

**Annual Report for Period:**09/2011 - 08/2012

**Submitted on:** 08/26/2012

**Principal Investigator:** Bales, Roger C.

**Award ID:** 0725097

**Organization:** U of Cal - Merced

**Submitted By:**

Bales, Roger - Principal Investigator

**Title:**

CZO: Critical Zone Observatory--Snowline Processes in the Southern Sierra Nevada

### Project Participants

#### Senior Personnel

**Name:** Bales, Roger

**Worked for more than 160 Hours:** Yes

**Contribution to Project:**

**Name:** Tague, Christina

**Worked for more than 160 Hours:** Yes

**Contribution to Project:**

Co-PI modeling water and nutrient cycles

**Name:** Conklin, Martha

**Worked for more than 160 Hours:** Yes

**Contribution to Project:**

Co-PI surface-groundwater interaction

**Name:** Glaser, Steven

**Worked for more than 160 Hours:** Yes

**Contribution to Project:**

**Name:** Riebe, Clifford

**Worked for more than 160 Hours:** Yes

**Contribution to Project:**

**Name:** Goulden, Mike

**Worked for more than 160 Hours:** Yes

**Contribution to Project:**

Flux tower Co-PI, CZO support.

**Name:** Johnson, Dale

**Worked for more than 160 Hours:** Yes

**Contribution to Project:**

Soil nutrients Co-PI. Soil carbon and nutrient analyses, nutrient fluxes, nutrient cycling.

**Name:** Molotch, Noah

**Worked for more than 160 Hours:** Yes

**Contribution to Project:**

Snow surveys and mapping

**Name:** Houlton, Ben

**Worked for more than 160 Hours:** Yes

**Contribution to Project:**

Nitrogen isotopes in streams - planning

**Name:** Hopmans, Jan

**Worked for more than 160 Hours:** Yes

**Contribution to Project:**

Co-PI for soil moisture

**Name:** Riebe, Clifford

**Worked for more than 160 Hours:** Yes

**Contribution to Project:**

Physical weathering rates

**Name:** Hart, Steven

**Worked for more than 160 Hours:** Yes

**Contribution to Project:**

Forest Ecology

**Name:** Berhe, Asmeret

**Worked for more than 160 Hours:** Yes

**Contribution to Project:**

Soil biogeochemistry

**Name:** Glaser, Steven

**Worked for more than 160 Hours:** Yes

**Contribution to Project:**

DUST wireless sensor networks

#### Post-doc

**Name:** Hartsough, Peter

**Worked for more than 160 Hours:** Yes

**Contribution to Project:**

Experimental design, implementation and ongoing maintenance

**Name:** Ray, Ram

**Worked for more than 160 Hours:** Yes

**Contribution to Project:**

Modeling

#### Graduate Student

**Name:** Malazian, Armen

**Worked for more than 160 Hours:** Yes

**Contribution to Project:**

Field installation and instrument calibration

**Name:** Palucis, Marisa

**Worked for more than 160 Hours:** Yes

**Contribution to Project:**

In preparation for Ph.D. qualifying exam, used stream and suction lysimeter data from the CZO to test a theoretical model for concentration-discharge relationships in porewaters and streams

**Name:** Alvarez, Otto

**Worked for more than 160 Hours:** No

**Contribution to Project:**

Data management

**Name:** Kelly, Anne

**Worked for more than 160 Hours:** Yes

**Contribution to Project:**

Evapotranspiration and water balance in forest

**Name:** Musselman, Keith

**Worked for more than 160 Hours:** Yes

**Contribution to Project:**

Snow surveys and mapping

**Name:** Kirchner, Peter

**Worked for more than 160 Hours:** Yes

**Contribution to Project:**

Water cycle, soil moisture

**Name:** Lucas, Ryan

**Worked for more than 160 Hours:** Yes

**Contribution to Project:**

Water cycle and meadow research

**Name:** Kamai, Timir

**Worked for more than 160 Hours:** No

**Contribution to Project:**

Datalogger programming and instrument calibration

**Name:** Swarowsky, Alex

**Worked for more than 160 Hours:** Yes

**Contribution to Project:**

Manufacture, calibration and installation of field instruments

**Name:** Kerkez, Branko

**Worked for more than 160 Hours:** Yes

**Contribution to Project:**

Installation, monitoring, and maintenance of DUST wireless network

**Name:** Fellows, Aaron

**Worked for more than 160 Hours:** No

**Contribution to Project:**

eddy-covariance tower field work

**Name:** Anderson, Ray

**Worked for more than 160 Hours:** No

**Contribution to Project:**

Eddy covariance tower field work

**Name:** Phelps, Gary

**Worked for more than 160 Hours:** No

**Contribution to Project:**

Website Manager

**Name:** Godsey, Sarah

**Worked for more than 160 Hours:** Yes

**Contribution to Project:**

geomorphology, the extensions and contraction of the stream network at the CZO in response to snowmelt

**Name:** Kandelous, Maziar

**Worked for more than 160 Hours:** Yes

**Contribution to Project:**

Field installation and lab calibration of soil moisture instruments

**Name:** Welch, Stephen

**Worked for more than 160 Hours:** Yes

**Contribution to Project:**

Wireless sensor network

**Name:** Hahm, Jesse

**Worked for more than 160 Hours:** Yes

**Contribution to Project:**

Geophysics

**Name:** Hayes, Jorden

**Worked for more than 160 Hours:** Yes

**Contribution to Project:**

Geophysics

**Name:** Zhang, Ziran

**Worked for more than 160 Hours:** Yes

**Contribution to Project:**

Wireless sensor network

#### Undergraduate Student

**Name:** Baumgartner, Thomas

**Worked for more than 160 Hours:** Yes

**Contribution to Project:**

Assisted with field installations

**Name:** Melendez, Denise

**Worked for more than 160 Hours:** Yes

**Contribution to Project:**

Assisted with field installations and data analysis

**Name:** Kelly, Sean

**Worked for more than 160 Hours:** Yes

**Contribution to Project:**

Field research and data analysis

**Name:** Rojas, Adrian

**Worked for more than 160 Hours:** Yes

**Contribution to Project:**

Field research and data analysis

**Name:** Loy, Garrett

**Worked for more than 160 Hours:** No

**Contribution to Project:**

Field research and data analysis

**Name:** Mckuin, Brandy

**Worked for more than 160 Hours:** No

**Contribution to Project:**

Field research and data analysis

**Name:** Pendleton, John-Marc

**Worked for more than 160 Hours:** No

**Contribution to Project:**



Field research and data analysis

**Name:** Xochihua, Ruth

**Worked for more than 160 Hours:** No

**Contribution to Project:**

Field research and data analysis

**Name:** Zumkehr, Andrew

**Worked for more than 160 Hours:** Yes

**Contribution to Project:**

Web site management

**Name:** Curtis, Chris

**Worked for more than 160 Hours:** Yes

**Contribution to Project:**

Field technician

**Name:** Roudeva, Katja

**Worked for more than 160 Hours:** No

**Contribution to Project:**

Field installation and lab calibration of soil moisture instruments.

**Name:** Ngo, Allen

**Worked for more than 160 Hours:** No

**Contribution to Project:**

Field installation and lab calibration of soil moisture instruments.

**Name:** Huynh, Sylvie

**Worked for more than 160 Hours:** Yes

**Contribution to Project:**

Field installation and lab calibration of soil moisture instruments.

**Name:** Hedge, Christine

**Worked for more than 160 Hours:** Yes

**Contribution to Project:**

Undergraduate summer intern for summer 2011.

**Name:** Cargill, Matt

**Worked for more than 160 Hours:** No

**Contribution to Project:**

Undergraduate student lab technician

**Name:** Corbiere, Rebecca

**Worked for more than 160 Hours:** No

**Contribution to Project:**

Undergraduate student lab technician

**Name:** Lester, Nichole

**Worked for more than 160 Hours:** No

**Contribution to Project:**

Undergraduate student lab technician

**Name:** O'Flannigan, Tracy

**Worked for more than 160 Hours:** No

**Contribution to Project:**

Undergraduate student lab technician

**Name:** White, William

**Worked for more than 160 Hours:** No

**Contribution to Project:**

Undergraduate student lab technician

**Name:** Hoang, Eric

**Worked for more than 160 Hours:** No

**Contribution to Project:**

Undergraduate student lab technician

**Name:** Roudneva, Ekaterina

**Worked for more than 160 Hours:** No

**Contribution to Project:**

Undergraduate research intern

**Name:** Hoang, Raymond

**Worked for more than 160 Hours:** No

**Contribution to Project:**

Undergraduate research intern

**Name:** Olderwald, Devin

**Worked for more than 160 Hours:** No

**Contribution to Project:**

Undergraduate research intern

**Name:** Schmidt, John

**Worked for more than 160 Hours:** No

**Contribution to Project:**

Undergraduate research intern

**Name:** Smith, Matt

**Worked for more than 160 Hours:** No

**Contribution to Project:**

Undergraduate research intern

**Technician, Programmer**

**Name:** Meadows, Matt

**Worked for more than 160 Hours:** Yes

**Contribution to Project:**

Research hydrologist in charge of continuing CZO field program

**Name:** Winston, Greg

**Worked for more than 160 Hours:** Yes

**Contribution to Project:**

Flux tower instrumentation

**Name:** Liu, Fengjing

**Worked for more than 160 Hours:** Yes

**Contribution to Project:**

Geochemical analysis

**Name:** Tuli, Atac

**Worked for more than 160 Hours:** No

**Contribution to Project:**

Field installation of soil moisture instrumentation

**Name:** Meng, Xiande

**Worked for more than 160 Hours:** Yes

**Contribution to Project:**

Data management

**Name:** Nasta, Paolo

**Worked for more than 160 Hours:** Yes

**Contribution to Project:**

Field installation and lab calibration of soil moisture instruments.

**Name:** Kluitenberg, Gerard

**Worked for more than 160 Hours:** No

**Contribution to Project:**

Field installation and lab calibration of soil moisture instruments.

**Name:** Saintnoy, Albane

**Worked for more than 160 Hours:** No

**Contribution to Project:**

Field installation and lab calibration of soil moisture instruments.

**Name:** Smith, Allyson

**Worked for more than 160 Hours:** No

**Contribution to Project:**

Project management, education and outreach coordinator

**Name:** Smith, Jason

**Worked for more than 160 Hours:** Yes

**Contribution to Project:**

Field hydrology technician, data management

**Name:** Lam, Lawrence

**Worked for more than 160 Hours:** No

**Contribution to Project:**

Website development and management.

## Other Participant

### Research Experience for Undergraduates

**Name:** Holling, Timothy

**Worked for more than 160 Hours:** No

**Contribution to Project:**

Undergraduate research project (Summer 2009)

**Years of schooling completed:** Junior

**Home Institution:** Other than Research Site

**Home Institution if Other:** California State University, Stanislaus

**Home Institution Highest Degree Granted(in fields supported by NSF):** Master's Degree

**Fiscal year(s) REU Participant supported:** 2009

**REU Funding:** No Info

### Organizational Partners

#### Pacific SW Research Station, USFS

The CZO is located at the Kings River Experimental watersheds, a set of research catchments operated by the Pacific Southwest Research Station (PSW), U.S. Forest Service.

## **Lawrence Livermore National Laboratory**

Jean Moran and Brad Esser collected samples for isotope analysis as part of the meadow experiment in summer 2008. Initial analysis has been completed; further sampling and analysis may be conducted in order to obtain adequate data for collaboration on papers.

### **Other Collaborators or Contacts**

The Center for Information Technology Research in the Interest of Society (CITRIS) is an interdisciplinary, and inter-campus collaboration between UC Berkley, Davis, Merced and Santa Cruz. Participants from this collaboration assist with installation, maintenance, and utilization of the Dust Networks wireless sensor platform in the P301 ground-based water balance instrumentation. Additional collaborators include Steve Glaser and the Civil Systems group at UC Berkeley.

Decagon Inc. Contact: Colin Campbell

Scott Tyler, UNR; summer 2008 deployed DTS system for meadow water cycle experiment, has provide input and insight on meadow deployment data processing and interpretation.

Crossbow Technologies; deployed a prototype wireless sensor network system in Wolverton.

### **Activities and Findings**

#### **Research and Education Activities: (See PDF version submitted by PI at the end of the report)**

See attached

#### **Findings: (See PDF version submitted by PI at the end of the report)**

See attached

#### **Training and Development:**

We have developed an instrument clusters for mountain water cycle measurements, which is a great learning experience for all. This sort of integrated measurement network across a catchment has not been done before in the mountains of the Western U.S., at the rain-snow transition. In fact, it has not been done before in a forest away from AC power, and is currently the largest such network we are aware of. Students, postdocs and research scientists are learning strategies that will need to be replicated much more widely in the future.

#### **Outreach Activities:**

The educational mission of the Southern Sierra CZO is to put CZO research in a spatial and temporal context by communicating with the public, stakeholders and peers to improve the understanding between the Sierra Nevada snowpack and state water resources in California. The CZO accomplishes this mission through K-12 partnerships, undergraduate experiences, communicating with peers, stakeholder education, and media projects.

Some of the most successful education and outreach activities over the past 4 years include building relationships with schools and local organizations. Colleagues and staff began working with Naturebridge at Yosemite (NB-Y) in 2009 to provide instructor trainings on hydrologic concepts and snowpack science. Each year, NB-Y instructors facilitate outdoor field experiences for thousands of students in Yosemite National Park. This coming school year (2012-2013) we will provide speakers for their instructor in-services focusing on CZO topics. Other K-12 partnerships include presenting each year at Southern California Edison's Science Days and the American Association of University Girls Science Camp. At these events CZO colleagues

facilitate hands on activities for students that focus on how Sierra Nevada hydrology impacts California's water resources. One most recent K-12 partnership is with The Center for Advanced Research and Technology (CART) in Clovis, CA, where CZO staff work with teams of CART students to conduct a comprehensive snow survey research project.

Since 2007, CZO colleagues have been providing opportunities for undergraduate students. Undergraduates from UCM and partnering universities have worked as field and lab technicians. The CZO summer undergraduate research intern program has given students the chance to apply their knowledge of scientific concepts. In addition to research interns, the CZO has developed field methods courses for undergraduates at UCM and UCD. A major component of these courses is visiting the CZO to learn about research and to collect data for use in class.

In cooperation with the US Forest Service Sierra National Forest, the Dinkey Collaborative Forest Landscape Restoration Project is an ongoing effort to collaborate on Forest Service projects as part of the Forest Landscape Restoration Act. Dinkey creek is located next to the CZO; Matt Meadows is a member of the group who represents CZO interests in land management projects.

This fall, SSCZO presented over 20 talks and posters during the American Geophysical Union's (AGU) meeting held this past December in San Francisco, CA. Data were presented by numerous PIs, graduate students, and research staff. The national CZO program was an exhibitor throughout the duration of the conference, providing information on all CZO sites.

