Project Summary

Transformative Behavior of Energy, Water and Carbon in the Critical Zone: An Observatory to Quantify Linkages among Ecohydrology, Biogeochemistry, and Landscape Evolution

We propose an interdisciplinary observatory that will improve our fundamental understanding of the function, structure and co-evolution of vegetation, soils, and landforms that comprise the Critical Zone (CZ). We posit that CZ systems organize and evolve in response to open system fluxes of energy and mass that can be quantified at point to watershed scales. These energy and mass fluxes include meteoric CZ inputs of radiation, water and carbon that are modulated by surficial biota to produce fluids and biogeochemicals that undergo further biotic and abiotic transformation during gradient-driven transport. We hypothesize that the coupling of physical, chemical and biological processes is related specifically and predictably to the timing and magnitude of these fluxes. Precipitation and energy inputs exhibit distinct temporal (seasonal and interannual) as well as spatial (elevation, slope and aspect) patterns over much of the earth’s surface. We propose to establish a CZ Observatory (CZO) to examine the impacts of this space-time variability in energy and water availability on coupled CZ processes along a well-constrained climate gradient on common rhyolitic parent material in northern New Mexico (Jemez River Basin, JRB-CZO). Measurement, modeling, and experimentation at sites that vary in elevation, aspect, slope, soil development, and vegetation along our climate gradient will enable quantification of the feedbacks between energy and mass fluxes (driven by chemical and physical gradients) and measured components of CZ structure. Our team has developed an iterative modeling and measurement strategy based on a management structure that fosters integration among disciplines. We will employ an integrated process-based modeling approach to (i) identify optimal sites for measuring structure and processes, (ii) refine hypotheses developed through field-based observation and measurements, (iii) explore feedbacks and emergent system behaviors, and (iv) develop transfer functions that can be used to link system components across scales. Novel CZO collaborations will be encouraged.

Intellectual Merit: Tools and approaches to disciplinary research in earth surface science have advanced dramatically in recent decades and confirmed independently the importance of energy, water and carbon availability in controlling geomorphology, hydrology, pedology, biogeochemistry, and ecosystem structure. However, the feedbacks and inter-relations among them – which define the essential characteristics of critical zone function – remain poorly understood. A coordinated effort focused on (i) quantifying how energy, water and carbon inputs are effectively partitioned and transformed by CZ structure while (ii) identifying how CZ structure develops in response to spatial and temporal variability in energy and mass fluxes will yield major advances in our understanding of CZ responses to climate and land use change. Toward that end, our CZO will be organized around a broad question that requires an integrated, multi-disciplinary approach: How does variability in energy input and related mass fluxes influence CZ structure and function, and how do feedbacks with water/carbon cycling and landscape evolution alter short- and long-term CZ development? A premise of this proposal is that during CZ evolution, feedbacks occur at a range of spatial and temporal scales as a result of the coupling of physical, chemical, and biological processes. To identify the couplings, our proposed research is organized around three crosscutting science themes that are both multi-disciplinary and multi-scale: Ecohydrology and Hydrologic Partitioning, Subsurface Biogeochemistry, and Landscape Evolution. Furthermore, we propose that the first logical step to quantify the couplings between these theme areas is to focus on the flows of effective energy, water and carbon. Our subsidiary hypotheses are intended to stimulate interdisciplinary advances within themes and to promote the identification of critical couplings and feedbacks among them.

Broader Impacts: The results from the JRB-CZO will improve our ability to predict CZ response to changes in climate and land cover, which is immediately useful to regional resource managers and will ultimately inform broad-scale decision making. We will coordinate closely with - and facilitate interactions between - both the CZEN cyberinfrastructure network and the CUAHSI Hydrologic Information System (HIS) to support data collection, storage, and dissemination. We will expand upon ongoing database and web services development funded by SAHRA for the CZO area for time-series data retrieval and mapping. Our education and outreach activities will build upon other highly effective educational efforts developed and led at UA through ISPE, CLIMAS, and SAHRA. We will develop a range of products and activities for K–16 students, the general public, and stakeholders, including summer Observatory field experiences for local high school and undergraduate students, graduate courses, and field camps in earth science, as well as coordination of related efforts by other science centers active in the region.
1. Introduction

What governs the structure and co-evolution of vegetation, soils, and landforms that comprise the Critical Zone (NRC 2001)? The central role of energy, water and carbon flows, driven by temperature, chemical and gravitational gradients, and modulated by vegetation, soil, bedrock and time, have been recognized for decades by ecologists (Tansley 1935), soil scientists (Jenny 1941), geomorphologists (Horton 1945), and hydrologists (Penman 1961). Prior research efforts largely have been conducted within these disciplines, whereas the current focus is motivated by the need for “a more holistic conceptual framework that encompasses regional hydrologic systems, land-atmosphere interactions, and biogeochemical cycles...” (this proposal call). The Critical Zone (CZ) exhibits tremendous structural organization across catchment scales (from hillslopes to river basins), and yet is commonly perceived as ubiquitously heterogeneous (Troch et al. 2007). Landscape heterogeneity makes accurate prediction of CZ response (e.g., water transit time and hydrochemical flux) and evolution (e.g., soil catena) a major challenge of Earth system sciences (Sivapalan 2005). Existing Earth science frameworks do not effectively integrate disciplines to address the fundamental challenge that is posed by the complex process couplings characteristic of the CZ.

We posit that CZ systems organize and evolve in response to open system fluxes of energy and matter driven by physical (gravitational, temperature) and chemical (concentration, solution saturation state) gradients. Energy and mass through flow facilitates system ordering when entropy is passed externally through dissipative processes (Prigogine 1961; Morowitz 1968; Smeck et al. 1983; Nicolis and Prigogine 1989; Addiscott 1994). Hence, CZ structural organization should be related to these transfers through the CZ system. The central importance of these fluxes is widely recognized, yet we still lack the ability to quantify the effective flows that are fundamental for understanding CZ function and predicting rates of CZ processes. CZ energy sources include solar radiation, and mass, momentum, and heat exchange with the atmospheric boundary layer. A portion of this energy is transformed into effective energy and mass transfer at the upper boundary of the CZ. A key goal of our project is to quantify the effective energy and mass fluxes that control CZ functioning and structural organization. As a first approximation, we propose to use a relatively simple but robust model based on the concept of “effective energy and mass transfer” (EEMT) to quantitatively link radiative and turbulent inputs to CZ cycling of energy, water, and carbon driven by chemical and physical gradients (Fig. 1). This approach, described in more detail in section 2.2, has been proven successful at predicting rates of pedogenesis, chemical weathering, and primary production at pedon scales (Runge 1973; Smeck et al. 1983; Rasmussen et al. 2005; Schneider and Sagan 2005; Rasmussen and Tabor 2007), but has not yet been applied systematically nor extended to coupled CZ processes at hillslope to watershed scales, where we assert it is equally valid. Our project will explore and generalize the EEMT approach to develop predictive models for rates of hydrologic, geomorphic, and biogeochemical evolution of the CZ that will be tested across spatial and temporal transitions in landscape structure using a well-constrained climate gradient within the proposed critical zone observatory (CZO). Identifying and quantifying specific relationships between effective energy and mass transfer will advance our ability to predict CZ response to changes in climate and land cover.

Our proposed CZO focuses explicitly on the process interactions mediated by climate-induced variation in energy and mass fluxes imposed on a common lithology in northern New Mexico (Jemez River Basin, JRB-CZO). On an annual basis, the range of water and energy availability spans that of ca. 70% of the continental U.S land mass. In addition, the JRB-CZO is an ideal location to study the role that spatial and temporal variability of mass and energy fluxes play in CZ processes. Our site is characterized by highly variable

![Figure 1: Conceptual model of CZ viewed as an open system where the transformation of available energy to effective chemical and gravitational energy and associated mass fluxes drive ordering and structural organization. Blue arrows represent feedback loops between catchment structure and effective energy transformation.](image-url)
precipitation and temperature patterns, including seasonal and interannual temporal variability, as well as distinct spatial patterning with elevation, slope and aspect. This variability exerts a first-order control on many important CZ processes including flood hazards (NRC 1996), fire regimes (Swetnam 1990), erosion rates (Molnar 2001), soil CO2 production (Tian et al. 1998; Knapp et al. 2002), and biological diversity (Kerr and Packer 1999). Measurement, modeling, and experiment at sites that vary in elevation, aspect, slope, soil development, and vegetation along our climate gradient will enable quantification of the feedbacks between energy and mass fluxes and various components of CZ structure and function. Toward that end, our CZO will be organized around a broad question that requires an integrated, multi-disciplinary approach: How does variability in energy input and related mass fluxes influence CZ structure and function, and how do feedbacks between water/carbon cycling and landscape evolution alter short- and long-term CZ development?

2. RESEARCH FRAMEWORK

2.1 Cross-Cutting Science Themes and CZO Hypotheses

Our proposed research is organized around three crosscutting science themes that are both multi-disciplinary and multi-scale (Fig. 2): (i) Ecohydrology and Hydrologic Partitioning (EHP), (ii) Subsurface Biogeochemistry (SSB), and (iii) Landscape Evolution (LSE). These themes, which are linked by fluxes of energy, water and carbon, are described below.

