The Eel River Critical Zone Observatory: exploring how the critical zone will mediate watershed currencies and ecosystem response in a changing environment

A. Scientific Justification

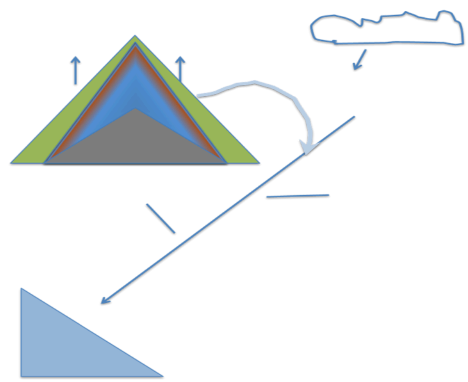


Figure 1*: The critical zone of vegetation (green), soil and weathered bedrock with perched water table (red to blue), overlying fresh bedrock (grey) that exchanges currencies (arrows) with atmosphere (cloud) and mediates effluents (curved arrow) to a channel network (lines) which drain to ocean (blue triangle).*

1. Watershed currencies and the Critical Zone

Concentrated flows cut a network of channels into landscapes. Channels then drive landscape evolution, form the boundary conditions for hillslope evolution, and drain the critical zones. The Critical Zone, extending vertically from the vegetation canopy to the fresh bedrock under the emergent hillslopes, mediates key currencies of the watershed that bounds a specific channel network. These currencies--- *water, solutes, gases, sediment, biota, energy and momentum*--- are exchanged, transformed, and transmitted vertically through rock, soil, vegetation and atmosphere, and laterally through the channel network en route to the sea. Critical Zone (CZ) currencies connect and create inter-dependence of the atmosphere, lithosphere, hydrosphere and biosphere; linking upland, channel, and ocean eco-systems. (Figure 1). For example, forests on hillslopes can extract moisture from deep in the critical zone and transpire it back to the atmosphere, modulating climate (Lee et al., 2005). Subsurface microbes, which strongly depend on moisture availability, can control chemical species in solutes and gas emissions (Chapin et al., 2011, Riveros-Iregui, 2009); river ecosystems during droughts are sustained entirely on groundwater discharge from the critical zone (Lake 2011), and coastal ecosystems may be subsidized by nutrients (inorganic and organic) originating from the critical zone and swept beyond the river mouth (Bruland et al., 2001, Caraco et al., 2003).

The critical zone may remain physically the same for hundreds of years, while its currencies and ecosystem functions and chemical dynamics change significantly as land use intensifies and extreme weather becomes the new normal (Dominguez et al 2012). Connections linking critical zone currencies to climate, rivers, and coastal oceans will have non-linearities, feedbacks, thresholds and tipping points (AC-ERE 2009, Palmer 2009). Therefore, anticipating and adapting to changes critical zone currencies will be challenging (Wagener, 2010, Foley et al., 2003). Questions are pressing: how will the critical zone, climate, and water resources co-evolve in the coming decades? What will be long-term legacies of extended droughts on ecosystems and water supplies? What actions can be taken to enhance ecosystem resilience to the effects of climate change and land use?

Here we propose a different, but complementary, kind of observatory to the first six selected in the previous competition. Our field work, organized around key questions, will be focused on the critical zone *currencies* to understand how they change, interact and propagate. Key questions and field observations are specifically designed to guide the development of a hierarchical modeling framework to ask "what if" questions about possible futures. Modeling is the only way to forecast the future of stressed ecosystems. Our goal is to advance an **A**tmosphere-**W**atershed-**E**cosystem-**S**tream-**O**cean **M**odel (AWESOM) that will be used to explore climate change and land use effects. AWESOM will be firmly rooted in strong, quantitative empiricisms and mechanistic description of how the system works. The model, in effect, will predict watershed currency dynamics as mediated by the critical zone and link them to climate and four distinct ecosystems: forests, subsurface (soil surface to the base of the weathered bedrock), streams, and coastal oceans. There are approximately five mechanistic eco/hydrological models currently employed at the CZO's (tRIBS (Ivanov et al. 2008); Flux-PIHM (Qu and Duffy 2007; Li et al. 2011); FemDOC_2D (Gu et al. 2012); CHILD (Tucker et al 2001 a,b, 2010); RHESSyS (Tague and Band 2004; Tague et al. 2008), hsB-SM (Troch et al. 2003; Carillo et al. 2011) and CATHY-NOAH (Niu et al. 2013). AWESOM will build upon some of these to explicitly explore critical zone influence on watershed currencies and link their dynamics to ecosystem fates in a changing world. A further distinction in our model is *full coupling with the atmosphere*. For example, different transpiration patterns or forest fires would change temperature, precipitation, and wind, which would feed back on the terrestrial ecohydrology and coastal circulation and productivity.

2 The Eel River Critical Zone Observatory

2.1 *The vision and goal*

We propose to develop an observatory that is rooted in intensive field monitoring in the critical zone. Observations will follow the watershed currencies through a subsurface physical environment and microbial ecosystem into the terrestrial ecosystem, up into the atmosphere, and out through diverse drainage channel networks in which aquatic ecosystems interact with these currencies, mediating the delivery of nutrients to coastal ecosystems at the river mouth. These investigations will contribute to a synthesis model that mechanistically links the critical zone to atmospheric processes, watershed routing, ecosystems dynamics, stream flow and coastal processes in order to investigate fundamental questions and to provide a modeling tool for management issues.

2.2 Location

The Eel River watershed and its southern neighbor, the Russian River watershed offer an ideal opportunity to conduct fine scale research within the critical zone, follow currencies to the atmosphere, streams and ocean as they drive and are altered by a succession of ecosystems, and explore consequences for management practices caused by changing climate and land use. The Eel and Russian rivers are the two large river systems of coastal Northern California (Figure 2), with the Eel draining northward through mostly timber and grazing lands (but with increasing irrigated agricultural use), and the Russian draining to the south through increasing vineyard and housing development towards Santa Rosa, the largest city in the basin. Although more developed than the Eel, only about 13% of the Russian watershed is in agricultural lands. The Eel has two dams in the mainstem headwaters where the Potter Valley diversion reroutes Eel flow into the Russian River. The Russia River has two dams, one in the headwaters (that receives flow from the Eel), and one on a major tributary, Dry Creek, farther down the river. But like other river systems in active agricultural lands, the Russian has some 500 small dams along the tributaries. Salmon (including the endangered Coho Salmon) spawn and migrate in both the Eel and Russian; their populations are in great decline, which is attributed to many factors, including reduced summer base flows and elevated temperatures (Katz et al. 2012).

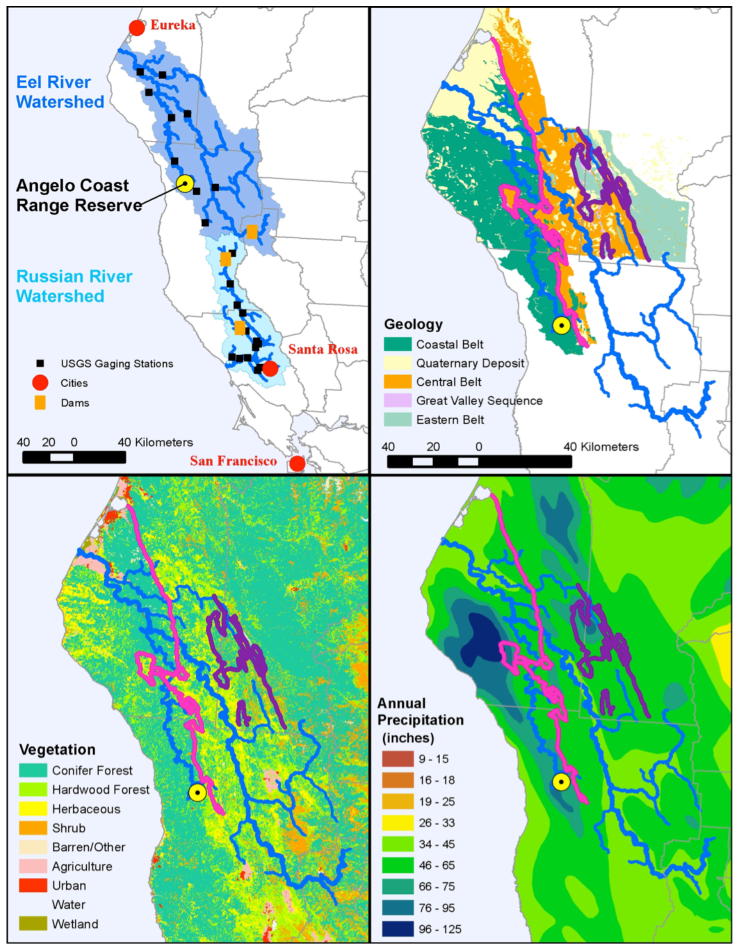


Figure 2. *Watershed and Angelo Coast Range Reserve locations and patterns of mean annual precipitation, dominant vegetation, and geology in Northern California. Pink line is the western boundary between the Coastal and Central Belt bedrock in all maps. Purple line denotes eastern boundary of Central Belt with Easter belt. Note their approximate correspondence with conifer and hardwood to hardwood/herbaceous boundary. Precipitation from Cal-Atlas geospatial clearinghouse (mean from 1900 -1960). Vegetation map from Cal-Atlas geospatial clearinghouse. Geology from California Geological Survey (data are lacking to the east and south).*

The Eel and Russian have over geologic time competed for drainage area at their mutual headwaters as tectonic pulses swept through the region (Lock et al. 2006). The underlying geology of this region records the complex accreted terrain of the North American plate margin, but there are three dominant rock types of the Franciscan terrain (Mclaughlin et al. 2000): the Coastal Belt (argillite, sandstones and conglomerates), the Central Belt (mélange) and the Eastern Belt (metasedimentary and metavolcanic rocks) (Figure 2), with the Central Belt swept by large, active earthflows in the mechanically weak rocks. Most of the Eel River watershed emerged above sea level in just the past 4 million years (Lock et al., 2006) and uplift rates increase from south towards the north from about 0.4 mm/yr to greater than 4 mm/yr (e.g. Merritts and Bull, 1989). Despite high uplift and erosion rates (Fuller et al., 2009), as discussed briefly below, a deep and well–developed, hydrologically active weathered bedrock zone has formed on Coastal Belt rocks (Salve et al., 2012) (no studies have been done yet on the other belt rocks).