Communicating research to stakeholders, the general public and peers is also an important outreach goal of the Southern Sierra CZO. Presentations at AGU provide an outlet for CZO colleagues to share their research with peers, meet and connect with people from the Southern Sierra and other CZOs. Colleagues also present at other national meetings, provide seminars for universities, and give talks to stakeholders and the general public. Facilitating field trips to the CZO such as the July 2011 Sierra Nevada Adaptive Management Project (SNAMP) allows stakeholders and the public to see the cutting edge research being conducted at the CZO. Additionally, in August 2011, California Senator Barbara Boxer toured UC Merced and learned about CZO research. CZO research has also been communicated to the general public through various media outlets from National Public Radio, PBS, the University of California Research, Portuguese public television, TV news, print and internet newspaper interviews.

Bibliography of talks, presentations and field trips incorporating topics relevant to the SSCZO  
2012

Bales, R. C. Forests and Water in the Sierra Nevada, El Dorado county Board of Supervisors, March 20, 2012.

Bales, R. C. Snowpack, climate change & water balance in a Sierra Nevada forest, Caltech, Jan 11, 2012.

Conklin, M. H. and Smith, A. S. Environmental engineering and water resources in the Southern Sierras. Presentation and activity for

American Association of University Women Girl's Science Camp - Engineering Day. UC Merced. January 2012.

Meadows, M. and Smith, A. S. Center for Advanced Research and Technology (CART) talks and student mentoring. September 2011-March 2012.

Smith, A. S., Meadows, M., and Hoang, R. The Hydrologic Cycle in and around the Critical Zone Tree. Southern California Edison's Science Days. Shaver Lake, CA. May and June, 2012.

Smith, A. S. The Southern Sierra Critical Zone Observatory. Talk presented to Golden Valley High School AP Environmental Science class. March, 2012.

2011

Bales, R. C. The California mountain water cycle: knowns & unknowns, NAE Regional meeting, UC Berkeley, March 31, 2011

Bales, R. C. Snowpack, soil moisture & water balance across the rain-snow transition in a Sierra-Nevada mixed-conifer forest. UC Berkley Seminar. January, 2011.

Bales, R. C. Sierra Nevada snowpack, climate change & water management. University of Utah Seminar. January 2011.

Conklin, M. H. California's water cycle: climate & snowpack. Talk presented at the Yosemite Institute Board Meeting. January 2011.

Conklin, M. H. and Smith, A. S. Environmental engineering and water resources in the Southern Sierras. Presentation and activity for American Association of University Women Girl's Science Camp - Engineering Day. UC Merced. January 2011.

Meadows, M. Southern Sierra Critical Zone Observatory: Integrating measurements for advances in hydrology & geochemistry. Reedley College, Watershed Ecology class guest speaker. February 2011.

Meadows, M., Smith, A. S., and Ghanbari, R. Bryant Middle School AVID (Advancement Via Individual Determination) UC Merced campus visit. February 2011.

R.G. Lucas; M.H. Conklin; S.W. Tyler; F.I. Suarez; J.E. Moran; B.K. Esser, 'Polymictic pool behavior in Sierra Nevada Streams', (2011). UC Merced Research Week. Graduate Student Poster Session.

Lucas, R. Climate Change and Water in California. Talk presented to the California Institute for Biodiversity Cal Alive Sierra Nevada Institute Encore Day. February and June 2011.

Rice, R. Mountain Hydrology and the Changing Climate: Measurements and Teaching Techniques. Talk presented at the Yosemite Institute instructor in-service day. February 2011.

Rice, R. Snow and climate in the Sierra Nevada. Talk and field day presented to Mariposa Middle School 8th grade class incorporating

manual and automated snow measurement techniques. February 2011.

Riebe, C.S. 'World Water Crisis' presentation to Good Mule Conference, Train Depot, Laramie, Wyoming. February 2011.

Smith, A. S., Meadows, M., and Hedge, C. How SSCZO Researchers Measure Parts of the Hydrologic Cycle in the Southern Sierra Nevada. Southern California Edison's Science Days. Shaver Lake, CA. May and June, 2011.

## 2010

Bales, R. C. Mountain Water Cycles and Instrumentation. Talk presented to the Sierra Nevada Alliance. April 2010.

Conklin, M. H. Groundwater Resources Presentation. Presentation and activity for American Association of University Women Girl's Science Camp - Engineering Day. UC Merced. January 2010.

Hopmans J.W. The California Critical Zone Observatory (CZO). Spring Hydrology Seminar, Institute for Water and Watersheds, Oregon State University. May, 2010.

Hopmans, J.W. Measurements and Modeling of Tree Hydrology Across Rain-to-Snow Transition in the Kings River Experimental Watershed, CA. Civil Engineering Seminar Series. University of California Irvine. March, 2010.

Kirchner, P. B. Interview featured in 'Clue Into Climate, Snow-Pack' internet video featured on KQED education network, science ready to explore. <http://www.kqed.org/education/educators/clue-into-climate/water-cycle.jsp>

Kirchner, P. B. Presentation of climate change impacts on snow and implications for the water resources of central California, Merced River Fair, Riverdance Farm, June, 2010.

Kirchner, P. B. Presentation of Critical Zone Observatory research to University of California, Merced Board of Trustees, February 2010.

Lucas, R. Climate Change: Central Valley Impacts and Implications. Talk presented to Great Valley Center's Institute for Emerging Area Leaders. April 2010.

Lucas, R. Climate Change: A Global Phenomenon with Local Implications. Talk presented to the Central Valley Air Quality Coalition. January 2010.

Lucas, R. Studying Water Processes in the Sierra Nevada. Talk presented to the Great Modesto Area Partners in Science. April 2010.

Lucas, R. Water Crisis: Where are We Headed? Talk presented to the University Friends Circle. March 2010.

Meadows, M. and Sullivan, L. Yosemite Institute hydrology curriculum development day. October 2010.

## 2009

Bales, R. C. California's water cycle: climate, snowpack & forest management. California Licensed Foresters Association annual meeting. Sacramento. March 2009.

Conklin, M. H. and Kirchner, P. B. Interviews featured in 'California at the Tipping Point' KQED Quest public television documentary on climate change science and California, first aired in April, 2009.  
<http://www.kqed.org/quest/television/climate-watch-california-at-the-tipping-point-part-one>

Lucas, R. Critical Zone Observatory ? Researching Hydrologic Processes in the Southern Sierra Nevada. Talk and symposium presented at the American Geophysical Union, Geoscience Information For Teachers. December 2009.

Kirchner, P. B. Environmental Monitoring for Hydrologic Resources; a look into the future. Presentation at the Geophysical Information for Teachers (GIFT) workshop, American Geophysical Union. San Francisco. December 2009.

Kirchner, P. B. Eastern Sierra Roadside Heritage project, Snow and Ice in the Sierra Nevada, NSF funded video interview and middle school outreach. September 2009. <http://www.roadsideheritage.org/index.html>

Lucas, R. Climate Change Implications to the Sierra Nevada and the Central Valley Presentation and Panel Member. Sacramento Valley Forum. October 2009.

Lucas, R. Critical Zone Observatory ? Researching Hydrologic Processes in the Southern Sierra Nevada. Talk presented to Merced High School District Excellence in Science. November 2009.

Meadows, M. Southern Sierra Critical Zone Observatory: Integrating measurements for advances in hydrology & geochemistry. Reedley College, NR12 Watershed Ecology class guest speaker. February 2009.

Tague, C. Modeling eco-hydrology under a changing climate, how much do subsurface drainage patterns matter? Berkeley Catchment Science Symposium. Berkeley, CA. December, 2009.

2008

Bales, R. C. Integrating measurements of snowpack, soil moisture, ET& streamflow for understanding the Sierra Nevada water balance. Yosemite Hydroclimate Meeting. October 2008.

Bales, R. C. Hydroclimate, ecosystem links & the Southern Sierra Critical Zone Observatory. Southern Sierra Science Symposium. Visalia, CA. Sept 2008.

Bales, R. C. Sierra Nevada snowcover patterns & watershed processes. Seminar presented at Oregon State University. April 2008.

Bales, R. C. California water, mountain hydrology, & UC Merced. Talk at UC-WRRC synthesis meeting. Woodlake, CA. April, 2008.



Conklin, M. H. and Kirchner, P. B. Interviews featured in 'California Heat' a KVIE View Finder public television documentary on climate change impacts in California, first aired in October 2008.  
[http://www.kvie.org/programs/kvie/viewfinder/california\\_heat/default.htm](http://www.kvie.org/programs/kvie/viewfinder/california_heat/default.htm)

Meadows, M. Sierra Nevada Research Institute: research update. Invited Presentation. California Cooperative Snow Survey Meeting, Bass Lake, CA. November, 2008.

Meadows, M. Southern Sierra Critical Zone Observatory: Integrating measurements for advances in hydrology and geochemistry. Invited Presentation. Society of American Foresters, High Sierra Chapter Meeting. October, 2008.

### **Journal Publications**

Johnson, D.W., W.W. Miller, R.B. Susfalk, R.A. Dahlgren, and D.W. Glass, "Biogeochemical Cycling in Forest Soils of the Eastern Sierra Nevada Mountains", *Forest Ecology and Management*, p. , vol. , (2009). Published, 10.1016/j.foreco.2009.01.018

Anderson, S. A.; R. C. Bales; C. J. Duffy, "Critical Zone Observatories: Building a network to advance interdisciplinary study of Earth surface processes", *Mineralogical Magazine*, p. 7, vol. 72(1), (2008). Published,

Hunsaker, C.T., Whitaker, T., Bales, R.C., "Water yield and runoff timing across the rain-snow transition in California's southern Sierra Nevada", submitted, p. , vol. , (2010). Submitted,

Johnson, D. W., Glass, D. W., Murphy, J. D., Stein, C. M., Miller, W. W., "Hot Spots and Hot Moments: Another Look at Nutrient Variability in Sierra Nevada Forest Soils", *Biogeochemistry*, p. , vol. , (2010). Accepted,

Kerkez, B., Glaser, S.D., Dracup, J.A., Bales, R.C., "A hybrid system model of seasonal snowpack water balance", *International Conference on Hybrid Systems: Computation and Control*, p. , vol. , (2010). Published,

Lui, F., Hunsaker, C.T., Bales, R.B., "Controls of streamflow pathways in small catchments across the snow-rain transition in the Southern Sierra, California", submitted, p. , vol. , (2012). Published, 10.1002/hyp.9304

Tague, C., "Assessing climate change impacts on alpine stream-flow and vegetation water use: mining the linkages with subsurface hydrologic processes", *Hydrological Processes*, p. 1815, vol. 23, (2009). Published, DOI: 10.1002/hyp.7288

Kizito, F; Campbell, CS; Campbell, GS; Cobos, DR; Teare, BL; Carter, B; Hopmans, JW, "Frequency, electrical conductivity and temperature analysis of a low-cost capacitance soil moisture sensor", *JOURNAL OF HYDROLOGY*, p. 367, vol. 352, (2008). Published, 10.1016/j.jhydrol.2008.01.02

Kerkez, B., Glaser, S.D., and Bales, R.C., "Wireless Sensor Networks for of Hydrologic Measurements: Performance Evaluation and Design Methods", *Water Resources Research*, p. , vol. , (2011). Submitted,

Fengjing Liu, Martha H. Conklin, Mark E. Conrad, and Glenn Shaw, "Determination of meteoric water contributions from lower and higher elevations to streamflow in the Upper Merced River, Sierra Nevada, California", *Journal*, p. , vol. , (2011). Submitted,

Johnson, D. W., D.W. Glass, J.D. Murphy, C.M. Stein, and W.W. Miller, "Nutrient hot spots in some Sierra Nevada forest soils", *Biogeochemistry*, p. 93, vol. 101, (2010). Published, 10.1007/s10533-010-9423-8

Granger, D. E., and Riebe, C. S., "Cosmogenic Nuclides in Weathering and Erosion", *Treatise on Geochemistry*, Volume 5. 2nd edition, p. , vol. , (2011). Submitted,

Kerkez B., Glaser S., Bales R., "Sensor Placement and Sampling Methods for Measurement of Hydrologic Phenomena", Water Resources Research, p. , vol. , (2011). Submitted,

Lin, H; Hopmans, JW; Richter, DD, "Interdisciplinary Sciences in a Global Network of Critical Zone Observatories", VADOSE ZONE JOURNAL, p. 781, vol. 10, (2011). Published, 10.2136/vzj2011.008

Bales, RC; Hopmans, JW; O'Geen, AT; Meadows, M; Hartsough, PC; Kirchner, P; Hunsaker, CT; Beaudette, D, "Soil Moisture Response to Snowmelt and Rainfall in a Sierra Nevada Mixed-Conifer Forest", VADOSE ZONE JOURNAL, p. 786, vol. 10, (2011). Published, 10.2136/vzj2011.000

Malazian, A; Hartsough, P; Kamai, T; Campbell, GS; Cobos, DR; Hopmans, JW, "Evaluation of MPS-1 soil water potential sensor", JOURNAL OF HYDROLOGY, p. 126, vol. 402, (2011). Published, 10.1016/j.jhydrol.2011.03.00

Nasta, P; Huynh, S; Hopmans, JW, "Simplified Multistep Outflow Method to Estimate Unsaturated Hydraulic Functions for Coarse-Textured Soils", SOIL SCIENCE SOCIETY OF AMERICA JOURNAL, p. 418, vol. 75, (2011). Published, 10.2136/sssaj2010.011

Johnson, DW; Hunsaker, CT; Glass, DW; Rau, BM; Roath, BA, "Carbon and nutrient contents in soils from the Kings River Experimental Watersheds, Sierra Nevada Mountains, California", GEODERMA, p. 490, vol. 160, (2011). Published, 10.1016/j.geoderma.2010.10.01

Johnson, DW; Miller, WW; Rau, BM; Meadows, MW, "The Nature and Potential Causes of Nutrient Hotspots in a Sierra Nevada Forest Soil", SOIL SCIENCE, p. 596, vol. 176, (2011). Published, 10.1097/SS.0b013e31823120a

Jessup, BS; Hahm, WJ; Miller, SN; Kirchner, JW; Riebe, CS, "Landscape response to tipping points in granite weathering: The case of stepped topography in the Southern Sierra Critical Zone Observatory", APPLIED GEOCHEMISTRY, p. S48, vol. 26, (2011). Published, 10.1016/j.apgeochem.2011.03.02

Brantley, SL; Megonigal, JP; Scatena, FN; Balogh-Brunstad, Z; Barnes, RT; Bruns, MA; Van Cappellen, P; Dontsova, K; Hartnett, HE; Hartshorn, AS; Heimsath, A; Herndon, E; Jin, L; Keller, CK; Leake, JR; McDowell, WH; Meinzer, FC; Mozdzer, TJ; Petsch, S; Pet, "Twelve testable hypotheses on the geobiology of weathering", GEOBIOLOGY, p. 140, vol. 9, (2011). Published, 10.1111/j.1472-4669.2010.00264.

