest to grassland transitions with a focus on high spatial and temporal resolution studies of how individual trees respond to water input;
o Initiation of three modeling efforts. The first focuses on how differences in energy associated with terrain influence hydrology partitioning and catchment scale hydrologic response. The second longer-term effort focuses on how phenology can be incorporated explicitly into hydrologic models. The third focuses on how redistribution of runoff at a mid-elevation semiarid woodland site relates to optimal concentration of water to herbaceous vegetation.

o   An EEMT vs mortality experimental transect is being initiated that overlays experimental hillslopes and soil work; mobile eddy flux towers for site specific, focused observing periods, real time isotopic measurements of water (carbon) fluxes, and what controls forest regeneration and how patterns on regenerate mediate EEMT fluxes.

o   Analysis of existing data sets at various sites along the elevation gradients, particularly mid elevation sites

1.2 Subsurface Biogeochemistry Theme

The SSB group worked closely with the other thematic groups via weekly meetings to develop the following **three hypotheses**:

Energy: Mineral weathering rate/transformation increases with EEMT resulting in concurrent changes in soil C stabilization.

Water: Ratio of inorganic carbon to organic carbon flux increases with increasing water transit time.

Carbon: Wet/dry cycles promote CO_2 production, enhancing mineral weathering and thereby promoting greater soil C stabilization.

The SSB research efforts evolved to focus on **two overarching questions**:

• *How does the critical zone partition total rock weathering into components of:*
(i) chemical denudation (elemental mass loss at pedon/hillslope scales);
(ii) primary to secondary mineral transformation (element retention in thermodynamically stable forms).
• *In the subsurface, how is net ecosystem exchange partitioned into:*
(i) DOC/POC, DIC export;
(ii) stable soil C pools;
(iii) physical erosion of soil C.

We developed a field design to address these questions and hypotheses across both the JRB and SCM CZO locations that encompasses:

- Identifying zero order basins (ZOB's) across gradients of EEMT and lithology that span high altitude mixed conifer forest, ponderosa pine dominated forest, and mixed conifer/hardwood woodland at both locations. The JRB lithology includes a mix of rhyolitic materials, whereas the SCM lithology includes both granite and schist. In addition, we have established a desert scrub location in the SCM CZO.

- Within each ZOB, we are in the process of establishing "catena" or hillslope transects that run perpendicular to the ZOB - running from ridge to hollow to ridge. Along these transects, locations are chosen for soil sampling, in situ monitoring of soil water content and temperature, and soil solution collection.

- A number of field campaigns have been undertaken to identify ZOBs, for opportunistic measurements, and for instrument installation. In particular, in the SCM CZO we have well established hillslope transects in both the desert scrub and mixed conifer ecosystems on both granitic and metamorphic parent materials and additionally have identified locations for the ponderosa pine and mixed woodland locations. Field campaigns to the JRB CZO have identified locations for mixed conifer and (tentatively) ponderosa pine ZOB's with initial sampling and preliminary site characterization underway. In addition,

we collected a number of surface soil samples from various aspects and landscape positions to begin to quantify variation in soil C and DOC content and quality.

- In anticipation of installation of subsurface instrumentation in the ZOBs, we are conducting bench-scale tests and calibration of both soil solution samplers and soil moisture/temperature probes, using soil from the field sites, so that efficacy in the medium of interest is established. An array of such tests was conducted during summer of 2010 with assistance from REU students associated with the B2 REU site program.

1.3 Surface Water Dynamics Theme
The SWD group worked closely with the other thematic groups (LSE, EHP, SSB), via weekly meetings, to develop the following set of research questions to be addressed as part of our CZO efforts:

- *How do chemical denudation rates vary as a function of EEMT?*
- *How do chemical denudation rates vary as a function of lithology?*
- *How do transit times vary as a function of EEMT?*
- *How does carbon transformation and storage vary as a function of lithology, EEMT, and transit times?*

These broad questions will likely promote cross-site comparisons between the Santa Catalina Mountains and Jemez River Basin, as well as with other CZO sites. We are starting with EEMT observations and moving towards more process-based hypotheses/understanding. Our research questions also place emphasis on determining water transit times and chemical denudation rates, which is a key focus of the SWD group. Research is being conducted from the pedon to hillslope to catchment-scale. Overarching goals of this research are to determine how chemical denudation rates vary as a function of transit times, which will hopefully provide insight into why natural versus laboratory weathering rates are orders of magnitude different. In addition, we hope to better constrain mountain block recharge, which has important implications for groundwater resources in adjacent alluvial basins.

- The SWD group conducted multiple field campaigns to begin to address these questions:
  - Surface waters and springs were sampled around Redondo Peak and the Valles Grande in the Valles Caldera Preserve (Jemez River Basin) in September 2009, and from March to August 2010 to capture spring snowmelt, premonsoon dry period, and summer monsoonal storms; bi-weekly sampling will continue at least through September 2010. Future sampling efforts will be conducted to address additional research questions.
  - Hydrometric and hydrochemical data were collected from summer 2006 onwards in two ZOBs located at the high elevation site (Marshall Gulch) in the SCM (**Figure 2**). Initial funding came from SAHRA (startup funding Peter Troch) and State of Arizona (Water Sustainability Program; Peter Troch and Jon Chorover). Stable water isotope concentrations in rainfall, snow melt, soil water and stream water were determined using Los Gatos DLT-100 laser spectrometer. On average weekly sampling took place during most of the year when sites were accessible (during winter snow pack soil water lysimeters could not be accessed). In total, ca. 2700 samples have been collected and analyzed for stable water isotopes and hydrochemistry from Marshall Gulch since the project began. A novel method was developed by Ingo Heidbuechel and Peter Troch to quantify the time varying nature of water transit times at zob and catchment scales. This method will be presented at the upcoming AGU Fall Meeting in San Francisco.

- Water samples were analyzed for major cations, anions, trace elements, nutrients, organic and inorganic carbon species, and water stable isotopes. Sample aliquots were preserved for additional analyses.
- The SWD group worked closely with the other thematic groups to select zero order basins in the Santa Catalina Mountains and Jemez River Basin for intensive observation.
- Field instrumentation for determining the water and carbon budgets and solute fluxes was ordered in Spring 2010.
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- Fall 2010 field efforts will be focused on installation of the field instrumentation in the Jemez River Basin and Santa Catalina Mountains.
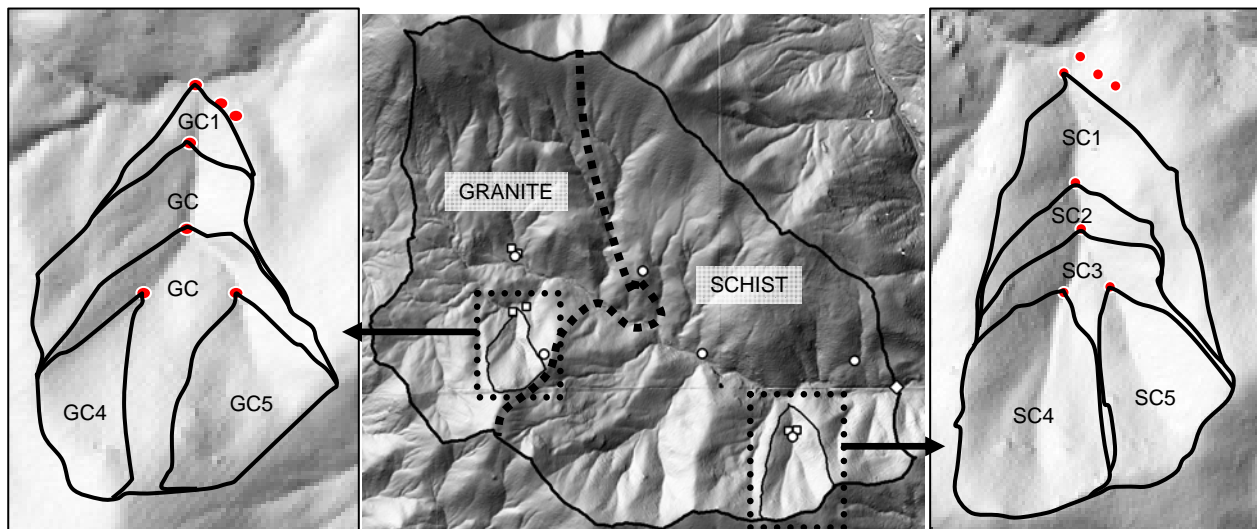- These field observations will be closely coupled to ongoing coupled process modeling efforts.