A striking pattern in the Eel watershed is the correspondence between the three geologic units and the dominant vegetation (Figure 2). The Coastal and Eastern Belts support conifer forests whereas hardwood trees and herbaceous vegetation predominate in the mélange. The vegetation distribution does not follow elevation or precipitation patterns. We hypothesize that the approximate correspondence of vegetation type with bedrock results from higher available moisture at higher water potential (less negative pressure) in the fractured bedrock of the Coastal and Eastern belts than in the fine-grained mélange.

2.3 Observatory Structure

We propose to develop an observatory based mainly in the Eel River watershed (Figure 2) composed of four nested components, increasing in scale from an intensively instrumented hillslope to a region encompassing both the Eel (and Russian) watersheds. The observatory component leverages the development and use of past infrastructure investments and historical research insights. These components include: (Figures 2 and 3):

(1) Rivendell-- 4000 m^2 sub-basin of Elder Creek in Angelo Coast Range Reserve, where hillslope-scale intensive field investigations have been under way since 2007.

(2) Angelo Coast Range Reserve, a Berkeley-administered research reserve in the University of California Natural Reserve System, protecting 31 km^2 of steep forested terrain, 5 km of the upper South Fork Eel River and entire watersheds of Elder Creek and several other tributaries. The Angelo Reserve has hosted > 25 years of prior NSF-funded field research and was the first collaborative field site for an NSF Science and Technology Center, the National Center for Earth Surface Dynamics (NCED) (2002-present).

(3) The entire Eel River watershed (9540 km^2), where watershed-climate-ocean productivity investigations have occurred (supported by prior NSF funds and in collaboration with Friends of the Eel River and the Eel River Recovery Project).

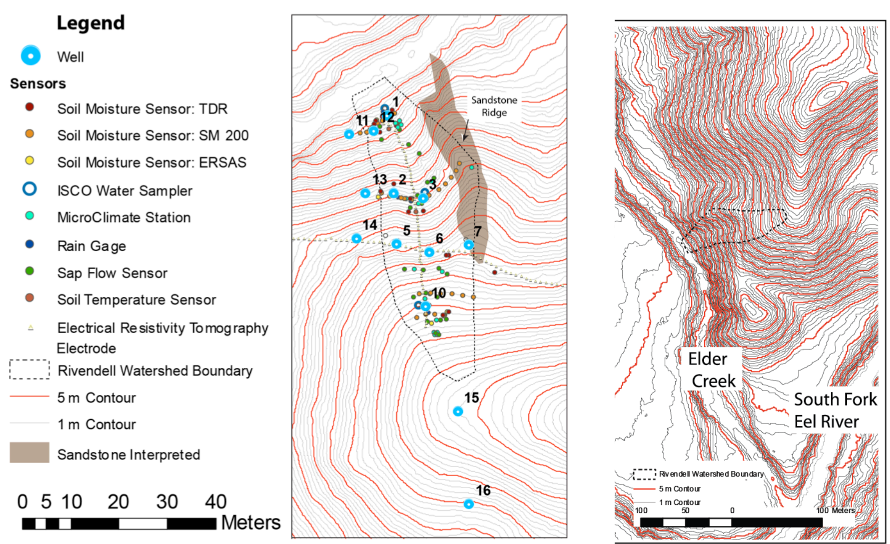


Figure 3 *Location of Rivendell site on Elder Creek (right panel)) and instrumentation field at the site (left panel). The instruments include time domain reflectometry probes (TDR), and Electrical Resistance Sensory Array System (ERSAS) (Salve, 2011) for relative rock moisture profiles. Contour interval is 1 m in both cases.*

(4) Rivers of the California North Coast, focusing on Eel and Russian River systems (13,800 km^2), where studies of Northern California water and ecosystem fate under changing climate and landuse have occurred (via collaborations with Friends of the Eel River, the National Marine Fisheries Service, the Klamath Basin Monitoring Program, the Karuk tribe, and NCED).

2.3.1 Rivendell

In 2007 with a $1.6M award from the W.M. Keck Foundation and support from the National Center for Earth-surface Dynamics (NCED), we began an intensive monitoring program of the critical zone on a small (~ 4000 m^2) steep sub-basin, nicknamed "Rivendell", on a north-facing hillslope adjacent to Elder Creek (Salve, et al., 2012). Elder Creek is a tributary of the South Fork Eel River in Northern California within the Angelo Coast Range Reserve (Figure 2). The ~30 degree hillslope at the Rivendell installation site is underlain primarily by nearly vertically dipping mudstone (argillite). Cosmogenic dating of sediments (Fuller et al. 2009), direct measurement of bedrock erosion (Stock et al. 2005) and modeling (Seidl and Dietrich, 1992; Sklar and Dietrich, 2006) document active channel incision driving hillslope processes, with a local pace of about 0.2 to 0.4 mm/yr. A wireless radio network, powered by tree-top solar panels, supports a dense sensor network for environmental monitoring. We have drilled a network of 12 wells as deep as 30 m down to fresh bedrock. Our installation includes extensive soil and rock moisture monitoring devices, sap flow sensors on 30 trees, and 4 meteorological stations (Figure 3). The entire system, some 750 sensors, together with a USGS stream gauge, record data at < 30 minute frequency. These data are transmitted every 4 hours to UC Berkeley and placed into a sensor data base (http://sensor.berkeley.edu, now over 144 million data entries that displays them near real-time. We have also automated four ISCO samplers to collect water samples (daily or more frequently during runoff events) for water chemical analysis, and carried out repeated campaigns to sample water for isotope analysis. Graduate student led research has been initiated on: 1) prediction of the critical zone development (Rempe and Dietrich AGU, 2012), 2) dynamics of runoff and rock moisture availability to the forest canopy (Oshun et al., AGU, 2012), 3) chemical evolution of water and gasses through the critical zone (Kim et al. AGU 2012), and 4) influence of vegetation on regional climate (Link et al., AGU 2012).

Rivendell is our critical zone laboratory where we can investigate in detail mechanisms controlling the currencies that then get released to the atmosphere and to the surrounding drainage channels. This proposed CZO leverages and builds upon the investment already made in Rivendell

2.3.2 Angelo Coast Range Reserve *(http://angelo.berkeley.edu/)*

The Angelo Reserve is one of thirty-nine natural reserves protected by the University of California Natural Reserve System for university-level teaching and research. Angelo will be the field base for the Eel River Critical Zone Observatory and where meetings and workshops will be held. Since 2004, Angelo has been used by researchers and students from 50 different institutions, including 19 California colleges and universities and 28 outside of California, with an average of 1571 user-days per year. Mapping, monitoring, and experimental field manipulations within the reserve over the past 25 years have documented summer low flow food web ecology and biogeochemical dynamics along the upper South Fork Eel River and twelve of its tributaries, including Elder Creek (Power et al., 2008, 2009; Finlay et al., 2002, 2011; Kupferberg et al., 2011; Sabo and Power, 2002a,b; Suttle et al., 2007, 2004; Wootton et al., 1996). Among the many findings, this work has identified a drainage area or network-based dependency in many ecosystem attributes, including total dissolved nitrogen, algae abundance and taxonomic distribution, salmonid densities and energy sources, and aquatic insect emergence. Current research is revealing remarkable patterns of aquatic insect migration and reproduction that link mainstem and tributary food webs in ways that support summer-rearing salmonids (Uno and Power, 2013). Other ongoing research probes environmental temperature, nutrient and flow thresholds that differentiate salmon-supporting ecosystems from those degraded by cyanobacterial blooms (Bouma-Gregson et al., in progress).

The Eel's summer baseflow is entirely derived from slow drainage of perched ground water in the critical zone, which also influences stream temperature and nutrient loading. Continuous thermal records (15-minute frequency) from iButton recorders deployed throughout the study basin are available for several years. Seven water level recorders in tributaries, established to investigate sediment transport (Scheingross, et al. submitted) also show strong diurnal oscillations in water level, a signal that can be seen down the South Fork Eel to drainage areas of 642 km^2. Interestingly, tributaries of similar location and size differ in magnitude and timing of fluctuations. These data offer an opportunity to establish more directly the link between terrestrial vegetation and stream flow and temperature.

In 2002, a gift from the Goldman Fund allowed the construction of an Environmental Center at the south boundary of the Angelo Reserve, which is still on the electrical grid. This complex of buildings includes a large (30-50 person) meeting room supported by a small kitchen, two laboratories and a microscope room supporting chemical, biological, and earth science research, a screened lathe house for experimental work under ambient light and temperatures, a computer room, and a small office. Wireless internet connections are available throughout the complex and user housing across the "street". In 2010, a Field Station and Marine Laboratory Facilities grant was awarded by NSF to improve housing for the increasing numbers of researchers using Angelo. This funding was leveraged with gifts and matched by the state of California (Prop. 84) so that 20-30 CZO researchers or visitors could be comfortably accommodated after construction of the housing in 2013.

2.3.3 Eel River watershed

By scaling up to the entire Eel River watershed (9540 km^2) we can explore how different rainfall, topography, vegetation and geology regimes affects critical zone currencies and their ecosystem consequences. We can also document how critical zone currencies transit through streams and are delivered to the coastal ocean. Recently, collaborations among climate scientists, ecologists, and ocean scientists have documented and predicted the influence of algae and nutrients flushed from the Eel River into coastal marine ecosystems (Ohlsson et al., 2013; Piovia-Scott et al., in prep; Ng, 2012; Ng et al., in prep). The plume from the Eel appears to be associated at times with increased coastal primary production (as visible from satellite records). Salmon and lamprey migrations also connect the ocean to the river. We propose to collaborate with two watershed groups: Friends of the Eel River and the Eel River Recovery Project, to make observations throughout the system to test our models. The Eel River watershed is also of sufficient size so that climate modeling scales can be applied. Seasonal water balance changes are detectable in GRACE imagery (http://www.csr.utexas.edu/grace/). The Eel River has 10 USGS Real Time stream gauges, which tap drainages of different mean precipitation, vegetation, and geology. We maintain an additional former USGS stream gauge ("Branscomb") within the Angelo Reserve on the South Fork Eel, and with calibration can add 7 more tributaries to the monitoring program. This network provides excellent data with which to calibrate our synthesis model.