Ferrier, KL; Kirchner, JW; Riebe, CS; Finkel, RC, "Mineral-specific chemical weathering rates over millennial timescales: Measurements at Rio Icacos, Puerto Rico", CHEMICAL GEOLOGY, p. 101, vol. 277, (2010). Published, 10.1016/j.chemgeo.2010.07.01

Stephen C. Welch, Branko Kerkez, Roger C. Bales, Steve Glaser, Karl Rittger, and Robert Rice, "Sensor Placement Strategies for SWE Estimation in the American River Basin", WRR, p. , vol. , (2012). Submitted,

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M.H. Conklin; R.G. Lucas, "Hillslope and stream connections to water tables in montane meadows of the southern Sierra Nevada, California", (2011). Conference presentation, Published Bibliography: AGU Abstract H43N-07

R.G. Lucas; M.H. Conklin; S.W. Tyler; F.I. Suarez; J.E. Moran; B.K. Esser, "Physical and biogeochemical controls on polymictic Behavior in Sierra Nevada stream pools.", (2011). Conference presentation, Published Bibliography: AGU Abstract H51B-1209

R.G. Lucas; M.H. Conklin; S.W. Tyler; F.I. Suarez; J.E. Moran; B.K. Esser, "Physical and biogeochemical controls on polymictic

Behavior in Sierra Nevada stream pools.", (2011). Conference presentation, Published  
Bibliography: AGU Abstract H51B-1209

### **Web/Internet Site**

**URL(s):**

<https://czo.ucmerced.edu/>

**Description:**

### **Other Specific Products**

**Product Type:**

**Instruments or equipment developed**

**Product Description:**

System and method for measuring water fluxes and partitioning across a landscape. Disclosure & patent application filed; pending. Will be included on UC Merced's report to federal government in June 2011.

**Sharing Information:**

Scalable water-balance instrument cluster.

### **Contributions**

**Contributions within Discipline:**

The CZO provides a multi-disciplinary platform for research. Most of the CZO data are available to the community, and other data to CZO cooperators who agree to data-sharing protocols.

**Contributions to Other Disciplines:**

The CZO fosters multi-disciplinary research. The site is also a candidate for a NEON investment, which could significantly enhance some of our CZO activities.

**Contributions to Human Resource Development:**

Several graduate students, undergraduates and recent Ph.D. graduates are involved with the CZO, and are preparing themselves for independent measurement and data analysis work in field hydrology and modeling.

**Contributions to Resources for Research and Education:**

The CZO is a research platform, i.e. infrastructure for multidisciplinary research.

**Contributions Beyond Science and Engineering:**

The high profile of our CZO helps communicate water and other critical zone issues to the public, and helps educate agencies about the need to modernize measurement and decision-making infrastructure.

### **Conference Proceedings**

Kerkez, B;Glaser, SD;Dracup, JA;Bales, RC, A Hybrid System Model of Seasonal Snowpack Water Balance, "APR 12-15, 2010", HSSC 10: PROCEEDINGS OF THE 13TH ACM INTERNATIONAL CONFERENCE ON HYBRID SYSTEMS: COMPUTATION AND CONTROL, : 171-180 2010

Anderson, SP;Bales, RC;Duffy, CJ, Critical Zone Observatories: Building a network to advance interdisciplinary study of Earth surface processes, "AUG 18-22, 2008", MINERALOGICAL MAGAZINE, 72 (1): 7-10 FEB 2008

Johnson, DW;Glass, DW;Murphy, JD;Stein, CM;Miller, WW, Nutrient hot spots in some sierra Nevada forest soils, "JUN 29-JUL 03, 2009", BIOGEOCHEMISTRY, 101 (1-3): 93-103 DEC 2010

**Special Requirements**

**Special reporting requirements:** None

**Change in Objectives or Scope:** None

**Animal, Human Subjects, Biohazards:** None

**Categories for which nothing is reported:**

**Southern Sierra Critical Zone Observatory  
Work Plan, updated October 8, 2010**

Contents

Core CZO measurements, data management and integration .....	2
KREW measurements and data management .....	3
Modeling of water and nutrient cycles.....	3
Near-surface soil-water processes .....	6
Physical controls on water and carbon exchange and plant production .....	15
Surface-groundwater interactions .....	17
Spatial variability in the KREW watershed: Effects on nutrient cycling and water quality.....	18
Nitrogen fluxes from soil.....	24
Baseline hydrologic, sediment and geochemical characterization.....	25
Water, geochemical cycles, and upscaling of in-situ measurements .....	26
Physical erosion and chemical weathering .....	28
Physical weathering rates .....	28
Snow processes.....	34
Biogeochemical processes/cycling .....	34

Topic. **Core CZO measurements, data management and integration**

*Updated 2010*

Investigator. **Roger Bales & Martha Conklin**

Students & research staff. **Matt Meadows, UG assistant, Xiande Meng, Communications Assistant.**

Scope.

**Field installations & support.** Core measurements made by the CZO team compliment those done by the KREW team. One focus is the water balance instrument cluster, which is anchored by an eddy-correlation flux tower but with ground measurements extending 1-2 km from the tower. The flux tower will provide point measurements of water, energy and carbon exchange with the atmosphere, which will be extended outward using the meteorological, snow/soil, remotely sensed and other spatial data. The proposed instrument cluster will include three embedded sensor networks, one located in the vicinity of the tower, one at a lower elevation with cold-season precipitation a mix of rain and snow lower met station vicinity) and one at a higher snow-dominated elevation upper met station vicinity). Measurements that are part of the instrument clusters include: snow depth, air temperature, solar radiation (open and under canopy), reflected radiation, soil moisture, temperature and matric potential (multiple depths), sap flow. Across the meadow and stream sections it is planned to measure water level, temperature, electrical conductivity in piezometers. Measurements on the tower include wind speed and direction, atmospheric water vapor flux, CO<sub>2</sub> flux, shortwave and longwave radiation (incoming/outgoing), precipitation, relative humidity, barometric pressure.

**Data management.** CZO data are archived in a digital library:

<https://eng.ucmerced.edu/snsjho>.

**Public Education & outreach.** We regularly (at least monthly) give talks across the region, to stakeholders with an interest in the Sierra Nevada and its resources. We attend other planning meetings related to resource management, where CZO knowledge may be applied.

**K-12 Education and outreach.** One focus is on training instructors of the Yosemite Institute (YI) in critical zone processes, with a particular focus on mountain hydrology. We will focus on activities that stress the mountain water cycle, the role of the Sierra Nevada snowpacks to CA water supply and their vulnerability of the snow to climate change.

**University education.** We plan to develop at least three university earth science “case studies” using data and observations obtained from the CZO. One module will combine a basic energy balance with state of the art technology, Raman-backscatter distributed temperature sensing, in a montane stream. Concepts to be stressed include the spatial heterogeneity of the stream as well as the role of obtaining system “snapshots” in time. These case studies will provide teaching notes for educators and will be posted on the CZO website; we will also post them on websites provided by professional organizations. These case studies will seek to provide earth science educators and students with current, peer-reviewed material.

**CZO integration.** The core office will also maintain a web site to facilitate project communications, organize an annual meeting of Southern Sierra CZO investigators,

maintain communication with PSW, communicate with the press and stakeholders, represent the CZO at professional meetings (when invited), and coordinate with NSF, the other CZO's and the CZO steering committee.

**Funding.** Largely CZO.

Schedule, including field work. Ongoing

Manuscripts in progress & planned. TBD

**Topic. Core KREW measurements and data management**

*Updated 2008*

**Investigator. Carolyn Hunsaker**

**Students & research staff. Tom Whitaker, field hydrologist**

**Scope.** PSW has agreed to share basic, relevant data with the CZO team and science community. Data that PSW is developing include: stream stage & discharge, meteorology, stream channel characteristics, stream condition inventory, stream physical habitat (macroinvertebrates), erosion & sedimentation, geology, soils & litter, shallow soil water chemistry, snowmelt & rain chemistry, streamwater chemistry, riparian & upland vegetation, fuel loading, algae & periphyton.

Schedule, including field work. Ongoing

Manuscripts in progress & planned. See below.

**Topic. Modeling of water and nutrient cycles**

*Updated 2008*

**Investigator. Christina Tague**

**Students & research staff. Kyongho Son**

**Scope.** Modeling will be carried out using RHESSys, a spatially distributed, dynamic model of coupled eco-hydrologic processes. Included in the model are mechanistic representations of vertical hydrologic processes (interception, soil and litter evaporation, canopy transpiration, infiltration, vertical drainage); lateral redistribution of moisture and nutrients and streamflow production; and soil and vegetation carbon and nitrogen cycling (<http://fiesta.bren.ucsb.edu/~rhessys/>). The CZO provides an opportunity to better integrate field measurements and analysis within a spatial modeling framework. My broad general goals are to collaborate with other CZO scientists and use the model to: i) contribute to the site selection of new monitoring locations by using the model to develop hypothesis about where significant gradients in response variables are likely to occur, ii) contribute to the spatial scaling of measurements by estimating spatial patterns of response variables, and iii) estimate response variables for a range of climate and land-cover scenarios. It will be very important to use field measurement to try to improve the model by: i) reducing uncertainty in model inputs and parameters, ii) contributing to quantification of model uncertainty, and iii) refining where necessary model structure (or representation of specific hydrologic and biogeochemical cycling



processes) The general approach will begin with looking at streamflow hydrology, followed by eco-hydrologic processes (e.g. transpiration) and then finally carbon and nitrogen cycling. Initial work will use the model as is - later work will incorporate measured data to try to improve model performance.

**Heterogeneity and spatial resolution.** At what spatial resolution must we resolve heterogeneity in snow accumulation and melt in order to capture streamflow responses to climate variation and differences in streamflow responses between study watersheds? The first step is to calibrate RHESSys using currently available inputs: DEM, basic vegetation and soils map, meteorological station data, to predict streamflow and variation in streamflow between the 4 instrumented watersheds. I will use GLUE type Monte-Carlo approaches for calibration and generate uncertainty bounds around streamflow predictions. I will also use some non-traditional streamflow metrics to try to better constrain model parameters, considering both peak and low flow metrics and year-to-year variation in these. I will also compare model estimates of ET, and storage discharge relationships with those derived by Jim using his hydrograph recession analysis techniques. I will repeat this model analysis using different model resolutions. Ideally it would also be useful to include estimate of very fine (meter) scale heterogeneity in snow cover and melt rates. The goal here is to examine sensitivity of streamflow predictions to modeling unit resolution and incorporation of variance within finest scale model units.

**Streamflow and climate.** What is the relationship between modeled streamflow and climate in site watersheds? How will streamflow in these watershed change under a warmer climate? Using the calibrated model of streamflow from above, we will estimate streamflow behavior under a range of climate conditions. Empirical analysis of streamflow data (in progress by Tom Whitaker) can provide a baseline analysis of climate-streamflow relationships. I will compare model predictions to this baseline analysis and highlight model weaknesses. If model performance is adequate, I will then use the model to estimate streamflow behavior under a warmer climate – initially using uniform increases in temperature (based on projections for California). Ideally it would be useful to also drive the model with downscaled GCM data.

**Spatial properties of vegetation.** How well does current model predict spatial patterns of vegetation LAI throughout the watersheds? As a carbon cycling model, RHESSys can be used to predict spatial patterns of vegetation leaf, stem and root carbon stores. Evaluation of model performance will help to determine where additional data must be incorporated to come up with reasonable estimates of vegetation productivity. Ancillary data such as remote sensing derived maps of canopy cover, for example, can be useful in estimating where soil depth is sufficient to support vegetation (something that must currently be prescribed in the model). LAI data for comparison can be derived from remote sensing data. It may also be useful to compare model predictions with vegetation surveys by the KREW team.

**Spatial variability in ET.** How does the modeled relationship between climate and evapotranspiration vary spatially within study watersheds? How well does model capture seasonal and spatial variation in vegetation water use evident from sap flow sensor measurement? I will use the model calibrated using streamflow, with any improvements associated with LAI comparison above, to estimate spatial patterns of ET and their relationships with peak annual SWE and growing season temperature. Results

from this analysis could be used to plan additional instrumentation associated with vegetation water use. There should also be a linkage with spatial soil moisture and sap flow.

**Nutrient export.** How well does RHESSys modeling capture streamflow nitrate export signatures, including seasonal patterns and differences between the watersheds? Can these signatures be used to better constrain model hydrologic parameters? Given that these are fairly “clean” streams this question may not be that informative but is needed as a baseline model run. There may be other tracers that can be used as part of biogeochemical calibration? Explore this with Fengjing and Carolyn, who are working on 3 papers.

**Biogeochemical stores and fluxes.** How well does the current model predict dynamics evident in plot scale measurements of biogeochemical stores and fluxes including plot sampling of soil carbon and nitrogen stores, flux tower estimates of NEP and ET etc. Note that it is unlikely that a model that is parameterized based on fairly coarse-scale data (10-m DEM etc.) will be able to accurately estimate point scale measurements of something like soil decomposition rates or soil moisture. There are several options – if there are sufficient, and stratified, samples – then comparison between sample means and modeled data may be reasonable. Alternatively, we can use intensively monitored sites to fully parameterize the model – and test whether, given these parameters the model performs as expected. For example, do equations used to estimate decomposition rates perform well if we assign temperature, moisture and soil carbon and nitrogen stores. Any adjustments based on this detailed analysis can then be incorporated in the model and would improve larger (watershed) scale distributed estimates. Suggestions from ecologically oriented Co-PIs on how this might best be done welcome.

**Spatial patterns and aggregation of biogeochemical fluxes.** Given model estimates of spatial patterns of these biogeochemical fluxes (NPP, NEP, Nexport, nitrification/denitrification) how representative (in a spatial sense) are these plot measurements likely to be – how reflective are they of basin scale aggregate carbon and nitrogen fluxes. How do model estimates of aggregate basin and spatial patterns of biogeochemical fluxes (nitrate export, carbon sequestration) change as assumptions about vertical and lateral hydrologic connectivity change? This final question is I think in many ways the most interesting one from a modeling perspective and will be the place where we can use model-measurement relationships to try to say something about the role of flowpaths, macropores, upland-riparian connectivity etc. . Understanding the hydrologic function of the subsurface critical zone is a key challenge – the model provides a mechanistic way of exploring the implications of different conceptual and quantitative models of subsurface hydrology. Measured data can be used to try to suggest which of these different models is realistic.

**Funding.** Largely CZO.

Schedule, including field work. The first 2 tasks are for year 1.

Manuscripts in progress & planned. Tasks 1-2 will yield 2 manuscripts. The main data sets needed for tasks 1-2 are the streamflow and meteorological data from KREW, the GIS data and soils information.

Topic: Near-surface soil-water processes

*Updated 2010*

Investigator: Jan Hopmans, UCD

Students & research staff. The following lab personal have worked on the project.