Figure 2. High elevation, mixed conifer zero order basins (ZOBs) in Marshall Gulch (SCM) are underlain by granite and schist bedrock, providing a natural experiment for lithologic controls on CZ structure and function.

1.4 Landscape Evolution Theme
The landscape evolution theme within the JRB-SCM CZO project seeks to understand and quantify how topographic measures (e.g. hillslope relief, valley density) and rates of fluvial and hillslope erosion are controlled by climate/EEMT and rock type/structure. Landscape evolution involves feedbacks with pedology, hydrology, and ecology, hence there are natural overlaps between LSE activities and those of all other project subthemes.

Work performed in preparation for this project focused on quantifying the climatic, lithologic, and topographic controls of soil thickness on hillslopes. PIs Pelletier and Rasmussen developed a broadly-applicable numerical model that predicts soil thickness using input data for climate/EEMT, rock type, and topography. This work led to two publications in 2009 (Pelletier and Rasmussen, 2009a,b). Our current work follows naturally from the foundation laid by those two papers. For example, we are using LiDAR data for the SCM to understand and quantify the controls on where cliffs occur. Cliffs (bare bedrock zones greater than 60º in slope) represent a beyond-threshold hillslope state in which soil production (a function of climate and rock type/structure) fails to keep pace with soil erosion

(predominantly a function of topography). The spatial occurrence of cliffs varies systematically with climate/EEMT, slope aspect, and rock type/structure in the Santa Catalina Mountains. Our soil thickness model described in Pelletier and Rasmussen (2009) can predict the observed spatial distribution of cliffs, thereby providing a process-based understanding of cliff formation and the "patchiness" of soil cover in semi-arid granitic landscapes generally. This work also dovetails nicely with recent work (Pelletier et al., 2009) quantifying the role of rock structure on the orientations and longitudinal profiles of fluvial channels in the SCM.

Progress is being made to quantify fluvial erosion rates in the JRB as part of an effort to apply landscape evolution modeling to testing alternative hypotheses for the evolution of Redondo Mountain over geologic time scales. The concentration and texture of suspended sediments are being measured regularly in seven flumes around Redondo Mountain. The particle-size distribution of each sample is being measured to constrain both sediment concentration/flux (using a rating curve approach that extrapolates high-resolution discharge time series data collected at each flume) and particle-size distribution as a function of time at each site. Our goal is to quantify modern erosion rates and how they vary as a function of topography, climate/EEMT, rock type, and time (both seasonally and interannually).

Numerical modeling and analysis of geospatial data is being performed to quantify the coevolutionary feedbacks between topography, pedology, hydrology, and ecology in the mountain ranges of the SW U.S. generally. In the SCM, a strong correlation exists between climate and elevation, with the climate at the highest elevations of SCM representative of low-elevation areas in southern Canada. Coincident with this strong climate gradient are systematic variations in soil thickness (thicker soils at higher elevations/EEMT values), vegetation type and density (higher density at higher EEMT), hydrologic measures such as runoff ratio (lower runoff ratio at higher EEMT), and geomorphic attributes such as hillslope relief and valley density (both lower at higher EEMT). We have developed a numerical model that includes feedbacks between topography, hydrology, soil thickness, and vegetation in a simplified way in order to test hypotheses for how positive feedbacks between geomorphology, hydrology, pedology, and ecology have led to these systematic variations observed in the mountain ranges of the SW U.S.

Redondo Mountain in the JRB provides an excellent opportunity to study the linkages between hillslope stability and soil/vegetation development. The hillslopes of Redondo Mountain are composed of a patchwork of recent landslide deposits separated by more stable zones where soils and vegetation have become established over millennial time scales. We hypothesize that, in locations where slopes are sufficiently stable, soil and vegetation have become established, thereby decreasing the probability of slope failure at those locations in a positive feedback (because soil and vegetation establishment increase cohesion via root growth). Using numerical modeling in conjunction with measures of vegetation density and soil development from Redondo Mountain, we aim to test this hypothesis. This work is currently on hold pending the delivery of LiDAR data, since accurate slope data are crucial for performing the slope stability and nonlinear-slope-dependence sediment transport calculations required by the model.

Members of the LSE working group are also performing work to ground truth and aid in the interpretation of the LiDAR data to be acquired in June, 2010. We have measured and surveyed over 2000 trees in 50 precisely-georeferenced plots to aid in the estimation of biomass from LiDAR and to address fundamental ecologic questions (e.g. species competition and coexistence). Once the LiDAR

data have been delivered to UA from NCALM, we will be well positioned to use the data to map biomass, topographic attributes, and use as input to hydrologic and geomorphic models.

2.   Major Findings from Research and Education Activities

Final products of high resolution EEMT calculations across the CZO are in process and are not yet available to be presented here. However, **Figure 3** shows digital elevation maps (DEMs, **top panels**) and corresponding EEMT surfaces (**bottom panels**) for the SCM (**left panels**) and Valles Caldera portion of JRB (**right panels**) on a common scale based on PRISM precipitation and temperature data at 800 m spatial resolution. These data show that the large elevation gradient captured by the SCM translates into a correspondingly large EEMT gradient (left side), whereas at similar spatial scale, the smaller elevation gradient captured within the Valles Caldera portion of the JRB hosts a finer resolution in EEMT (right side). Also indicated on these maps (outlined in black) are the zero order basins (zobs) located within the SCM at high (mixed conifer), intermediate (ponderosa pine to pinyon-juniper-oak transition) and low (Sonoran desert) elevation with corresponding EEMT gradient, as well as the candidate high (mixed conifer) and intermediate (ponderosa pine) elevation zobs located in the JRB. ZOBs targeted for
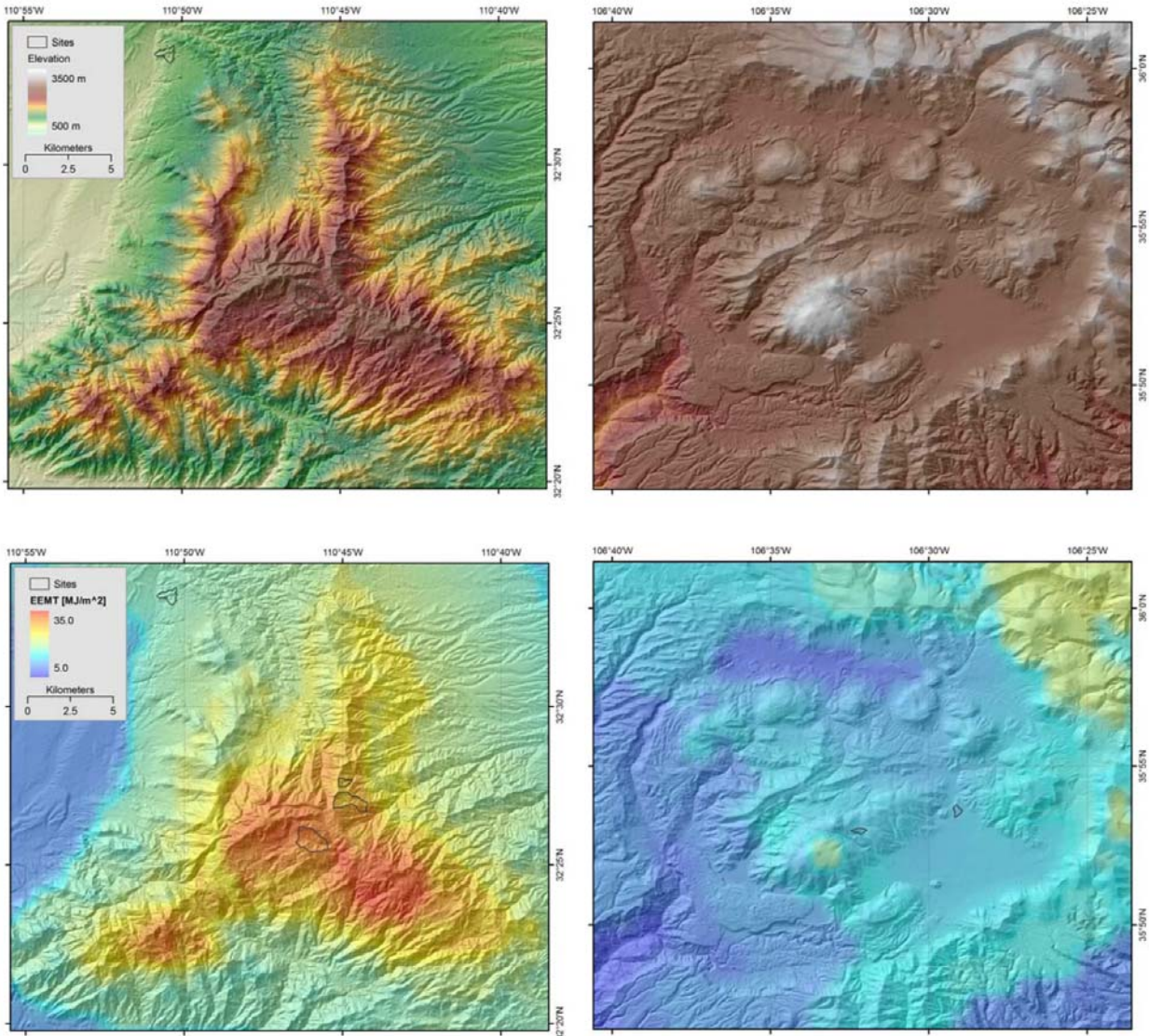