2.3.4 California North Coast region, focusing on Eel and Russian Rivers

We plan to develop understanding on the simpler (i.e., less landuse disturbance) Eel River, build our synthesis model, and then apply it to the Russian River, where water diversions are much more significant. There are 21 stream gauges operated by the USGS on the Russian River, and another 17 operated by the State Water Resources Control Board and National Marine Fisheries Service (NMFS). This high level of monitoring reflects the importance of water in the Russian River, especially for agricultural and domestic use and as critical flow for survival of salmonids. NMFS is especially concerned about significant drawdown during water spraying in the spring (to protect vineyards from frost) and its effects on survival of the juveniles of the endangered and threatened salmon species (Deitch et al. 2008, NMFS 2009). Rising stream temperature, perhaps due to reduced summer flows, is also a concern. NMFS will work with us to provide us with monitoring data and will use our findings in guiding management decisions (see letter of support).

3. Initial Questions

For the five years of this CZO, we propose to focus on four key questions that highlight the multi-faceted linkages in the critical zone and currencies issuing from it. The research team will work together on all four questions and graduate students will be co-supervised, as the nature of these questions calls for significant cross-disciplinary understanding.

3.1 Lithology-Vegetation-Atmosphere Coupling in the Critical Zone: Does lithology control rock moisture availability to plants and therefore overall resilience of vegetation to climate change in seasonally dry environments?

A growing body of research has shown that in hilly landscapes mantled by a thin soil, vegetation can draw on moisture seasonally stored in the underlying bedrock (reviewed in Schwinning, 2010). The availability of this "rock moisture" (*sensu* Salve et al., 2012) should depend on bedrock properties and how it weathers and thus generates porosity creating the capacity to store water that is then available for root uptake. Hydrologically, this rock moisture zone is virtually unexplored—it is not explicitly accounted for in climate models and yet may play an important role in sustaining transpiration and alleviating droughts, especially in seasonally water-limited environments. The success of regional to global models

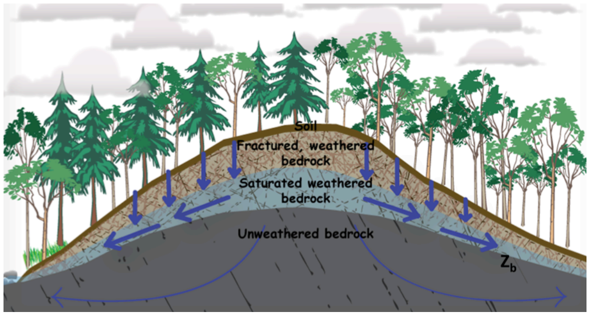
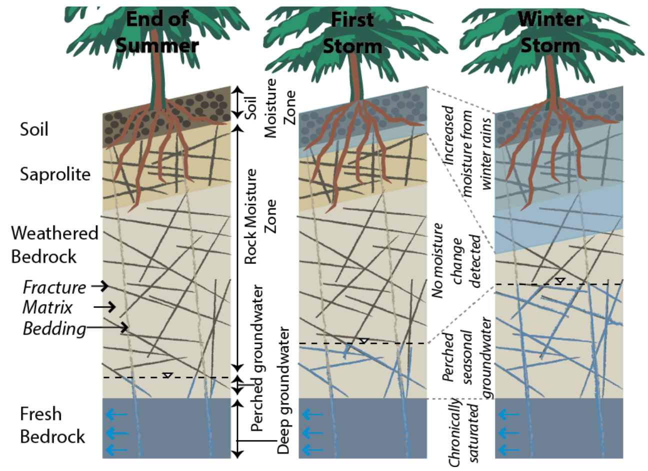


Figure 4. Idealized cross-section through the Rivendell hillslope (left) and profiles (right) showing vertical structure and seasonal rapid injection of winter rain via fracture flow to a perched water table as soil and saprolite and weathered bedrock more slowly gain moisture (Salve, et al., 2012) . Zb in the left figure is the boundary to fresh bedrock (Rempe and Dietrich, 2012)



in predicting the co-evolution of climate, vegetation, and water resources may depend on accounting for this bedrock-dependent moisture availability. This accounting will need a theoretical framework to guide prediction of the availability of rock moisture across landscapes with varying degrees of critical zone development.

Our prior intensive hydrologic monitoring at other sites in the coastal mountains of the western United States (e.g. Wilson and Dietrich, 1987; Montgomery et al., 1997; Ebel, et al., 2007a,b) and now at our Rivendell site (Salve, et al., 2012) have demonstrated that the development of weathered, fractured bedrock beneath the soil creates a deep hydrologically dynamic critical zone that controls storm runoff (Montgomery et al., 1997), pore pressures (Montgomery et al, 2009), chemical evolution of water (Anderson et al., 2002), rock moisture availability to plants (Oshun, et al..2012), and summer base flows. Many other recent studies point to the hydrologic significance of this zone (see review in Salve, et al., 2012). Figure 4 shows what these studies imply about processes inside hillslopes.

We hypothesize that the striking correlation between lithology and dominant vegetation in the Eel River watershed (Figure 2) is driven by relatively high water availability at high water potential in the weathered, open-fractured Coastal Belt rocks (Figure 4) versus low water availability at low water potential (high negative values) in the clay-rich mélange.

Our initial stream flow data analysis indicates that the ratio of summer low flow to mean annual runoff is much less in watersheds primarily underlain by mélange than in watershed draining the Coastal Belt rocks. Two years of frequent stable isotope measurements at Rivendell in trees, soil, weathered bedrock, and groundwater (Figures 4 and 5) demonstrate that Douglas fir (*Pseudotsuga menziesii*) relies primarily on rock moisture, whereas the hardwoods (live oak (*Quercus)*, madrone (*Arbutus menziesii)***,** and bay (*Laurus nobilis*)) use soil water throughout the year, even during the driest periods at the end of summer (Oshun et al., 2012). In comparison to the hardwoods at our site, Douglas fir trees are far less tolerant to soil water deficit (Link et al., 2012), and therefore having access to and using the rock moisture reservoir allows this species to persist (J. Oshun, unpublished, Sawyer, 2006, Brooks et al., 2010). *We suggest, then, that the lithologic-forest correlation emerges from the evolutionary difference in tree physiology and the evolutionary difference in critical zone development*

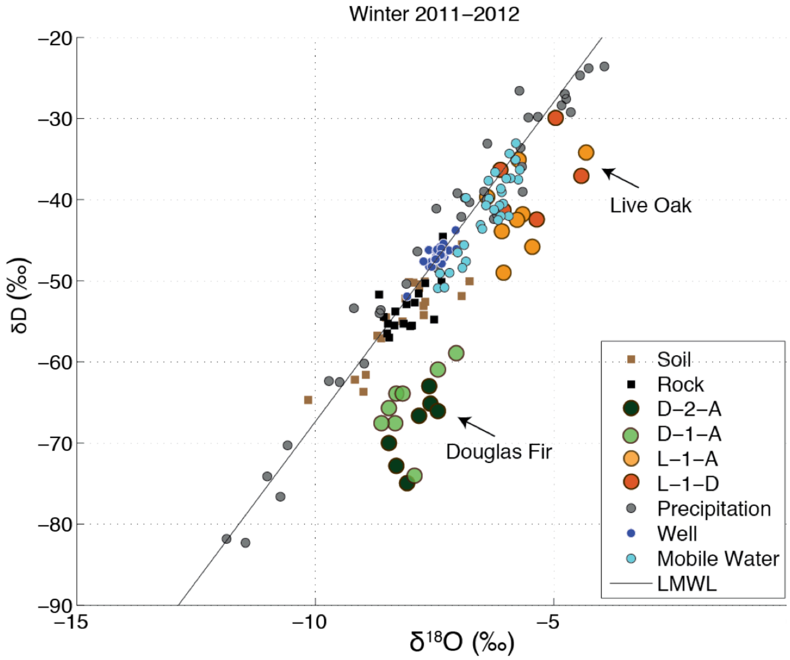


Figure 5. *δD(‰) versus $\delta^{18}O$ (‰) in precipitation, bulk soil, shallow bulk saprolite (rock),water extracted by lysimeter in the soil (mobile water), the groundwater in the wells (well) and two Douglas fir xylem samples (up to 52 m tall trees; D-2_A, D-1_A), and two Live Oak trees (L-1-A,L-1_D) at Rivendell during the winter rain period. Bulk rock water includes winter rain. Summer values of rock moisture are similar to the Douglas fir values shown in this figure. The Douglas fir shows small seasonal variation. Live oak shows evaporative enrichment in the summer and is similar to rain in the winter. Douglas fir and live oak use isotopically distinct water in winter and summer, despite growing adjacent to each other.*

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3.2 *Chemical Coupling in the Critical Zone: How are solute and gas effluents from hillslopes influenced by biota in changing moisture regimes?*

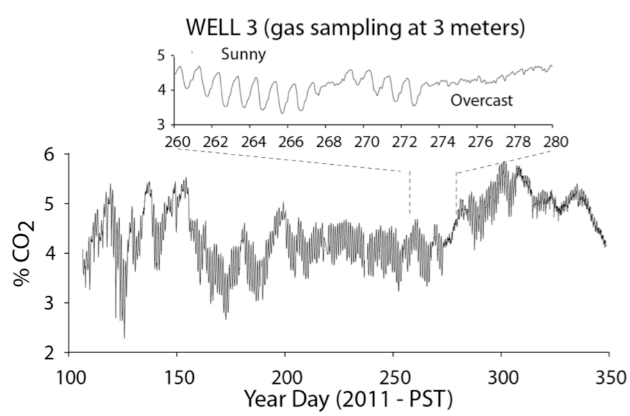

Figure 6. *CO_2 concentrations in the headspace in above the groundwater table in well 3 (see Figure 3 for location).*

The microbe and roots present in the critical zone are primary drivers of chemical weathering in the subsurface and are controllers of the solute species to effluent surface water as well as the CO_2 efflux to the atmosphere; CZ microorganisms are also the primary controllers of redox potential at given depth and are the sole producers and consumers of N_2O and CH_4. At a given location, and at times during the year, the microbial community composition (and metabolic activity) will change with increasing depth below the surface, and the form of the change will depend primarily on water content (directly, and via impact of water on redox conditions). We have automated high frequency monitoring of CO_2 in the head (using a portable SenseAir instrument) that reveals abundance at depths 3-6 m below the surface is high (~2-8%) and shows remarkable diurnal cycles and variations that track the weather (Figure 6). The CO_2 variations suggest respiration from a microbial population that is very sensitive to the fluctuations in moisture depletion by evapotranspiration. Chemical analysis (ICPMS) of our daily ISCO water samples shows the rapid transformation of the composition of the water from rainfall to groundwater to stream, as well as the abrupt transition, within several days, from oxic to anoxic conditions and hence in metals mobilization in the subsurface.