*a. Total hours contributed < 160*

Tamir Kamai (Graduate Student) – Datalogger programming and instrument calibration

Gerard Kluitenberg (Visiting Scientist) – Field installation

Toby O'Geen (Collaborator) – Pedology

Dylan Beaudette (graduate student) - Pedology

*b. Total hours contributed > 160*

Armen Malazian (Graduate Student) – Field installation and instrument calibration.

Paolo Nasta (Postdoc) Field installations, lab work and modeling

Peter Hartsough (Postdoc) – Experimental design, implementation and maintenance

Sara Enders (Graduate Student) – Field sampling

Katya Roudneva – Field and Lab Technician

Jennifer Storch – Field and Lab Technician

Eric Hoang – Field and Lab Intern

Scope.

**Progress 2008-2010**

In August 2008 we instrumented a white fir (*Abies concolor*) tree (CZT-1) in the SSCZO with soil moisture, temperature, matric potential (MPS) sensors and tensiometers. We placed the sensors in a radial array around the tree to capture the changing dynamics of the water content across the growing season and through the winter season (Figure 1). The tree is located within the Kings River Experimental Watershed (KREW), at an elevation of 2018m. The tree itself was also instrumented with sap flux sensors and time domain reflectometry (TDR) for determination of changes in stem water content. Ninety soil sensors are spread over a spatial array at 30 cm depth and also distributed across 6 vertical pits to a depth of 90cm. Collocated within this plot are four water balance clusters (UCM pits) consisting of additional soil moisture measurements, snow depth and solar radiation. All sensors are autonomously powered (solar panels) and use radio transmission to the P301 Flux tower. From there, data is transmitted by cell modem to UC Davis. Also installed on the CZT-1 site was a camera to monitor changes in snow depth (Figure 2).

Two summers of data show very dry soil conditions at summers end, typical of the Mediterranean conditions at the site. Winter precipitation arrived in December in the form of snow. Moisture conditions in the soil soon reached field capacity (Figure 3), after precipitation and snow melt events. The snowmelt patterns are captured in a time lapse video ([http://hopmans.lawr.ucdavis.edu/nsf\\_czo\\_experiments.htm](http://hopmans.lawr.ucdavis.edu/nsf_czo_experiments.htm)). Soil temperature data show that the shallow (15cm) sensors are responding to diurnal fluctuations in air temperature (Fig. 4). Under dry soil moisture conditions, the soil

temperature typically decreases with soil depth, whereas in the winter months the soil temperature profile is inverted with the highest temperatures at the larger soil depths. During short periods of snow melt, soil temperature is largely independent of soil depth because of infiltrating melt water.

Soil water storage was estimated by integrating soil moisture profile depth (Figure 5). Using total soil moisture storage (cm) values, tree transpiration rates for the initial 43 day dry period was estimated to be about 0.2mm/day, indicating severe soil moisture stress. The first precipitation of the season fell on 10/4, 3.3cm as measured at the NADP site 2km away. Only approximately half of this rain event was recorded by the soil moisture sensors, with the remainder likely stored in the litter layer and shallow soil above the 15cm sensor. The next precipitation event of 3.7cm on 11/1 increased storage in the upper profile by 2.7cm, perhaps indicating that the lower soil profile was wetted, with changes in soil water storage reflecting precipitation amounts. The following large storm in mid-December falls mostly as snow and the water entering the profile is delayed until melting begins in early January. After the big storms in December and January, there was additional water input into the soil profile, because of soil water drainage after reaching field capacity. The receding limb in the soil water storage plot (Figure 5) is a measurement of the drainage rate out of the profile.

Ongoing research into summer 2010 will involve integrating measurements at the tree, stem water content, sap flux, and stem water potential, with measurements of changing conditions in the subsurface. A Ground Penetrating Radar (GPR) survey was conducted to determine root architecture. Moreover, we will calibrate the soil water potential sensors (MPS) with co-located tensiometers, thereby allowing evaluation of soil water stress and its spatial distribution on tree transpiration. Co-monitoring the tree and the soil across the developing moisture stress conditions of the Mediterranean summer will provide valuable data on the interaction of surface/subsurface water dynamics in a mid latitude alpine forest. Measurements taken at the tree can be scaled up to catchment scale using data from the 50m P301 flux tower adjacent to the plot.

## **New and Ongoing projects**

### 1. Second Tree Instrumentation

We are currently in the process of instrumenting a second tree at an adjacent site within the watershed (CZT-2). The second instrumented tree is a 20m tall Ponderosa Pine (*Pinus ponderosa*) growing on a 10-15% slope. We selected the second site to better represent some of the thinner and dryer sites within the watershed. The tree is located approximately 300m SW of CZT-1 at an elevation of 2030m, with good southern exposure. The tree is more isolated from surrounding trees and sits on soils that are rocky and generally less than 90cm thick. The soil instrumentation consists of 24 MPS-1, co-located with 24 ECHO-5TE sensors distributed across eight vertical pits, around the critical zone tree and hard wired into a central data logger. Tensiometers were installed in eight locations co-located with the vertical pits at 30-80cm depths. As was done previously, we instrumented the tree with heat pulse sapflux sensors on four sides corresponding to the soil measurements. This site is also wired to a central datalogger

located at the tree. From there, the data is sent wirelessly, first to the tower and then on to UC Davis via cell modem.

## 2. Root excavation

At the end of the 2010 summer, we plan to excavate the root from a tree adjacent to the CTZ-1 to map root structure and location in response to moisture deficit in the soil profile. This tree has been previously characterized using surface geophysical techniques. While we can approximate the spatial distribution of active rootwater uptake, from measurements of soil moisture and water potential around the tree, using an inverse modeling approach, we would benefit from a complete excavation of a tree, to ensure local root architecture and rooting depth. In our monitored tree we have seen the tree switch to water extraction from deeper soil zone or even fractured bedrock as upper layers of soil dried out. Excavation will allow us to confirm the lateral and vertical extent of the root system and provide a better estimate of the area of influence of moisture removal for the tree. We hope to excavate roots down to the saprolite interface, a depth greater than 1m. Soil will be removed using compressed air, leaving roots intact and available for 3-D mapping.

## 3. Modeling of the Critical Zone Tree

We have developed a quantitative model parameterizing the soil-tree hydrologic system as a dual-porous media, calibrating the reduction of the potential evapotranspiration (through the Jarvis model), and the hydraulic properties of the tree and the root distribution. In this approach, we use a parameter optimization approach to estimate the soil and tree conducting tissues as two interactive independent porous media, each with conductive and capacitive properties that are a function of water potential. The simulations are run using the HYDRUS 2D flow code (Simunek et al., 1999). As data input for the model, we are using measurements made at the tree, meteorological data collected at the P301 flux tower and soil hydraulic properties measured from samples taken adjacent to the tree instrumentation. Data include soil water content and water potential in 3 spatial dimensions in the root zone, tree stem water content and sap flux, canopy water potential, and atmospheric variables such as net radiation, air temperature and humidity.

## 4. Nitrogen fluxes from soil

See section on Nitrogen fluxes from soil below.

## 5. Sourcing water accessed by trees using stable isotopes

See section on Nitrogen fluxes from soil below.

## 6. Depth to bedrock

A soil depth model was built from 57 soil depth observations, collected from the experimental watershed by manual excavation, and a combination of DEM, ASTER, and NAIP data (Figure 6). The model was built using multiple linear regression, with

predictor variables selected according parameters that typically affect or are affected by soil depth: surface slope, tree location, and vegetation density. Slope angle was computed from USGS 10 meter resolution DEM data, obtained from the NED website (date). Tree location and vegetation density were approximated with the Normalized Difference Vegetation Index (NDVI), calculated from a ASTER bands 2 and 3n, and the first principal component of a 3-band NAIP scene. The expected non-linear relationship between soil depth and predictor variables was accommodated by generating restricted cubic spline (RCS) basis functions with three knots for each predictor variable. The resulting model accounted for 52% of the variance in soil depth (adjusted  $r^2$ ), and predictions were characterized by a root-mean squared error (RMSE) of 17.7 cm. Predictions were truncated to the original range of the soil depth measurements (0 to 100 cm), and smoothed with a 5x5-cell mean filter. A revised version of this model that uses a larger dataset of soil depth measurements is in development.

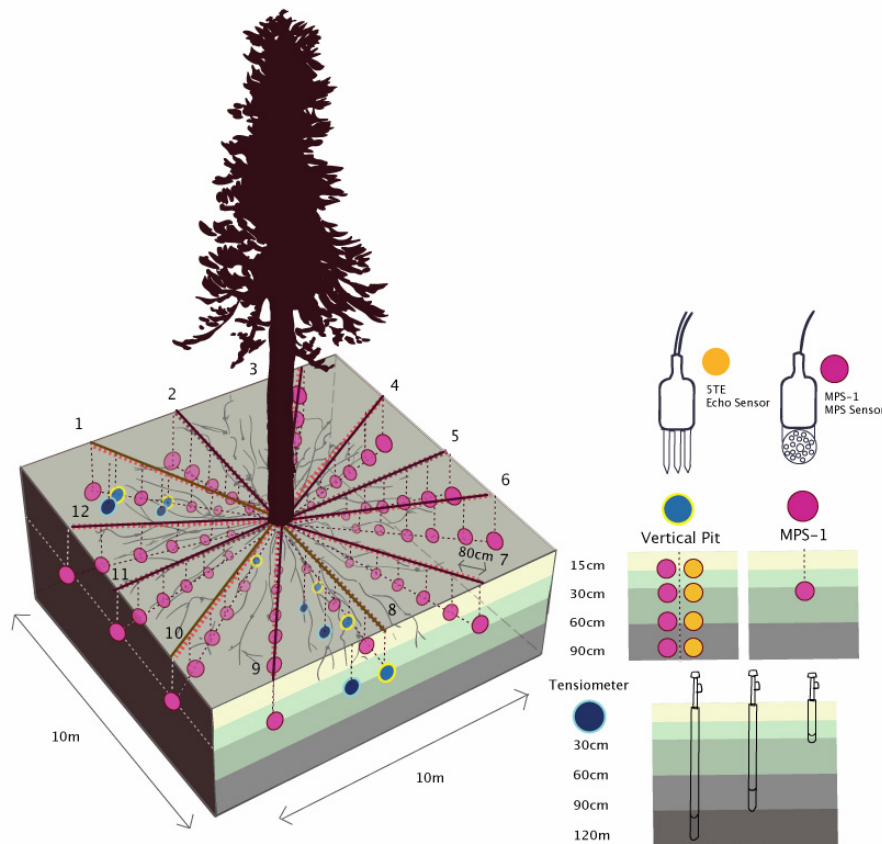


Figure 1. Site Layout showing radial array of soil sensors and locations of vertical pits and tensiometers at CZT-1.



Figure 2. CZT-1 instrumentation



### Volumetric Water Content at Four Vertical Pits (VP) at CZT-1

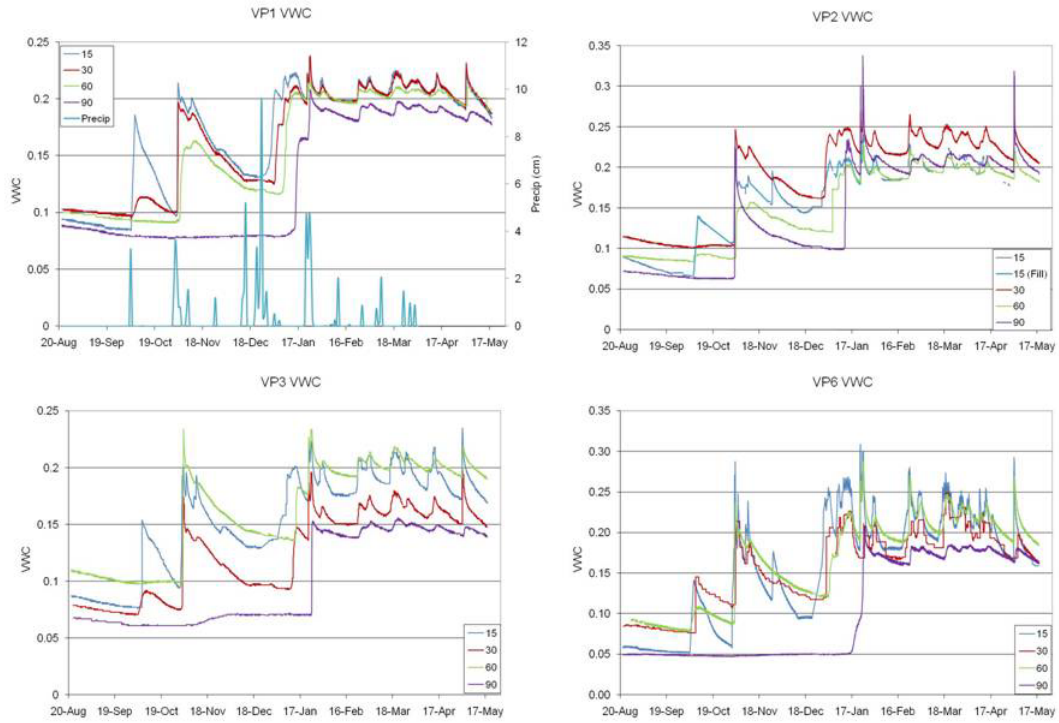


Figure 3. Distribution of soil moisture across four vertical pits. All pits show extremely dry conditions in late summer, even at the 90cm soil depth. Soil profiles are increasing in soil water content, in response to precipitation starting in October and reach field capacity during snow melt in December/January.



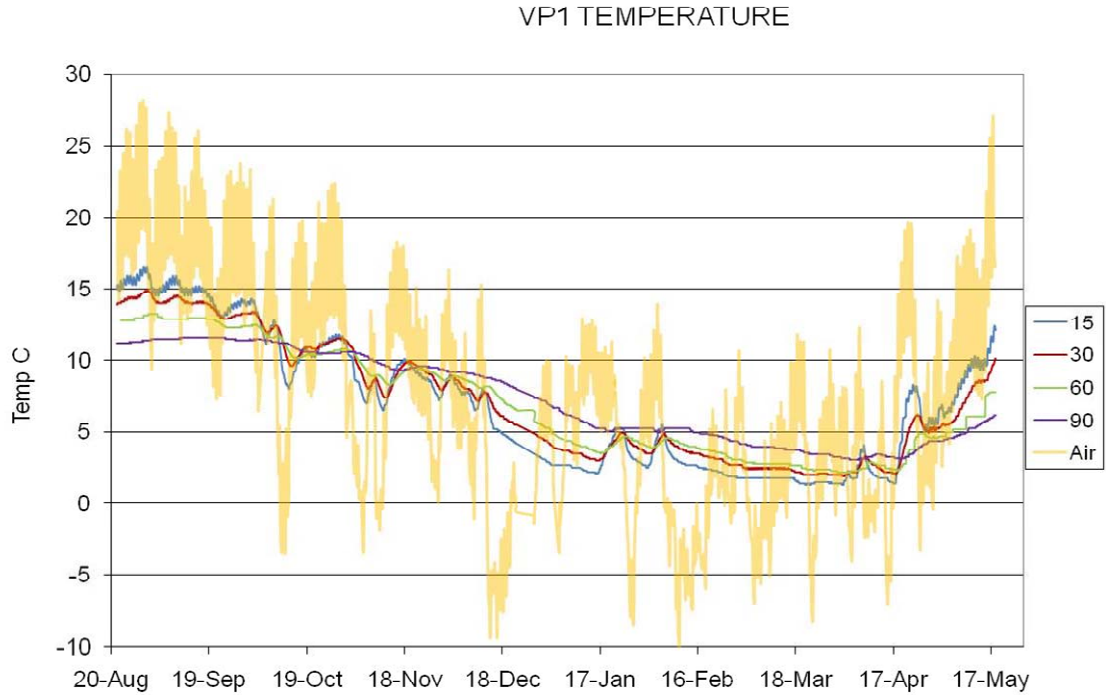


Figure 4. Soil Temperature profile in a representative vertical pit (VP-1). Soil temperature stay above freezing for the entire winter, despite air temperatures falling well below freezing. The shallow (15cm) sensor responds to diurnal fluctuations while the deeper soil temperature are attenuated. During periods of snow cover, soil temperature increases with soil depth. Soil temperature is almost depth independent during melting periods, because of infiltrating cold snow melt water.