EHP Theme: Vegetation, soils, landform morphology, and bedrock play key roles in the partitioning of precipitation into canopy interception (Helvey and Patric 1965), infiltration (Philip 1967), storage (Beven 1982), soil evaporation (Penman 1948), sublimation (Pomeroy et al. 1998), plant transpiration (Shuttleworth 1988), recharge (Gee and Hillel 1988; Phillips et al. 2004), runoff (Horton 1933), and stream flow (Dunne and Black 1970). Hydrologic flow paths also feed back to affect vegetation structure (Liao et al. 2001), microbial community development (Lee and Foster 1991), soil formation and hydraulic characteristics (Rasmussen et al. 2005), landform morphology (Tucker and Bras 1998), mineral surface areas (Alsaaran and Olyphant 1998), and carbon transport (Tate and Meyer 1983; Hornberger et al. 1994; McDowell and Asbury 1994; Boyer et al. 1997; Brooks et al. 1999). This theme is organized to capture these linkages between hydrology and CZ evolution.

![Figure 2](image-url)  
*Figure 2.* Three CZO science themes related to how energy, water and carbon are transformed by open system CZ processes and example linkages among them.

![Figure 3](image-url)  
*Figure 3.* Implementation of our CZO has the goal of evolving our conceptual understanding of coupling between biological, physical and chemical processes via iterative measurement, experiment and process modeling at the hillslope and watershed scales.
SSB Theme: Subsurface reactions respond to energy, water, and carbon fluctuations that are superimposed on the spatial variability of solids and fluids distributed along water flow paths (McClain et al. 2003). Plants play a key transformative role because they convert water and atmospheric CO₂ to photosynthate, translating highly-variable radiant energy into a more persistent subsurface reactant enriched in protons and electrons (Drever 1994; Kelly et al. 1998; Chadwick and Chorover 2001). Organic carbon (C), CO₂ and chemical fluxes into and out of the soil zone and into the deeper subsurface represent boundary conditions for geochemical weathering along local and regional flow paths (Rademacher et al. 2001; Szramek and Walter 2004). These weathering reactions affect ecosystem nutrition (Landeweert et al. 2001; Calvaruso et al. 2006), subsurface transmissivity (White et al. 2005), and the poorly quantified surficial to deep inorganic and organic carbon sequestration (Chorover et al. 2004; Jardine et al. 2006).

LSE Theme: The landscape is a complex system with many feedbacks and nonlinear relationships between landform structure, soil development, vegetation cover, and water partitioning. Hillslope topography co-evolves with the subsurface weathering front (Heimsath et al. 1997; Mudd and Furbish 2004), while erosion, vegetation and weathering affect the storage of C and weathering products in the soil profile (Amundson 2005), influence soil hydrologic conductivity (Schaap et al. 2001; Young et al. 2004; Lohse and Dietrich 2005; Pelletier et al. 2005) and affect the partitioning of surface and subsurface runoff, which, in turn, feeds back to vegetation cover (Hamerlynck et al. 2002) and erosion.

To effectively coordinate among the three themes, our CZO goal of evolving our understanding of CZ processing in relation to energy and related mass flux is addressed through an iterative approach that includes experimentation, measurement, and modeling (Fig. 3). Specific hypotheses concerning the roles of energy, water and carbon through flow provide a framework to quantify the linkages and feedbacks between themes. These research hypotheses, presented in Table 1, address how the availability of energy, water and carbon drive mass flux and transformation throughout the CZ.

<table>
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<th>Table 1: Thematic Hypotheses Linked by Energy, Water and Carbon Fluxes</th>
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<td><strong>Central:</strong> The coupling of physical, chemical and biological processes can be related to the timing and magnitude of energy, water, and carbon fluxes.</td>
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<th>EHP theme</th>
<th>SSB theme</th>
<th>LSE theme</th>
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<td><strong>EEMT</strong></td>
<td>Hydrologic partitioning is uniquely related to the rate of effective energy and mass flux quantified as EEMT.</td>
<td>Mineral transformation rates increase with effective energy and mass flux (EEMT), giving rise to threshold changes in subsurface organic C stabilization.</td>
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| Water | Vegetation structure is the dominant control on pedon scale water transit time, whereas geomorphologic structure is the dominant control on catchment water transit time. | With increasing water transit time, the ratio of organic to inorganic carbon flux decreases, while Si and base cation flux increase. | The hydrological behavior of a hillslope is controlled by effective mass and energy flux through its effects on pedogenesis and feedbacks to surface and subsurface flow paths. |

| Carbon | Hydrologic partitioning and transit time of water control the input of DOC, CO₂ and DIC to the subsurface through effects on plant available water and hydrologic flushing. | Increasing frequency of soil wetting and drying promotes greater soil CO₂ production, enhanced secondary mineral formation, and greater sequestration of stable soil organic C. | Vegetation structure controls hillslope sediment flux through effects on depth distribution of soil organic C, hydrologic partitioning, and soil resistance to erosion. |
2.2 Critical Zone Modeling Approach

As one component of our work, we propose to develop an integrated, process-based model designed to (i) identify optimal sites for measuring structure and processes that interface the three project themes, (ii) refine hypotheses developed through field-based observation and measurements, (iii) explore feedbacks and emergent system behaviors, and (iv) develop transfer functions that can be used to link components of the system across scales. Our modeling work is not designed to be an end in itself but rather as a compliment to field-based efforts and as an instrument of synthesis. Modeling, field-based measurements, and synthesis will be performed iteratively throughout the course of the project (Fig. 3) in small work groups that require field scientists and modelers to interact. This process will allow each work group to pose questions to the model and update/modify the model over time.

We hypothesize that CZ systems organize in response to effective energy and mass fluxes. Our starting point for quantifying the effective energy and mass flux is based on the EEMT approach to pedon development (Arkley 1963; Runge 1973; Lieth 1975; Smeck et al. 1983; Rasmussen et al. 2005):

\[ E_{\text{EEMT}} = E_{\text{NPP}} + E_{\text{PPT}} \quad [J \, m^{-2} \, s^{-1}] \quad [1] \]

where \( E_{\text{NPP}} = NPP \cdot E_{\text{bio}} \), \( E_{\text{PPT}} = \Delta T \cdot C_w \cdot P_{\text{eff}} \). \( NPP \) is net primary production of biomass \([kg \, m^{-2} \, s^{-1}]\), \( E_{\text{bio}} \) is biomass energy content \([22 \times 10^6 \, J \, kg^{-1}]\), \( \Delta T = \text{ambient air} - 273 \, [K] \), \( C_w \) is the specific heat of water \([J \, kg^{-1} \, K^{-1}]\), and \( P_{\text{eff}} \) (net precipitation) = \( P_{\text{PTT}} - \text{Interception} \) \([kg \, m^{-2} \, s^{-1}]\). Here, the EEMT model converts mass influx into a single parameter that represents the primary driver for geochemical weathering and pedogenesis. In this particular example, effective energy is introduced via available water and biomass. This definition of EEMT has recently been shown to effectively predict soil development for stable summit hillslope positions (Rasmussen and Tabor 2007). EEMT can be averaged over any spatial and time scale, but its principal components are expected to exhibit some dependence on the CZ process targeted. Hillslope erosion processes, for example, are likely to be controlled primarily by gravitational potential, the momentum of net precipitation, and biomass. Thus, our proposed project seeks to develop generalized expressions relating energy and mass flux to CZ structure and process across the theme areas (Table 1).

Relations between EEMT inputs and CZ response will be refined by process modeling at the hillslope scale. Initially, this detailed hillslope measurement and modeling (DHMM) work (Fig. 4) will involve coupling of available modeling codes already in use within our group including: (i) an EEMT-based empirical model of pedogenesis (Rasmussen et al. 2005), (ii) a flexible geochemical reaction code for kinetically-limited reactive transport at soil column scale (Steefel et al. 2005), (iii) a distributed hillslope and catchment hydrology model (Paniconi and Wood 1993), (iv) a biogeochemical flux model at the hillslope scale (Parton et al. 1993; Parton et al. 1998), and (v) a model of sediment transport using the nonlinear diffusion equation (Roering et al. 1999). Sediment transport and bedrock weathering rates will be inputs to a mass conservation model that evolves hillslope topography, pedogenesis, and geochemical concentrations forward in time over geologic time scales.

