NSF Workshop Report: Towards a Unifying Theory of Critical Zone Structure, Function and Evolution

Figure 1. The 2011 CZO All Hands meeting hosted by the Jemez River Basin – Santa Catalina Mountains Critical Zone Observatory included 139 researchers from 31 institutions.

National Critical Zone Observatories Program
All Hands Meeting May 8-12, 2011
Biosphere 2
University of Arizona
Tucson, Arizona

1. Activities

Early in 2007 the National Science Foundation created the Critical Zone Observatory (CZO) program and awarded funds to establish three initial observatories: Southern Sierra (California), Boulder Creek (Colorado) and Susquehanna Shale Hills (Pennsylvania). During 2009, an additional three observatories were established in Arizona/New Mexico (Jemez River Basin/Santa Catalina Mountains), Delaware (Christina River Basin) and Puerto Rico (Luquillo).

Since that time, the interdisciplinary research teams at each site and across the network have been working to develop their site-specific science and cross-site research and education activities. During the summer of each year, PIs from each CZO meet with NSF program managers and the CZO National Program Steering Committee. Meetings in 2008, 2009 and 2010 were held at Southern Sierra, Susquehanna Shale Hills, and Boulder Creek CZOs, respectively. The annual meetings focus on research, education and outreach occurring and planned at each CZO and also collectively across the CZO (X-CZO) network. Prior to the All Hands meeting of 2011, these annual meetings included ca. 2 principal investigators from each CZO, the CZO steering committee, and NSF personnel. The annual meeting typically includes two days of in house meetings plus a day in the CZO field site, where investigators have presented their CZ research components. While this meeting structure enables essential direct discussions among PIs, the NSF and the Steering Committee, there is also a need to facilitate periodic (perhaps every 2-3 years) larger group interactions that enable face-to-face encounters of graduate students, postdocs, faculty and staff *network-wide*. In proposing this All Hands Meeting to NSF, we suggested that the CZO National Program could catalyze the development of *new* X-CZO activities, including novel research collaborations initiated by graduate student and postdoctoral researchers, particularly since these are the young scientists that are actively engaged in the nuts and bolts of day-to-day CZO research.

Four years into the CZO national program, the All Hands Meeting of May 8-12, 2011 brought together this larger group of **139 CZO researchers from 31 different CZO-collaborating institutions** listed in this report. The workshop participants included steering committee members, NSF program managers, the Steering Committee, Collaborators, postdoctoral scientists and graduate students, as well as others invited from the broader community working on critical zone processes – to discuss progress in our understanding of what controls the structure, functioning and evolution of the critical zone, and to start the process of synthesis of this knowledge across national and international CZOs.

In order to guide the discussion and information exchange, and in response to the 2010 report recommendations of the CZO Steering Committee, the central theme of the workshop focused on outlining the requirements for elucidating a unifying theory and techniques needed that can explain the observed structure and function of the critical zone across environmental gradients, and that can help predict the evolution of the critical zone in a changing environment. Even though such unifying theory is well beyond our reach at

this stage of the program, the theme was appropriate for developing an efficient and common language across CZO researchers as well as to initiate the process of synthesis.

Workshop Program

The workshop was organized around four half-day meeting sessions, each focusing strongly on investigator interactions: (i) *Ecosystem Exchange and Hydrologic Partitioning, (ii) Subsurface Biogeochemistry*, (iii) *Ground and Surface Water Dynamics*, and (iv) *Critical Zone Evolution*, a one-day field trip into the Santa Catalina Mountains CZO, and a day dedicated to working group discussion and syntheses. The focus in the sessions on processes rather than drivers of the critical zone (geology, climate, time) provided a framework that was common across the CZOs, and that was meanwhile sufficiently broad to stimulate discussions between scientists with different backgrounds.

The workshop kick-off took place on Sunday evening (5/8), and included an invited key-note lecture by Larry Band (University of North Carolina), a leading watershed hydrologist not involved in the National CZO program, but who has been actively involved in developing an understanding of interactions among CZ vegetation, soils and landform shape in controlling catchment hydrologic response.