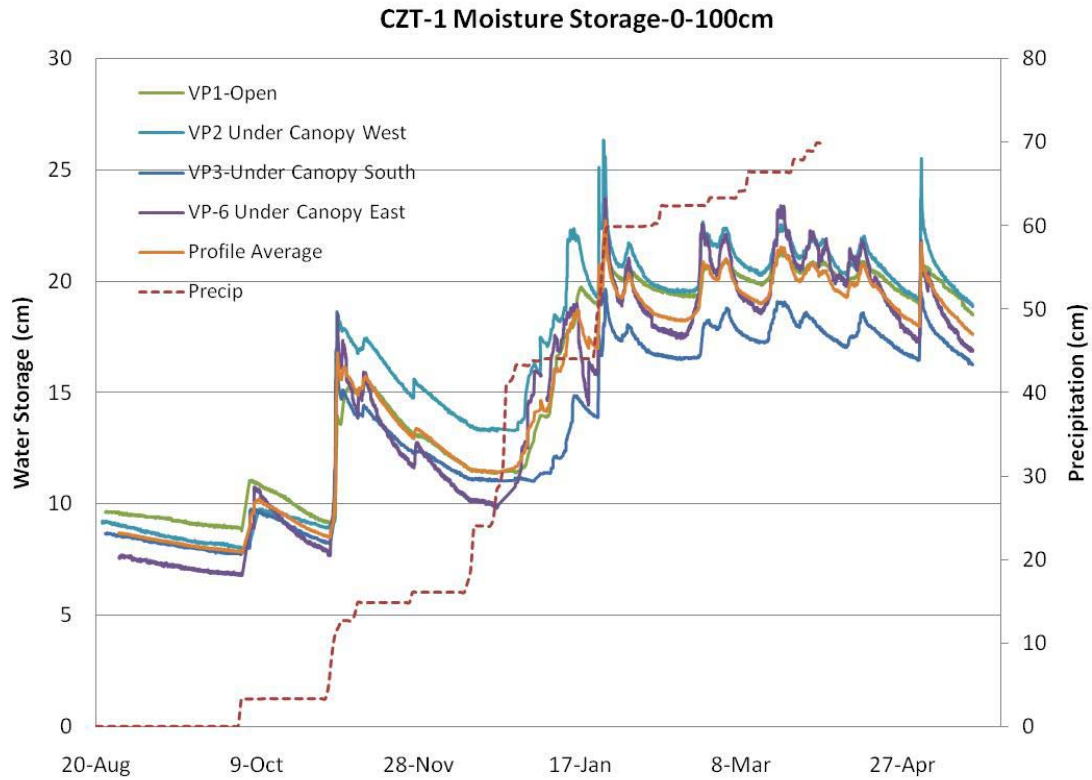


Figure 5. Soil Moisture Storage in the upper 1m surrounding the CZT-1 for summer 2009. Moisture loss from the profile during the initial dry period shows a very low ET rate of 0.2mm/day indicating very little water removed from the upper 1m of the profile. After the big storms in December and January, there is little net change in water stored in the profile for the rest of the winter, indicating soil drainage and lateral water flow downslope contributing to stream flow.

**Funding,** CZO, with significant leveraging from ongoing NSF Biocomplexity award 0410055-Development of multi-functional heat pulse probe for ecological and hydrological monitoring of plant root zones. Soil moisture sensors will be purchased as part of instrument cluster grant.

Schedule, including field work. On going.

Manuscripts in progress & planned

Kizito, F. C.S. Campbell, G.S. Campbell, D.R. Cobos, B.L. Teare, B. Carter, and J.W.Hopmans. 2008. Frequency, electrical conductivity and temperature analysis of low-cost moisture sensor. J. Hydrology 352:367-378. DOI:10.1016/j.jhydrol.2008.01.021

Malazian, A., P.C. Hartsough, T. Kamaï, C.S. Campbell, D.R. Cobos and J.W. Hopmans Evaluation of MPS-1 soil water potential sensor. J. of Hydrology. (Submitted)

Nasta, P., S. Huynh, and J.W. Hopmans. Simplified Multistep Outflow method to estimate unsaturated hydraulic conductivity for coarse-textured soils. Soil Science Society America Journal. (Submitted)

Hartsough, P.C., A. Malazian, E. Roudneva, T. Kamaï, P.Nasta and J.W. Hopmans Monitoring of Critical Zone Processes in a Southern Sierra Nevada Ecosystem (in preparation)

Topic. Physical controls on water and carbon exchange and plant production

*Updated 2010*

Investigator. **Mike Goulden**, UCI

Students & research staff. **Anne Kelly** (PhD student, UCI); **Greg Winston** (Specialist, UCI)

Background and rationale

Our research focuses on the bi-directional interactions between ecosystem function and water balance. The local water balance helps control vegetation type, density, and function through the effects of drought on primary production, plant establishment, mortality, and physiology. The vegetation within an ecosystem helps control the local water balance through the effects of plant physiology and vegetation density on evapotranspiration, snow melt, and soil development. We hope to mechanistically understand all these interactions, with the long-term goal of determining how climate change will impact montane vegetation, and how changes in vegetation will impact water balance.

Activities

*Continuous micrometeorological measurements*

We have deployed and are operating four eddy covariance towers to continuously measure the fluxes of water vapor, energy and CO<sub>2</sub>. The sites are deployed along a climate/elevation gradient, which is allowing us to understand how climate influences ecosystem structure and function. The sites were installed in 2008-10, and are expected to operate for ~5 years.

<b>Name</b>	<b>Installed</b>	<b>LATITUDE</b>	<b>LONGITUDE</b>	<b>Jurisdiction</b>	<b>Vegetation</b>
San_Joaquin_tower	July 10	37.10872222	-119.7315611	PSW	Oak/Pine woodland
Soaproot_Saddle	Oct 09	37.03106944	-119.2564306	SNF	Ponderosa pine
KREW_P301_tower	Sept 08	37.06767222	-119.1932167	SNF	Midmontane white fir
Courtright_Road	Oct 09	37.06659722	-118.988475	SNF	Subalpine lodgepole

*Ecological measurements at tower sites*

We are making a range of measurements at the tower sites to better understand the functioning of the local ecosystems. Ecological measurements at each site include sap flow by ~20 trees using Granier type sensors, litter fall collected in ~50 litter traps, and stem increment by ~100 trees using stainless steel dendrometer bands. These ecological measurements will match up with the tower measurements. For example, wood increment measured by dendrometers plus litterfall provides a measure of above ground Net Primary Production, which can be related to the Gross Primary Production determined by the tower. Similarly, the sapflow measured for all of the trees can be related to whole forest Et measured by the tower. Likewise, the sapflow measured for an

individual tree can be related to the stem increment of that tree measured by the dendrometers.

*Ecological measurements along elevation gradients*

We have established a series of plots at intermediate elevations that are being used to better understand the relationships between elevation and ecosystem function, and also to determine whether the tower sites are representative. The elevation gradient plots are located at 400' elevation intervals from 3600' to 8800' and include detailed observations of species composition, along with litter traps and dendrometers. These observations will allow us to further characterize the relationship between elevation and above ground Net Primary Production. Additionally, the gradient measurements will help us to understand the distribution of the various tree species with elevation, as well as the relative rates of growth between species within an elevation, and the relative rates of growth between elevations within a species.

Funding. NSF instrument cluster grant to Merced; NSF CZO grant to Merced; DOE-PER grant to UCI; approx \$200k in instruments purchased by previous grants to UCI.

Schedule, including field work.

Summer 2008-2010 – Winston and Merced collaborators install and operate flux towers. Kelly installs ecological measurements at tower sites and establishes elevation gradient sites.

Summer 2010 and beyond – Kelly conducts PhD research. Towers continuously operated.

Manuscripts in progress & planned. TBD. (include data sets used/needed)

Topic. **Surface-groundwater interactions**

*Updated 2010*

Investigator. **Martha Conklin**, UCM

Students & research staff. Ryan Lucas, grad student; Reza Ganbhari, Post Doc

Scope. A series of meadow experiments and measurement campaigns have been completed or are in progress.

**Groundwater exchange in Long meadow.** The objective of this experiment is to determine variations in diel temperature change, inflow and outflow of groundwater into the stream, quantify interactions between vegetation and water, and understand the water balance and hydrologic processes in Long meadow, Sequoia NP. In our initial campaign, we will exploit temperature as a hydrologic tracer using a distributed temperature sensor (DTS) and Tidbits, plus use data from piezometers and observation wells (temperature and pressure). The DTS system includes a computer, two 1-km long fiber optic cables and a power source. The DTS system provided stream temperatures with high resolution and high accuracy over the length of the stream for a duration of 5 days. The DTS deployment led to the observations of polymictic pool behavior in the meadow pools. This daily thermal stratification and nightly was further assessed in 2008 and 2009 using Hobo Tidbit temperature loggers, for vertical temperature profiles, and Radon-222 analysis. These data were used in constructing a 2-D model in Fluent, a fluid dynamics equation solver.

In addition to temperature and geochemical tracer activities, evapotranspiration (ET) and ground water level and pressure head measurements have been collected in 2008, 2009, 2010. ET was measured at discrete points in space and time utilizing an ET chamber. These chamber measurements were compared to calculations of ET, calculated using groundwater level data and the White equation, and PET, calculated using meteorological data and the Penman-Montieth equation.

Monitoring well and piezometer analysis have shown that much of the meadow remains saturated well past senescence of the meadow vegetation—soil moisture data from this area indicates that the mineral soil on the surrounding hillslopes is very dry in the late summer early fall. This indicates that there is significant sub-surface water contribution well past snow melt. We think that much of this contribution is from sap rock through flow of the surrounding area. In order to better understand the link between saprock through flow from the adjacent hillslopes and the meadow hydrology, up to 3 sap rock piezometers will be installed in Long Meadow. These piezometers will be screened in the sap rock complex below the mineral soil.

**Groundwater exchange in P301 meadow.** Most of the wells and piezometers have been installed in the P301 meadow. In addition to the initially planned wells/piezometers, we installed, in summer 2010, three sap rock piezometers. These range from 205 to over 500 cm in total depth and 40-400 cm of screened casing in the sap rock complex. We also installed one stilling well in the stream between the middle and lower meadows; we will install one more stilling well below the lower meadow. All told there will be 24 monitoring wells, stilling wells, piezometers, and sap rock piezometers installed in the P301 meadow complex.

ET chamber measurements commenced in June 2010 and will continue Fall 2010 and before, during, and after meadow vegetation growing season 2011. ET will

be calculated from ground water level monitoring wells using the White method and PET will be calculated using the nearest meteorological data. We would like to compare these measurements and calculations with ET measurements being collected at the nearby P301 flux tower.

Salt dilutions have commenced at the installed stilling well. These will continue in the fall 2010 and recommence after snow melts 2011. Salt dilutions will be start at the second stilling well once it is installed. Salt dilution activities will continue until enough data is collected to establish a sufficient rating curve.

**Funding.** Largely CZO.

Schedule, including field work. field work in both meadows is ongoing. Saprometers will be installed in Long Meadow in fall 2010. Total station surveys of both meadows will be completed in fall 2010 or spring 2011.

Manuscripts in progress & planned. TBD. (include data sets used/needed)

Topic.

**Spatial variability in the KREW watershed: Effects on nutrient cycling and water quality**

*Updated 2010*

Investigator. **Dale Johnson**, UNR

Students & research staff. Cassandra Woodward, MS student

Scope. (updated 8/22/08) After reconsideration of project priorities/budgets, and consultation with the other investigators, the work plan has been modified from the original plan to manipulate snowpack duration to one that focused on spatial variability in nutrients on several scales and a pilot study to investigate the potential for inconspicuous, nutrient-laden runoff, as seen frequently in the eastern Sierra Nevada. The new work plan consists of four basic components: 1) analysis of soil samples taken from a gridwork across the entire watersheds; 2) a pilot study of runoff in selected locations, 3) an analysis of spatial variability in nutrient availability in the scale of meters or less, and 4) measurement of resin-based fluxes of N and P in conjunction with detailed soil moisture measurements being made by other investigators in the project.

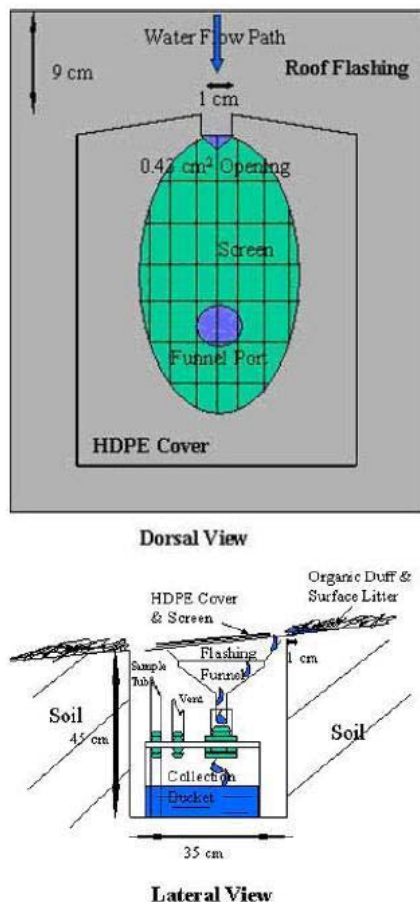
**Analyses of soils from the KREW grid.** On the broadest spatial scale, funding from this project has allowed the analysis of soils taken from 87 grid points on the KREW watersheds, which, along with data laboriously collected in quantitative soil pits at these grid points, were converted soil nutrient contents to a  $\text{kg ha}^{-1}$  basis. As of this writing, A paper on this data has been submitted to Geoderma, sent back for revision, and revisions have been submitted (Johnson et al., in revision). We await final work on acceptability of the revision. Results showed that Bull watersheds had significantly greater C, N, and B contents and significantly lower extractable P, exchangeable  $\text{Ca}^{2+}$   $\text{Mg}^{2+}$ , and  $\text{Na}^{+}$  contents ( $\text{kg ha}^{-1}$ ) and lower pH than the lower elevation Providence watersheds. Soil  $\text{NH}_4^{+}$  and mineral N contents were high in both the Bull and Providence watersheds and could not be related to any measured soil property or attributed to known rates of atmospheric

deposition. Nutrient analyses on satellite samples were comparable to those taken from pits when averaged on a watershed or site (Bull and Providence) scale, but quite variable on an individual grid point basis. Elevated Zn values from the quantitative pit samples suggested contamination by field sieving through a galvanized screen. Had the amount of large rocks within the soil sample not been accounted for with quantitative pit analyses, estimates of fine earth and associated C and nutrient contents ( $\text{kg ha}^{-1}$ ) would have been overestimated by 16 to 43%.