Finally, our modeling approach will involve translation of the DHMM into a prediction model applicable at the watershedscale via a suite of upscaling procedures, such as empirical transfer functions (Schaap et al. 2001), similarity indices (Troch et al. 2004; Berne et al. 2005; Lyon and Troch 2007), and reduced-complexity flow and transport equations (Troch et al. 2002; Troch et al. 2003; Hilberts et al. 2007). Thus, detailed flux measurements at hillslope scales will be linked with integrated flux measurements of water and solutes at the watershed scale. Upscaling will rely on using EEMT and similar expressions derived for other processes as the primary driving variables for CZ processes and will also rely on developing transfer functions between local and basin-wide water/carbon/sediment fluxes.
3. THE JEMEZ RIVER BASIN (JRB) CRITICAL ZONE OBSERVATORY

The Jemez River Basin (JRB)-CZO will be located in northern NM, at the southern margin of the Rocky Mountains ecoregion (Allen et al. 1991) between 1700 and 3432 m (Fig. 5 and 6). Vegetation ranges from semi-arid juniper savannah to high elevation mixed conifer forest, with soil types that are characteristic of the region, including Aridisols, Alfisols, Mollisols and Inceptisols (Allen et al. 1991; Allen and Breshears 1998; Allen et al. 2002). The geological and geomorphic history of the basin, which is underlain by rhyolitic parent material ranging in age from 1.13 Ma to 0.13 Ma, is well characterized (Heiken 1986; Truesdell and Janik 1986; Vuataz and Goff 1986; White 1986; Goff and Shevenell 1987; Woldegabriel and Goff 1989; Heiken et al. 1990; Woldegabriel and Goff 1992; Goff and Gardner 1994; Formento-Trigilio and Pazzaglia 1998; Broxton and Vaniman 2005). The paleoclimatic and paleovegetation constraints on the site are virtually unique in the SW US due to recent coring of lacustrine sediments in the caldera (Fawcett 2006).

The JRB-CZO represents ca. 70% of the North American continent’s variability in water and energy expressed using the EEMT formulation in Eq. (1) (Fig. 7). Temperature and the amount, seasonality, and form of precipitation vary with elevation (Bowen 1996) presenting an ideal opportunity to array a set of nested sites/watersheds to capture thresholds in CZ structure driven by water and energy availability (Allen 1989). The well documented lithology across the gradient allows for selection of sites with comparable geochemical composition and age. Mean annual temperature (MAT) at the nearest long-term climate station (Los Alamos 2100 m) is 9 °C and mean annual precipitation (MAP) is 475 mm (data from the National Climatic Data Center). In contrast, precipitation 7 km east of Los Alamos at the Quemazon SNOTEL station (2896 m) located on the caldera rim is 720 mm (i.e., 50% higher). The Jemez River Basin is part of the larger Rio Grande watershed.

A central feature of the JRB is the Valles Caldera located at the top of the watershed (Fig. 5-6). The caldera is a collapsed magma chamber, 25 km in diameter, that encloses several resurgent lava domes formed after the chamber collapsed ca. 1.2 Ma (Heiken 1986; Goff and Gardner 1994). The caldera interior is a single watershed unit draining through a breach in the caldera wall. The largest of the resurgent domes, Redondo Peak, is located in the center of the caldera resulting in the unique situation where headwater streams of the Jemez River originate on different aspects of the same mountain, providing the opportunity to probe contrasting microclimates on a uniform parent material with a common precipitation regime (Fig. 5).

4. HYPOTHESIS-DRIVEN CZO RESEARCH

The well-constrained JRB-CZO gradient is an ideal experimental setting for testing how vegetation, soils and regolith co-evolve as minerals weather in the presence of biota (Fig. 6). Testing our central hypothesis that the coupling of physical, chemical, and biological processes can be related to the timing and magnitude of energy, water, and carbon fluxes requires process coupling of ecohydrology and hydrologic partitioning (EHP), subsurface biogeochemistry (SSB), and landscape evolution (LSE). We organize our approach by testing sub-hypotheses within these cross-cutting...
science themes, and integrating them using the framework of (1) effective energy and mass transfer, (2) water and (3) carbon flows (Table 1). A brief rationale for testing each hypothesis is provided in this section, and an integrated methodology is provided in the Implementation Plan. While these hypotheses represent the research focus of the current proposal, they are only subset of those that could potentially be tested at the JRB-CZO.

4.1. Energy Hypotheses

**EHP1**: Hydrologic partitioning is uniquely related to the rate of effective energy and mass flux as quantified by EEMT.

The most fundamental question in hydrology is “what happens to precipitation?” (Penman 1961). Hydrologists address this question by quantifying the terms of the water balance equation:

\[ P = \Delta S + E + T + Q + R \]  \[ \text{[2]} \]

where \( P \) is precipitation, \( \Delta S \) is near-surface water storage, \( E \) is evaporation/sublimation, \( T \) is transpiration, \( Q \) is runoff, and \( R \) is groundwater recharge. Even though the different external controls (e.g. soil properties, vegetation type, landscape position) on the partitioning of precipitation have been studied for decades, there is no unified hydrologic theory available to scale the quantities of the water balance components in time and space. Here we hypothesize that, when lithology is uniform across a geophysical province, the external controls on hydrological partitioning depend on effective mass and energy fluxes in current time and over the course of geomorphic development since rock exposure. The starting point for our work is the EEMT formulation introduced in Section 2.2. Preliminary work has established transfer functions to be developed between EEMT, clay content, and saturated hydraulic conductivity (Fig. 6). We recognize, however, that a more complete understanding of hydrologic partitioning will require additional input variables (e.g. gravitational potential).

**SSB1**: Mineral transformation rates increase with effective energy and mass flux (EEMT), giving rise to threshold changes in subsurface organic C stabilization.

Stabilization of subsurface organic C against microbial degradation results from (i) inherent recalcitrance, (ii) interaction with metals and surfaces, and (iii) occlusion within aggregates (Sollins et al. 1996). We postulate that chemical denudation rates should increase with EEMT because of higher water and dissolved organic matter (OM) fluxes. At low elevation, low water and OM inputs result in slow chemical weathering with minimal C stabilization by clays, metals.

**Figure 6.** JRB-CZO elevation gradient with representative photos of vegetation and CZ properties: [A] mean annual precipitation (MAP) and air temperature (MAAT); [B] EEMT, net precipitation (P\text{eff}) and above ground net primary production (ANPP); [C] Soil production and silica denudation rates simulated with EEMT; [D] Estimated clay content and saturated hydraulic conductivity (K\text{sat}). Dashed drop lines and stars indicate transitions in CZ properties and proposed field sites.
and aggregates, and with predominant preservation of recalcitrant particulate OM. At intermediate elevations incongruent chemical weathering of primary minerals (e.g., glass, feldspar, mica) will predominate (Yokoyama and Banfield 2002) resulting in both crystalline (e.g., kaolinite and halloysite) and poorly-crystalline secondary minerals (e.g., allophane and ferrihydrite) (Chorover et al. 2004). At higher elevation sites, deeper organic soil horizons and organic complexation of Al and Fe (Ugolini et al. 1988) will result from low pH, high leaching rates and low microbial degradation rates of OM. Hence, we expect the principal mechanisms of subsurface C stabilization to transition from (i) recalcitrance to (ii) mineral/aggregate stabilized to (iii) metal-complex stabilized organic C with increasing EEMT.

**LSE1**: The dominant processes of landscape denudation transition from physical to chemical following patterns in effective energy and mass flux (EEMT) and vegetative cover.

The transformation of bedrock to soil and subsequent mineral transformations that occur via physical and chemical weathering processes are a fundamental component of landscape evolution. Soil production rate is a function of erosion, the physical breakdown of rock to saprolite, and chemical weathering within the pedon and at the soil-bedrock interface. All of these are related to parent material, landform and EEMT. Pedon scale mass conservation models allow for quantitative estimates of chemical denudation and physical changes that occur during the soil formation process (Brimhall and Dietrich 1987), particularly Si and other cation fluxes that are proxies for long term rates of mineral weathering and CO₂ consumption. We hypothesize that gross patterns in the relative importance of physical and chemical processes will vary with effective mass and energy fluxes across the JRB gradient, whereas local scale dynamics of hillslope morphology, vegetation structure and stream channel incision will control hillslope to pedon scale denudation.

**4.2. Water Hypotheses**

**EHP2**: Vegetation structure is the dominant control on pedon scale water transit time, whereas geomorphologic structure is the dominant control on catchment water transit time.

Transit time is a fundamental hydrologic descriptor that reveals information about storage, flow pathways and water source in a single characteristic (McGuire and McDonnell 2006). From Darcy’s law we can estimate the average transit time τ as:

\[ \tau = \frac{n_e (\Delta l)^2}{K \Delta h} \]  

where \( n_e \) is an effective porosity, \( K \) is hydraulic conductivity, \( \Delta h \) is the difference in hydraulic head over the distance \( \Delta l \). We hypothesize that, at the pedon scale, the transit time is most strongly controlled by vegetation and soil structure (controlling the \( \Delta h \) and \( K \) terms), whereas at the hillslope to catchment scale, it is most strongly controlled by the geomorphologic structure of the landscape (controlling \( n_e \) and \( \Delta l \)). Presumably, feedbacks between vegetation structure, subsurface biogeochemistry, and landform development result in a range of transit time distributions throughout a catchment (McDonnell et al. 2006; Troch et al. 2007).

**SSB2**: With increasing water transit time, the ratio of organic to inorganic carbon flux decreases, while Si and base cation flux increase.