We propose:

(i) At a given site, there will be one or more “critical transitions” (shifts in microbial community character) in soils and the underlying vadose region that separate the profiles into zones with different metabolic potential and overall function. The transitions, in particular between oxic and anoxic conditions, may depend nonlinearly on the hydrologic history of the site.

(ii) The response of the microbial community at any depth to pulsed organic inputs (e.g., due to litter degradation following the first rain) will depend on the nature of the resident community prior this event.

(iii) The delivery of solutes and solids to the river and ultimately to the coastal ocean integrates over the critical transitions in subsurface chemistry and microbial dynamics.

The implications of these hypotheses are that with climate change and land use, altered rainfall patterns (amount and timing of rainfall) and extraction of subsurface water from transpiration will govern the depths of the "critical transitions" and the contributions of processes occurring within each zone to overall carbon turnover and production of atmospherically reactive gases. If water inputs and depletions impact microbial zonation, and if zones with different microbial community compositions respond differently to organic influx, then changing water status will alter the form and abundance of organic compounds and other nutrients leaving the soil and vadose zone and passing into streams.

3.3 *Hydrologic Coupling in the Critical Zone: What controls the spatial extent of wetted channels in the channel networks of seasonally dry environments?*

In seasonally dry environments, the wetted portions of channel networks retract downslope, shrinking river habitat and surface water resources (for wildlife and human consumption) and also drying and heating the local atmosphere (due to lack of evaporation). This stream network and its depth, width, velocity, temperature, and chemistry define the upstream extent of habitat, and it is the path flow takes as it is subject to progressive heating downstream. Channel classification typically distinguishes ephemeral, seasonal, and perennial flows. While the USGS's practice in making topographic maps has included assigning channels into each of these categories, this mapping is based solely on aerial photography and the choice of the map maker, and no sense of timing for seasonal flows is suggested. The dynamic extent of the stream (wetted channel) network has not been systematically mapped at the watershed scale, and there appears to be no theory to predict the extent of wetted channel shrinkage as watersheds progressively dry. This is a major observational and theory gap. Empirical studies of gauging stations have provided valuable analyses of regional base flow (e.g., Santhi et al., 2008), but this does not enable us to map the wetted channel extent. With increasing human water demands and the likelihood of more severe droughts, we need to be able to predict the evolution of the extent of wetted channels and specifically link it to climate and source water usage. The water flow that sustains the wetted channels is derived from the critical zone, creating an explicit link between critical zone properties and hydrologic dynamics, climate, vegetation, and the resilience and sustainability of river ecosystems.

We have mapped the entire extent of wetted channel in a 17 km^2 watershed in the Eel River system for early and late summer. The entire 75 km channel network was walked each time, during which stream and air temperature, relative humidity, wetted channel dimensions, and velocity were documented. Nearby, a 2.3 km^2 basin was walked at a similar time. The wetted channel length was 2.1 and 1.9 km/km^2 for the large and small basin respectively for early summer and both were 1.4 km/km^2 at the end of summer. The similarity of these data suggests that systematic surveys will yield characteristic stream densities that can be explored using theory. *Questions to be considered include: how does the development of the critical zone influence wetted channel patterns; how strong a linkage is there between vegetation and wetted channel length; how does the wetted stream density depend on climate and water extraction; how does the extent of wetted channel influence downstream stream temperatures, and how important is the pattern and thickness of channel sediment*?

3.4 *Human-Ecosystem Coupling in the Critical Zone: Will changes in critical zone currencies induced by climate or land use change lead to threshold-type switches in river and coastal ecosystems?*

River habitats and the ecosystems they sustain depend on delivery of three currencies from the critical zone: groundwater discharged into channels, its temperature, and its solutes. Local river environments reflect both discharge from critical zones adjacent to the channel and integration of currencies from critical zones upstream, which may be transformed during transport. During warm dry periods, ecological activity in rivers peaks as critical zone discharge wanes. These are the periods of greatest vulnerability for aquatic ecology to changes in the critical zone.

Like many western North American rivers, the Eel historically supported iconic Pacific salmon populations, now in severe decline throughout California (Katz et al., 2012). At the southern edge of their range, California native salmonids represent critical genetic resources for adaptation to a warming world

(Nielsen, 1999; Nielsen et al., 2001). In the Russian River, springtime withdrawal of water to protect grapevines from frost threatens juvenile salmon (Dietsch et al., 2008, NMFS 2009). Eel River salmonids are fueled by edible algae and invertebrates (Power et al., 2008). Edible algae, primarily diatoms, are favored in rivers flushed with relatively cool discharge, under low extrinsic nutrient loading. As flows decrease, nutrients increase and temperatures warm, the algal base of river food webs shifts toward less edible, then toxic, algae (bloom-forming cyanobacteria (Paerl and Huisman, 2008, 2009)). Under these eutrophic states, fish cannot survive and degraded water quality threatens the health of humans, pets, and livestock. The Eel River is showing the first disquieting signs of potential transition from salmonids to cyanobacteria, with 11 dog deaths attributed to toxic cyanobacteria since 2002 (Figure 9, Puschner, 2008; Hill, 2002; Mozingo, 2012). In the Eel River, linkages between critical zone dynamics and ecosystem transitions of widespread conservation, economic, and public health concern can be studied in a landscape just as it first approaches the edge (NAS 2010).

4. CZO Synthesis: the Atmosphere-Watershed-Ecosystem-Stream-Ocean Model

Critical zone currencies have consequences for climate, ecology (terrestrial-to-riverine-to-coastal ocean), and human welfare. A broad model framework is needed to guide data collection and analysis in our four focal questions, to synthesize the data into a self-consistent framework, and to project how the critical zone and its currencies will change with climate and landuse. While there are sophisticated representations of these processes in models of each reservoir (e.g., atmosphere, watershed, ocean), the processes outside the reservoir are either specified (e.g., atmospheric temperature and precipitation for watershed model), or highly parameterized (e.g., runoff in climate models). These models typically do not permit the multi-faceted interactions among the currencies and the propagation of CZ currencies from one reservoir to another and back again. Critical zone processes that include the weathered bedrock are essentially missing in regional-to-global climate models. Historically, land surface modeling schemes represent the subsurface environment as a one-dimensional, unsaturated soil column. Recently, more sophisticated models that link the regional water table to soil moisture dynamics have improved the robustness (Gulden, 2007) and accuracy (Fan et al, 2007; Miguez-Macho et al., 2007; Leung, 2009) of climate models, and uncovered significant aquifer–climate feedbacks (Yuan, 2008; Lam et al., 2011; Lo and Famiglietti, 2011; Maxwell et al., 2007; Sulis et al., 2011), which are increasingly supported by field and remote sensing evidence (Alkhaier, 2012). Such improvements are needed because modeled sensible and latent heats are sensitive to the runoff parameterization (Huo et al., 2012). High-resolution land surface modeling schemes are adopting increasingly detailed representations of the critical zone that can capture the redistribution of water and resulting spatial patterns of saturation and surface fluxes (Niu et al., 2012, 2013).

There are two issues. Fully coupling critical zone and regional climate dynamics requires that (i) the dynamics of water redistribution in small watersheds (Niu et al., 2013) be coupled to atmospheric and vegetation dynamics and upscaled to regional scales. The global climate models incorporating hydrological dynamics represent groundwater flow on kilometer-length-scales. For these models, critical zone dynamics represent ‘subgrid’ variations—the representation and scaling of which is unclear and remains controversial (c.f., Rodriguez-Iturbe, 2011; Thompson et al., 2011). A major obstacle to resolving the nature of such subgrid variability is that (ii) the representation of the critical zone dynamics in most land surface models is generic (Richard’s Equation, hydraulic groundwater theory) and has not been amended to reflect specific critical zone processes or lithology variations. In particular, generic representations are not well suited to describing water tables perched on fresh bedrock where non-Richards, fracture flow prevails (e.g., Montgomery et al, 1997; Salve et al, 2012). Ecological modeling frameworks applied to the CZOs are similarly generic in nature: they apply physiological representations of vegetation dynamics to plant functional types (Ivanov, 2008). These models are poorly suited for capturing species-specific structure and functioning (cf Figure 2) and predicting ecological change and disturbance (Thompson et al., 2013; Suttle et al., 2007) as we anticipate will be induced by climate shifts.

These are challenging, complex, interconnected problems and systems. It is fundamentally unclear that applying generic tools—Richards Equation, plant functional type-based relationships, standard groundwater flow representations—will provide a robust basis for making projections about the interaction of ecosystems, climate, and the critical zone. Yet this interaction—the exchange of energy, water, and trace constituents between the atmosphere and the critical zone—shapes their co-evolution under changing climate and landuse. And one product of this interaction, the runoff, sediment, organic matter, and solute loads to the coastal ocean, links the critical zone to coastal processes as well. We anticipate the Atmosphere-Watershed-Ecosystem-Stream-Ocean Model (AWESOM) we will assemble will provide a framework that can be applied at other CZOs.