This data will not only allow us to place results of the more intensive studies described below into context for the CZO project, but also allow USFS researchers to place the results of several years of nutrient flux data collected with resin lysimeters (Susfalk and Johnson, 2002). The data for soil and rock mass from the quantitative pits has also been shared with Cliff Riebe for his analysis of historical erosion regimes.

**Runoff and meter-scale measurements of spatial variability in nutrients.** Forests in the KREW watersheds are similar in many ways to those in the eastern Sierra Nevada (see text box for background), including hydrophobicity of mineral soils in summer and lack of rooting in O horizons in many forests. Thus, we hypothesized that:

1. Runoff through the O horizons over the mineral soil will occur in KREW watersheds, as it does in eastern Sierran ecosystems;
2. Runoff will have high concentrations of inorganic N and P, as in the eastern Sierran ecosystems; and
3. Infiltration of nutrient-rich runoff into preferential flowpaths will create hot spots of nutrient availability in O horizons and mineral soils.

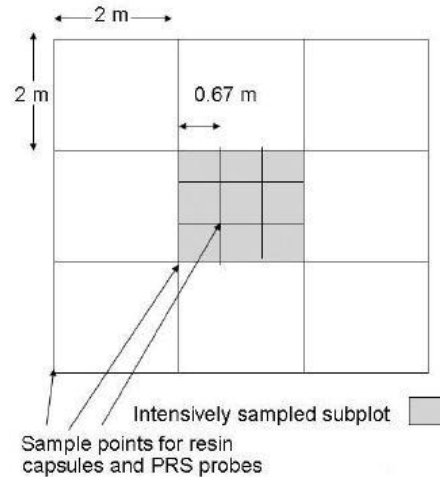


**Figure 1—Schematic of runoff collector**

In order to test these hypotheses, we are conducting a pilot study which includes runoff collections (Figure 1) and a resin-based study of small-scale spatial variability in O horizon and soil nutrient levels at two sites in the KREW/CZO system: 1) the upper meteorological station and 2) Prenart lysimeter site P301. These sites were chosen because 1) they have now or soon will have a substantial amount of ancillary data to compare these results with and 2), of equal importance, they will be accessed frequently during the snowmelt season where frequent sampling of runoff collectors will be necessary. This pilot study includes three runoff collectors at each site and one 6 x 6 m plot within which resin-based nutrient sampling to investigate the possibility of hot spots will be conducted. For the 2008-2009 snow season, twenty-eight grid points in the latter plots have been instrumented with Plant Root Simulator (PRSTM) anion- and cation exchange membrane probes (Western Ag Innovations, Inc) and Unibest mixed bed resin capsules, both placed within



the O horizon. The gridpoints include 16 on a 2 x 2 m interval and 12 additional grid points in the 12 central 2 x 2 m plot which are placed at a 0.67 x 0.67 m interval, this allowing us to examine spatial variability at two scales (Figure 2). Results from this first year study are being written up for publication, and include the following highlights. First, O horizon interflow runoff does indeed occur at the KREW watersheds and is enriched in nutrients, as is the case in the eastern Sierra Nevada. Secondly, There is ample evidence of nutrient hotspots not only for ammonium and nitrate, but also for ortho-P, K, Ca, and Mg in the plots established in year 1. We found that hotspots for water-extractable cannot be attributed to any traditional measure of soil nutrients, but do resemble the chemical characteristics of runoff waters. We hypothesize that these water soluble hotspots are in fact preferential flow paths into which nutrient rich O horizon interflow enters. For the 2009-2010 snow season, we changed the design somewhat: the new plots had 16 gridpoints, and at each grid point four resin capsules and four resin stakes were installed. Two of the four were removed just after the first precipitation event in the fall of 2009, and the remaining two were removed in June 2010 after snowmelt. With this design, we hope to obtain temporal information on the hot spots (hot moments) that we know occur in these systems. The 2010-2011 plot layout will differ somewhat in that we have installed resin lysimeters (Susfalk and Johnson, 2002) in one grid and in the second grid, we will install not only stakes and capsules, but also prototypes for resin-based O horizon runoff collectors. Finally, we will install a Decagon soil moisture/temperature/electrical conductivity monitoring system in the lower (Prenart) site.



**Figure 2—Layout of 6 x 6 m spatial variability plots. A PRS probe and resin capsule was installed at each 2 x 2 m gridpoint in the main plot and also at each 0.67 x 0.67 m gridpoint in the center 2 x 2 m subplot.**

### Background on spatial variability in nutrients

The measurements of runoff and (sub)meter-scale variability in nutrient availability are closely conceptually linked and therefore are described together. By way of background, Schimel and Bennett (2004) built upon the hot-spot and hot-moment concept described by McClain et al (2003) and others and posed a new paradigm for plant-microbial competition where trees can effectively compete with soil microbes by invading N-rich microsites (hot spots) that exist at least temporarily (hot moments) even in relatively N-limited conditions. Roots, with their elongated structure and exploratory habit can presumably tap into these hot spots and hot moments, and thereby might effectively mine the soil for N over time.

We have found that hot spots and hot moments are characteristic of nutrient cycling in Sierran ecosystems (Johnson et al., in press). However, we also believe that the new paradigm posed by Schimel and Bennett (2004) for plant-microbial competition is moot

for the many Sierran forest ecosystems. Because of the extreme summer drought, rooting is often entirely absent in the forest floors Sierran forests; thus, decomposition and vegetation uptake processes are spatially decoupled, and the intense competition for N between roots and decomposers which characterizes the more humid forest soils is absent. Because of this vertical decoupling, nutrients released during decomposition in O horizons are not immediately taken up and can be solubilized by rain or snowmelt to create solutions with very high inorganic N and P concentrations. Miller et al. (2005, 2006) have installed runoff collectors at the O horizon – mineral soil interface at many sites throughout the eastern Sierra Nevada and found that, contrary to common textbook knowledge that runoff in forest ecosystems is minimal, runoff over the mineral soil and through the root-free O horizon and over the top of the mineral soil is very common, not only during snowmelt when soils may be saturated but also during summer storms when mineral soils are extremely hydrophobic. Not only is runoff routinely collected, but concentrations of ionic N and P in these solutions are often extraordinarily high, including  $\text{NH}_4^+$  (concentrations as high as 87 mg N L<sup>-1</sup>) and ortho-P, (concentrations as high as 13 mg P L<sup>-1</sup>), ions that are strongly adsorbed to mineral soils and are therefore found in very low concentrations in soil solution only a few cm deeper into mineral soil. We believe that these high concentrations of ionic N and P are a result of mineralization of N and P in the O horizons, and because rooting is absent in the O horizons mineralized N and P is not taken up as it would be in more mesic ecosystems. We also believe that fire exclusion over much of the 20th century in these systems has resulted in litter buildup that has provided an increasing source of nutrients in this runoff, perhaps contributing to the well-documented deterioration of water quality in nearby Lake Tahoe (Goldman, 1981; Miller et al., 2005, 2006). We are not as yet able to precisely quantify the area from which this interflow runoff is generated nor can we pinpoint where it infiltrates. We hypothesize that this interflow could be a major factor in the creation of hot spots if it enters into the mineral soil via preferential flow paths (Burcar et al., 1994a), or alternatively could be a significant source of mineral N to streams, perhaps contributing to the peaks in mineral N concentrations that are sometimes seen during cycles of snowmelt runoff (e.g., Johnson et al., 1998).

Table 1. Schedule of Activities

2008-9					2009-10				2010-11			
Activity	Sum	Fall	Win	Spr	Sum	Fall	Win	Spr	Sum	Fall	Win	Spr
Analyze KREW soils for C, N, NH <sub>4</sub> , and NO <sub>3</sub>									X			
Analyze KREW soils for other nutrients									X			
Establish and instrument plots									X			
Collect data						X				X		
Analyze data					X		X			X		
Preliminary analysis and reports						X				X		
Re-evaluate and modify designs and re-install equipment for subsequent years						X				x		
Final report and publication									Begin in spring, continuing to summer & fall 2011			

**Measurement of resin lysimeter fluxes in conjunction with detailed soil moisture measurements.** The KREW project as well as many others in the eastern Sierra Nevada mountains (Murphy, et al., 2006 a and b) and elsewhere (Johnson et al., 2003; Kjonnas 200x) use resin-based lysimeters as cheap and low-maintenance method of measuring nutrient leaching fluxes. The resin-based methods rely on the ability of resins to capture nutrients that can later be extracted, and, with measurements of the lysimeter collection area, converted to a kg ha<sup>-1</sup> flux. While resin-based flux measurements are cheap and convenient, they provide no information as to the relative contributions of water flux and nutrient concentrations in soil solution to the total fluxes measured. Thus, we have installed resin lysimeters of the design described by Susfalk and Johnson (2002) near the “tree” for the last three years now to compare our leaching results with the very detailed measurements of soil moisture are being made there. Specifically, we have installed resin lysimeters at the outer perimeter of 10 of the 12 “spokes” of the wheel of sensors installed around the “tree”. These lysimeters are removed (and replaced) and extracted after snowmelt to see if the fluxes correspond to any indicators of soil moisture status made in the nearby collectors.

#### **Funding.** CZO

Schedule, including field work. We have started this research in the August of 2008.

After a winter season of data collection, we will evaluate protocols and designs, modify as needed, and re-install equipment during the following summer seasons. The intent is to not only capture data worthy of publication in its own right, but also to continue to refine and develop sampling techniques most suitable for nutrient work in snow-dominated Sierran ecosystems.

Manuscripts in progress & planned:

Johnson, D. W., Glass, D. W., Murphy, J. D., Stein, C. M., Miller, W. W. Hot Spots and Hot Moments: Another Look at Nutrient Variability in Sierra Nevada Forest Soils. *Biogeochemistry* (in press)

Johnson, D.W., Hunsakeer, C.F., Glass, D.W., Rau, B.M., Roath B.A. Carbon and Nutrient Contents in Soils from the King's River Experimental Watershed, Sierran Nevada Mountains, California. *Geoderma* (submitted and returned after revision)

Johnson, D.W., W.W. Miller, B.M. Rau, and M. W. Meadows. Spatial Nutrient Variability in a Sierran Forest Soil: an Investigation into the Nature and Potential Causes of Nutrient Hot Spots. In prep for Soil Science Society of America, Journal.

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**Topic.** Nitrogen fluxes from soil

*Updated 2010*

**Investigator.** Ben Houlton, UCD

**Students & research staff.** Sara Enders (PhD student)

**Scope.** We will use natural nitrogen (N) isotopic variations in dissolved inputs, soils and stream waters to examine the dominant vectors of N inputs and losses from forested watersheds across an elevation gradient to compare processes at higher and lower elevation watersheds, across the rain-snow transition. Isotope mass-balance approaches are especially useful for modeling hard-to-measure gaseous N fluxes, such as loss via denitrification.

Since microbial denitrification strongly fractionates N stable isotopes, the  $^{15}\text{N}/^{14}\text{N}$  ratio of streamwater N is elevated relative to N inputs when this process is important. We will also use measures of O isotopes in nitrate to further examine gaseous N production in soils and streams. For example, our previous work indicates that denitrification elevates both the  $^{18}\text{O}/^{16}\text{O}$  and  $^{15}\text{N}/^{14}\text{N}$  of nitrate, imparting a slope  $\sim 0.6$  on these isotope systems. In combination, these isotopic measurements will be used to inversely model N gas fluxes across snow vs. rainfall dominated forests.

For sampling, 8 first order streams in Providence (3) and Duff (1) catchments and Bull (3) and Teakettle (1) catchments will be measured monthly for TN, DIN, and  $\delta^{15}\text{N}$  and  $\delta^{18}\text{O}$  of  $\text{NO}_3^-$  and DON to identify temporal patterns in N isotopes in losses. We will monitor the  $^{15}\text{N}/^{14}\text{N}$  and  $^{18}\text{O}/^{16}\text{O}$  of N deposition inputs based on collectors established at various locations within the watersheds or proximate, such as NADP site CA28. We will measure the isotopic composition of N in plant leaves and soils, and combine these measures with input-output analyses and models to construct budgets of the N cycle. Archive stream, soil, litter, and precipitation samples will additionally be analyzed as available. Finally, we will monitor  $\delta\text{D}$  and  $\delta^{18}\text{O}$  of stream waters at catchment outlets to complement current understanding of rain vs. snow contributions to the hydrology of respective catchments.

**Nitrogen isotopic modeling.** Combining the isotopic information collected across the various scales of sampling, we will use N budget models such as DAYCENT and DNDC, and integrate N data to integrate with RHESSys to further constrain the flux of N inputs and losses from the watersheds.

**Funding.** Funding is largely CZO, through Hopmans, with leveraging from UCD.

**Schedule, including field work.** We began collecting preliminary stream, soil, and foliar samples in July, 2010. An intensive mid-canopy foliar sampling is planned for early September, 2010, in which sun leaves will be accessed by shotgun. Sampling will then intensify over the next two years, shaped by our preliminary findings.

**Manuscripts in progress & planned:** TBD.

**Topic. Baseline hydrologic, sediment and geochemical characterization**

*Updated 2008*

**Investigator. Carolyn Hunsaker, PSW**

**Students & research staff. Tom Whitaker, Fengjing Liu, others TBD**

**Scope.** Although this work is part of PSW's original KREW project, doing it is essential to progress on CZO research and one or more of the CZO investigators will assist as needed.

**Hydrologic characteristics.** Elevational transition of mixed rain/snow to snow, seasonal transitions, snowmelt to baseflow, time lags in the system, seasonal responses to precipitation.

**Sediment.** Analysis of sediment data from sediment ponds, turbidity, sediment fences, headcuts and bank pins. Also modeling.

**Geochemical characteristics.** Annual cycle of geochemistry, sources of streamflow across catchments, flow paths result in chemical differences, seasonality of streamflow sources. Can mixing models help us determine if KREW is over sampling (frequency), identifying important nutrients to sample for?