The thematic session program began Monday (5/9) at 8:00 am. Each of the four half-day sessions was introduced by the Jemez – Santa Catalina CZO session convener and a key-note lecture (25 min + 10 min discussion), given by a non-CZO investigator: Russ Monson – Univ. AZ, Libby Hausrath – Univ. NV, Kip Solomon – Univ. Utah, , and Oliver Chadwick – Univ. CA, Santa Barbara. Each keynote was followed by three shorter (10 min + 5 min discussion) research oral presentations by CZO investigators (including students, postdocs, and Assistant Professors), and brief (2 min – 1 slide) invitations to the posters submitted to that specific session (12-16 per session, 30 min total).

The focus on posters throughout the workshop enabled the full "All Hands" group to present research results in the context of a single session (rather than concurrent session) format. This format also made it possible for the full group to interact over the full range of critical zone science topics covered and maintain a group-wide workshop experience that was consistent across CZ science disciplines.

During and after coffee breaks there was ample time to visit the posters for extended discussions. Rapporteurs, represented by the PIs from each of the other five CZOs, were assigned to summarize each poster session and to lead the discussion that concluded each session. This portion of the schedule turned out to be difficult to accomplish and was twice "allowed to slide form the program" because it required moving the full group from the poster session in the first floor of the convention center back to the group meeting room in the visitor's center.

Each session took about 3.5 hours and included almost 2 hours of discussion. The workshop included a two-hour period on Monday for group tours of the Biosphere 2

facility, and on Wednesday for breakout group discussions of the workshop theme (exploring what is needed to develop unified theory of the critical zone). Time was also allocated for student/postdoc interaction with the CZO Steering Committee, as was requested at the Boulder Annual CZO meeting in May 2010.

On Wednesday evening, the workshop sessions were completed by an invited closing lecture given by Ronald Amundson (Univ. CA, Berkeley) who was asked to discuss, in part, what has been learned from the workshop and how we can move forward.

***CZO Working Groups*:** Given that numerous CZO investigators, graduate students and postdocs had made the trip concurrently to Biosphere 2, we convened a fourth day of the workshop dedicated to developing (i) questions, (ii) hypotheses, (iii) approaches and (iv) methods for X-CZO network pursuit. The working groups that self-organized for this purpose following the Wednesday breakout group sessions included those dedicated to:

- Soil formation
- Landscape Evolution
- Biogeochemistry
- Ecohydrology
- Data Management

Field Trip to the Santa Catalina Mountains (SCM) Critical Zone Observatory

On Tuesday, May 10, the group convened at 7:00 am in two charter buses to visit the Santa Catalina Mountains Critical Zone Observatory adjacent to the Biosphere 2 meeting location. The field trip included stops at Soldier Canyon (Geomorphic and Ecologic Overview), Mt. Bigelow eddy covariance tower (Land-Atmosphere Exchange), and Marshall Gulch Catchment (Ecohydrology and Subsurface Biogeochemistry Experiments). Details on the field trip can be found in the "**Mt. Lemmon – Santa Catalina Mountains Field Trip**" booklet that is included at the end of this report.

Figure 2. SCM CZO field-trip stop 1 in Soldier Canyon. JRB-SCM CZO Co-PI Jon Pelletier describes a numerical model of non-linear relations among vegetation, soil and landform development in the the "sky islands" of southern Arizona.

Venue

The Biosphere 2 Conference Center provided an exciting and economical venue for the meeting. It is a locus of current and future Critical Zone research "under glass", and it contains a large meeting room that holds 160 people in theater style seating, as well as several other smaller meeting rooms for smaller symposia and breakout sessions (http://www.b2science.org/institute/conf.html). The site also contains 106 sleeping rooms with 85 bathrooms within apartment-like casitas that were constructed in the late 1990s, which allow groups of this size to remain on site throughout the meeting. Within those 106 sleeping rooms are 195 beds (i.e., many are double occupancy rooms, which is ideal for graduate student attendees). Hence, the Biosphere 2 conference center accommodates well over 100 participants with single and double occupancy, with some sharing the bathrooms. All food was catered and provided on site by a variety of vendors.