Figure 3. Digital elevation maps (top) and EEMT maps (bottom) for the SCM (left) and JRB (right) CZO. Locations of zero order basins (ZOBs) are identified in black outline. Image – Matej Durcik.

instrumentation in both SCM and JRB were located during field trips attended by groups of PIs equipped with mapped GIS information on catchment boundaries, topography, vegetation types, and geology (**Figure 4**).

Figure 4. Field trips to the SCM (**left**) and JRB (**right**) to select ZOBs for intensive instrumentation and study were attended by multiple PIs, graduate students, and associated staff, in order to have sufficient disciplinary representation for consensual site selection.

2.1 Ecohydrology and Hydrologic Partitioning Theme

Snow water equivalent: Precipitation inputs to the CZ represent a key forcing that controls subsequent processing that leads to CZ structure formation. In snow dominated systems such as the JRB, a large fraction of incoming precipitation occurs as snow, which can undergo sublimation prior to surface runoff, soil infiltration and/or plant uptake. We have found that variation in snow water equivalent
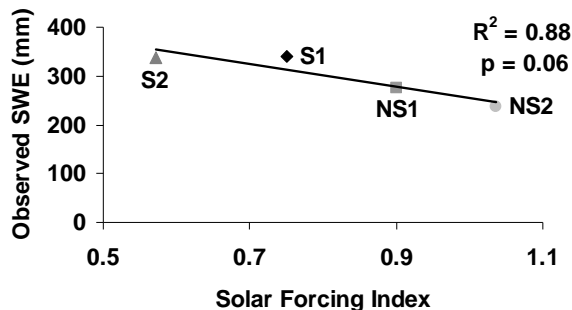

Figure 5. The observed variability in SWE (snow water equivalent) at maximum accumulation correlates well with solar forcing index at sites with similar total winter snowfall. Up to 25% of winter snowpack sublimates at locations with high solar energy input, and thus never enters soil to be partitioned among runoff, recharge, or plant water use. (From "Estimating snow sublimation using natural chemical and isotopic tracers across a gradient of solar radiation" Joseph R. Gustafson, P. D. Brooks*, N. P. Molotch, and W. C. Veatch In press with Wat. Resour. Res.)

(SWE) correlates with solar forcing (**Figure 5**).

Partitioning of Evapotranspiration in mid-elevation woodlands: Partitioning evapotranspiration into its evaporation and transpiration components is critical for understanding ecohydrological processes in

drylands. However, existing partitioning estimates have not adequately accounted for the heterogeneity associated with woody plant canopy patches and intercanopy patches so characteristic of dryland ecosystems. We evaluated measured water contents, stable isotopes (δ^2H and δ^{18}O), chloride, and nitrate from core samples collected in canopy and intercanopy patches in piñon-juniper woodland associated with JRB (Newman et al. 2010). Average δ^2H values from shallow soil (<0.1 m) were 11 to 17 ‰ lower in canopy patches, suggesting lower soil evaporation losses compared to intercanopy patches. However, significantly larger chloride inventories in canopy patches indicate up to four to six times more total evapotranspiration. Taken together, lower evaporation and greater evapotranspiration suggest that canopy patches have substantially larger transpiration rates and lower evaporation/transpiration ratios than intercanopy patches. Our results support a basic but untested conceptual model of patch connectivity where woody plants utilize substantial amounts of intercanopy water that has been redistributed from intercanopy to canopy patches via hydraulic gradients created by root uptake—a finding not generally modeled but potentially relevant to globally extensive patchy-structured drylands.

A central tenet of ecohydrology is that runoff redistribution from bare to vegetated patches concentrates the key limiting resource of water, which can then enhance vegetation growth and biomass. Conversely, a reduction in vegetation patches, particularly those associated with herbaceous plants, can lead to a threshold-like response in which bare patches become highly interconnected, triggering a large increase in hillslope runoff and associated erosion. However, generally lacking is an assessment of how maximization of runon to herbaceous patches relates to minimization of hillslope-scale runoff. Our modeling effort in piñon-juniper woodland associated with JRB (Urgeghe et al. 2010) showed total amount of runon to all herbaceous patches was greatest when amount of bare cover was intermediate, highlighting a tradeoff between source area for generating runoff and sink area for capturing runon. We suggest that a more robust suite of such relationships could be valuable for managing rangelands by explicitly accounting for optimality and tradeoffs in biomass per herbaceous patch, total herbaceous cover, and prevention of hillslope-scale connectivity of bare patches that triggers a large increase in runoff and associated sediment and nutrients.

Redistribution of runoff is a fundamental ecohydrological processes in semiarid woodlands. Runoff is often generated from intercanopy patches that separate the canopy patches of woody plants, particularly from locations with bare soil, and subsequently captured by vegetation patches, where the concentration of resources can be ecologically significant. Although redistribution by erosion also occurs, less well documented is the extent to which biogeochemical patterns such as total C and total N are affected, particularly in rapidly eroding hillslopes where redistribution might be greatest. We evaluated measured total soil C and total soil N at two hillslope positions (upslope and downslope) for interill areas including two patch types (canopies of woody plants and intercanopies separating them) and for rill areas in a rapidly eroding piñon-juniper woodland associated with JRB (Law et al., in prep). Our preliminary analyses indicate downslope interill locations of either patch type had greater concentrations of total C and total N than corresponding upslope locations of the same patch type, with canopy patches having greater concentrations than intercanopy patches as is commonly observed. Conversely, downslope rill locations were depleted in total C and total N relative to upslope rill locations by about 15% in both cases. These results, in concert with related studies, suggest total C and total N are being concentrated via runoff downslope from intercanopy locations, are captured rather than bypass canopy patches, and are depleted as moving down rills and the associated developing ephemeral channel network. More generally, our findings indicate a potentially important but poorly documented coupling between EHP and SSB processes in eroding semiarid landscapes.