The flux of C, nutrients and base cations from soils to deeper flow systems in the CZ and eventually to surface discharge and the oceans is linked to the transit times of groundwaters, contact time with primary mineral surfaces, mineral solubilities, and biogeochemical processes (Bullen et al. 1996). Weathering of highly reactive silicate minerals common to rhyolitic parent materials, such as volcanic glass, plagioclase and amphiboles, facilitates rapid drawdown of CO₂ in surface soil horizons (Dahlgren et al. 2004; Wolff-Boenisch et al. 2006). Weathering of less soluble minerals, such as quartz and orthoclase, may be an important contributor of solutes and DIC in deeper soil profiles and fractured bedrock (Walker et al. 2003). Groundwaters with short transit times will quickly efflux weathering products, DOC, and CO₂ to surface waters, and release CO₂ back to the atmosphere (Richey et al. 2002). In contrast, groundwaters with longer transit times will contain lower DOC concentrations due to microbial degradation, and transport higher concentrations of conservative alkalinity-associated DIC (Szramek and Walter 2004) and base cations to surface drainages (Rademacher et al. 2001).
LSE2: The hydrologic behaviour of a hillslope is controlled by effective energy and mass flux through its effects on pedogenesis and feedbacks to surface and subsurface flow paths.

The hydrologic response of drainage basins and hillslopes to water and energy is controlled by the near-surface landscape properties that function as hydrologic filters. Accurate depiction of the governing processes for these landscape properties, and their spatial distribution, is a prerequisite for understanding the hydrologic behavior of hillslopes and drainage basins and the evolution of this behavior through time (Troch et al. 2007).

Hillslope hydrology is controlled by landform curvature and pedogenic development (Beven 1982; Troch et al. 2003). EEMT may be used to define a landscapes’ “pedogenic regime”, providing an estimate of the degree of soil development and properties important to hillslope hydrology (e.g., development of a clay-rich argillic horizon; see Fig. 6). We expect that controls on hydrologic behavior transition from landform-dominated to soil-dominated between low and high EEMT. Low EEMT systems possess shallow soils (<50 cm) so that water is routed dominantly overland and through fractured bedrock, whereas high EEMT ecosystems possess deep soils (>100 cm) with subsurface diagnostic horizons and thick saprolite over bedrock facilitating greater movement of water through the soil.

4.3. Carbon Hypotheses

EHP3: Hydrologic partitioning and transit time of water control the input of DOC, CO$_2$ and DIC to the subsurface through effects on plant available water and hydrologic flushing.

The aboveground NPP (ANPP) response to precipitation across many biomes shows decreasing sensitivity with increasing mean annual precipitation (MAP) (Huxman et al. 2004). The traditional view (e.g., Aber et al. 1998)) of this decrease in rain-use efficiency (RUE) is that leaching and progressive nutrient limitation diminish site fertility at greater MAP sites. However, the ratio of runoff to precipitation also increases at these sites (Zhang et al. 2001). As a result, decreasing RUE is likely not a function of biogeochemical constraints (e.g., progressive N limitation with higher MAP), but rather due to the increasing size of ‘physical’ reservoirs for water in deeper soils.

SSB3: Increasing frequency of soil wetting and drying promotes greater soil CO$_2$ production, enhanced secondary mineral formation, and greater sequestration of stable soil organic C.

Heterotrophic respiration is highest for systems with repeating wet-dry cycles (Huxman et al. 2004; Huxman et al. 2004; Miller et al. 2005) due to accumulation of reactants necessary for respiration during intervening dry periods, increased physical access to soil C, and cell lysis during soil wetting (Fierer and Schimel 2003). The resulting elevated PCO$_2$ increases the rate of carbonic acid attack on primary silicate minerals (Drever 1994; Kelly et al. 1998), and increases silica and bicarbonate efflux during periods of high water flux (Riebe et al. 2003). Subsequent drying events result in solution phase super-saturation with respect to secondary clays, which can stabilize C against degradation via sorptive interactions and aggregate formation. Rapid weathering as a result of frequent wet-dry cycles can lead to greater accumulation of clays (Weitkamp et al. 1996). Clay accumulation enhances plant available soil moisture and
evapotranspiration, thereby providing a positive feedback on NPP. Additionally, greater clay content slows water transport in the soil and thus increases rates of mineral weathering per unit water volume (Schaap et al. 2001).

**LSE3**: Vegetation structure controls hillslope sediment flux through effects on depth distribution of soil organic C, hydrologic partitioning, and soil resistance to erosion.

Vegetation impacts hydrologic partitioning and soil resistance to erosion through addition of organic C to surface and subsurface horizons. This C facilitates aggregation of soil particles and increases porosity, infiltration and soil stability (Oades 1988; Six et al. 2004). The distribution of C within the profile varies with vegetation, i.e., trees and woody plants concentrate C in surface litter, whereas grasses deposit C in the upper portion of the mineral soil via root turnover (Buol et al. 2003). Hence, vegetation structure and the distribution of C within the soil interact to control hillslope sediment flux. We posit that sediment transport in soils with substantial structural resistance (deep rooting, high soil C) will be confined to brief periods during large storms or mass wasting events. Conversely, on poorly-structured soils (patchy plant cover and root distribution, low soil C) wet-dry cycles may reduce aggregate stability and resistance to sediment loss, thereby counteracting the enhanced local C sequestration effects discussed under the prior hypothesis.

5. IMPLEMENTATION PLAN

We will coordinate observations, experiments, and modeling activities to address our hypotheses and integrate results into an improved, interdisciplinary understanding of CZ structure and function. An iterative process of experimentation (both field and model), measurement, and model development will be employed to: 1) identify and quantify the mechanistic underpinnings of CZ dynamics, and, 2) evaluate the integrated effects of these processes on catchment-scale CZ structure and function. Our approach operates at two complementary levels (see box below), referred to as coupled watershed measurement and modeling (CWMM) and detailed hillslope measurement and modeling (DHMM).

We will focus DHMM activities on spatial transitions in CZ structure (e.g. forest-grassland: regolith-colluvial boundaries) and temporal transitions in water/energy input (e.g. date of snowmelt; initiation of summer monsoon) to improve the mechanistic description of CZ function. CWMM activities will utilize nested watersheds along an elevation / EEMT gradient in the JRB to develop scaling rules and transfer functions needed to describe the integrated, catchment-scale effects of pedon to hillslope scale processes. The iterative nature of our modeling and measurement activities, and its ability to refine and test hypotheses, will be important to integrating our two levels of investigation. Our hypothesis testing (see Table 2 on page 11) – which depends on data deriving from multiple disciplines, exercises and scales – provides a mechanism to (i) cut across theme areas, (ii) establish the groundwork for complementary observations, and (iii) promote synergistic experiments at disciplinary interfaces. This approach also provides an adaptive framework for responding to new research opportunities posed by collaborators or enabled by leveraging.

5.1. Developing Nested Research Sites

Our intensive research sites for plot- to hillslope-scale DHMM are nested within instrumented catchments of increasing size for CWMM. Co-locating and nesting of sites of intensive process measurement and modeling will enable upscaling of mechanistic understanding derived from local (e.g., pedon) scale to improve process understanding of watershed and CZ dynamics. We will establish five key nested research sites derived from lithology of similar age and geochemistry at elevations within the JRB-CZO gradient (Fig. 6) identified by our preliminary effective energy and mass flux (i.e. EEMT-based) model as representing key transitions in CZ structure and function. For example, the **Ponderosa Pine to Mixed Conifer transition (~ 2600m asl)** marks an inflection point in effective energy and mass flux, where we expect increases in EEMT to correspond to decreased rates of bedrock conversion to soil but increased rates of chemical denudation. DHMM activities will be focused on these five intensive research sites to evaluate specific aspects of CZ structure associated with our thematic areas and hypotheses. Within each catchment, additional hillslopes with
contrasting aspect, vegetation, or other physical characteristics that allow for specific hypothesis testing will be exploited. The integrated measurements, modeling and experimentation are discussed in more detail below, in relation to the pedon-to-basin scales where they will be conducted. We recognize that the CZO as a whole is needed to access the full range in EEMT required for testing of several of our hypotheses.

5.2. Coupled Watershed Measurement and Modeling (CWMM)

**Task – Develop coupled watershed model** A key primary step toward developing a model-measurement iterative framework for investigation within our entire program is to evaluate initial EEMT predictions of CZ structure (e.g. Fig. 6), and to develop needs for distributed data or process-based field research – to allow modeling and data collection to co-evolve. We will compare model predictions with distributed soil samples (mineral weathering, C stabilization mechanisms) by genetic horizon to the depth of bedrock at hillslope catena positions along a CZO-wide transect in EEMT (*SSB1* and *LSE1*) (yrs 1-2). Total denudation rates at the pedon, hillslope and watershed scale (*LSE1*) will be estimated through cosmogenic radionuclides (CRN, $^{10}$Be and $^{26}$Al) (*Granger et al*. 1996; *Heimsath et al*. 1997), which combined with pedon mass balance (*Chadwick et al*. 1990; *Anderson et al*. 2002) will provide a direct measure of the relative importance of physical and chemical weathering processes (*LSE1*) (*Riebe et al*. 2004). From initial results and subsequent modeling/measurement efforts (yrs 3-5), we will develop, evaluate, test, and refine either theoretical (*Troch et al*. 2004) or empirical (*Budyko*, 1974) transfer functions relating the principal input driver, EEMT, to CZ structure and function (*Jakeman and Hornberger* 1993; *Herbst and Diekkruger* 2002; *Romano and Palladino* 2002; *Rasmussen et al*. 2005).