2. Workshop Outcomes

2a. Oral and Poster Sessions

The 2011 All Hands Meeting achieved its principal objective of assembling a network-wide group of CZO researchers including investigators, postdoctoral scientists, and graduate students, for extended and meaningful interactions with each other, as well as with NSF program managers, the CZO Steering Committee, and non-CZO funded, but leading scientists, in the field of Critical Zone research. Those that attended the meeting seemed to be in agreement that this type of "All Hands" meeting should take place regularly in future years, and could be made a central feature of CZO science activities. For example, as indicated in the 2011 CZO National Program Steering Committee Report, submitted soon after the All Hands Meeting:

"*The Committee members and other attendees gave high marks to this mix; without exception everyone felt that this format encouraged cross-site thinking and fostered a sense that exciting science was being done, with more to come. In particular the Committee felt that the All-Hands meeting provided a great opportunity for students and post-docs to see and experience the breadth of CZO science and enable them to place their research in the context of larger research questions. As noted in our Committee recommendations, we suggest that this type of All-Hands format be followed in the future, at least every other year.*

The oral and poster sessions stimulated a significant amount of X-CZO dialogue throughout the meeting. In order to enhance the continuation of such dialogue, we asked all workshop participants to send PDF versions of their poster and slide presentations to our CZO data management team for posting on the web. This has been accomplished, and now all of those abstracts and presentations that were sent (ca. 90% of the presenters contributed!) are posted on line at the All Hands meeting website: http://web.sahra.arizona.edu/czo_reg/. This website provides an excellent archive of the full workshop and should be consulted for details extending beyond the scope of this report. In total, 71 abstracts and posters were presented, along with six keynote lectures,

and 12 CZO talks. Most of these presentations are available on the meeting website for viewing.

A video on the CZO National Program was produced by Shipherd Reed and the UA Flandrau Science Center team, and can be downloaded from the Jemez River Basin – Santa Catalina Mountains CZO website (www.czo.arizona.edu).

2b. Working Group Breakout Sessions

At the opening of the All Hands Meeting, a specific charge was posed to the working groups in the form of the following question:

How can the cross-CZO-network be used to develop unified theory of the critical zone that links long-term geomorphic evolution and architecture to short-term hydrologic and biogeochemical responses?

The main idea, therefore, was to address the question of how the network of CZO sites (rather than individual sites themselves) could effectively develop the theory of critical zone evolution and contemporaneous response in a way that takes advantage of the network of sites, ideas and people (i.e., how can the whole network be made greater than the sum of its parts?).

In the first working group session on Wednesday, breakout groups focused on developing questions that would be the basis of hypotheses and research approaches developed on Thursday.

Breakout groups were self-organized and developed questions within each of full-group selected categories as:

1. Climatic and lithologic forcings and disturbance
    a. How does climate forcing (e.g., EEMT) vary in space and time across sites?
    b. When does hydrological and biogeochemical response reflect current forcing or past forcing?
    c. How does CZ architecture reflect long-term co-evolution of climate forcing and geology versus short-term disturbance (anthropogenic or "natural")?
    d. How do we connect long-term mean records back to individual events?
    e. How does the distribution of events respond to climate change?
    f. Is it possible to employ reduced complexity characterization of events in long-term geomorphic models?
    g. How does the event distribution influence different CZ processes and how does this distribution play out across different climate scenarios?

2. Role of biota in CZ function
    a. What is the role of trees in the evolution of the critical zone?

b. Can the Holdridge Life Zone (see below) scheme effectively describe weathering regimes both within and across parent materials?