Net ecosystem exchange in JRB mixed conifer forest: In collaboration with the Valles Caldera National Trust, several flux towers were installed with prior NSF funding as part of the Sustainability of semi-Arid Hydrology and Riparian Areas (SAHRA) Ecohydrologic Observatory, beginning in 2005.   These towers are now continuing to operate as part of the JRB-SCM CZO. Data deriving from the Mixed Conifer tower show the partitioning of net ecosystem exchange (NEE) into gross primary production and ecosystem respiration, as well as evapotranspiration and meteorological data for the site (**Figure 6**). The NEE data indicate that the JRB MC site operates as a significant carbon sink on an annual basis, 2-3 times as large as more northern mixed conifer forests in Colorado.
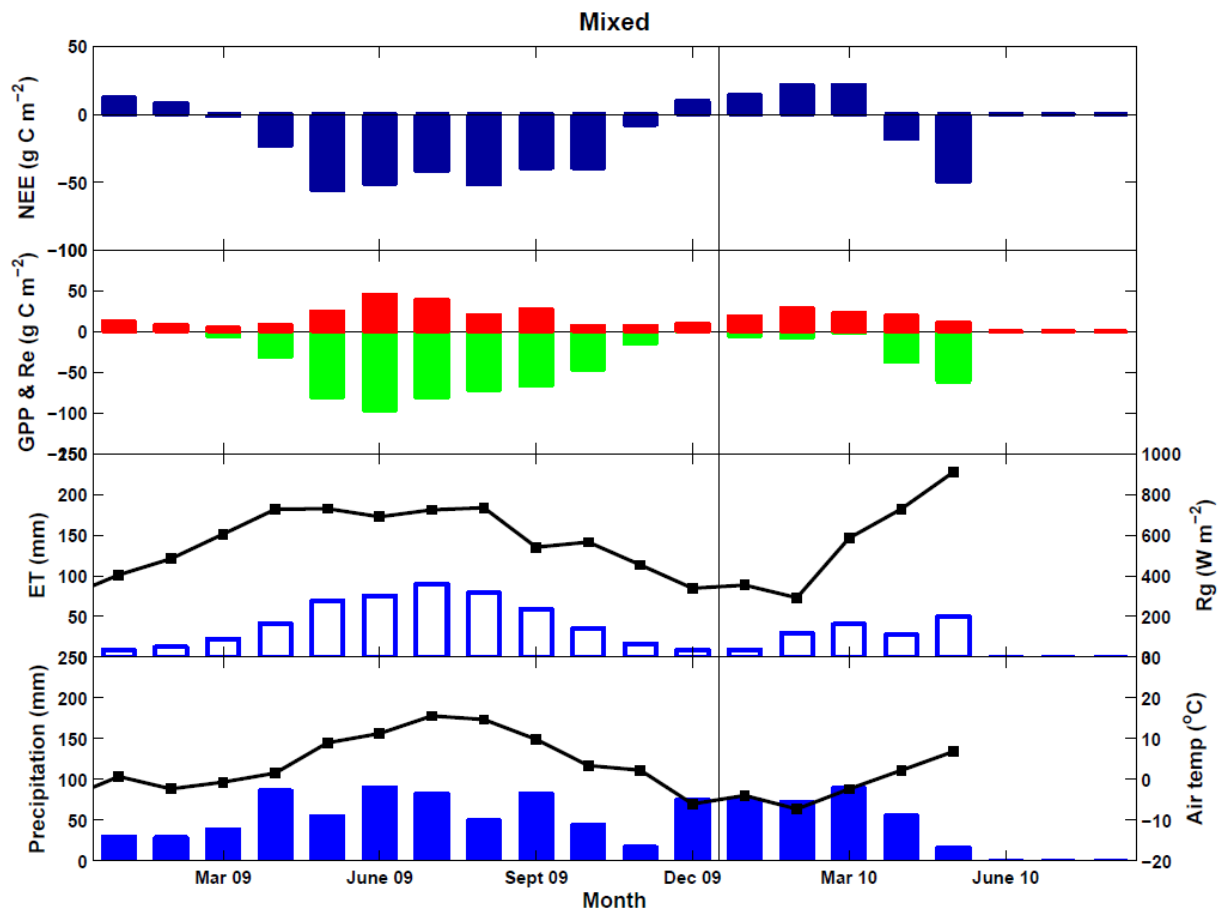
Figure 6. Eddy covariance calculations of carbon and water flux collected during period 2009-2010 for the JRB Mixed Conifer flux tower providing a time series of net ecosystem exchange of carbon (top panel), NEE partitioning into gross primary productivity and respiration (second panel), evapotranspirative and radiative flux (third panel), precipitation and air temperature (bottom panel). (M. Litvak, UNM, unpubl. data.)

2.2 Subsurface Biogeochemistry Theme

Landscape position controls on soil solution chemistry and mineral assemblage in SCM mixed conifer ecosystems: Solution and solid phase sampling and analyses in the low and high elevation sites of the SCM have been ongoing since the initiation of the CZO project. Solution chemistry data indicate that

mean and modal aqueous concentrations of Si, Al and non-hydrolyzing cations are elevated in convergent relative to divergent landscape positions. This likely reflects solute accumulation associated with higher overall substrate-solution contact and kinetic limitations on mineral dissolution along convergent flow paths, whereas greater through flux and greater solution phase undersaturation with respect to primary mineral phases appears to predominate in divergent zones.

In addition to acquisition of major element geochemistry, we are testing the use of rare earth elements (REE) as reactive tracers of geochemical weathering processes in CZO soils. Because REE fractionation occurs in response to incongruent mineral dissolution and organic complexation, we predict that variation in REE patterns in CZO time and space will be provide useful tracers of this component of subsurface biogeochemistry (**Figure 7**).
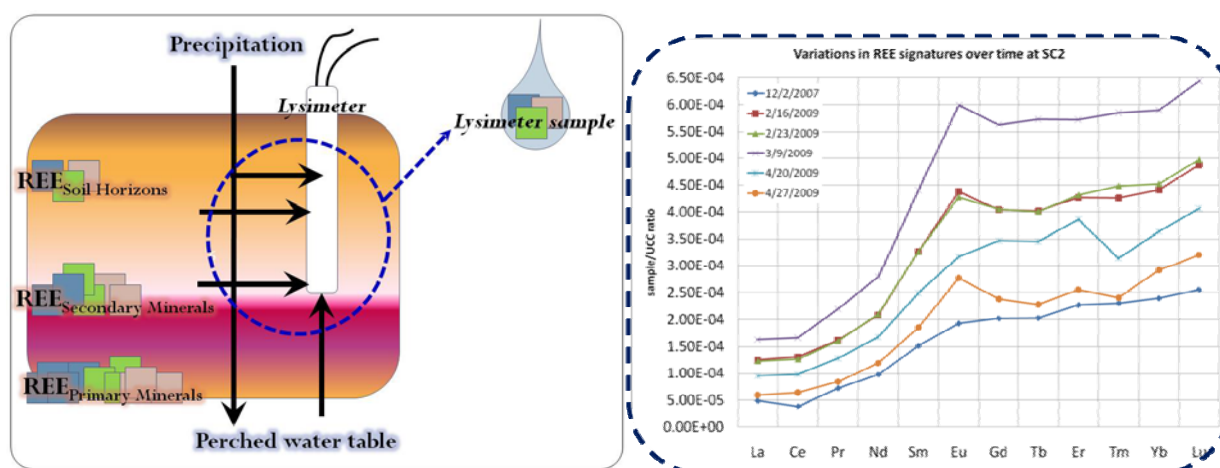

Figure 7. Left: Schematic of rare earth element (REE) use for measuring incongruent weathering in the CZ soils. We are monitoring hydrologic flux within soil horizons via soil moisture probes and piezometers. Co-located are soil solution samplers ("lysimeters") to monitor changes in aqueous chemistry through weekly suction cup sampling. Our goal for this research is to better characterize how variations in both major and trace element concentrations can be used to capture the hydropedologic development of the CZ. **Right:** Winter 2009 time series of upper continental crust (UCC) normalized REE signatures for one lysimeter in Marshall Gulch, SCM. The REE profiles (overall shape) show small variation for a given sampler, but large variation in space (not shown), creating a "fingerprint" for a given lysimeter. However, the total concentrations are shown to vary in time, in this case rising consistently throughout the snow melt period, returning to low values post melt, reflecting time variable changes in weathering intensity. We are working to correlate these changes to soil water and carbon flux measured concurrently. (A. Jardine, UA, unpubl. data.)

We quantified variation in bulk soil mineral abundance for divergent and convergent landscape positions in both granite and schist parent materials in the mixed conifer ecosystem of the SCM CZO. Substantial variation in soil mineral assemblage as determined by x-ray diffraction was noted both between parent materials and between landscape positions. Briefly, the granite profiles were less weathered than schist profiles. The mineral assemblage of both granite profiles were dominated by quartz and feldspar, with a lesser amount of mica and other accessory minerals. Granite weathering reactions appear to be dominated by the transformation feldspar to kaolinite, and more specifically the pseudomorphic transformation of plagioclase feldspar to kaolinite. The schist profiles were dominated by a mix of primary minerals such as quartz, orthoclase and plagioclase feldspar, biotite, and hornblende, in addition to secondary 2:1 and 1:1 phyllosilicates. The general weathering reactions appear to be

dominated by transformation of biotite to a secondary 2:1 mineral, and the transformation of plagioclase to kaolinite.

In terms of landscape position effects, the divergent hillslope positions from each parent material exhibited a greater degree of primary mineral weathering relative to convergent positions. Greater weathering in divergent positions suggests sufficient water input and mean residence time to drive weathering reactions, and sufficient water through flux to remove weathering products from the profile. In contrast, the convergent profiles exhibited very little primary mineral weathering in either parent material, but in general a greater abundance of clay sized material. The lack of primary mineral weathering in this landscape position likely corresponds to these positions collecting solute rich waters from upslope divergent landscapes, i.e., collection of concentrated soil solutions in convergent positions inhibits weathering reactions. Furthermore, convergent landscape data suggest the clay fractions in theses profiles may be dominated by neogenic clays, such as smectite, suggesting precipitation from solute-rich soil waters. Hence, spatial distribution of soil mineral composition appears consistent with contemporaneous solute fluxes measured by lysimetry, suggesting a heterogeneous distribution of weathering intensity that is governed by hillslope hydrologic flux.