**Task – Implement distributed/integrated measurements** A primary JRB-wide task is to interpret the time dependency of basin scale fluxes (water, biomass, solutes, sediments) in terms of understanding how processing of those constituents is distributed throughout the observatory. Our collection of basin-wide data distributed in both space and time will result in transfer functions and scaling rules for our detailed process results, quantitatively linking research from pedon-to-basin.

**Catchment-scale** hydrological, biogeochemical, phytological and meteorological data will be collected using 14 nested, gauged catchments (existing structure maintained by our partners and collaborators) to link hillslope research activities to the sub-catchment scale. Specifically, we will instrument zero- and first-order subcatchments for discharge, hydro-meteorological, and both routine and event-based hydrochemical sampling. Soil- and ground waters will be analyzed along with surface water discharge and chemistry to calculate pedon-to-hillslope-to-catchment water and solute fluxes. Synoptic surveys of key variables (e.g., soil moisture, snow water input, sap flow, tree-rings, soil water isotopes, elemental tracers) and remote sensing products (e.g. snow cover, ET) will be used to develop distributed data sets to scale beyond our pedon/hillslope specific process relationships. Water budget partitioning and NPP estimation will be conducted to test whether maximum phytomass production occurs where $Q$ and $R$ [Eq. 2] increase in magnitude (*EHP3*). Eddy covariance estimates from existing sites in different vegetation types will translate the production data to ecosystem C exchange. DOC/DIC, DON/DIN, particulate and inorganic solute export will be quantified and compared to measured subsurface biogeochemical reactions (e.g. *Brooks et al*. 1997; *Brooks et al*. 1999) (*SSB2*).

**Basin-scale** water samples, collected from pedon-to-basin scale, will be analyzed for stable and radiogenic isotope composition to estimate mean transit time (*McGuire and McDonnell* 2006), a dominant control on hydrologic and biogeochemical processes within the CZ (*EHP3, SSB2*). Groundwater geochemical and isotopic data, including CFCs, SF$_6$, stable (O, H, C) and radiogenic isotopes ($^3$H, $^{14}$C), from groundwater wells, will be used to identify water residence times within the groundwater system. Real-time measurements of $PCO_2$ in and around groundwater discharge zones will allow us to identify key locations and periods where CO$_2$ from groundwaters arriving at the surface may be effluxed in significant quantities to the atmosphere. Chemical and isotopic tracers with mass-balance and mixing models (e.g., PHREEQC, NetPath) will allow us to couple CWMM and DHMM activities (below) to determine the solute and water sources to stream discharge, fluid and solute residence times, mineral saturation states, and biogeochemical modifications along flow paths.
Table 2: Approach to Hypotheses Listed in Table 1

**Goal:** Establish CZO along a gradient in water and energy input that emphasizes correlated transitions in biological, geochemical and geophysical characteristics of CZ structure. Predict transitions with CWMM, validate by field observation and elucidate process by field experiments and DHMM.

<table>
<thead>
<tr>
<th>Flows</th>
<th>EHP theme</th>
<th>SSB theme</th>
<th>LSE theme</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Energy</strong></td>
<td>Locate paired hydrometric stations designed to capture key CZ structural transitions including vegetation, aspect, and slope. Quantify daily, weekly, monthly and annual water balances for the study period. Scale individual water budget components by incoming precipitation and correlate to EEMT at river basin and annual scales. Use these measurements to drive, evaluate, and calibrate our hydrologic model components through a split sample and land cover change approach.</td>
<td>Determine soil and regolith mineralogy and its relationship to soil OM content and chemical characteristics in hillslope transects at the principal EEMT transition zones. Correlate measured parameters with soil C forms, aggregation, recalcitrance, mineral/metal associations and turnover times. Use DHMM to simulate biogeochemical weathering reactions at sub-pedon (column) scale to assess the reaction front in relation to C storage. Utilizing measurements to evaluate model performance.</td>
<td>Sample soils along hillslopes to bedrock in the principle EEMT transition zones. Quantify the elemental mass balance for each hillslope position based on total elemental analyses by genetic horizon. Quantify total denudation rates at the pedon, hillslope and catchment scales using cosmogenic radionuclides. Pedon scale mass balance will be scaled to hillslope scale via numerical models with DHMM and further upscaled to the watershed scale using local patterns of EEMT and CWMM.</td>
</tr>
<tr>
<td><strong>Water</strong></td>
<td>Combine isotopic and biogeochemical tracers to evaluate flow path length and transit time at pedon to basin scales under controlled comparisons for vegetation type (tree, shrub, grass), geomorphology (hillslope length, curvature, contributing area), and flow system (hydraulic geometry, channel network structure, hypsometric curve). Test DHMM with pedon and hillslope transit times. Test CWMM with the large scale data.</td>
<td>Sample lysimeters, wells, springs and surface waters to measure C forms, element concentrations, (^{87}\text{Sr}/^{86}\text{Sr}, \text{H}, \text{CFCs}, \text{SF}_6) and stable isotopes (O,H,C) to constrain residence times. Combine analytical data with mass-balance, reaction-path and mixing models to determine sources/fluxes of solutes, fluid pathways, and biogeochemical transformations. Identify hot spots of CO(_2) efflux around groundwater discharge zones. Use relations between transit times and C forms to constrain C processing in DHMM and transit times in CWMM.</td>
<td>Quantify variation in soil physical properties (depth, horizonation, clay content, conductivity) that partition water above and below ground. Correlate with water movement across hillslopes determined using tensiometers and piezometers in conjunction with TDR probes situated along axis of each watershed valley and on convergent hillslopes above the channel head. Predict soil development from DHMM as a means to couple pedologic, geomorphic and hydrologic processes at the watershed scale with CWMM.</td>
</tr>
<tr>
<td><strong>Carbon</strong></td>
<td>Estimate ANPP and water partitioning at principle EEMT transitions to assess where maximum ANPP occurs in relation to Q and R [Eq. 1]. Use Eddy covariance sites to ‘anchor’ studies by vegetation type and to translate the ANPP data to net ecosystem C accumulation. Exploit contrasting vegetation types and hydrologic partitioning for fixed MAP. Determine DOC and DIC transport at sites of production and relate to soil development and organic matter stabilization/turnover.</td>
<td>Measure soil solution and gas phase composition over wetting-drying cycles at principle EEMT transitions. Relate CO(_2) production-consumption dynamics to the fate and transport of labile OM, HCO(_3^-) efflux and dissolved mineral weathering products. Assess the temporal dynamics of mineral saturation states and evaluate their relation to mineral assemblage and carbon sequestration at the pedon, hillslope, catchment and basin scale. Use DHMM to test the relative importance of wetting-drying versus vegetation and mean EEMT.</td>
<td>Measure vegetation structure, depth distribution of roots and OM &amp; correlate with estimated sediment transport rates, assuming steady-state between soil production and erosion at each hillslope site. Derive sediment flux estimates from high-resolution DEM’s, landform morphology and soil-production rate (calculated with the EEMT-based DHMM and refined with CRN measurements). Estimate carbon erosion/deposition by equating OM transport to a depth integrated velocity profile. Measure overland flow by flumes to determine flow resistance and critical shear stress across a range of vegetated surfaces.</td>
</tr>
</tbody>
</table>

-Jemez River Basin CZO – Project Description-
5.3. Detailed Hillslope Measurement and Modeling (DHMM)

Task - Develop Detailed Hillslope Model To interface results of disciplinary teams obtained at the plot-to-hillslope scale we will couple established, discipline-specific, codes (including code verification1) into a Detailed Hillslope Model. Coupling will be accomplished using the Flexible Modeling System (FMS) flux coupler approach developed at the Geophysical Fluid Dynamics Laboratory (Zhou 2005). The flux coupler establishes a strict protocol of input/output for each submodel. Each submodel is compiled as a Dynamic Link Library (DLL) that is executed sequentially by the flux coupler according to a “master clock” schedule during each time step. This modular approach allows us to (i) couple established models with minimal changes to the source code, (ii) facilitate scaling exercises among processes occurring on inherently different spatial or temporal domains, and (iii) swap model components to evaluate the sensitivity of system behavior to each submodel. Following code verification, we will employ an iterative model–experiment framework to establish DHMM activities and refine model representations of coupled CZ processes2. This means that input values for water, energy, and substrate properties will be increasingly constrained by field characterization. Topography will be used to quantify elevation and slope-aspect controls on energy input using point-based field measurements in addition to driving hydraulic flow. Short-term outputs of sediment flux and water quantity / chemistry will be validated against field-based measurements in order to refine the model inputs and process interactions iteratively during the project period and to better constrain long-term estimates of weathering rates, soil chemistry and depth, and hillslope morphology predicted by the model. Comparison with pattern inferred from cosmogenic nuclide concentration profiles in soil and saprolite will further inform model performance. For short-term simulations, the hillslope evolution and pedogenesis components of the model will be turned off. For seasonal-scale simulations, changes in energy and water input will modulate hillslope hydrology, geochemical reactions and weathering. For long-term model runs, results from event-based processes will be integrated to simulate soil depth and hillslope evolution over geologic time.