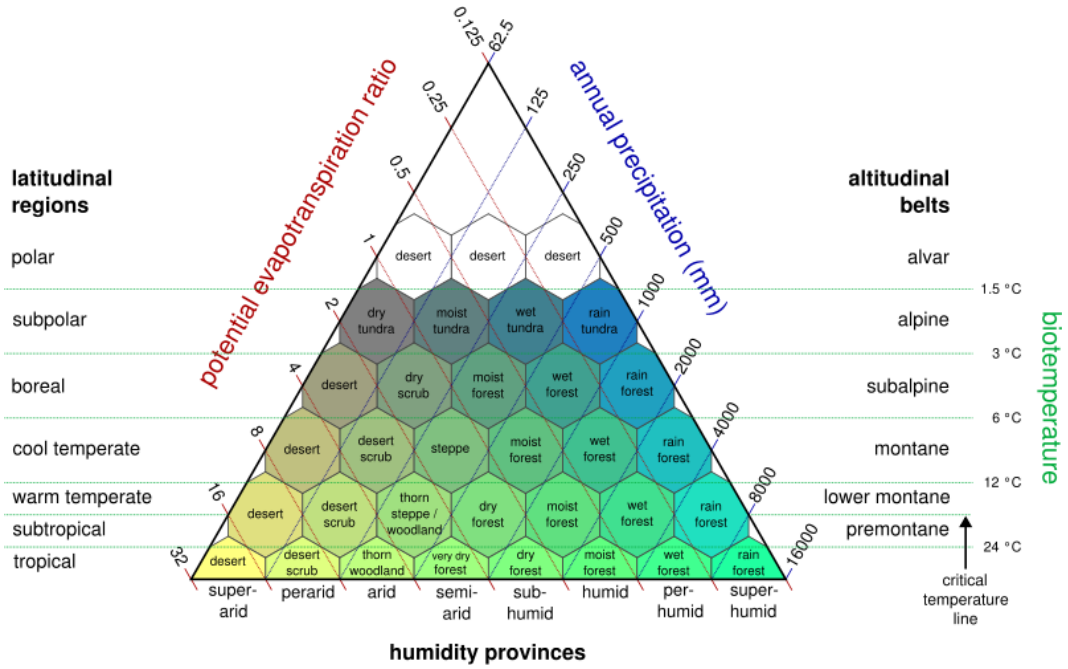

Figure 3. Holdridge Zone Schema.

3. <u>Time scales of CZ evolution</u>
   a. On what time scales do components of CZ architecture change (hillslope form, soil structure, biological composition)
   b. What is the resilience of CZ systems to climate change?
   c. What are the mechanisms of stability for different processes and how are these connected to the process timescale?
4. <u>Prediction of CZ structure and effects on response</u>
   a. When do hydrological and biogeochemical responses reflect structure?
   b. Can we develop models that predict the basic features of the CZ such as the residence time distribution of hydrologic flows, the denudation rate of the landscape, and the soil thickness?

On the basis of these initial questions, a second set of new breakout groups were formed for in depth discussions on Thursday, where specific hypotheses and approaches for developing CZO network science were discussed.

The groups formed on Thursday were initially intended to focus on specific aspects of these questions, including the development of hypotheses and approaches to address them by X-CZO collaborative research. However, it also became clear in the large group discussion that there was a strong interest among various groups to meet on more disciplinary lines

across the CZO teams. In particular, the "Geomorphology" group wanted to have significant time to discuss the questions raised regarding CZ architecture and structure evolution questions raised the previous day. Other disciplinary groups (Ecohydrology, Biogeochemistry, Pedology) and a technique group (Residence times and Tracers) also felt that much could be gained by such a X-CZO approach. So, the Thursday breakout groups were:

1. Ecohydrology
2. Biogeochemistry
3. Pedology
4. Geomorphology
5. Residence times and tracers

These five groups made progress down various and diverse paths toward the goal of (i) questions, (ii) hypotheses, (iii) approaches and (iv) methods toward X-CZO research. The reporting back to the full group from each of these breakout groups on Thursday is summarized below, based on their reporting, which took a variety of formats.

1. Ecohydrology

This group developed a large set of questions that relate to using the X-CZO network for understanding ecosystem impacts on hydrologic response, as well the impacts of hydrology on ecological function.

-What are the feedbacks between biological processes, critical zone architecture, and fluxes with implications for:

a. *Water availability*
b. *Carbon cycling*
c. *Nitrogen cycling*
d. *Limiting factors from soil perspective*
e. *Weathering and plants*

Additional questions from the group: How does soil moisture storage relate to forest / water relations and the how does this impact the role of forests in catchment water balance? What are the impacts of species variation? What is the role of aspect across the CZO's in controlling coupled land, atmo, bio, litho system? How will forest structure change with climate change and/or disturbance and how will that impact water balance at the catchment scale? How does the critical zone influence vegetation community structure at landscape scales (km)? What is the role of phenology on critical zone processes and how will climate change impact these feedbacks? Can we close the water balance everywhere at every CZO? How does vegetation influence hydrologic partitioning and what vertical and horizontal (pedon - plot – catchment) scales are important? How do ecohydrologic variables respond to climate change (snow, soil moisture, microclimate)? What is the spatial variability of snow water inputs and isotopic and chemical inputs and influence

catchment scale fluxes and residence times? What are the feedbacks between vegetation structure / function and water and how sensitive are these feedbacks to changes in climate?