Variability in subsurface structure and soil moisture content in JRB Mixed Conifer (MC) ZOB: The JRB MC ZOB selected for intensive study by the CZO is located in the upper La Jara creek basin (**Figure 8, left**). This ZOB was selected on the basis of its proximity to - and representativeness of - the site hosting the existing Eddy covariance flux tower that is situated just to the northeast. In addition, this ZOB contains a wide range of ecohydrologic and soil characteristics that suggest a broad range of characteristics ideal for co-location of CZ measurement activities. Approval of installation of CZO instrumentation in the MC ZOB is nearing completion now in August 2010. This process has involved interaction with multiple parties including the Valles Caldera National Preserve (VCNP), Department of Cultural Resources, and the Jemez Pueblo tribe. Much of the discussion of installations was mediated by Dr. Robert Parmenter, Chief Scientist at VCNP. Plans for installation of equipment include an array of meteorological stations co-located with sap flow equipment, snow lysimeters, subsurface probes and samplers, piezometers, and stream gages (**Figure 8, right**). Now that the approval process is nearing completion, we plan to have much of this instrumentation installed by October, 2010.

Preliminary subsurface data were collected during the initial ZOB survey during week of May 24, 2010. Five soil pits were excavated on a east-west transect across the ZOB, soil samples were collected by genetic horizon, and pedons were described. The depth to low permeability subsurface features was measured (**Figure 9**), and a TDR transect of soil water content was obtained (**Figure 10**).

Soil carbon and nitrogen variation with EEMT in JRB: We collected 27 surface soils O and A horizons (0-30 cm depth) in the JRB (Valles Caldera NP) distributed by aspect, vegetation, and elevation, and measured soil carbon (C) and nitrogen (N), bulk densities, and extractable pools of dissolved organic carbon and nitrogen. We hypothesized that variability in energy input and related mass fluxes (EEMT) would determine quality and quantity of carbon and associated nitrogen at surface of CZ soil for subsurface processing. Differences in vegetation (live-dead, coniferous, deciduous, grass) would affect the quality of C and N input.
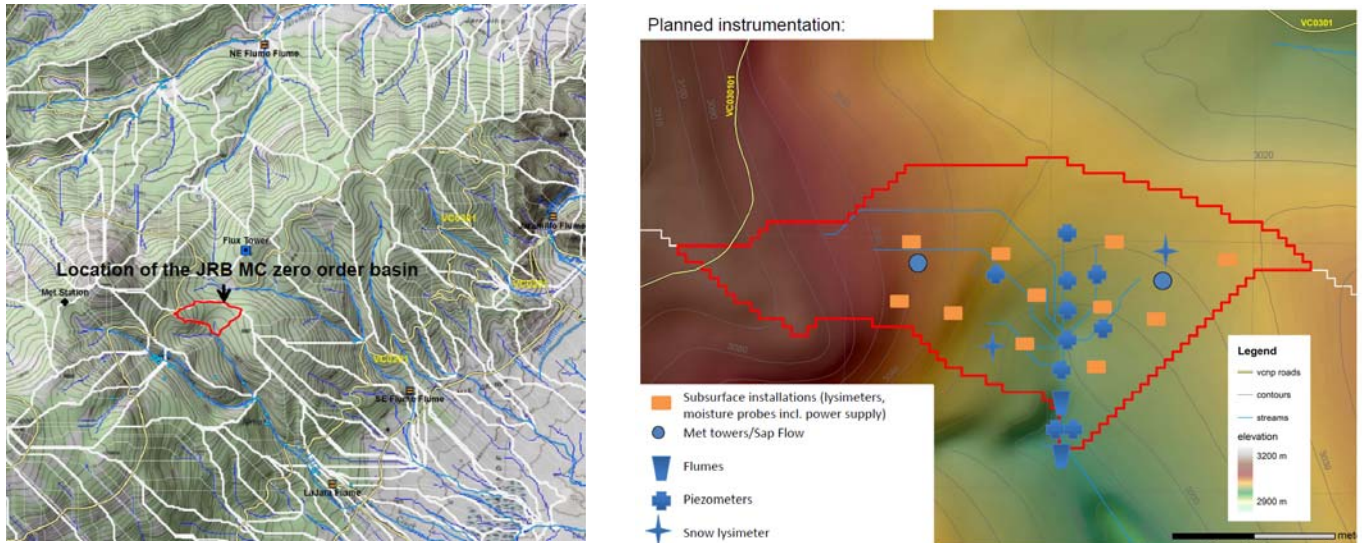
Figure 8 . Mixed conifer ZOB location in JRB in headwaters of east branch of upper LaJara Creek (**Left**). Planned instrumentation array for the JRB MC ZOB (**Right**).

Soil organic matter (SOM) determined by loss on ignition (LOI) was high across the sites, averaging 18% in surface horizons and 6.6% in mineral horizons, and did not vary significantly with vegetation or aspect, used as a preliminary surrogate of EEMT. Preliminary analysis of soil-water extracts from the JRB showed that soil-water extractable dissolved organic carbon (DOC) and total dissolved nitrogen (TDN) (g m^{-2}) were higher in subsurface mineral horizons compared to surface organic/mineral horizons across all sites. Soil-water extractable DOC and TDN did not vary significantly with aspect. However, soil-water C:N ratios were significantly higher in surface horizons in mixed conifer and Ponderosa pine vegetation types (mean C:N 16-18) relative to grass sites (mean C:N 9.3). C:N ratios in spruce fir and aspen extracts were similar (mean C:N 13) and not significantly different than mixed conifer, aspen or grass. In contrast to the surface soils, soil-water extractable DOC and TDN were significantly higher in grass and aspen in subsurface mineral horizons compared to conifers; meanwhile C:N ratios in subsurface mineral horizons did not vary significantly with vegetation.