Pedon Scale Measurements We will measure real-time fluxes and stores of water (EHP1 and EHP2), dissolved and colloidal OM (EHP3), CO₂, and mineral weathering products to assess contemporary weathering processes (White et al. 2005), soil respiration, and subsurface C transport (Stieglitz et al. 2003). Hydrological, biogeochemical, and (latent and sensible) heat fluxes will be measured in both vertical and horizontal directions using CZO-pedon stations including the ‘anchor’ eddy covariance flux (H₂O/CO₂) towers and soil gas efflux chambers at key vegetation types, precipitation gauges, soil / vegetation lysimeters, sap flow sensors, tension and zero tension lysimeters, soil gas samplers, soil moisture sensors, tensiometers, soil heat flux plates and resin collection methodologies (McDonnell et al. 1991; Hendry et al. 1999; Arzberger et al. 2004). Solution chemistry data will be used to calculate saturation state [Ω, (Bethke 2005)] with respect to secondary mineral phases and thereby relate contemporary reactions (SSB1) to long-term pedogenesis (LSE1). Saturation indices will be calculated as a function of time (seasonal and event-based sampling along the EEMT gradient) to determine trajectories and thresholds in mineral weathering (SSB1), including their relation to CO₂ dynamics (SSB3), EHP variation (LSE2) and C flux (SSB2). Buried mineral specimen bags will assess weathering extent and C accumulation (Robert and Berthelin 1986).

Hillslope Scale Measurements Pedon scale measurements will be distributed within hillslopes in order to provide a fine-scale, distributed depiction of matter and energy fluxes and stores. Measurements to be made at the hillslope scale include surface runoff, subsurface flow and saturated storage (EHP1), sediment fluxes (LSE3), and a combination of isotopic, geochemical and biogeochemical tracers to evaluate flow path length and transit time as function of geomorphic properties and vegetation types (EHP2) (Table 2). In addition, at each hillslope position, we will measure (i) resistivity of surface soils (shear and tensile strength), (ii) soil C and N content, infiltration and water holding capacity, and (iii) flow resistance and critical shear stress to overland flow (Prosser et al. 1995) (LSE3). Flow resistance and sediment transport data from vegetated surfaces, as well as critical shear stress, will be obtained from these experiments and compared among hillslope sites (Istanbulluoglu and Bras 2005).

1 Verification is the process of ensuring that the computer program and its implementation are correct.
2 This step includes model validation, the process of determining the accuracy of the model and degree to which it represents CZO measurements.
6. PREVIOUS AND ONGOING RESEARCH

The proposed JRB-CZO will build on and collaborate with two ongoing research efforts. The first is a multi-institution eco-hydrological research effort begun in 2004 and coordinated by the NSF-funded Science and Technology Center for Sustainability of semi-Arid Hydrology and Riparian Areas (SAHRA). This effort focuses on assessing the hydrologic impacts of vegetation change, thereby necessitating coordinated measurement, experimentation and modeling in land-atmosphere, vadose zone, surface water, and groundwater hydrology. Eco-hydrologic infrastructure includes snow and rain precipitation sensors, eddy covariance towers, land surface, vadose zone, and subsurface hydrologic arrays, groundwater wells, geochemical and isotopic tracer work, and biogeochemical measurements, all nested within gauged catchments. The second ongoing effort is that of the Valles Caldera National Preserve (VCNP), a primary partner of the JRB, facilitating many of the proposed observations and undertaking ongoing measurement, monitoring, and experimentation. The VCNP has inventoried natural resources (fauna, flora, geology, soils, water quality) and performs ongoing resource monitoring. In 2007 the VCNP will expand research funded by the NM state water board including: i) installing additional discharge weirs, ii) installation and operation of a SNOTEL site, iii) installing ISCO® automated water sampling stations to characterize water quality during episodic flow events, iv) developing a wireless background network to connect remote instruments into a real-time, or near real-time wireless, data transmission system, and v) implementing a public education/volunteer group to assist with water quality sampling campaigns.

7. CYBER-INFRASTRUCTURE

We plan to build from an existing database developed by SAHRA for the CZO area to include a universal web service and interface for time-series data retrieval and mapping. The SAHRA Geo-Database (SGD) was designed as a centralized multi-user database accessible for users to store, disseminate and coordinate field and model research development. The database is structured into four parts: i) public schemas containing high- and medium-resolution datasets for the southwestern United States; ii) materialized views of datasets for the JRB at multiple resolutions; iii) private and semi-private data generated by research activities; and iv) documentation on rules, procedures, catalogs, and database contributors. SGD is implemented in the Oracle Relational Database Management Systems (RDBMS), which allows multi-user data access and editing. Geospatial data are managed in RDBMS using ArcSDE, which provides functionalities to store and retrieve vector and grid data in the relational database. While we view data storage as the responsibility of the local CZO, we will coordinate closely with - and facilitate interactions between - both the Critical Zone Exploration Network (CZEN) and CUAHSI efforts. The Center for Environmental Informatics at Penn State is creating the cyberinfrastructure for CZEN. This effort is currently building a web-based knowledge management portal and designing a “virtual” CZEN data and information system by creating a semantic infrastructure that can be accessed by sophisticated data search and retrieval mechanisms. Likewise, the CUAHSI Hydrologic Information System (HIS) is designed to support data collection, storage, and dissemination through a community-enabled set of data and metadata standards. Presently the SAHRA database uses the HIS ArcHydro data models and tools for surface water and groundwater to store and process the hydrographic and hydrologic data.

Data collected by CZO researchers will be governed by a data policy that will largely be based on that developed by the LTER network and SAHRA (www.sahra.arizona.edu/about/datapolicy.html). Key aspects include: i) requirement for all investigators to submit data within 6 months of collection or analysis to ensure continued funding; ii) the provision for data to remain private for 1-year from date of collection where only those given permission by the collector may view the data; iii) semi-private data for another year during which all CZO researchers may view the data; and iv) all data will be public after two years.

8. EDUCATION AND OUTREACH

Our goal in education and outreach is to help our students, stakeholders and the public as a whole to grasp the interconnectedness of CZ processes, the continuing evolution of the landscape, and, therefore, to appreciate the societal implications of a dynamic, open CZ system whose function depends on climate and land cover. Our education and
outreach plan builds on highly effective collaborations between SAHRA and the VCNP. The main theme of our effort is providing graduate and undergraduate students with a problem-based, interdisciplinary and collaborative field experience at the JRB-CZO. A new two-week field methods camp will be required for incoming CZO graduate students and will be open to students at all partner institutions. Faculty and senior researchers from each of the three CZO research themes (EHP, SSB and LSE) will provide a hands-on, field-based introduction to these topics as well as more basic topics such as field mapping, sensor calibration, data acquisition and synthesis, and survey design. SAHRA’s existing one-week spring snow hydrology camp (led by Co-PI Brooks) complements the summer field methods course and provides opportunities for students to conduct field measurements at the peak of snow accumulation in the JRB. A centrally-directed application procedure and existing winter accommodations link this effort to our broader educational mission. Throughout these programs, we will focus on peer mentoring, and building a well-integrated and tightly-bonded cohort of students who have a uniquely integrated view of the critical zone.

All research and education activities at the JRB-CZO will be shared with the public through web-based materials and leveraged outreach collaborations with the VCNP, Explora Science Center, and the NM Museum of Natural History and Science in Albuquerque. We will continue to assist VCNP in developing high school field trip guides and in developing plans for a new, on-site visitor center/research base station with content that could be developed in collaboration with the NSF-funded investigators to introduce the Critical Zone and highlight CZO research. SAHRA currently has supportive infrastructure and expertise in all these areas, based on development of watershed visualizations and public displays at many informational science centers (Phoenix Zoo, Kartchner Caverns, Sabino Canyon).

We will promote CZO activities and draw outside investigators into the CZO at local, regional, national, and international levels, by: providing funds for participant and associated field-staff support; developing and continually updating a web site that builds on the existing website developed by the SAHRA STC center (www.sahra.arizona.edu/valles); providing information to the public, professionals, and the media; representing the CZO at conferences, meetings, and through visits to other organizations/institutions; and participating in key local, national and international committees and research initiatives.