Approach: Exploration of X-CZO hypotheses can include (i) common measurements, (ii) common models, (iii) common perception (classification).

- LiDAR
- Met station data
- Flux data
- Soil Moisture
- Piezometers
- Sap Flow
- Geophysics
- Snow (ultrasonic)

This group identified a need to be concerned with measurement strategies and their consistency. They also identified several methodological questions and potential shortcomings of the current network that need to be addressed in developing a strategy for meaningful X-CZO research: How do we capture variability? How do we identify areas that control processes? Can we observe the hot spots and hot moments in ecohydrology?

Does a suitable network exist for making the most of X-CZO ecohydrological studies? In other words, can we classify CZOs into "regimes" where we have a framework to address common questions? For example, the Holdridge Life Zones (Figure 3) classification might provide an avenue to classify CZOs and begin to correlate that classification with CZ functions observed. Does the CZ fit into the "life zone" concept? How much of the Holdridge "range" is captured within and across CZOs?

The goal of effective X-CZO research sheds light on a need to fill funding gaps that exist due to biases in each CZO initial proposal. Some gaps exist at all CZO's (e.g., human components, biological foci), and some CZO's are stronger in one area versus another.

Additional Ecohydrology group recommendations:

- Cross CZO post doc funding
- RFP's devoted to cross CZO.
- There is some low hanging fruit for X-CZO research but to develop transformational science across CZO's we need to fill these key gaps.

2. Biogeochemistry

This group developed three distinct questions related especially to CZ biogeochemistry, focusing on carbon cycling and CZ structure and resilience, with subservient and more specific questions underlying each one:

-What characteristics of the CZ make it a carbon source or sink?

Hypotheses: The X-CZO network can be used to better close the C, N, P balance at the catchment scale by collecting requisite data on (i) land-atmosphere exchange (eddy covariance), (ii) internal CZ reservoirs, redistributions, transformations and fluxes, (iii) stream water output (e.g., DIC/DOC/POC), (iv) deep groundwater flows that bypass stream output.

Approach: In order to use the CZO network to understand the roles of climate, lithology, disturbance and time on CZ carbon cycling, we need to have X-CZO measures of carbon fluxes as determined from eddy covariance, stream discharge, deep groundwater flows, and internal redistribution and transformation.

-What is the coupling between mineral transformations and carbon dynamics?

- How do these interactions affect the chemical evolution of water along flow paths?
- How do changes in periodicity and magnitude of precipitation inputs and temperature drive the interactions between minerals and carbon?
- What are the characteristic time scales of reaction versus those of transport?
- How does rock type affect the carbon balance over time (for fixed climate)?

Approach: This research question overlaps with a similar one raised by the Pedology breakout group (below), and could take advantage of campaign style sampling of soils and weathered rock across the diversity of lithologic and climatic conditions present at CZO sites.

-How does the structure of the CZ affect its ability to provide services?

- How sensitive is CZ structure to perturbation?
- How is this sensitivity distributed across CZ components (e.g., soil aggregate dynamics)?
- When does the change in structure diminish the ability of the CZ to attenuate disturbance?

3. Pedology

This group refined questions of relevance to soil formation and structural development and its role in CZ processing of water and carbon.

Questions related to water:

What is the distribution of soil water storage capacity and the controls on this distribution?
How does soil architecture exert first order control on CZ hydrological and biogeochemical processes across space and time?

Approach: Strengthen the link between COSMOS and CZO to better couple temporal pattern of watershed scale hydrologic dynamics to soil moisture time series. Take advantage of potential SMAP connection to CZO.

Questions related to carbon:

-What is the residence time and storage capacity of soil carbon across the CZOs?
-Can we link observed patterns in vegetation distribution to spatial patterns in soil properties (depth, water storage, carbon content)?

Approach: Utilize the diversity of climate and lithology space afforded by the CZO network to initiate common methodological procedures for characterization of carbon pools, storage and residence times.

Questions related to soil evolution:

-How can CZO help the development of quantitative pedologic models?
-Can we identify positive and negative feedbacks and thresholds in soil properties and evolution?
-How does the flow of energy influence the formation, evolution and distribution of soil?
-How do we quantify clay (carbonate) neogenesis and translocation across lithologic and climate space?