In addition to guiding data collection and analysis, more specific questions that we can explore with our model include: (1) how will projected periods of drought influence vegetation and climate feedbacks and how severe must a drought period be to shift dominant vegetation?; (2) can vegetation management (including fire use and control) be used to improve and sustain summer baseflow?; (3) will climate extremes influence significantly heterotrophic respiration and thus CO_2 production to the atmosphere?; (4) will future climate conditions drive streams to ecological tipping points between states that support either salmonids (and other aquatic native species) or toxic cyanobacteria?; (5) how might the Eel River sediment, solute, organic matter, and river discharge, which drives ocean coastal productivity, shift with climate and landuse change?; and (6) how will agricultural and other water use practices in the Russian River influence salmonid survival? (See in supplement documents, Letter of Support from the NOAA National Marine Fisheries Service)

5.0 Outcomes

The Eel River CZO will have the following outcomes by completion of the fifth year, in addition to arriving at answers to our four questions:

1) A locally rooted large watershed scale observatory (Angelo Coast Range Reserve) dedicated to documenting change in the Critical Zone and to detecting, explaining, and predicting driving mechanisms connecting watershed currencies to critical zone processes, climate and land cover interactions, and dynamics of terrestrial and aquatic ecosystems.
2) A modular coupled model (AWESOM) that provides local predictions over a regional scale and that can be used to ask “what if” questions about possible future climate and landuse scenarios and the consequences on runoff and ecosystem states.
3) A generation of students and postdocs who have worked together across the disciplines of climate science, hydrology, ecology, geobiology, geochemisty and geomorphology and made discoveries at the interface of these fields.
4) Strong interactions with other CZOs, including shared: (a) measurement technology, (b) data and data management procedures, (c) research questions, and (d) modeling, with the intention of applying the AWESOM framework to other CZO sites.
5) Active collaborations with resource managers and watershed residents to finds ways to build resource and ecosystem resilience in the Eel and Russian river watersheds.

6.0 The CZO Team

Nine Berkeley faculty from four departments and three different colleges have worked closely together in the development of this proposal and are committed to the continued strong interaction the proposed CZO requires. Our faculty have expertise in geomicrobiology and biogeochemistry (Banfield), low temperature geochemistry (Bishop), microbial ecology (Firestone), salmonid ecology (Carlson), food web ecology (Power), geomorphology and hydrology (Dietrich), tree physiology (Dawson), ecohydrology theory and observation (Thompson), and climate modeling (Fung). Six of these senior personnel are women and two them are assistant professors. Fung, Bishop, Dawson, and Dietrich have collaborated at the Rivendell site since 2007 and have shared supervision of graduate students who are working across their disciplines. Our diversity gives us the strength to pursue deeply many fundamental questions that lie at the interface of many disciplines

B. IMPLEMENTATION PLAN

We propose to coordinate research on our four questions throughout the five-year funding period. These questions are joined through shared dynamic currencies that originate in the critical zone. Discoveries made while investigating one question will influence the research direction and analysis conducted for the other questions. The synthesis model will also be developed throughout the 5-year period, with a shift from model development and calibration to application, especially to practical problems in the Russian River, in later years

B.1 Through its influence on rock moisture availability does lithology influence dominant vegetation cover and the resilience of vegetation to climate change in seasonally dry environments?

Prior research suggests that Douglas fir produce a weaker maximum pull on water from the subsurface than do roots of hardwood trees (e.g., Bond and Kavanagh, 1999; Knops and Koenig, 1994), but if they have adequate water sources they may outgrow and outcompete oak (e.g., Devine and Harrington, 2007). Douglas fir thus may be more favored in the higher moisture levels maintained in the underlying fractured saprolite and weathered bedrock of the coastal belt mudstones, and they are less able to become established in a clay-rich fractured-closed mélange bedrock, which may require a lower water potential to extract water. We will rely on predawn water potential in dominant vegetation types to inform us of subsurface conditions.

We propose to explore this question by (1) comparing relative water potential gradients and plant water use on north versus south facing slopes on mudstones at the Rivendell site, (2) comparing these observations with similar data collected on a hillslope underlain by mélange, and by (3) modeling moisture storage dynamics, evapotranspiration, albedo, and temperature for hillslopes under different aspects, lithology, and vegetation.

We will continue the ongoing monitoring at Rivendell, which is mostly on the north facing slope under a forest canopy dominated by old growth Douglas fir (up to 60 m tall) but mixed with shorter hardwoods (bay, live oak, madrone), and expand the Rivendell monitoring field to the south facing slope which is dominated by madrone and oak, with small young (15 to 25 years old) Douglas fir saplings scattered underneath. As Link et al. (2012) have shown, on the north side a sharp decline in sap flow (and thus transpiration) in the Douglas fir occurs as critical zone moisture levels fall through the summer. Sap flow rapidly increases, however, with first fall rains. Hardwood sap flow peaks when mid-summer energy levels peak, and, on the north side, rates do not recover with the first rains. Limited data on the south side, however, indicate the hardwoods may increase transpiration with the first fall rains. We will add soil (TDR) and rock (Electrical Resistance Sensory Array System, Salve et al., 2012) moisture dynamics monitors and an array of 2 m hand drilled holes for neutron probe measurements on the south side to compare moisture dynamics with those under north-facing conditions. The key measurement will be to periodically track relative predawn water potential in the Douglas fir and the array of hardwoods on the north and south sides from late spring to the end of the dry season and through the first rains of the fall. At set points in the growing season (e.g., spring, early summer, and late summer/fall and winter), we will also measure midday plant water potentials at the same tree crown position to obtain measures of maximum water deficit (lowest water potential) for each species. We hypothesize that above a critical water potential, Douglas fir sap flow declines but that sap flow recovers when fall rains elevate moisture levels and therefore water potentials in the soil and weathered bedrock, which in turn permit plant transpiration (sap flow) to increase. In contrast, we hypothesize that hardwood predawn potentials continuously decline throughout the summer, but low rate of sap flow area is maintained because hardwood trees are more drought tolerant: sap flow only declines as available energy declines into the fall and winter period. The early rains may permit some increased sap flow in the fall before the hardwoods nearly shut down. Furthermore, we anticipate that the scattered Douglas fir in the subcanopy >20 years old will have predawn values below critical values for several months in the late spring and into the summer and thus able to slowly gain on the hardwoods. The north-south dominant vegetation contrast, therefore, may be a legacy of native American burning (who practiced low intensity fires favoring hardwoods, e.g., Devine and Harrington, 2001), and current fire suppression may be allowing Douglas fir to slowly replace hardwoods, even on the south facing slopes due to deeper rock moisture resources.

To compare with Rivendell, we will select a similar scale hillslope underlain by melange in an oak woodland and drill three holes to fresh bedrock, one near the base of the slope, one midslope, and one at the divide. In each hole we will install a well monitoring system. Drill core samples will be described for fracture density and will be collected for rock moisture stable isotope analysis. A weather station will be set up, including a simple system for collecting water for stable isotope analysis (to establish the local meteoric line). Sap flow devices will be attached to three large oak trees. We hypothesize that water potential measurements in these oaks will fall below the limiting value for Douglas fir much earlier in the year, effectively limiting the ability of Douglas fir to establish.

The drilling will also enable us to characterize the critical zone development in mélange and compare the depth to fresh bedrock with that predicted from a simple model based on groundwater level controls (Rempe and Dietrich, AGU 2012). This will be used to estimate relative water availability in AWESOM, the synthesis model.

We will expand our monitoring field to the south at Rivendell and add the mélange hillslope monitor in the first year, so that measurements can be made over the five full years. We have found that successive years of data of the same measurements greatly enhance our understanding and confidence in data interpretation.

B. 2 How are solute and gas effluents from hillslopes influenced by biota in changing moisture regimes?

Water Chemistry. The mobilization of Fe and Mn in subsurface waters, and mechanisms of Fe and Mn transport to the creek bed, and subsequent delivery down stream is a focus of our studies. Water sample chemistry (particulate and dissolved) will continue to be monitored using four autonomous network-controlled 24 bottle ISCO water samplers at three wells (1,3,10; see Figure 3) and at Elder Creek on the Rivendell site. These will be augmented by a new twin ISCO sampler near the Eel River mouth to assess the year round solute and reactive metal oxide fluxes to the ocean; a second remote unit will be opportunistically deployed in the wider Angelo Reserve (and off Reserve) locations to support the ecological field campaigns described below. The ISCO samples are routinely analyzed for alkalinity, dissolved organic carbon (DOC), and for major, minor and trace species by High Resolution Inductively Coupled Plasma – Mass Spectrometry (Element II). Major ion composition has been successfully monitored for the past three years. Beginning October 2012, a new methodology (Kim et al., 2012) has enabled preservation of the initial partitioning of dissolved and particulate constituents for 30-60 days, particularly the troublesome redox sensitive metals Mn and Fe, despite the fact that the subsurface samples are far from chemical equilibrium at the time they were collected. Analytical methodology is described in Bishop et al., 2008, 2012; Kim et al., 2012. YSI probes will be redeployed to continuously log temperature, conductivity, dissolved oxygen, pH, and turbidity in Elder creek, and for shorter durations and in selected wells.

Gas Sampling. CO_2 from root systems and microbial sources are the dominant drivers of chemical weathering of the rock matrix. We hypothesize that the high subsurface CO_2 shown in Figure 6 may be the product of microbial respiration of dissolved and particulate organic matter, including root exudates (Tinker and Nye, 2000), in the soils and fractured rocks (see below). Soil CO_2 levels 50-200 times atmospheric are not at all surprising in themselves (e.g., Graf *et al.*, 2008; Taneva *et al.,* 2006; Maiera *et al.,* 2010), but our study has uncovered this phenomenon occurring *deeper* in the subsurface than has been reported previously. A central hypothesis from these observations is that water withdrawal by surface vegetation, suppresses the respiration of the microbial community. In close cooperation with microbial studies described below we will establish a multi depth gas sampling in at least two wells (initially CO_2 and O_2 and relative humidity, and temperature). The sampling will extend from surface to just above the ground water level; our current single depth system has already been configured to avoid both intake of water due to rise of ground water and the poisoning of sensors by corrosive gases such as SO_2. We will conduct exploratory manual well profiling for other reduced gases and implement additional sensors in our autonomous well gas sampling system as can be practically achieved within power and resource limits.

Microbial community characterization. Our field sampling plan, and conceptual illustrations of expected results from our microbial community characterization research, are shown in Figure 7. The analyses will be conducted at two sites (in years 2 and 4) at locations that differ in moisture regime. The analyses will not compare microbial communities between sites, but rather seek evidence for the expected patterns of behavior over time and depth at each site. However, compositional data will be available for comparative and organism-specific analyses, should others working at the CZO find them of interest.