9. PROJECT MANAGEMENT

9.1 CZO Management Structure

The two PI’s (Troch and Chorover) carry overall responsibility for the CZO, assisted by 3 co-PIs (Brooks, Pelletier and Rasmussen), who carry responsibility for the management and integration of activities within each of the three focus areas. These persons constitute the Executive Committee (EC) which will meet at least monthly to set the vision and goals of the CZO and which is responsible for overall coordination and integration of science, education and knowledge transfer activities. Decision-making will be largely by consensus with ultimate authority and responsibility carried by the PI’s. Day-to-day administrative affairs will primarily be managed by PI’s and administrative support staff. Weekly meetings ensure communication and coordination. An External Advisory Board (EAB; Chris Paola, Steven Banwart, James Shuttleworth, Randy Dahlgren, John Melack) will meet at least once a year to provide feedback to the EC and collaborators. Our management structure is designed to be resilient yet flexible when faced with changes in personnel and professional commitments. For example, over the 5-years it is possible that several researchers will move to other institutions or take temporary positions of administrative leadership. New faculty hires and shifting faculty interests at UA and other institutions also create new opportunities for CZO activities, collaborations, and partnerships. Our CZO Executive Committee will evaluate these challenges and opportunities to ensure continuity, smooth transitions, and the best use of new personnel and linkages.

9.2 Goals of Management

The goals of management (EC and senior staff) are to: i) develop and implement a strategic plan including a detailed timeline of activities needed to achieve the research objectives within the five-year timeline; ii) support communication between and integration of research, cyberinfrastructure and education and outreach activities; iii) manage for transition
in CZO staff and scientists; iv) promote CZO activities and opportunities at local, regional, national, and international levels; v) meet the contractual obligations to NSF; and vi) work toward sustainability of the JRB-CZO beyond the five years of support. We will integrate recommendations from the EAB, CZO research teams, relevant stakeholders, and NSF to ensure integration of projects and allocate resources as needed.

9.3 Building an Integrated CZO

We will ensure that the CZO’s impact far exceeds the sum of its individual parts by insisting on a high degree of communication and coordination of research activities directed toward major knowledge gaps. A central feature will be an annual CZO-wide meeting where all researchers, students and stakeholders will gather to discuss scientific results, provide feedback, and conduct observatory-wide discussion and planning. We will also undertake activities to: acquire, manage and maintain infrastructure; recruit and maintain a diverse staff and student population; manage finances by shifting resources between research areas based on performance and relevance of scientific issues; and manage communication and information by coordinating meetings, workshops, and report preparation. We will manage the JRB-CZO efficiently by: streamlining and automating reporting processes through online forms for updating and linking databases and reimbursing expenses; utilizing performance and management indicators; and integrating and developing hardware and software to create better facilities for remote teleconferencing. Finally, we will continue to work towards long-term sustainability by supporting proposal preparation, developing collaborative relationships, building useful infrastructure, and developing activities that are considered valuable by the CZ research community.

10. PARTNERSHIPS AND STAKEHOLDERS

Our project benefits from and contributes to the efforts of a strong coalition of regional partners (letters of collaboration attached). Major research partners outside of UA include: Prof. Marcy Litvak (UNM), Dr. Nate McDowell, Dr. Matthew McCabe and Dr. Thom Rahn (LANL), Dr. Roy Rasmussen and Dr Dave Gochis (NCAR), Prof. Eric Small (UC Boulder), Prof. Jan Kleissl (UCSD), Prof. Egbert Schwartz (NAU), Prof. Fred Phillips, Prof. Enrique Vivoni, Prof. John Wilson and Prof. Jan Hendricks (NMT), Dr. Noah Molotch (UCLA), Prof. Claudio Paniconi (CNRS, Quebec). We expect this list to grow as our observatory develops and have budgeted funds for participant support to facilitate this expansion. Major Institutional and Stakeholder partners include: the Valles Caldera National Preserve and Trust who provide on-site coordination and oversight of field projects, ongoing monitoring, and conduct public educational activities; the New Mexico Environment Department who assist with field measurements and calibrations of weirs for rating curves of discharge; the Natural Resource Conservation Service who are responsible for installing and operating the SNOTEL site; and the Valles Caldera Coalition and Jemez Watershed Group, both citizen groups who aid public education programs, water quality field sampling campaigns, restoration action strategies.

11. RESULTS OF PRIOR NSF SUPPORT

Paul Brooks is a theme leader for one of three integrating science questions (What are the effects of vegetation change on basin scale water balance?) in the NSF-Science and Technology Center “Sustainability of Water Resources in Semi-Arid Regions” award EAR 9876800, PI Shuttleworth 1/05-1/09 (JRB-CZO investigators Troch, Hogan, Huxman, Schaap, Kurc, Meixner are also SAHRA investigators). As of January 2007 there have been over 400 publications and 68 M.S. and Ph.D. theses resulting from SAHRA funding. One of Brooks' primary roles in SAHRA is overseeing the development and coordination of ecohydrological research in the Jemez River Basin designed to quantify hydrologic flux from the atmosphere through soil, vegetation, surface and ground water. There are currently 17 Co-Investigators and over 20 students working on this effort. Craig Rasmussen and Jon Chorover are PIs on a grant entitled “Aluminum control of organic carbon cycling in temperate forest ecosystems”, DEB 0543130. The project (4/06 to 3/09), is in its first year with no publications to report as yet. Peter Troch is one of three PIs on "Understanding the hydrologic implications of landscape structure and climate - Towards a unifying framework of watershed similarity", a proposal recently recommended for funding by EAR-NSF 6/07-6/10. Jon Pelletier was PI on EAR-0309518 “Fluvial systems and climate in the western U.S.” 6/03-5/06. The project resulted in 10 peer-reviewed publications (see his Biosketch) dealing with hillslope and drainage network evolution, and mountain belt denudation.
REFERENCES TO PROJECT DESCRIPTION


Principal investigators: Jon Chorover (SWES), Peter Troch (HWR), Paul Brooks (HWR), Jon Pelletier (GEOS), Craig Rasmussen (SWES), David Breshears (SNR), Travis Huxman (EEB/B2), Kathleen Lohse (SNR), Shirley Kurc (SNR), Jennifer McIntosh (HWR), Thomas Meixner (HWR), Marcel Schaap (SWES), University of Arizona.

Proposed Revision to Proposal Scope: The Jemez River Basin (JRB) CZO will be expanded to include a satellite in the Santa Catalina Mountains of southern Arizona.

The JRB CZO will remain the primary focus of NSF-funded research (70-75% of the grant funds), but we propose to use a portion of NSF funds (25-30%) for research along an equally extensive elevation gradient in close proximity (< 10 miles) to the University of Arizona (UA). These satellite sites will benefit the overall project scope by linking to ongoing eco-hydrological research, enhancing education opportunities, and expanding the transferability of our results. Because the primary focus of our CZO proposal is on climate and the terrestrial water cycle in semi-arid systems, the proposed modification will allow us to:

1. Extend comparable CZ observations to a larger range in climate and thereby assess the impacts of warmer and drier climates (projected for the entire southwestern US) on critical zone processes;

2. Build strong linkages to the National Ecological Observatory Network (NEON) transect, which extends from the Santa Rita Mountains, near the southern boundary of Arizona, to Phoenix, through the rapidly expanding metropolitan corridors of Tucson and Phoenix; and

3. Facilitate education and outreach tasks of the CZO by providing observatory infrastructure in close proximity to the UA campus and the Biosphere 2.

Figure 1. Shaded relief map showing the locations of the Jemez River Basin (JRB) and Santa Catalina Mountains (SCM) critical zone observatory sites in northern New Mexico and southern Arizona, respectively. Base map images from http://fermi.jhuapl.edu/states/.
The Santa Catalina Mountains Satellite CZO: The Santa Catalina Mountains (SCM) contain a climate (elevation) gradient of similar extent to that contained in the Jemez River Basin (JRB), but shifted to a lower range in latitude and elevation, extending the CZO parameter space into warmer conditions (see Figure 1). One consequence will be a larger observatory range in environmental energy and mass transfer (EEMT, as described in our original proposal). Vegetation types in the SCM extend from Sonoran desert at 750m elevation to montane fir forest at 3000m, with intermediate elevations that include desert-grassland, open oak woodland, pygmy conifer – oak scrub, and ponderosa pine forest. Like the JRB, the SCM exhibits a bimodal distribution of annual precipitation (winter & summer). The two sites are also linked through climate model predictions of drier-warmer winters in future decades as a result of climate change for the entire region. For example, the 2007 water year in the JRB had the driest winter followed by the second wettest summer on record with the amount and distribution of precipitation more similar to SCM than to climatological norms. Although unusual, climate predictions suggest this pattern will become more common in the future. As a result, the SCM sites will provide critical observations for potential climate change alterations to the water balance in semi-arid systems.

Furthermore, the SCM broadens our ability to understand CZ structure and response to changes in climate by including a broader range of parent materials, with the JRB a rhyolitic site and the SCM predominantly granite and schist. The ability in SCM to study comparable hillslopes and catchments underlain by either granite or schist parent materials provides a powerful context for pair-wise studies of lithologic impacts on CZ structure and function along a well-constrained climate gradient. Including the additional lithologies provides direct scientific benefit and expands the transferability of our observations to a larger portion of semi-arid elevation gradients and water source areas of the western US, including headwaters of the Rio Grande (JRB) and Colorado (SCM) rivers.