Approach: Develop a working group to produce "Ped 1.0", the first process-based, process-coupled, quantitative model of soil genesis. Combine state-of-the-art GIS approaches with novel field methods to enable systematic 3D mapping of soil physical properties (coupling of tools – models and measures -soil production, soil thickness, reactive transport, and predictive soil mapping techniques).

4. Geomorphology

The geomorphology group (Figure 4) identified four priorities for X-CZO research into long-term landscape evolution. How these activities would interface with other CZO disciplines (e.g., biogeochemistry and hydrology) was also discussed.

1. Develop geomorphic models to explain the evolution of CZO architecture (soil thickness, topography, rates of geomorphic processes such as soil transport, production of soil from saprolite and saprolite from bedrock, and so on). These models might initially be conceptual models, but a useful goal would be to develop these as numerical models. Ideally, a single model with different parameter values could be used to represent the geomorphic evolution of all the CZO sites.

Discussion also focused on the desirability of developing models that not only predict changes in length scales (such as elevation of the ground surface, soil thickness, and so on), but that also predict quantities with dimensions more useful to biogeochemists and

hydrologists. For example, models could be developed that predict units of soil and regolith mass. This would require predicting the development of porosity. Mineral surface area distribution might be a different unit of prediction that would require understanding the distribution of minerals within the subsurface, and how they evolve through time.

Predictions of surface area and porosity could provide results useful for hydrologists and geochemists, who need to know the distribution (and connectivity) of subsurface pore space and the area of reactive mineral surfaces. This would allow these disciplines to benefit directly from geomorphic models in their work. Additional connections would arise because the use of this information in hydrologic and geochemical models would feed back to geomorphic models; the evolution of the landscape is controlled in part by hydrologic and geochemical processes.

Figure 4. The Landscape Evolution breakout group meeting on the Biosphere 2 café patio.

The group saw this effort as a key opportunity for developing interactions between the disciplines of geomorphology, hydrology, and biogeochemistry. It also presents a useful means for connecting the long geomorphic timescales with shorter hydrologic timescales, and the variable timescales associated with geochemical processes.

2. Develop improved methods for interpreting measurements of ^{10}Be. Nearly all the CZO groups are using ^{10}Be to infer long term rates of geomorphic processes. Typically, these data are interpreted in terms of steady-state processes, an approach that we know is untrue. A cross-CZO effort to develop long term models that incorporate varying climatic

and geomorphic processes would greatly benefit all the CZOs, and would also advance geomorphic science in general.

3. Develop studies that investigate the influence of trees and other vegetation on geomorphic processes at the six CZOs. Vegetation provides important controls on geomorphic processes through its influence on physical and chemical weathering, hillslope hydrology, and particle transport processes. Exploring the differences and similarities in these processes between CZO sites could prove useful.

4. Conduct workshops for graduate students in Landform Evolution Modeling. These workshops would allow students to gain proficiency in numerical modeling of landform evolution developed by CZO scientists. The group discussed having students come to the meeting with data from their own CZO projects, so they could learn modeling methods applied to their own problems and projects. Meetings could be held once a year, or at some other appropriate frequency.

5. Residence Time and Tracers

This group had a lively conversation with hydrologic focus about the use of tracers and other methods to estimate residence times and flow paths in hydrologic systems. The age of water in streams was highlighted as a significant conceptual bridge from hydrology to long-term geochemical and landscape evolution processes. Discussion focused on two principal questions:

What catchment and climate properties impact surface water and groundwater residence time distributions?

Understanding residence time distributions is key because time is a master variable in CZ science. Determining controls over residence time is needed toward the goal of integrating knowledge across sites and getting beyond "place-based" science. This approach must account for the relative importance of geomorphology, vegetation type, rainfall regime, etc.

How can we assess residence times at point to catchment scale?

Approach: The first challenge this group identified was the need for coordination on methodologies used by the various CZO groups. This challenge can be divided into three categories. First, there is a need to coordinate between groups on the specific analytical techniques for chemical and isotopic tracers. This problem may be resolved by better communication among groups through a wiki or listserv approach. Second, specific sampling procedures (temporal, spatial and technical approaches) need to be discussed within the group. Some methods will be very site specific, but in order to do some types of analysis and comparison across sites there is a need to coordinate methodologies. One example would be an approach that uses very fine resolution temporal sampling of water isotopes in order to conduct transfer function residence time analysis. Stable isotopes, however, only give short term residence times, anything on the order of decades requires

tritium or another longer time-scale tracer. Third, there isa need for coordination and education on data analysis techniques across the CZO's. One component of low hanging fruit is a comparison of the sites using the water isotope transfer function approach to estimating residence time distributions. Another is the use of end member mixing analyses (EMMA) across the various CZO sites.