<u>Field sampling and lab analyses</u>: Cores will be taken sequentially from the surface down to 2-3 m depth by hand auger or a mobile coring unit. CZ material will be kept on dry ice 3-4 h for transport and stored at $-80^{o}C$ for molecular analysis and/or used for assays of process rates. During year 1, we will optimize our DNA extraction protocols, calibrate extraction efficiencies, and evaluate the amount of genomic DNA/volume for the relevant soil or sediment. In year 2 we will begin sampling four times per year in conjunction with the gas sampling wells. At least one of the sampling times will be during spring and another in fall, immediately following the first rainfall event after the dry summer period. Both the Banfield and Firestone labs have extensive prior experience with DNA (as well as RNA) based analyses of soil and the sub-soil regions (e.g., Cruz-Martinez et al., 2009, 2012; Wrighton et al., 2012; Handley et al., 2012; Placella et al., 2012; DeAngelis and Firestone, 2012). The Banfield lab has verified (by deep metagenomic sequencing of sediment samples in collaboration with JGI) that sample handling protocols in place are robust to avoid introduction of detectable contaminants.

DNA extracted from the complex CZ microbial communities will be used for genomic analysis of the metabolic capacities (as well as identities) of the indigenous microorganisms. If sequencing costs decrease substantially, we will assess the value of transcriptomic analyses as well. We have chosen to start with metabolic potential analyses (i.e., the seed bank) and will combine that information with *in situ* assays of critical process rates: methanogenesis and methane oxidation (Blazewicz et al., 2012), nitrification, and denitrification (Petersen et al., 2012). Such assays provide information relevant to actual field dynamics and can commonly be directly related to functional gene information (Petersen et al., 2012). In addition, the bank of functional genes can be more directly related to the physical and chemical characterization of CZ materials and solutes. Specifically, results will inform analyses of outputs from the CZ, measured in adjacent groundwater well and at discharge points into streams. Metabolic profiling and prediction and genome reconstruction will yield models of the overall zonation patterns of metabolic capabilities (Figure 6, panel E). This analysis of spatial variation in community composition and metabolic repertoire will then be related to solute and gas efflux data. Effluents as defined here do not include nanoparticles, but this CZO will provide an excellent platform for cognate work on this topic.

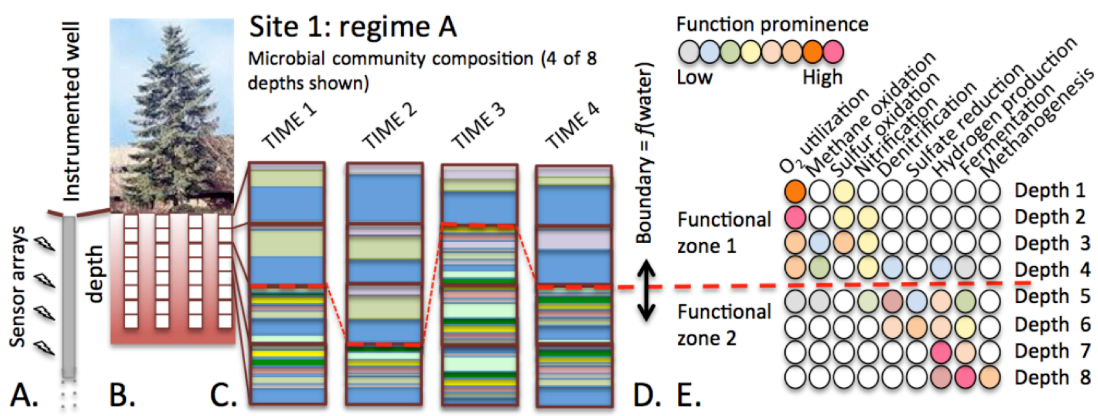

Figure 7. *Overview of the sampling scheme at one of two sites and conceptual diagrams showing results. Associated with instrumented groundwater wells (A), we will collect four replicate depth profile sample series, including soil and the underlying vadose zone (B). Sample collection at this site will occur four times per year (C) and, over the grant period, two sites differing in water inputs, will be studied. We expect that community composition results (C) will reveal distinct zones, separated by relatively marked discontinuities (dashed red line), the depth of which will vary with time of year (C), reflecting changes in water abundance (D). The major task for goal 2 is to delineate metabolic functional zones, based on genomic reconstruction. Nine examples of functions that predict metabolic process are shown (E), with color indicating the frequency of the pathway in the community (function prominence). The system output to the deep vadose zone and water table (monitored in A and at discharge points in creeks) should depend strongly on microbial zonation, particularly during peak times of carbon dynamics, such as after the first rainfall.*

Our analyses will be genomically resolved, meaning that we will reconstruct draft (and potentially complete; Kantor et al., in prep.; Di Rienzi et al., in review) genomes for the more abundant organisms. We anticipate very even species abundance levels and, based on recent experience, the planned sequencing allocation (combined with the spatial/time series approach; see Sharon et al., 2012) should yield extensive genome recovery for organisms > ~0.1% of the community. For less abundant organisms, we anticipate recovery of more fragmentary genome sequences suitable for gene- rather than organism-centric analyses. All genomic data will be analyzed in the context of a knowledgebase (ggKbase) that has been developed specifically to enable simultaneous metabolic analysis of hundreds of genomes (http://genegrabber.berkeley.edu/). All genomic data will be released immediately via release through the open ggKbase infrastructure and, upon publication, in NCBI.

The interpretation of the microbial community results will be made in conjunction with the water chemistry and CO2 observations described above, as well as with the subsurface hydrology and sapflow data described in Section B.1.

B. 3 What controls the spatial extent of wetted channels in the channel networks of seasonally dry environments?

This question will be pursued through four related tasks.

TASK 1) We will exploit the spatial variation in precipitation, topography, and bedrock geology in the Eel River watershed (Figure 2) to contrast the spatial extent of wetted channels in watersheds of 2 to 20 km^2 in drainage area in different settings. We hypothesize that wetted channel density (length/watershed area) will be less in drier areas underlain by mélange and with less relief. Sediment fill may be locally important, and contribute to fragmentation of the wetted channel network. For the same rainfall, we hypothesize the mélange has higher winter runoff and less summer base flow due to a less conductive weathered rock zone (which will be explored in pursuit of question 1). Initial comparison of USGS gauging stations records do indicate a much higher summer base flow for the same mean annual runoff in stations primarily underlain by coastal belt rocks versus basins primarily underlain by mélange.

We will conduct annual mapping surveys to evaluate controls and test these hypotheses. Two surveys will be conducted each year in the same watershed, first in late spring after the rainy season has ended and again in late September before the onset of fall rains. In each case a team of four (including an aquatic ecologist and a geomorphologist/hydrologist) will walk the entire channel network and delineate where wetted channels occur. The team will periodically measure wetted and bankfull channel width, wetted channel depth, and velocity; visually estimate grain size into whole phi dominant grain size categories; and note bed morphology, occurrence of large woody debris, and presence of bedrock or thick alluvium in the bed. In addition they will measure stream and air temperature and relative humidity and take photographs and mark waypoints on a GPS. Where bedrock is exposed in the bed, a hammer blow and exposure description will be used to characterize the degree of weathering. We specifically hypothesize that bedrock will remain relatively fresh where the flows remain throughout the year, and will show evidence of weathering where periodic drying occurs.

The team will also hike up the adjacent slopes and, at three to four intervals towards the adjacent divide, measure air temperature and take soil cores (for bulk moisture determination). For surveys of aquatic biota, they will survey 3-6 cross-channel transects at 25 m intervals down the channel, starting where channels first hold water. Flow depth, velocity, and substrate will be recorded, along with point counts quantifying algal or moss cover and invertebrates (noting aquatic vs terrestrial mosses and invertebrates). Temperature recorders at five locations along the networks will be installed to record diurnal variations and when the channel dries out (as signaled by more marked diel oscillations). Based on experience, each survey will take about three weeks. Stream network maps and data will be plotted onto to digital elevation data and hypotheses regarding topographic, aspect, lithologic, and vegetative controls on seasonal patterns of the extent of wetted channel will be investigated.

In 2013, we will repeat our 2012 measurements in Fox and Elder Creek to check for repeatability of measurements and to refine our methods. Then, over the next four years (2014-2018), we will survey wetted channel extents in two areas underlain by the Central belt (mélange) and in another area underlain by the Coastal belt (predominantly mudstone) and one area underlain by the Eastern belt rocks (metasedimentary and metavolcanic rocks). Collaborations with local watershed groups will expand these observations (Dissemination and Engagement Plans).

TASK 2) We will upgrade our current network of 7 tributary water level recorders in the Angelo Reserve by adding a temperature probe to each and conducting field measurements using salt dilution techniques to create rating curves for each water level recorder. This will add fine scale runoff and temperature data to test and guide our runoff model. Several of the tributaries seasonally become dry, which will refine our sense of the timing of wetted channel retraction. Initial modeling which couples the stream temperature model developed by Zanardo et al. (in prep.) with a distributed rainfall runoff model will be used to predict diurnal oscillations and flow depths throughout the system.

TASK 3) The 38 active flow gauges on the Russian River offer an extraordinary opportunity to characterize summer drawdown across the stream network. We will follow trends in stream temperature and amplitude of diurnal oscillations to characterize the drying of the stream network during drawdowns for frost protection of vineyards, and to identify effects of water diversions on low flow conditions.

TASK 4) We have developed a spatially distributed rainfall-runoff model that divides watersheds into representative elementary watersheds and routes water via rapid and slow subsurface storage reservoirs. This reduced complexity model has seven parameters and reproduces reasonably well the gauging record on Elder Creek. It is similar to GSFLOW but with less parameterization required. This simple model has been coupled to a stream temperature model and can apply across the entire Eel Watershed. We will explore the effects on stream network contraction by adding a conductive zone beneath the stream bed that will cause the bed to become dry when flow is sufficiently low. We anticipate this simulation of water table lowering will enable us to estimate crudely the wetted channel dynamics. Other models of greater complexity will be needed for greater understanding of network dynamics. Through CZO collaborations, we anticipate exploring further GSFLOW (Markstrom et al., 2008) and hsB (Troch et al., 2003).