Synthesis of climate and tectonic controls on granite weathering: We participated in and led a cross-site synthesis of regolith weathering in granitic terrain to gain better understanding of linkages among climate, erosion and weathering that are central to landscape evolution. This synthesis was organized and facilitated by the Critical Zone Exploration Network (CZEN). We approached these linkages through synthesis of regolith data for granitic terrain compiled with respect to climate, geochemistry, and denudation rates for upland profiles with low slopes. Focusing on Na as a proxy for plagioclase weathering, we quantified regolith Na depletion, Na mass flux, and the relative partitioning of denudation to physical and chemical contributions. Regolith Na depletion increased significantly with water availability except for locations with mean annual temperature < 5 ºC that exhibited little Na depletion, and locations with physical erosion rates < 10 g m^{-2} yr^{-1} that exhibited full regolith Na depletion. Sodium mass flux was three orders of magnitude greater in the fully depleted, low erosion rate locations. The fully depleted locations also exhibited strong supply-limitation of Na weathering rates, with apparently little connection of weathering rate to climate. Weathering rates in the cool, wet locations were predominantly supply-limited, but also exhibited strong correlation
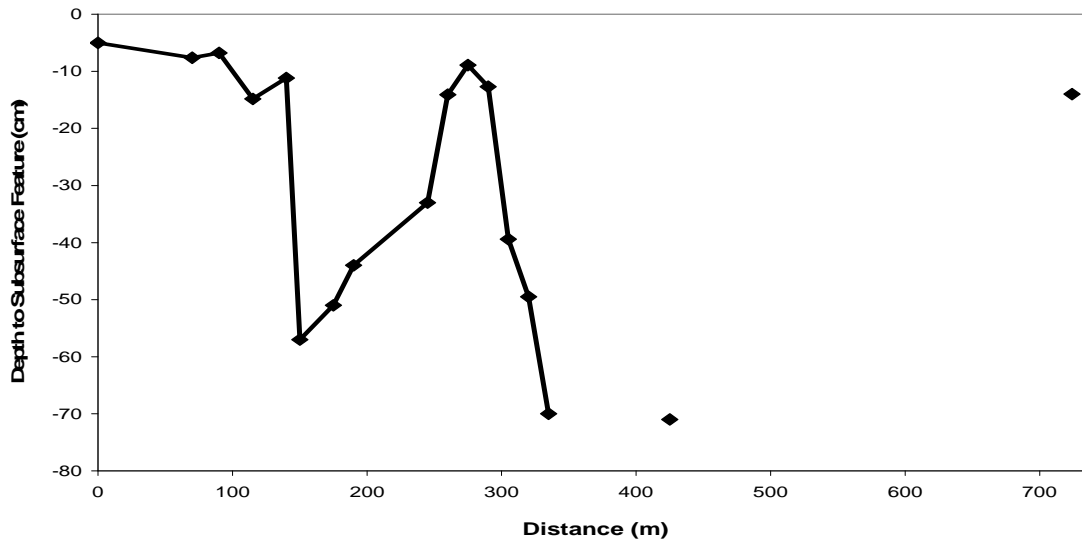
Figure 9. East-west transect of subsurface soil features. The symbols represent locations with data from both auger and pedon sample locations. Auger data were only collected for the eastern half of the transect providing greater density of sample point. The subsurface line is not interpolated for the western half of the ZOB because of the lack of data. The eastern portion of the ZOB is underlain by fractured rhyolite and andesite that transitions to a weathered rhyolitic tuff conglomerate. The contact with weathered tuff conglomerate generally coincides with the presence of a subsurface clay increase and argillic horizon. (C. Rasmussen, unpubl. data.)
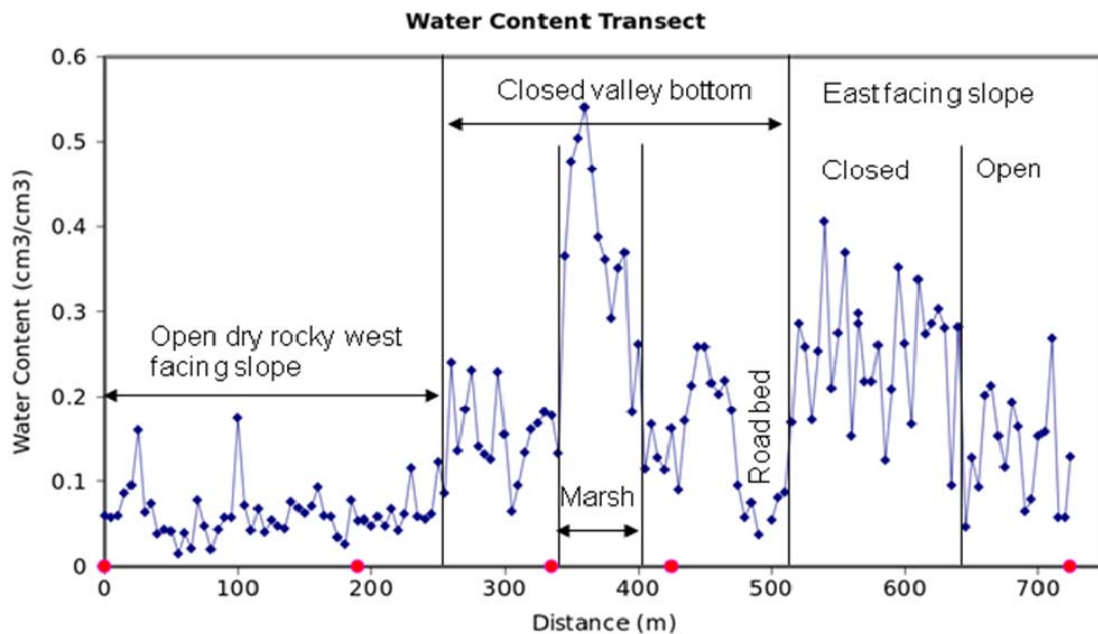

Figure 10. East-west transect of volumetric water content in a zero order basin, two weeks after snowmelt (date of transect: May 26, 2010). Water content was measured by inserting a 10 cm Time Domain Reflectometry probe into the mineral surface every 5 meter. Red dots indicate the position of soil pits for detailed pedological descriptions, labels approximate the landscape features, with open and closed indicated the nature of the canopy cover. (M. Schaap, unpubl. data.)

to temperature with Na activation energy $\approx$ 86 kJ mol^{-1} Na. The remaining warm, dry locations exhibited minimal relation of Na weathering rate to mineral supply or temperature, indicating water availability as the dominant rate limiting factor. These data demonstrate that uniform treatment of climate-erosion-weathering interactions masks important nonlinear transitions in the relative importance of each factor. Key nonlinearities were noted at the transition to low physical erosion rates and the transition from negative to positive water balance (Rasmussen et al., 2010b).

2.3 Surface Water Dynamics Theme

JRB Water Transit Time Distributions: Transit times, which describe the time between when water enters the catchment as precipitation and when it leaves as stream flow, capture many hydrologic features such as flow path variability and the combined effects of water storage and water fluxes. We conducted an experiment that involved field data collection, isotopic analysis of stream and precipitation samples, and the estimation of transit times using lumped-parameter convolution for 15 sites in small (1–15 km^2) catchments that drain different aspects of Redondo Peak (**Figure 11**) (Broxton et al., 2009). The data suggest that isotopic variability and estimated transit times are both related to aspect (**Figure 12**).
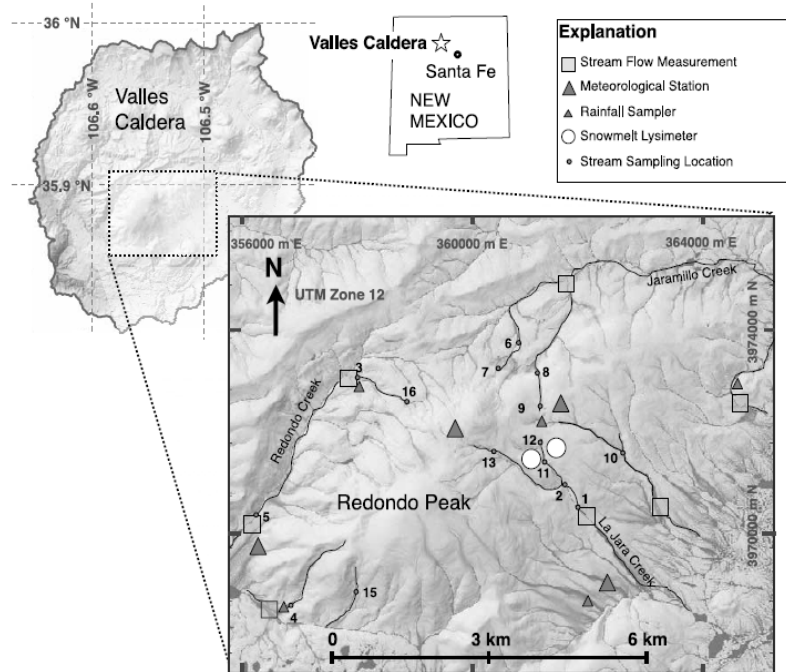

Figure 11. Location of instrumentation used in the Broxton et al. (2009) study.
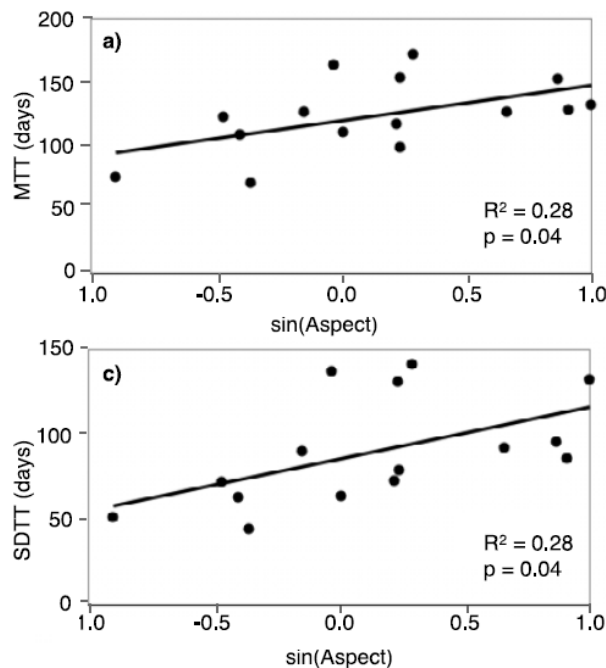

Figure 12. Statistically significant relationship between aspect of small catchments around Redondo Peak (see **Figure 11**) and mean transit time (a) and the standard deviation of transit time (c).