**Funding.** Leveraged, PSW.

**Schedule, including field work.** Ongoing. Goal is to complete as much related to papers 1-6 during 2008 as possible. Field measurements will continue.

**Manuscripts in progress & planned.**

1. *Hydrologic response of rain-snow transition and timing of snowmelt and streamflow.* Whitaker and Hunsaker (Bales assist). Uses daily/hourly discharge data, temperature data from met stations, precipitation data.
2. *Sediment basin, turbidity & suspended sediment.* Hunsaker and Whitaker. Annual measurements from sediment basins and continuous turbidity data.
3. *Sediment budget for Providence.* Hunsaker & CSU/UCM collaborators. Need paper 2 plus MS thesis results from Sarah & Abby.
4. *Geochemical response across rain-snow transition: ions, pretreatment – system characterization – gradients in system.* Hunsaker and Liu. Use ion data, 2002-2006; build on first paper 1.
5. *Sources of stream water across rain-snow transition – streamflow generation.* Liu and Hunsaker. Use EMMA, diagnostic tools of mixing models, ion data. Need sampling of wells first.
6. *Nutrient response to streamflow sources; nutrients as reflection on biological activity.* Hunsaker and Liu.

Topic. Water, geochemical cycles, and upscaling of in-situ measurements

*Updated 2008*

Investigator. Roger Bales, UCM

Students & research staff. Peter Kirchner, PhD student

**Scope.** In cooperation with KREW researchers, we will estimate components of the water and geochemical cycles in the Providence catchments, as noted above. Parallel observations will take place at the Wolverton watershed of Sequoia National Park for cross comparison between the rain snow-transition and snow-dominated ecosystems.

**Patterns of snowcover and soil moisture.** It is our hypothesis that spatial variations in tree canopy cover are as important as slope and aspect for variability in snowcover and soil moisture. An implied hypothesis is also that soil moisture patterns will be influenced by patterns of snowcover accumulation and depletion in a predictable manner (the Hydrus 1D model will be used to aid in interpretation of soil moisture data). Soil moisture measurements will also help to discriminate snow versus rain. Our spatially dense measurements of snow depth and soil moisture are placed to capture the variability in physiographic features and vegetation across the catchments as part of our core measurement program. Radiation will be quantified by using a combination of insitu sensors and a portable canopy imager such as the CI-110 by CID, Inc. We will also place tidbit temperature loggers on grid and ordinal patterns in key locations to provide a mesoscale record of snowmelt. It is also thought that soil moisture and ET respond systematically to differences in water inputs and energy balance along gradients of elevation and aspect. That is, distributed system responses to seasonal transitions, changes in soils and vegetation, and longer-term climate changes are predictable based on physiographic features and soils/vegetation characteristics. However, within those gradients, heterogeneity caused by differences in bedrock and vegetation not captured by modeling will limit that predictability.

**Upscaling of forest snowcover and soil moisture distribution.** Scaling depends to some extent on how well distributed measurements capture the inherent variability across a catchment. The high frequency and spatially dense core measurements will provide the basic data for this. Synoptic measurements conducted at mesoscales will provide the ability to bridge these high-frequency data to larger scales. Synoptic surveys of snow soils, and bedrock using non-invasive geophysical methods, will be used, to characterize the snow covered area and the vadose zone on a broader spatial scale. These findings will provide a basis for linking our high frequency temporal measurements with high spatial resolution satellite images.

**Evapotranspiration.** In addition to flux tower and sap flow measurements, we will examine ET by analysis of diel variations in streamflow across seasons following the approach outlined previously by J. Kirchner. In addition to data analysis, we will use the RHESys watershed model to integrate data, investigate partitioning between ET and streamflow, and predict watershed behavior, as noted above.

**Geochemical processes.** It is our hypothesis that the distribution of soil moisture throughout the catchments controls the extent of coupling among the carbon and nitrogen cycles, as well as the weathering and mobility of ions. Because soils beneath the snowpack normally remain moist and unfrozen, snow-dominated sites will have higher rates of litter decomposition, nutrient cycling and solute production compared to

rain-dominated sites, where soil drying limits decomposition and weathering rates and thence coupling (this is not explicitly planned to be part of P. Kirchner's dissertation).

**Funding.** Largely CZO.

Schedule, including field work Ongoing. Core instrumentation in the Wolverton watershed was completed in 2007. Mesoscale surveys of snow distribution, and soil moisture were conducted in 2007 and 2008 and will continue through 2009. Real-time communication links with data loggers are planned for late 2008.

Manuscripts in progress & planned.

1. Hydrologic response of snowmelt, streamflow, and evapotranspiration in a snow dominated forested catchment. Kirchner, Bales. Uses CZO core measurement data from the Wolverton watershed: discharge, meteorologic parameters, snow depth, precipitation, soil moisture, and sap flow. Water chemistry data collected 2006-present will also be used.
2. Snow accumulation and melt distribution in forest ecosystems. Kirchner, Bales. Uses CZO core measurement data from the Providence and Wolverton watersheds: radiation, snow depth, precipitation, and soil moisture, coupled with synoptic surveys of depth and snow water equivalent and long-term data collected at the snow courses and pillows.
3. Mesoscale representation of snow and soil moisture in forested ecosystems. Kirchner, Bales. Uses same datasets as above in addition to repeated geophysical surveys conducted at target locations throughout the Wolverton watershed. If LIDAR or hyperspectral imagery of the study areas becomes available prior to publication they will be used also.



## Topic. Physical erosion and chemical weathering

*Updated 2010*

Investigators. **Clifford S. Riebe**, U Wyoming; **James W. Kirchner**, UCB, WSL, ETH. The base of operations for lab work and analyses will be the University of Wyoming. Analysis of cosmogenic nuclides by Accelerator Mass Spectrometry (AMS) will be conducted at Prime Lab (Purdue University) where we have an ongoing collaboration. Riebe will be the primary investigator and advisor of graduate and undergraduate students. Kirchner will be involved as an advisor throughout the project. **Bryan Shuman** and **Steven Holbrook**, two experts in geophysical methods for shallow subsurface characterization will be involved in advisory roles. CZO investigator **Carolyn Hunsaker** will be involved in interpretation of sediment yield data, collected as part of the core KREW measurement program.

Students & research staff. This work will be conducted over the course of three years and will employ a team of researchers including one Masters student (who will be responsible for the day-to-day operations of the project), and several undergraduate assistants (who will be involved in field and lab work). Update as of August 2010: Riebe has completed two field seasons with his Masters student, **Barbara Jessup** and has had several undergraduates working part time on preparation of samples collected so far.

Scope. A combination of measurements, including cosmogenic nuclide concentrations, a solid-phase mass balance of catchment soils, and shallow (<10 m) geophysical imaging, will be used to (1) document how long-term rates of erosion and weathering vary across the Southern Sierra Nevada Critical Zone Observatory, and (2) test a series of hypotheses about variations in rates of erosion and weathering across a range of spatial and temporal scales. These measurements will be integrated into other elements of the CZO work plan as outlined below.

### *Comparisons of short-term and long-term rates of physical erosion*

To measure long-term (*i.e.*, millennial timescale) erosion rates of the CZO catchments, we will collect stream sediment from each of the CZO catchments for analysis of cosmogenic radionuclides (CNRs) in stream-borne quartz. These measurements will allow us to infer spatially averaged erosion rates for the sediment contributing areas (e.g., Binnie et al., 2006; Granger et al., 1996). Including replicates, and samples from other KREW-monitored catchments to the south (*i.e.*, Bull and Teakettle), we will need to analyze 15 sediment samples for CNR concentrations. Because CNRs accumulate over thousands of years, as minerals are eroded through the upper meter or so of soil to the landscape surface, CNR-based erosion rates reflect long-term averages that can be used as benchmarks for comparison with the present-day (multi-year average) rates that are currently being measured from sediment traps as part of the core-KREW measurement plan. We will need to coordinate extensively with Carolyn Hunsaker in interpreting the data from the sediment traps.

As part of this work, we may be able to assess the importance of fire and post-fire responses by comparing flux measurements in the thinned versus control and the burned versus unburned catchments. However, in light of funding constraints, it remains to be seen whether the thinning and burning experiments will be conducted as planned. If they are, then the long-term measurements based on cosmogenic nuclides will be used to test for site-to-site differences in "background" rates of erosion and weathering between the burned and unburned catchments, and thus will be vital for quantifying the effects of burning (the and differences in background rates need to be accounted for in the analysis of short-term fluxes from the treated and untreated slopes).

We envision several plausible outcomes of the comparisons between short-term and long-term rates of physical erosion:

*Outcome 1: Episodic erosion dominates.* Our working hypothesis, based on a similar study in forested catchments in Idaho (Kirchner et al., 2001), is that the long-term averages from the cosmogenic nuclides will be significantly greater than the short-term averages from the sediment traps. We expect that the sediment trapping record may be too short to incorporate the full effects of episodic erosion from landslides and post-fire erosion; although these erosion events may be infrequent, they are likely to be important contributors to sediment flux over the long term.

*Outcome 2: Anthropogenically accelerated erosion dominates.* If the effects of episodic erosion are minimal and if land use has accelerated erosion in the recent past, then long-term averages of erosion rates could be systematically lower than the short-term averages. Such a pattern would suggest that anthropogenic factors (e.g., logging or grazing) are important contributors to the modern erosional flux. If this is the case, then it may be reflected in CNR profiles within soil columns; when the surface of a well-mixed soil is stripped away, the CNR profile will be truncated to a degree that reflects the depth of stripping (Granger and Riebe, 2007). Hence, if long-term erosion rates are slower than short-term averages, we should be able to test whether accelerated erosion of the recent past was accompanied by significant stripping of surface soils. This would have important implications for the biogeochemistry of the catchments, because of the tendency of nutrients to be concentrated in the upper levels of the soil profile, which are most prone to stripping. Hence these results should inform interpretation of soil nutrient data collected in other phases of the CZO project (e.g., by CZO Investigators **Dale Johnson** and **Ben Houlton**)

The possibility of soil stripping will need to be investigated in any case, because stripping has the potential to expose material with low cosmogenic nuclide concentrations that do not accurately reflect the long-term, background rate of erosion. To spot check soil profiles, and ensure that their CNR inventories are consistent with measurements from stream sediment, we will need to take an additional 8 samples of soil and saprolite for cosmogenic nuclide analysis.

*Outcome 3: Erosion rates are roughly similar across time.* If erosion rates are broadly similar at short and long timescales, it may suggest that there is little diversity in erosional processes. For example, it may be that the incremental day-to-day erosion measured in the sediment traps is able to persist steadily over the long term, without significant contributions from episodic erosion or recent anthropogenic disturbances. However, this seems unlikely given the diversity of processes in the catchments today and the history of land use in the region. For example, there are signs within the catchments of diverse processes such as shallow landsliding, headcut erosion, tree-throw, and down-slope creep (via bioturbation and freeze thaw), which should contribute sediment periodically to streams over a range of timescales, both long and short. Moreover, anthropogenic factors are likely to have perturbed erosion somewhat over the recent past. Taken together, anthropogenic factors and the apparent diversity of erosional processes make it unlikely that erosion rates will agree over the cosmogenic and conventional measurement timescales.

#### *The Soil Production Function*

The presence or absence of soils in mountainous landscapes reflects the interplay between erosional removal of soil and its production from saprolite at depth (Dietrich et al., 1995). Cosmogenic nuclides in saprolite and soil can help shed light on this interplay (Heimsath et al., 1997). If soil removal exceeds production, soils will become increasingly thin and eventually

vanish, leaving exposed saprolite or rock. Conversely, thick sequences of soils can develop if soil production outpaces removal. Soil production and removal may also be balanced such that soil depth remains roughly steady over time.

Whether soils tend to become thinner, thicker, or have steady thickness over time has profound implications for watershed hydrology and biogeochemistry, because bare rock (exposed when soil removal exceeds production) is able to quickly shed meteoric water, whereas a soil with steady or increasing thickness may retain water and thus make it locally available for biogeochemical processes and enhanced weathering. Decades of theoretical considerations (e.g., Gilbert, 1877) and modeling (e.g., Cox, 1980; Dietrich et al., 1995) suggest what field studies (e.g., Heimsath et al., 1997) have only recently been able to confirm—that the rate of soil production in hilly, temperate landscapes may often depend on soil depth. However, recent work by Dixon et al. (2009) suggests that soil production rates do not vary systematically with depth in the CZO landscape. Instead, the rate of soil production is nearly uniform, within uncertainties, over depths ranging from <20 cm to >100 cm both within the CZO (along a hillslope transect in the Providence Creek drainage) and at other localities nearby. Although the range of depths considered by Dixon et al. (2009) is nearly as broad as the range we have observed at the site, her data do not shed light on whether denudation rates for bare rock are higher or lower than denudation rates of soil mantled terrain. We expect that bare rock erodes much more slowly than soil mantled rock, and will test whether this is the case using CNR analyses of 20 samples of bare rock to characterize soil production rates under the condition that soils are absent.

Soil production rates, when integrated over the entire catchment, should roughly equate over long timescales with sediment delivery rates to channels and streams. We should be able to test whether this is the case by comparing our catchment-wide average erosion rates (from cosmogenic-based measurements of stream sediment samples) with catchment-integrated soil production rates. We expect that the most significant difference in soil production rates will be in a contrast between rates of production on bare rock and rates of production under a soil cover. Hence, to effectively integrate soil production rates over each catchment we will need to estimate the abundance of bare rock in each of the watersheds. Together, our data on soil production rates and bare rock abundance will also help us compare the catchment-wide soil production rate with short-term erosion rates inferred from sediment trapping data collected by **Hunsaker** in the core-measurement program for KREW watersheds.

*Stepped topography of the Sierra Nevada: quantifying hydrologic controls on weathering rates*

The Southern Sierra Nevada Critical Zone landscape exhibits both bare bedrock (typically near the ridges) and soil-mantled topography (typically at midslope and lower, near channeled and unchanneled valley axes). This juxtaposition of bare and soil-mantled topography is common in granite (the underlying bedrock at the CZO), despite the apparent tendency towards steady soil thickness in other granitic landscapes (Heimsath et al., 1997). The dichotomous presence of bare granite and granitic soil (or gruss) was cited as an explanation for the apparent broad-scale organization of Sierra Nevada topography into an inter-fingered set of steep “steps” and gentle “treads,” that account for step-wise increases in elevation to the east (Wahrhaftig, 1965). More specifically, Wahrhaftig (1965) proposed that this so-called “stepped topography” arose due to hydrologic control of weathering rates.