B. 4 Will changes in critical zone currencies induced by climate or land use change lead to threshold-changes in river ecosystems?

We will link critical zone dynamics and currencies to river ecosystems down the Eel River drainage with: 1) Detailed observations of hydrological, thermal and chemical fluxes and biotic responses in three mainstem South Fork Eel sites near the Rivendell Critical Zone but linked to it in different ways (Figure 8). 2) Surveys of physical conditions and key biota in six comparison reaches within Angelo that differ in critical zone inputs and their degree of fragmentation (physical or ecological isolation) during summer drought. 3) Extensive monthly surveys distributed throughout the Eel basin to document seasonal changes and biophysical relationships affecting salmon, algae, and cyanobacteria. For the third effort, we will collaborate with citizen science teams (Engagement and Dissemination Plans), and coordinate with the CZO network mapping effort (Question 3) to form the basis for a simple upscaling models linking environmental conditions and ecosystem responses throughout the Eel River network. These models will be tested against observations in new sub-basins of the Eel and in other North Coast rivers where our partners are engaged.

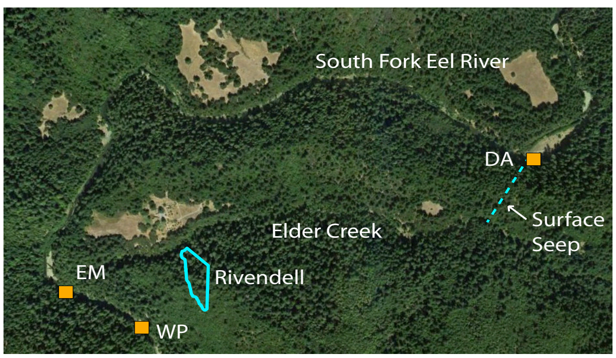

Figure 8. *Elder Creek near its confluence with the South Fork Eel River (flowing from south (bottom of figure) to north, then east). The three mainstem sites near the Rivendell Critical Zone proposed for detailed observations are: EM (where Elder discharges into the South Fork Eel); WP (the warm pool upstream and isolated from Elder Creek discharge), and DA, the summer-discontinuous lateral side channel that receives subsurface discharge from Elder Creek, as evidenced by a spring that surfaces along the dashed line, and blooms of iron oxidizing bacteria associated with cool groundwater seeps in mainstem pools along the south bank. Elder Creek is ~45 m higher than the South Fork Eel at this point.*

Detailed monitoring will occur at three sites near Rivendell (Figure 8). '**DA**' is a secondary mainstem channel that fragments longitudinally to become a 'dead arm' backwater at low flow. Toward late summer, DA becomes one of the more eutrophic sites within the Angelo Reserve. The dominant green macroalga *Cladophora* senesces and small but conspicuous overgrowths of the cyanobacteria *Anabaena* appear. We hypothesize that nutrient enrichment from subsurface seeps derived in part from Elder Creek, along with decay of organic matter imported from upstream, would make DA vulnerable to cyanobacterial blooms were it not for the cooling influence of groundwater discharge. Specifically, we predict that this site would become a focus for cyanobacterial blooms when critical zone discharge wanes to levels incapable of cooling DA below 25^{o}C, a temperature threshold beyond which cyanobacteria are strongly favored over more edible algae (Paerl and Huisman, 2009). At the mouth of Elder Creek ('**EM**'), the receiving pool of the South Fork Eel is cooled 1-2^{o}C by surface flow and groundwater and enriched by insect drift from Elder's 17 km^{2} basin. Juvenile salmonids in mainstem aggregate at this confluence, as is widely observed in other salmon-bearing streams. Under prolonged drought, EM would be predicted to sustain salmonids and resist cyanobacteria longer than other sites, and could serve as a refuge for recovering salmonid populations when flows are restored. Upstream from the Elder Confluence, a mainstem pool '**WP**' receives critical zone currencies from the south-facing (madrone and oak covered) slope of the main Rivendell installation. Partially isolated from incoming mainstem discharge by emergent boulders upstream, WP receives no cooling surface runoff from Elder Creek and becomes 2-4^{o}C warmer than the adjacent mainstream. At WP, we would study how warming without eutrophication affects biota.

At DA, we will install an Isco sampler to measure fluxes of reduced Fe and other micronutrients from the critical zone into the channel. We hypothesize that these micronutrient fluxes sustain the high levels of biological productivity, including spring blooms of iron-oxidizing bacteria observed in backwater pools. At all three sites, we will monitor vertically distributed temperature, dissolved oxygen concentrations, stage,, and flow velocity using fixed i-Button thermistor arrays, and manual measurements of dissolved oxygen and flow velocity at the deepest points and along cross-sections upstream and downstream from each pool. Sondes installed at these positions will record dissolved oxygen (indicating stream metabolism), pH, conductivity, light, and (in DA) cyanobacterial exudates. A fifth sonde will be installed in Elder Creek, for analyses of currencies delivered in runoff and subsurface flow paths, locally and from upstream sources. We will install piezometers near cold temperature anomalies in bottom waters to estimate groundwater head and inputs to the pools through seeps and take monthly samples of stream and groundwater to estimate the local input rates of groundwater and key solutes (TDN, PO_4, Fe).

Twice monthly during low flow, we will quantify depth, surface flow, substrate and algal or cyanobacterial abundance and condition at 15-20 points along each of three fixed cross-stream transects in each of the three focal sites. We will also monitor algae on stream cobbles slightly elevated on submerged plastic food containers, which limit access by the major grazers (caddisflies and snails), to evaluate grazer impacts on accrual and phenology. These measurements will allow us to relate local (modeled) radiation (Bode et al., 2012 AGU), flow, substrate, and temperature to algal phenology, accrual, condition, and taxonomic dominance over the course of the biologically active low flow season. Three water samples will be collected from each site for analysis of total dissolved nitrogen, ortho-phosphate, and dissolved organic carbon. We will also survey fish with snorkeling observations. We will use these data to develop and calibrate coupled biological–physical models that account for the key environmental transformations during summer: formation and destruction of thermal stratification, oxygen depletion and flow fragmentation, and their relationship to salmonid survival and growth, algal and cyanobacterial proliferation, species succession, and senesence.

At four other pool-riffle units, two in Elder Creek along Rivendell and two in Fox Creek, a salmon-bearing tributary ~4 km downstream, we will mark and recapture fish in 10-20 pools across the drought season to study fish performance (survival, growth) over the low flow season. We will implant these fish with uniquely coded pit-tags at the beginning of the summer and resurvey fish twice a month during the summer low flow season, using a portable antenna. These data will allow us to estimate survival probabilities to pinpoint periods of extreme mortality. We will measure growth by recapturing fish once per month across the dry season to re-measure body size. These measurements will allow us to relate local flow, water depth, dissolved oxygen, and temperature to fish performance over the course of the biologically active low flow season. A stationary antenna installed in the mainstem Eel just downstream of the confluence of both tributaries will allow us to detect emigration during the low flow season, allowing a separation of emigration and mortality.

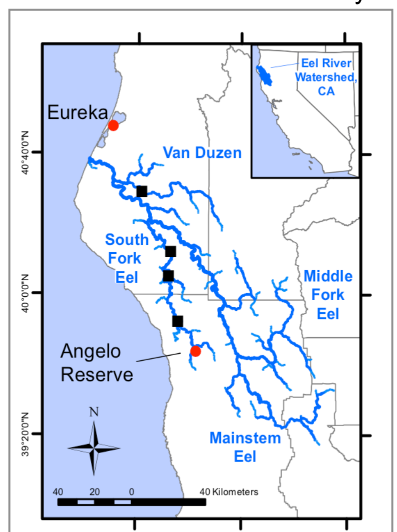

Figure 9. *The Eel River watershed. Squares = locations of dog deaths suspected or shown to be caused by cyanobacteria since 2002.*

We propose developing low-complexity coupled biological–physical models for our study reaches. The filling-box model proposed by Killworth and Carnack (1979) will serve as a point of departure for representing the mass balance and thermal stratification in the pools. This model was explicitly developed for lake systems with surface throughflow due to river input, appropriate analogues for the step-pool or bar-pool structure of the tributary and mainstem sites we will study during summer. The model will be adapted to account for groundwater inputs, and coupled to a transport model for DO, and calibrated against one of the set of replicated pool data. We will use the other three monitoring reaches to validate the model, with the aim of reproducing temporal and spatial patterns of the thermocline and hypoxia development, which we anticipate to be the major controls on the ecology.

The validated physical model will be coupled to empirically derived relationships between algal variables (accrual rates, peak biomass, time or biomass at onset of sloughing, and timing of changes in dominance from one taxon to another) and fish performance variables (survival, growth, movement) with separate and interactive effects of key physical and chemical factors (flow velocity, temperature, light, nutrient concentrations). We will use our 3 mainstem and 4 tributary study reaches to derive relationships, evaluating our results relative to relationships documented in previous studies in the Eel and other similar systems. We will then test the predictive performance of our derived relationships with data from the more extensive array of sites to be surveyed monthly throughout the Eel basin in conjunction with our watershed partners and the network mapping team (Question 3). Several of these sites will be in areas where dog deaths have been linked to cyanobacterial blooms since 2002 (Figure 9)

B. 5 Synthesis modeling.

At the highest level, we view the critical zone as *mediating* the effect of climate and land use on terrestrial sub-systems: terrestrial vegetation, hydrologic dynamics in the critical zone and the channel network, solute and sediment fluxes, and ultimately the quality of in-stream and near-shore aquatic ecosystems. The CZ also mediates feedback from terrestrial systems to the local and regional climate. Our understanding of the propagation of influence between climate and these terrestrial systems, via the CZ, is complicated by complex, coupled nature of the relevant processes. We propose developing a numerical platform to assist with developing this understanding: the Atmospheric, Watershed, Ecological, Stream and Ocean Model (AWESOM) (Figure 10). We will use AWESOM to synthesize the findings from smaller scale studies, couple the different CZ subsystems together, and explore long-term and large-scale consequences of the dynamics of the CZ in the context of changes in climate, land use, and water management policy.