An additional technological component of low hanging fruit is the use of distributed temperature sensing (DTS, http://ctemps.org/) at the various field sites, since this could help to interpret moisture dynamics in a manner complementary to the isotopic tracer approach discussed above.

In the longer term, CZOs need to coordinate on observing residence times of waters within their catchment systems. Doing so could enable fundamental advances in understanding the effect of residence time and flowpath on critical zone structure and function. Coordinated modeling and identification of differences in recharge regimes across sites would yield important big science results that would also justify the CZO network.

Other themes discussed by this group included: (i) quantifying the space-time groundwater input to streams; (ii) the potential complementary utility of DTS (distributed temperature sensors), geophysical techniques, and dilution tracer experiments; (iii) determining the architecture of flowpaths within the basin systems; (iv) the need to sort research into "input questions", "output questions", and "time of storage questions".

Final CZO All Hands 2011 Workshop Schedule

Sunday, May 8th

6:30 PM – Icebreaker reception and dinner

8:00 PM – Keynote lecture introducing the theme of the workshop (Larry Band, UNC-Chapel Hill) *Climate, geomorphic and ecohydrologic controls of nitrogen cycling and export along a continental transect*

Monday, May 9th

Session 1 – Ecosystem Exchange and Hydrologic Partitioning (eddy covariance water and carbon flux measurements, ecosystem production and respiration, snow and rain partitioning, infiltration dynamics, evapotranspiration, ground water recharge)

8:00 AM: Introduction by session convener (Shirley Papuga)

8:05 AM: Keynote lecture (Russ Monson - UA) *Surface atmosphere fluxes of H_2O and CO_2 in the subalpine ecosystem critical zone* (25 min + 10 min discussion)

8:40 AM: Mike Goulden et al. (SS-CZO) *Relationships between elevation, photosynthesis and evapotranspiration in the Sierra CZO* (10 min + 5 min discussion)

8:55 AM: Greg Barron-Gafford et al. (JSC-CZO) *Sensitivity of soil CO_2 efflux to climatic and topographic factors in a montane drainage system* (10 min + 5 min discussion)

9:10 AM: Martha Scholl et al. (LM-CZO) *Use of stable isotopes to understand recharge sources and streamflow generation in the Luquillo Mountains, Puerto Rico* (10 min + 5 min discussion)

9:25 AM: Poster introductions (brief 2-min, 1 slide overviews of poster content; 15 posters ~ 35 min)

10:00 AM: Coffee break & poster session

11:00 AM: Rapporteur from SS CZO to summarize poster session and to lead plenary discussion

11:30 AM: Break for lunch

1:00 PM – 1:30 PM: X-CZO Data Management (Mark Williams)

1:30 PM - 3:00 PM: Biosphere 2 Tours

Session 2 – Subsurface Biogeochemistry (vadose/saturated zone mineral weathering processes, root and microbial dynamics, mineral/water and microbe/mineral interfacial processes, carbon sequestration, pedogenic element mass balance, topo-, litho-, chrono- and climo- sequences)

3:00 PM Introduction by session convener (Craig Rasmussen)

3:05 PM: Keynote lecture (Libby Hausrath - UNLV) *Biogeochemical weathering of serpentine minerals from bedrock to soil* (25 min + 10 min discussion)

3:40 PM: Chunmei Chen et al. (CR-CZO) *Elucidating the interaction between organic matter and mineral components along a pasture hillslope: Importance of iron-redox coupling processes* (10 min + 5 min discussion)

3:55 PM: Lixin Jin et al (SSH-CZO) *Water chemistry reflects hydrological controls on weathering in Susquehanna/Shale Hills CZO (Central Pennsylvania, USA)* (10 min + 5 min discussion)

4:10 PM: Eve-Lyn Hinckley (BC-CZO) et al. *Integrated study of critical zone architecture, near-surface hydrology, and biogeochemistry to understand the fate of N in montane catchments* (10 min + 5 min discussion)