JRB Stream water DOC fluxes: Quantitative C analysis from flume samples around Redondo peak showed high dissolved organic carbon (DOC) concentrations at the onset of snowmelt (mid April). Highest DOC concentrations (12 mg L^{-1}) were measured in lower Jaramillo discharge at flume E of Redondo (**Figure 13, top**). DOC in both La Jara and Jaramillo drainages correlate with discharge (e.g. **Figure 13, middle**).

Fluorescence spectroscopic analysis provides valuable information on source and molecular properties of DOM. Excitation – emission matrixes (EEM, not shown) reveal several maxima characteristic of plant-(e.g., lignin and associated aromatics) and microbial-derived compounds. Whereas the former derive largely from decomposition of terrestrial biomass (allochtonous DOM), the latter derive also from in-stream algal biomass (authochtonous). The relative contributions of these are indexed using the fluoresence index (FI). A strong negative correlation between discharge and FI for La Jara drainage (**Figure 13, bottom**) indicates increasing contributions of allochtonous DOM with increasing discharge, with maximum values occurring at early onset of snowmelt.

Total dissolved nitrogen (TDN) data show similar trends with highest values from Lower Jaramillo samples and a steady decrease for the other flumes around Redondo (counterclockwise). However, DN concentration values are offset in time relative to peak DOC values, with highest concentrations at end of April (4-26-10) rather than Mid-April (4-16-10).

2.4 Landscape Evolution Theme

Contemporary versus long term erosion rates in JRB: Preliminary data suggest that modern erosion rates are at least one order of magnitude lower than erosion rates inferred geologically for the past one million years. Long-term erosion rates can be inferred from the age of Redondo Mountain and the extent of valley incision since the initiation of uplift. The reason for this vast difference between short-term and long-term erosion rates is unknown but could be due to changes in vegetation during the Pleistocene (colder climates likely led to a decrease in vegetation cover and hence higher erosion rates at the high elevations of Redondo Mountain). An alternative hypothesis, proposed by Kirchner et al.
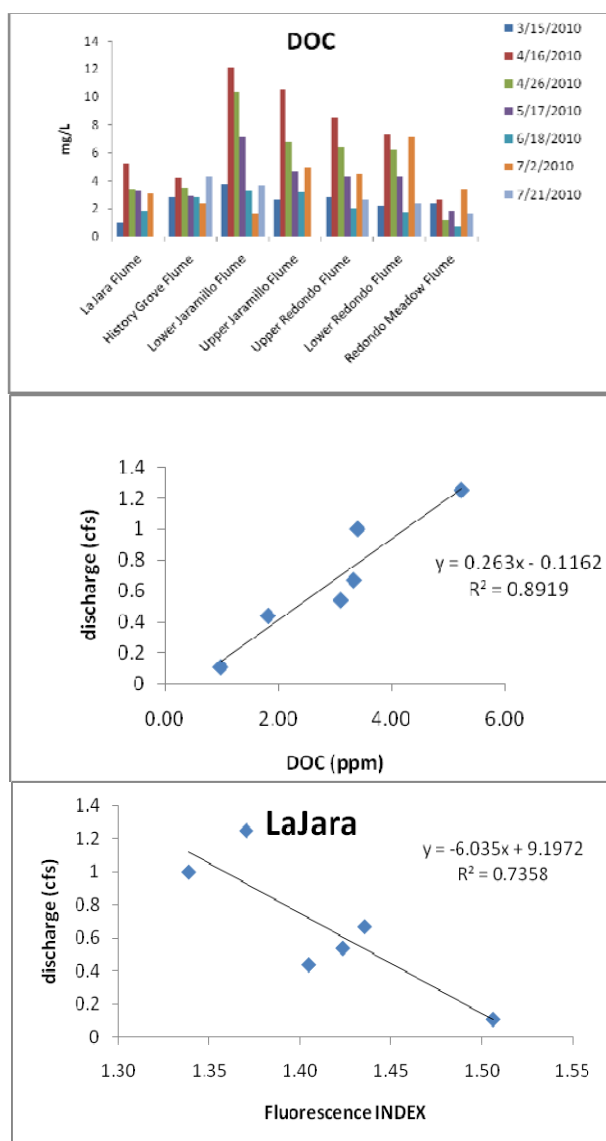

Figure 13. Dissolved organic carbon (DOC) concentrations deriving from streams draining Redondo peak during spring snowmelt and summer 2010 is shown in **top panel**. Positive correlation between stream discharge and DOC concentration for La Jara drainage is shown in **middle panel**. Negative correlation between discharge and fluorescence index is shown in **bottom panel**. Low FI corresponds to terrestrial sourcing whereas higher values tend to indicate greater autochtonous (i.e., algal) contributions. (J. Perdrial unpubl. data.)

(2001) to explain a similar difference between short and long-term erosion rates at a high-elevation site in Idaho, posits that low modern erosion rates are due to the absence of extreme erosional events in short-term erosional records. Numerical modeling will further test these alternative hypotheses using the data collected from Redondo Mountain.

Model of soil production on granite: In our numerical model, wetter, higher-elevation portions of these mountain ranges, soil development from bedrock proceeds more rapidly than in drier, lower-elevation portions. Thicker soils then promote a lower runoff ratio, thereby increasing the vegetation carrying capacity of the landscape, further increasing soil thickness and decreasing the runoff ratio in a pedologic-hydrologic-ecologic positive feedback. Lower runoff ratios and higher biomass in wetter climates also decrease fluvial erosion rates and increase colluvial transport rates, thereby driving the topography towards lower drainage densities and leading to a further decrease in runoff ratio via an additional geomorphic-hydrologic feedback. We are quantifying these feedbacks using a numerical landscape evolution model and a principal component analysis of available geospatial data for hillslope relief, valley density, runoff ratio, soil thickness, and vegetation density in the SCM and Pinaleno Mountains, i.e. two predominantly granitic mountains range where high-quality LiDAR data are publically available. A manuscript documenting this work is in preparation (Pelletier and CZO team, in prep.)

3.   Opportunities for Training, Development, and Mentoring Provided by the Project
The multiple graduate and undergraduate students involved in this project have gained invaluable field and laboratory skills, and research experience working as part of a large interdisciplinary team. In addition, funding of a new REU site proposal at Biosphere 2 (B2) has provided excellent opportunities for undergraduate research experiences associated with the JRB-SCM CZO. Several B2 REU students were involved in CZO research during summer of 2010, as described in "Personnel" section of this report. Two postdoctoral scientists (Dr. Julia Perdrial and Dr. Adrian Harpold) are also receiving training and mentorship experience as part of this grant. Finally, Breshears hosted PhD student Anna Urgeghe from Universidad de Alicante, Spain, in a three month program that provided writing training and lead to publication of Urgeghe et al. (2010).

4.   Outreach Activities Undertaken by the Project
Jon Chorover was interviewed on National Public Radio about the new CZO grant in January, 2010. He discussed the definition of the critical zone, and its importance for a variety of ecosystem services, such as water delivery (e.g., from sky island environments) and purification. Peter Troch was interviewed by a local television news program and discussed the interdisciplinary nature of critical zone research. Breshears attended the Aldo Leopold Leadership Program 2010 All Cohort training program in June to receive additional training on how to improve communication with public media and will apply those skills to CZO outreach activities.

5.   Publications Resulting From Research:
Published and Submitted Papers:
Adams, H. D., C. H. Luce, D. D. Breshears, M. Weiler, V. C. Hale, C. D. Allen, A. M. S. Smith, T. E. Huxman. (in review). Ecohydrological consequences of drought- and infestation-triggered tree die-off. *Ecohydrology*.
Broxton, P. D., P. A. Troch, and S. W. Lyon. 2009. On the role of aspect to quantify water transit times in small mountainous catchments. *Wat. Resour. Res.* W08427, doi:10.1029/2008WR007438

Chorover, J. 2010. Impact of soil physicochemical and biological reactions on transport of nutrients and pollutants in the Critical Zone. Chapter F10 in Handbook of Soil Science. Taylor and Francis Group LLC. *In press*.

Gustafson, J. R., P. D. Brooks, W. C. Veatch, and N. P. Molotch, (in revision) Snow sublimation estimates using natural tracer concentration and isotopic fractionation in a semi-arid forested catchment *Wat. Resour. Res.*

Newman, B. D. , D. D. Breshears, and M. O. Gard. 2010. Evapotranspiration partitioning in a semiarid woodland: ecohydrological heterogeneity and connectivity in vegetation patches. *Vadose Zone Journal*: in press.