Our group of CZO investigators is highly motivated to pursue a strong linkage of the JRB and SCM sites and will do so by encouraging the full group of CZO students, postdocs and faculty to engage in research at both sites. Additionally the collective group of PIs has been aggressive in pursuing alternative funding for their Critical Zone research objectives. Research is already underway in the SCM as a result of smaller grants from two other sources. The first is a 2006 subcontract seed grant for $18,000 through EAR 0632516 to establish the SCM as a node within the Critical Zone Exploration Network (CZEN). The second is a 2008 grant for $80,000 from the State of Arizona Technology Research Infrastructure Fund (TRIF, Water Sustainability Program) to lay the groundwork to use SCM as a CZO that is akin to what we described in the NSF proposal for the JRB. Although the present funding level is insufficient to enable the instrumentation and research required for an NSF-scale CZO effort, the NSF funding of the current grant would make that possible. Like the JRB, the SCM site has triggered great interest among other Earth scientists. For example, a group at University of Illinois Urbana-Champagne, Arizona State University and Purdue University has recently submitted a collaborative research proposal, together with colleagues at UA, to the Hydrologic Sciences program of NSF. The SCM also plays an active role in the CZEN community as demonstrated by an ongoing CZEN-organized synthesis of climate-weathering interactions in granitic terrain (led by Rasmussen) that includes regolith geochemical data from the SCM as a central component. This synthesis includes collaboration and data from CZEN sites, including the Boulder Creek CZO, and thus demonstrates an existing level of community interest and synergy among CZO investigators. Therefore, the prospects of developing a community-wide CZO effort in semi-arid southern Arizona are excellent.

Integration with the Desert Southwest NEON Domain: The SCM resides within the Desert Southwest Domain of the National Ecological Observatory Network (NEON) (Domain 14). This provides a valuable opportunity to integrate regional CZO and NEON efforts more closely. More than other NEON Domains, Domain 14 is pursuing development of satellite sites rather than solely investing in a core site. The southern Arizona NEON transect, which extends from the Santa Rita Experimental Range (core site) northward through the urban LTER in metropolitan Phoenix, and eastward to Jornada Experimental
Range, seeks to take full advantage of the rich range of land uses and ecosystem types (including urban) that occur in this varied and rapidly changing semi-arid landscape. In addition to being one of the largest elevation gradients along that transect, and among the most important watershed sources of aquifer recharge in S. Arizona, the SCM is also increasingly surrounded by the growth of metropolitan Tucson. Therefore, the establishment of the SCM as a satellite CZO presents unique opportunities for synergistic CZO-NEON collaborations. Every effort will be made to use SCM findings to inform NEON objectives and research, and vice versa. In particular, we will maintain a close communication with NEON investigators in order to learn from them as they proceed through development of instrumentation arrays and common platforms for data assimilation. One or more members of our CZO team will regularly attend southwest NEON meetings to maintain the connection. Communication will be facilitated by David Breshears and Travis Huxman, both members of the UA-CZO team that are also closely involved in Arizona NEON planning.

Proposed Research in the SCM: In the proposed expansion of the CZO to include the SCM, data acquisition networks, comparable to those described in our earlier proposal for the JRB will be installed at three elevations on both rock types in the Sabino Canyon and Cañada del Oro Creek watersheds (both watersheds are part of the larger Santa Cruz River watershed) to study (i) the partitioning of precipitation into various flow paths, (ii) the effects of climate and lithology on these partitioning processes, and (iii) the feedbacks between hydrologic partitioning and subsurface biogeochemistry, ecosystems dynamics and landform evolution. The placement and design of these sites has been chosen to take advantage of ongoing research as described in the sections below. Equivalent instrumentation arrays will be installed in both JRB and SCM sites (fully described in original proposal) to allow direct comparison.

Pedon to hillslope investigations in the SCM: As in the JRB, samples from SCM will be collected within functional landscape units (pedons embedded in zero-order catchments with planar, convergent and divergent hillslopes) in different EEMT settings to assess the composition of the solid, aqueous and gas phases, and to measure hydrologic and geomorphic processes. Solid phase samples (biomass, soil and rock) will be taken in single group field campaigns, whereas the liquid and gas phases will be sampled by in situ collectors, to assess dynamic changes in flux and quality across seasons and hydrologic events. Bulk rainfall samplers and two nests of three tipping bucket rain gauges will be used to measure the spatial distribution of precipitation influx and quality. Canopy through-fall samplers will be used to assess impacts of above-ground biomass on water influx to the subsurface. Subsurface in-situ instruments will include soil solution samplers, shallow automated piezometers, and automatic soil moisture and soil temperature profile stations. We already have instruments installed in paired zero-order basins at 2400m (Ponderosa pine to montane fir site; Figure 2) and, with NSF funds and existing field experimentation infrastructure available at the investigators’ laboratories, we will match this at 1800m (oak scrub to pygmy conifer site) and 1400m (desert grassland to open oak woodland site). Our State of Arizona TRIF funds are being used to instrument a fourth site at 800m (Sonoran desert site). This array of sites, in addition to sampling campaigns in the transition zones between them, will permit us to capture climatic controls on CZ processes and structure. Vegetation structure including species diversity, plant functional type, above- and below-ground biomass, leaf- and plant-area index, root length density, productivity, stoichiometry, and isotopic composition, and pedologic information including depth to bedrock, hydraulic properties, bulk density, clay content, mineral composition and soil organic matter will be collected during the installation of these instruments. Water samples will be analyzed for major and trace inorganic and organic solutes (rock-, vegetation- and human-derived metals, nutrients, cations, anions, biomolecules and pollutants) to assess inputs, attenuation and weathering patterns, as well as for stable water isotopes to assess soil water residence time.

Nested-catchment investigations in the SCM: Additional sampling at catchments of increasing scale will be conducted to assess the aggregation of hillslope response into catchment response. An extensive hydrometrical and hydro-chemical monitoring network in nested SCM catchments is currently operational.
(e.g., Fig. 2) comprising 24 tipping bucket rain gauges (two of which are equipped to automatically collect rainwater samples to investigate spatial variation in rainwater chemistry), and five automatic surface water level stations (three of which are equipped with auto samplers). Funding of this proposal will allow us to extend and supplement the current observation record, as well as to equip the existing raingauge network with telemetry. Having real-time information about space-time variability of rainfall is essential for accurate prediction of natural hazards such as flash floods and debris flows, as well as for the timely planning of additional field campaigns.

![Figure 2. Site map of Sabino Creek in the Santa Catalina Mountains near Tucson, AZ.](image)

**Training and Outreach Potential of the SCM and Linkages to Biosphere 2:** The potential for training students at all levels (undergraduate, MSc, PhD and postdoctoral) in the multi-disciplinary field of Critical Zone science will be dramatically improved through this revision because it facilitates the use of a common set of sites for hydrology, pedology, geomorphology and ecology field courses organized by the UA faculty involved in this effort (see list of investigators). The fact that the SCM is in the UA’s “backyard” enables rapid access for field laboratory courses at the University, and for rapid-response, hydrologic event-based sampling campaigns. The research, teaching and outreach will also be embedded in the activities of the Biosphere 2 (B2) Earthscience program (http://www.b2science.org/) of the University of Arizona, which includes a collaborative study of CZ processes in an instrumented, synthetic hillslope subsystem. The B2 receives over 50,000 visitors per year, and it has an active teaching and outreach program aimed at K-12, undergraduate, and graduate students, STEM teachers, and the general public. The CZO investigator group is active in the development of B2 programs and experiments. Several investigators (Troch, Breshears, Pelletier, Chorover and Huxman) are on the B2 Science Steering Committee, and Huxman is the Biosphere 2 Director. The JRB, SCM and allied CZO research activities will be highlighted in the B2 through interactive public displays that translate research questions, approaches and findings of this NSF-funded research for a public audience.

**Reduction in Scope of Proposed JRB Investigations:** Because the inclusion of the SCM site will not be accompanied by a comparably scaled increase in NSF CZO funding, the expansion of activities into southern Arizona necessitates a reduction in the proposed activity for the JRB. This will be done by reducing from five to three the number of intensive measurement sites that we propose to focus on at the JRB, although synoptic field campaigns and existing instrumentation will allow us to maintain a reduced level of activity at lower elevations. In the proposed revision, we will limit the instrumented sites to those that exist at the three higher elevations (pinyon-pine to Ponderosa pine, Ponderosa Pine to mixed conifer, and mixed conifer to spruce-fir). This will maximize advantage of the higher elevation components of the JRB, while also providing for significant overlap in ecosystem types between the JRB and SCM gradients to allow for cross-site comparison. Through comparison with the warmer, high elevation sites in the
SCM we can address directly the effects of changes in climate on hydrologic partitioning and water sources within the context of CZ development. In addition, to enable a more efficient use of education and outreach funds, we will transfer a portion of these programs to the SCM and Biosphere 2 operations that are not only closer to the University of Arizona, but are also subjected to high visitation. In particular, we will take fuller advantage of the Biosphere 2 as it provides unparalleled opportunities for public outreach and education on the role of climate and water in critical zone structure and function.