4:25 PM: Poster introductions (brief 2-min, 1 slide overviews of poster content; 15 posters ~ 35 min)

5:00 PM: Beverage break & poster session

6:00 PM: Rapporteur from CRB-CZO to summarize poster session and to lead plenary discussion

6:30 PM: Break for dinner; JRB-SCM CZO overview with Jemez Basin Virtual Tour (Group)

Tuesday, May 10th

Tour of Santa Catalina Mountains CZO Buses leave Biosphere 2 at 7:00 am – Babad Doag Vista - Mt. Bigelow eddy covariance tower - Marshall Gulch catchment experiments

Wednesday, May 11th

7:45 Wireless Sensor Demonstration - B2 Lawn (Steve Glaser)

Session 3 – Ground and Surface Water Dynamics (hillslope and ground water hydrology, deep subsurface fluid flow, stream water response, hydrograph separation, end-member-mixing, catchment biogeochemistry, sediment transport)

8:30 AM: Introduction by session convener (Jen McIntosh)

8:35 AM: Keynote lecture (Kip Solomon, U. Utah) *Groundwater Surface Water Interactions: Historical Context and the Transit Time Distribution as a Unifying Theoretical Framework* (25 min + 10 min discussion)

9:10 AM: Marek Zreda et al. *COSMOS project*. (10 min + 5 min discussion)

9:25 AM: Louis Kaplan et al. (CR-CZO). *In-situ measurements of stream water organic carbon, nitrate, and suspended solids with a UV-VIS diode array spectrophotometer probe* (10 min + 5 min discussion)

9:40 AM: Peter Hartsough et al. (SS-CZO). *Soil moisture and tree water status dynamics in mixed-conifer forest, Southern Sierra CZO, CA* (10 min + 5 min discussion)

9:45 AM: Poster introductions (brief 2-min, 1 slide overviews of poster content; 15 posters ~ 35 min)

10:20 AM: Coffee break & poster session

11:30 AM: Rapporteur from SSH-CZO to summarize poster session and to lead plenary discussion

12:00 AM: Break for lunch (Steering Committee to meet with NSF and PIs)

1:30 PM – 2:30 PM: X-CZO Breakout Group Discussions Six or so X-CZO/X-disciplinary subgroups (ca. 15 people each): What is needed in a roadmap to a unified theory of critical zone structure, function and evolution?

Concurrent: Steering Committee to meet with NSF and PIs.

2:30 PM – 3:00 PM: Reporting back of subgroups (5 min each)

Session 4 – Critical Zone Evolution (geophysical characterizations of subsurface structure, landscape evolution over geologic time scales, valley density development, surficial erosion, soil production functions, flow path development, geomorphology)

3:00 PM Introduction by session convener (Jon Pelletier)

3:05 PM: Keynote lecture (Oliver Chadwick, UCSB) *Climate/weathering control on hillslope morphology in tectonically quiescent regions* (25 min + 10 min discussion)

3:40 PM: Douglas Jerolmack (LM-CZO) *Controls and feedbacks of particle size and mobility: Bringing down mountains one grain at a time* (10 min + 5 min discussion)

3:55 PM: Nicole West et al. (SSH-CZO) *Toward an understanding of landscape change in the Susquehanna Shale Hills CZO: Preliminary estimates of soil residence using* ^{10}*Be* (10 min + 5 min discussion)

4:10 PM: Bob Anderson et al. (BC-CZO) *Of damage zones, reactors and conveyor belts: a geomorphologist's view of the long-term evolution of the critical zone* (10 min + 5 min discussion)

4:25 PM: Poster introductions (brief 2-min, 1 slide overviews of poster content; 15 posters ~ 35 min)

5:00 PM: Beverage break & poster session

6:00 PM: Rapporteur from BC-CZO to summarize poster session and to lead plenary discussion

6:30 PM: Break for dinner; Landscape Evolution Overview (Steve DeLong)

8:30 PM: Closing lecture: *What have we learned?* (Ron Amundson, UCB)

Thursday, May 12th

Workshop to develop (i) questions, (ii) hypotheses, (iii) approaches, and (iv) methods for X-CZO network pursuit (open to all).
Concurrent Data Management Group breakout session.

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