Pelletier, J.D., and C. Rasmussen, Geomorphically-based predictive mapping of soil thickness in upland watersheds, *Wat. Resour. Res.*, **45**, W09417, doi:10.1029/2008WR007319, 2009a.

Pelletier, J.D., and C. Rasmussen, Quantifying the climatic and tectonic controls on hillslope steepness and erosion rates, *Lithosphere*, **1**, 73-80, 2009b.

Pelletier, J.D., Engelder, T.M., Comeau, D., Hudson, A., Leclerc, M., Youberg, A., and S. Diniega, Tectonic and structural control of fluvial channel morphology in metamorphic core complexes: The example of the Catalina-Rincon core complex, Arizona, *Geosphere*, **5**, 363-384, 2009.

Rasmussen, C., P.A Troch, J. Chorover, P. Brooks, J. Pelletier, and T. Huxman. 2010a. An open system framework for integrating critical zone structure and function. Biogeochem.. DOI 10.1007/s10533-101-9476-8.

Rasmussen, C., S. Brantley, D. Richter, A. Blum, J. Dixon, O.A. Chadwick, and A.F. White. 2010b. In Press. Strong climate and tectonic control on chemical weathering in granitic terrain. *Earth Planet. Sci. Let.*

Urgeghe, A. M., D. D. Breshears, S. N. Martens, and P. C. Beeson. 2010. Redistribution of runoff among vegetation patch types: on ecohydrological optimality of herbaceous capture of runon. *Rangeland Ecology and Management* 63: in press.

Papers "In preparation" - to be submitted within the next 12 months:

Chorover, J., P. Troch, P. Brooks, C. Rasmussen, J. Pelletier, J. McIntosh, K. Lohse, M. Schaap, D. Breshears, T. Meixner, S. Papuga, and T. Huxman. Submitted to *Vadose Zone J.* (Special issue on the Critical Zone.)

Heidebuchel, I. et al. (in prep) Estimation of long transit times from relatively short data sets in ephemeral catchments.

Heidebuchel, I. et al. (in prep) Geologic and topographic controls on hillslope mean transit times in a semi-arid mountain catchment.

Jardine, A., P. A. Troch, J. Chorover, and others (in prep) Dissolved rare earth elements in a semi-arid mountain critical zone.

Law, D. J., D. D. Breshears, M. H. Ebinger, C. D. Allen, and C. W. Meyer. (in preparation) Soil C and N hydrological functional units within an eroding woodland hillslope: ecohydrological-biogeochemical coupling via runoff-driven redistribution and loss. For planned submission to *Journal of Arid Environments*.

Lohse, K.A., P.D. Brooks, C. Stielstra, J. Chorover, and C. Rasmussen. Variation in soil carbon and nitrogen with EEMT and vegetation in the Jemez River Basin Critical Zone Observatory

McIntosh et al. (in prep) Influence of mean transit times on chemical denudation rates in a rhyolitic semi-arid catchment.

Pelletier, J.D. and CZO team, Large-scale coevolution of topography, hydrologic pathways, soil development, and vegetation in mountain ranges of the southwestern United States.

Published Abstracts & Presentations of Results:
*Invited, **Students*

*Chorover, J., P. Troch, C. Rasmussen, J. Pelletier, P. Brooks, J. McIntosh, K. Lohse, D. Breshears, M. Schaap, T. Huxman, T. Meixner, S. Papuga. The Jemez River Basin – Santa Catalina Mountains Critical Zone Observatory. Annual Meeting of SAHRA NSF Science and Technology Center, Tucson, AZ. April 2010.

*Chorover, J., P. Troch, C. Rasmussen, J. Pelletier, P. Brooks, J. McIntosh, K. Lohse, D. Breshears, M. Schaap, T. Huxman, T. Meixner, S. Papuga. The Jemez River Basin – Santa Catalina Mountains Critical Zone Observatory. Annual Meetings of the Soil Science Society of America, Long Beach California, November 1-6, 2010.

**Jardine, A., P. A. Troch, J. Chorover, J. McIntosh, and C. Rasmussen. Rare earth elements as reactive tracers of critical zone hydrology. American Geophysical Union Annual Meetings, San Francisco, CA December 2009.

**John, G.P., Papuga, S.A., Barron-Gafford, G., Wright, C.L., and +Nelson, K. August 2010. Using digital photography to investigate the impact of temporal and spatial variations in spring snow melt on summer soil respiration. 1st Annual B2 REU Symposium, Tucson, AZ.

Law, D. J., D. D. Breshears, M. H. Ebinger, C. D. Allen, and C. W. Meyer. 2010. Soil C and N in hydrological functional units within an eroding semiarid woodland hill slope: Ecohydrological-biogeochemical coupling via runoff-driven redistribution and loss. Annual meeting of the Ecological Society of America. August 1st-6th, 2010. David L. Lawrence Convention Center, Pittsburgh, Pennsylvania.

*Lohse. K., and CZO team, (2009) Jemez River Basin and Santa Catalina Mountain Critical Zone Observatory. Biosphere Advisory Board Meeting, National Academy of Sciences, Washington DC. (Presented to National Academy of Sciences, NSF Directorate of Geosciences, NSF Directorate of Earth Surface Processes, NSF Program Director EAR), Oct 29, 2009.

**Nelson, K., Papuga, S.A., Barron-Gafford, G. March 2010. Using Time-Lapse Digital Photography to Monitor Changes in the Critical Zone. 20th Annual El Dia del Agua Student Symposium, Department of Hydrology and Water Resources, University of Arizona, Tucson, AZ.

Papuga, S. A. April 2010. It's not easy being green: Linking hydrology, phenology, and climate change. Southwest Watershed Research Center Brown Bag Series, USDA-ARS, Tucson, AZ.

**Wright, C., Barron-Gafford, G.A. , Papuga, S.A., *John, G.P. August 2010. Soil respiration along paired drainages during the North American Monsoon. 1st Annual B2 REU Symposium, Tucson, AZ.

**Wright, C., G. A. Barron-Gafford, S. K. Papuga, G. John. Soil respiration along paired drainages during the North American Monsoon. Annual Meetings of the Society for Advancement of Chicanos/Latinos and Native Americans in Science. Anaheim, California, September 30 - October 3, 2010.

6. Contributions to within Discipline:
Critical zone science is a new, interdisciplinary science that focuses on couplings between typically segregated earth and biological science disciplines. Hence, contributions to the field will best be assessed on the basis of new discoveries resulting from disciplinary integration. One goal of our CZO is to establish an instrumented, natural laboratory where disciplinary researchers across the earth surface sciences (ecology, soil science, hydrology, geomorphology, geochemistry) can conduct highly integrated research that leads to such new discoveries. Toward that end, our most important collaborative contributions in year 1 relate principally to laying the groundwork for construction of JRB-SCM CZO infrastructure. In addition, several of our initial findings have relevance as well.

Our results of isotopic analysis in piñon-juniper woodland patches (Newman et al. 2010) support a basic but untested conceptual model of patch connectivity where woody plants utilize substantial amounts of intercanopy water that has been redistributed from intercanopy to canopy patches via hydraulic gradients created by root uptake—a finding not generally modeled but potentially relevant to globally extensive patchy-structured drylands.

Our runoff redistribution modeling in effort in piñon-juniper woodland (Urgeghe et al. 2010) highlight a tradeoff between source area for generating runoff and sink area for capturing runon, leading us to suggest a need for explicitly accounting for optimality and tradeoffs in biomass per herbaceous patch, total herbaceous cover, and prevention of hillslope-scale connectivity of bare patches that triggers a large increase in runoff and associated sediment and nutrients.

Our soil C and N analyses in the eroding JRB woodland (Law et al. in prep) indicate a potentially important but poorly documented coupling between ecohydrological and biogeochemical processes in eroding semiarid landscapes.

Our cross-site comparisons of plagioclase weathering rates (Rasmussen et al., 2010b) have provided predictive data on chemical versus physical denudation rates in granitic terrain as a function of climatic drivers (temperature and precipitation).

7.   Contributions to Resources for Research and Education:

In so far as the principal intent of the CZOs is to establish natural laboratories for use by the broader earth sciences community, we have made significant progress in this respect through installations of sampling equipment and sensors in the SCM at both low and high elevation sites, and through the planning of intensive instrumentation arrays very soon to be installed in the JRB high elevation site.

8.   Contributions to Society:

Our results on redistribution of runoff in semiarid woodlands as related to optimal capture of water by herbaceous vegetation can contribute to improved management of semiarid rangelands.