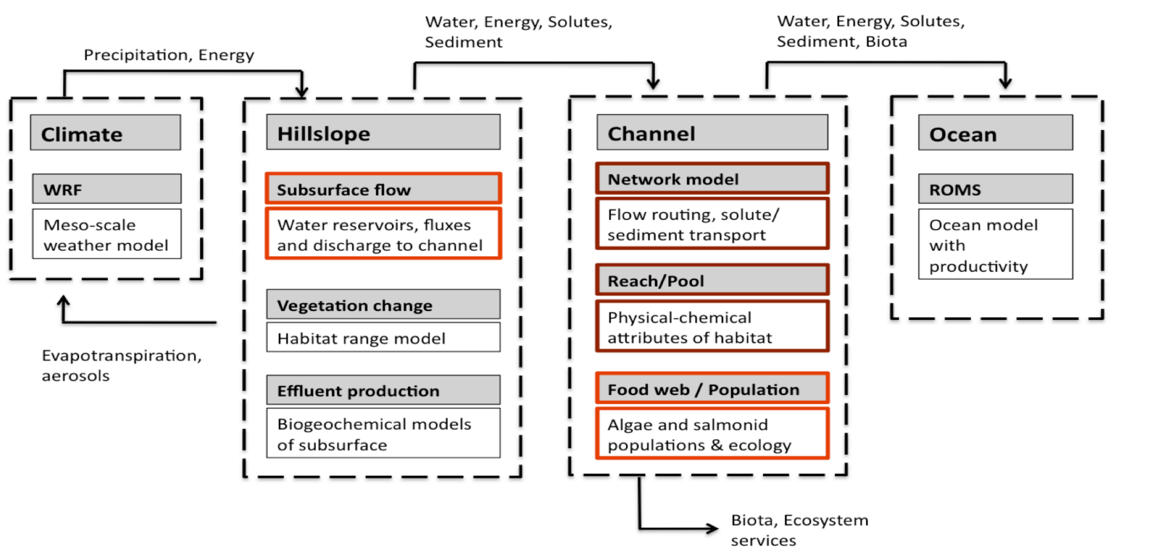

Figure 10. Modular components of the AWESOM framework

AWESOM will include some pre-existing model components that are well established and well validated and that we are confident provide a robust representation of the key processes that arise in the Eel River System. These components include a kinematic channel routing model for the Eel River network (Lighthill and Whitham, 1955); the Weather Research and Forecasting Model (WRF, http://www.wrf-model.org), which we have adapted to Northern California to represent meso-scale atmospheric dynamics and interactions with the land and ocean; the Regional Ocean Modelling System (ROMS, http://www.myroms.org/) and a simple ecosystem model NPZD, which we have adapted to the North Pacific to link the outputs of the Eel River to satellite observations of nearshore ocean productivity; and a modification of the "river-dominated lakes" model to describe the development of thermal stratification in aquatic habitat (Killworth and Carmack, 1979). The AWESOM framework will also include novel model components—which will be developed, refined and improved in conjunction with the field research in the Eel River Basin. Amongst these components will be: (1) a hillslope scale groundwater discharge model that can represent the partitioning of rainfall into the vadose zone, saturated saprolite, and weathered bedrock that accounts for rapid bypass of water along fractures to the water table perched at the base of the critical zone (Figure 4) and delivers summer base flow to the channel network; (2) a species- and lithology-dependent differential uptake of water by trees from the subsurface critical zone; (3) a moisture-microbial community dynamics model; (4) a coupled stream temperature and runoff model that operates throughout the entire stream network and predicts their diurnal oscillations; and (5) an optimization procedure to project the effects of climate on future vegetation distributions. We hypothesize that the physics of these processes are radically different from that embedded in standard hillslope hydrological models (which rely on continuum porous media flow assumptions derived from Darcy's Law) and requires a new kind of physical model (Salve, et al., 2012). Similarly, new models for food web dynamics, algae and salmonid population fluctuations, and in-stream transport and processing of critical solutes and sediment fluxes will be developed from our field campaigns and system data analysis.

WRF and ROMS are community models and follow the protocol of the Earth System Modeling Framework (ESMF) to facilitate "plug-and-play". We will similarly develop AWESOM in a modular fashion, in which the fixed model components provide a back-bone into which the novel modules will be coupled. This approach will allow us to use empirical or existing models as placeholders for the novel modules, to develop novel modules "offline" from the full modeling system, and of course to run the coupled model even while the novel components are still being developed. We anticipate interaction and exchange with modeling teams at the other CZOs to contribute to and build upon their efforts. The assembled model will be used to explore the six questions posed in the Scientific Justification section.

C. ENGAGEMENT PLAN

We will actively engage with scientists locally and worldwide who are concerned with critical zone linkages to terrestrial and freshwater ecosystems. Designating the Angelo Reserve as the Eel River CZO will support our ability to use the reserve and its existing infrastructure to serve as a test bed and environmental laboratory for investigating drivers and feedbacks that will affect the resilience of these watersheds under changing climate and land use. One focus will be collaboration with academic, consulting, tribal, and citizen scientists working in California North Coast watersheds. Residents and watershed groups along the California North Coast are well-organized, observant, knowledgeable, deeply concerned with the future of coastal forests, rivers, and human communities (Friends of the Eel River, Eel River Recovery Program, Klamath Basin Monitoring Program, the Karuk tribe, and the Redwood Forest Foundation). Members of our CZO team are eager to collaborate with these and other groups and agencies (e.g., NOAA-Fisheries, Klamath Basin Monitoring Program) in the Eel, Russian, Napa, and Klamath River basins, many of whom we have collaborated previously, and this interest is reciprocated (see letters of support). We will invite environmental scientists and students from North Coast tribes, watershed groups and regional colleges to workshops and short courses at the Angelo Reserve. We will also help compile, organize, and interpret observations of change along as much of the Eel River basin as possible. Our citizen science engagement will focus on collaborative observations of change during declining summer baseflow (Dissemination Plan).

We will also engage with colleagues across the US and the world who are investigating water, climate, and land use sustainability. A University of Minnesota (U of M) team has just begun a 5 year initiative under the Water Sustainability and Climate NSF program emphasizing the identification of landscape locations that are particularly sensitive to human-amplified natural change (like DA, our Dead Arm hot spots for eutrophication). We plan to coordinate with this group (see letter of support from PI Foufoula-Georgiou), offering Summer Institutes alternately at Angelo and the U of M, following a series sponsored by the NSF-National Center for Earth Surface Dynamics (NCED) in which several investigators from the proposed Eel River CZO participated. Instructors with critical zone expertise in diverse ecosystems from U of M, Franklin and Marshall College, Cornell, LSU, UCSC, Oregon State, and other institutions will be invited to teach short courses, including laboratories, model construction and use, and field methods. They will instruct competitively selected national and international students invited to either the 3 week Summer Institute session at the Angelo or the U of M. Bringing these students and instructors to Angelo would expand the already broad range of collaborators who work in and around the Angelo Reserve on projects relevant to critical zone dynamics. The Angelo Reserve, as part of the University of California Natural Reserve System network, is dedicated to university level teaching and research, and is well set up to accommodate it (see descriptions of new investigator housing, laboratory facilities, hydrologic and forest instrumentation, and the wireless infrastructure network supporting environmental monitoring in the Facilities section).

D. DISSEMINATION PLAN

We will share products of our CZO with local watershed partners and national and international colleagues in three ways:

(1) Training local youth to join the next generation of field scientists, modelers, and "EcoGeeks" (engineers skilled in using technology to study natural ecosystems). One initial focus will be on youth in tribal communities committed to the environmental future of their ancestral lands on the California North

Coast. We have already discussed environmental science youth programs with leaders in the Karuk, Yaruk, Cahto, Wailaki, and Pomo tribes (in the Klamath, Eel and Usal River basins), and they are enthusiastic about this possibility (see letters of support).

(2) Developing (in coordination with active watershed groups FOER and ERRP) web-based tools for sharing environmental monitoring methods and data in close to real time (e.g., the bluegreen algal tracker for the KMBP).

(3) Publishing papers for both technical and broad audiences, and making publically available the protocols, model code, data, and analyses underlying our predictions for how critical zones will respond to climate, land cover, and land use and how these responses will affect delivery of critical zone currencies and consequent ecosystem shifts in recipient terrestrial, riverine, and coastal environments. A particular focus will be on connecting forest cover and land management (including forest thinning) to river flows and temperatures (and other currencies) during drought, and thus to the fate of salmonids and potential regime shifts from salmon to cyanobacteria under reduced flow, enhanced nutrients, or warming.

We will ask our citizen scientist collaborators—primarily residents who live along or near the rivers—to take repeated photographs from fixed photo-points with cell phones or cameras that date and locate (GPS) images of reaches of river they can frequently access during low flow conditions. We will provide scale bars and color standards to use in their photographs. We would also request dated, located photos that documented key events (salmon migration or spawning, algal blooms, dewatering). From photographs, we would assess: (1) changes in the connectivity and area of wetted channel area; (2) macroscopically-visible algal proliferations and their color (which in proliferations of the dominant green macroalgae (*Cladophora)* and its epiphytes can indicate (semi-quantitatively) algal abundance, viability, local rates of atmospheric nitrogen fixation, food value, and associated insect emergence rates (Furey et al., 2011; Power et al., 2009). Harmful cyanobacterial blooms are also distinctively colored (*Anabaena* is dark blue-green, *Microcystis* olive-green); (3) microhabitat availability, quality, and access to passage for salmonids at various life history stages using bar inundation and surface flow patterns (e.g., W. Trush, Shasta River KBMP report). With other watershed groups (FOER, ERRP), we would collect, visualize, and share this information in as close to real-time as possible over collaborative, linked web sites, using tools now available (FaceBook, I-Naturalist.org, Google Earth Engine). Watershed partners would be invited to short courses at the Angelo Reserve for training in basic fluvial hydrology methods,algal ecology and identification (microscopic identification, use of passive (SPATT) samplers for evaluating cyanotoxins (Kudela et al. 2011); experimental procedures for evaluating limiting factors, and fish ecology (fish identification, methods for estimating fish abundance). We will also learn from approaches, insights, and ideas of individuals and groups who are already engaged in watershed watch efforts how, collectively, to better track, document, understand, and forecast changes in our river basins and coastal shorelines.