*Hypothetical mechanism for developing stepped topography.* According to Wahrhaftig (1965) bare rock sheds water more quickly and therefore does not weather as quickly as soil-mantled rock. Over time, he argued, this should drive the formation of a series of bare steps that shed water, never develop a soil, and thus erode relatively slowly (and thus become more pronounced

in relief) compared to the more gentle treads which remain soil covered and thus can more effectively hold moisture (which in turn promotes further weathering and thickening of the soil). Although Wahrhaftig's (1965) hypothesis has been invoked to help explain the juxtaposition of steep and gentle terrain elsewhere in granitic terrain of the Sierra Nevada (Granger et al., 2001), it has never been tested in the "type" section of Wahrhaftig's observations, in the southern Sierra Nevada. In this study we will be able to readily test Wahrhaftig's (1965) hypothesis in the very heart of the "steps," because it encompasses the Southern Sierra Nevada Critical Zone Observatory catchments. The soil moisture data, collected in other phases of the CZO project (e.g., by **Hopmans, Johnson, and Bales**), will be crucial in investigations of this hypothesis, because of the insight the data will yield about the proposed link between moisture and weathering rates.

*Verification of the existence of the steps.* As part of this analysis, it will be crucial to first test whether there really is a topographic signature of stepped topography that needs to be explained. Do the steps and treads actually emerge from an objective, computational analysis of the topography? If so, are they as regular and pervasive as Wahrhaftig (1965) suggested? In the early 1960's, when Wahrhaftig was drafting his paper, methods for analyzing topography were crude and much more subjective than the methods we have at our disposal today. It is possible that Wahrhaftig's (1965) maps of the steps exaggerate their pervasiveness. For example, many of the biggest (i.e., highest relief) steps are shown to occur along river canyons (Wahrhaftig, 1965). This potentially misrepresents the mechanism of canyon formation, which presumably depends on river incision, rather than any moisture-driven differences in weathering rates on slopes. To quantify the existence and pervasiveness of steps we will reduce Digital Elevation Model (DEM) data from the landscape into a series of topographic indices. If the stepped topography is as pervasive as Wahrhaftig (1965) suggests, we expect the landscape should group roughly into three zones. On steps we expect to see roughly planar slopes (i.e., with high hillslope gradient and low curvature). At step-tread transitions, we expect to see high curvature and intermediate gradients. On treads, we expect to see low gradients and low curvature. Hence, if the steps are pervasive, the landscape should be roughly organized into three zones on a gradient-versus-curvature plot. By itself, such a three-zone plot would not be uniquely diagnostic of "stepped topography." To corroborate the supposedly ubiquitous existence of alternating steps and treads, there would need to be an identifiable eastward-trending cyclicity of topographic parameters, from high-gradient/low-curvature to intermediate-gradient/low-curvature to low-gradient/low-curvature and so on, marking steps, step-tread transitions, and treads (respectively) in sequence. To complete this task, we would ideally need 1-m LIDAR data for the watershed. However, it may be possible (given the purportedly large (~100 m) scale of the steps) to conduct this analysis with 10-m DEM data.

*The soil production function and soil depth as a test of the stepped-topography hypothesis.* If it turns out that the steps are as salient as Wahrhaftig (1965) suggests, and if he was correct in suggesting that hydrologic control of weathering is the mechanism behind the stepped topography, then we should expect to see a particular pattern of soil production rates as a function of depth. Namely, we expect that steps should be eroding significantly slower than treads. We will need to analyze an additional 20-30 samples for CRN, to determine whether this is the case.

We should also be able to leverage soil moisture measurements from other facets of the CZO project (**Johnson, Hopman, and Bales**) for improved understanding of controls on variations in rates of soil production and chemical weathering across the watersheds. (Methods for measuring long-term chemical weathering rates are described in the next section.) This should

enable a direct test of the Wahrhaftig's (1965) hypothesis about hydrologic (i.e., moisture-related) control of erosion and weathering in soils in the region.

Taken together, the combination of topography, soil depths, soil moisture, and CNR measurements will set this study apart as an important test of Wahrhaftig's (1965) long-standing hypothesis about hydrologic controls on weathering rates.

#### *Chemical weathering rates from solid phase mass balance*

We will also compile a suite of long-term, baseline measurements of chemical weathering rates for each of the catchments within the CZO. These measurements rely on the bulk chemistry and mineralogy of samples of soil, saprolite, and protolith to quantify weathering losses that occur as minerals are exposed to meteoric water during exhumation to the surface (Riebe et al., 2001; Stallard, 1985). In earlier versions of the work plan, we expressed initial concerns that our approach to making long-term weathering rate measurements would be hindered by site-to-site heterogeneity in the underlying bedrock composition across the CZO. We estimate that we will need to sample and analyze approximately 600 samples of soil, 200 samples of saprolite, and 200 samples of rock by XRF (to measure bulk chemistry) and XRD (to measure mineralogy). We will also need to prepare 100 thin sections for characterization of bedrock mineralogy.

Finally, with the in-kind support of a new collaborator, **Tony Dosseto** (University of Wollongong, Australia), we should be able to employ new isotopic methods (Dosseto et al., 2008) to yield a new quantitative perspective on the timescales of weathering in the CZO. Although the cosmogenic nuclides techniques described above represent a powerful approach for interpreting rates of landscape denudation and soil production from saprolite, they do not generally yield any information about the timing of the initiation of weathering at the regolith/rock interface, which is often meters below the surface, below the penetration lengthscales of cosmic radiation. In contrast, recent applications of U-series isotopic dating shows promise in the quantification of weathering timescales (Dosseto et al., 2008) and we are fortunate to have enlisted one of the field's leaders for support in some preliminary U-series analyses at the CZO. No analysis costs are required for this in-kind support, but we will cover Dosseto's expenses for one field visit in August 2010.

*Funding* Mostly CZO with some leveraging from ETH and U. Wyoming (in the form of on-site measurements) if possible.

Schedule, including field work. Collection of soil, rock and stream sediment samples, beginning Summer 2009 (initial pilot samples have already been collected); analysis of topographic data beginning fall 2009 and continuing through 2010; analysis of samples beginning winter 2010; GPR and shallow seismic surveys beginning fall 2010; additional sampling of rock and soil as needed in summer 2010. Fall 2010 continued analysis and interpretation of data.

Manuscripts in progress & planned. TBD. Need data from core measurement program and need to coordinate with Carolyn Hunsaker for access to sediment trapping data. Data from moisture probes also needed.

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Topic. **Snow processes**

Investigator. **Noah Molotch**, UCLA

Students & research staff. Keith Musselman, PhD student

**Scope.**

Wolverton basin snow distribution. Snow surveys and mapping.

Providence Creek studies. TBD

**Funding.** Largely leveraged

Schedule, including field work. Wolverton Creek in progress. Providence Creek TBD.

Manuscripts in progress & planned. TBD (include data sets used/needed)

Topic. **Biogeochemical processes/cycling**

Investigator. Discussions with additional investigators in progress

Students & research staff. TBD (graduate fellowship available at UC Merced)

**Scope.** TBD.

Schedule, including field work. TBD

Manuscripts in progress & planned. (include data sets used/needed)

## Findings

**Summary.** Results from the CZO research over the past 4 years are described in several papers that are published, submitted and in preparation (year 1 was a start-up year with only partial funding). Some highlights of more-mature results follow.

- The water-balance instrument cluster, with its over 380 individual sensors and other characterization, is giving an unprecedented window on the catchment-scale water cycle. Snowpack, soil moisture, evapotranspiration (ET), runoff, and catchment water yield all vary systematically across the elevation (temperature) gradients of the rain-snow transition in the Southern Sierra Nevada.
- The deeper regolith (below mapped soils) is critical for supplying water for ET and baseflow in streams for several months each year. At least the saprolite layer is important for water storage, as roots extend into this layer.
- End-member mixing analysis confirms that streamflow is dominated by a combination of near-surface runoff and baseflow, with storm runoff being a much smaller contributor.
- Sap flow in intensively instrumented trees tracks soil moisture and matric potential from spring through late summer each year.
- Our water-balance instrument-cluster design, using strategic sampling, can capture both the spatial average and spatial patterns of water-balance variables. This design is being replicated at other locations.
- Vegetation transpires year round, in contrast of climatological indices of water deficit that predict significant summer shutdown as soils dry and winter shutdown due to sub-freezing air temperatures.
- Spatial patterns of snow accumulation, snowmelt and soil moisture depend in a systematic way on temperature and solar radiation, as indicated by elevation, aspect, slope, and canopy cover.
- Meadow groundwater levels and ET respond in a coordinated way with the water balance in the surrounding forest, indicating a high-degree of year-round hydrologic connectivity despite travel times for water that are much longer than response times.
- Cosmogenic nuclides and terrain analysis of the stepped topography of the CZO area show that the steps are often soil-mantled as often as the treads, and that erosion rates of treads are lower than erosion rates on steps. This is directly counter to the classical hypothesis for formation of the stepped topography.
- Nutrient hotspots in soil, or a high degree of heterogeneity in nutrient fluxes, were found to be present for all solutes studied, and were not correlated with locations of preferential water flow.



**Core CZO and KREW Measurements and Data Management.** Measurements of precipitation, snow accumulation and melt, streamflow, soil moisture and meteorological variables from a multi-year database have undergone analysis to assess the hydrologic and geochemical response of rain-dominated versus snow-dominated catchments.

Figure 1 shows the measured snow water equivalent (SWE) and cumulative precipitation measured for the upper, snow-dominated Bull watersheds and the lower, rain-dominated Providence watersheds for 2005 and 2006. For both years, cumulative precipitation is similar for the upper and lower watersheds. Snow at lower elevations exhibits multiple accumulation and melt cycles throughout the cold season. Snow at higher elevations exhibits a single main melt period in spring. The Bull watersheds show a greater fraction of cumulative precipitation comes in the form of snow.

Figure 2 presents cumulative discharge for all eight of the KREW watersheds. The lower watersheds, depicted with dashed lines, indicate that mean cumulative discharge occurs earlier than in the upper watersheds, depicted with solid lines, in both the wet and dry precipitation years presented. Earlier runoff in lower elevation catchments reflects the greater proportion of rainfall.

Figure 3 shows a subset of the ground-based water balance instrument cluster data; soil moisture and temperature at 11 instrument nodes. These data show soil wetting and drying cycles and corresponding soil temperature at different depths. Soil moisture declines rapidly in the first week after snowmelt has ceased, followed by a more-gradual decline thereafter.

Local difference in the timing of soil drying between north versus south aspects and shaded versus open sites are about one month, comparable to elevation differences in the average response. These responses are related to variability in snow melt timing at the instrument cluster sites. Water content measurements recorded at the instrument nodes as part of the water balance transects are doing a good job of capturing the variability of the Providence watersheds (see Snow and Soil Processes section).

**Wireless Sensor Network.** The ability of the wireless sensor network to capture catchment-wide snow depth and soil moisture variability was confirmed by comparison to LIDAR data and multiple comprehensive synoptic surveys (Figure 4). The stratified sampling strategy of the network was particularly effective in capturing the distribution of snowdepth (Figure 5), both when compared to LIDAR data and synoptic surveys. Given this agreement, it is evident that a stratified placement strategy based on evenly instrumenting major physiographic parameters performs well with regard to characterizing the distribution of catchment-wide snow depth at the km<sup>2</sup> scale. Increases in soil moisture variability over the spring period explained the lack of agreement between the synoptic survey and data collected by the network. This was attributed to small-scale soil moisture variability that cannot be captured by a sparse stratified sampling strategy.

*Spatiotemporal variability of soil moisture and snow depth.* Canopy cover was the major explanatory variable of snowdepth variability (Figure 6). Furthermore, the overall variability of snowdepth was highest under canopy, as has been suggested by a number of previous studies. These studies used sparse surveys to propose this variability behavior. With the high density spatiotemporal data collected at our catchment however, we were able to validate these claims in detail, showing a temporal stability in this variability behavior. We also witnessed a significant decrease in snowdepth variability during springtime for sensor nodes located near drip edges of trees, something which has not been observed in previous studies, and which is most likely guided by a complex interaction of long wave and short wave radiation during the spring period. Furthermore, our findings regarding soil moisture variability showed an increase

in variability at deeper soils (Figure 7). A clear convex relationship between mean soil moisture and variability was only evident at shallow soils. These findings agree with similar, but less spatiotemporally dense studies in mountain catchments, and suggest a specific variability behavior for soil moisture in complex mountain terrain.

*Spatiotemporal variability of evapotranspiration.* A cross-CZO effort was conducted to compare estimates of evaporations derived from wireless sensor network readings, the eddy flux tower, a hydrologic model, and a number of wells. This project was the result of tight collaborations between graduate students at four different CZO institutions and the findings were presented at the 2011 AGU meeting. The results showed that the ET estimates at eddy flux tower were equal to the snow water coming into the forest. The trees thus use up most of the snow water deposited during the winter. Furthermore, ET estimates made by wells and sensor nodes within the forest were equal to those made by the eddy flux tower. This suggests that the meadows are the main source of springtime runoff, and that runoff is proportional to the contributing meadow areas.

**Snow and Soil Processes.** Observations made during the three snow surveys and two soil moisture surveys from WY2010 have been compared to observations made by the ground-based water balance instrument cluster. Figure 8 shows that the variability in snow depths observed during the surveys were also observed by the sensor network. Approximately 30 cm of melt occurred between the first and last survey. The mean snow depths observed by the network were 131, 107, and 101cm, while survey means were 137, 121, and 103cm. The network means were within 2 to 14cm of the survey means, with the smallest difference occurring during the April peak accumulation survey. During the April 7, 2010 survey, snow depth observations ranged from 20 to 239 cm, while the Network ranged was 8-222cm. Observations during the March 14th and March 20<sup>th</sup>, 2010 surveys included no-snow observations. However, the network did not observe any zero values.

Figure 9 shows that the variability in soil moisture observed during the surveys were also observed by the sensor network. The instrument cluster observations are from 10-cm probe, survey observations are from integrating over top 20 cm of soil. Some of the outliers with high volumetric water contents were located in meadows or near streams. Both the network and the survey observations were about 11% drier during the September survey. The mean volumetric water contents observed by the network were 22 and 11%, while survey means were 19 and 9%. The network means were within 2 to 3% of survey means, which is within the error of the soil moisture sensors. Zero values reported during the survey are grid locations that are bare rock. Ignoring the zero values the June survey ranged between 2 and 67% volumetric water content and the September, 2010 survey ranged between 4 and 43%. The network volumetric water content observations ranged between 6 and 52% in June, and between 2 and 49% in September, 2010.

For the April 7-9, 2010 peak-accumulation survey, we used a Gaussian process non-linear regression model to predict snow depth throughout the basin. The model used a 30-m DEM along with our network observations to model the snow depth distribution and is based on variables that include: solar radiation, slope, aspect, elevation, and northness (Figure 10). We estimated the error of this model by comparing the model predicted snow depths to the snow depth survey observations (Figure 11). Spatial proximity to sensors is not indicator of model performance. Rather, prediction error is directly tied to ability to capture the physiographic features of solar radiation, slope, aspect, elevation, and northness with the instrument cluster observations. The average predicted depth was 106 cm with a mean error of 35 cm. That said, the preliminary result from the model gives about 33% error while using less than 50 network observations.

Because a 30-m DEM was used for this analysis, multiple sensor nodes are incorporated into a single pixel, which reduces our usable number of network observations.

We have captured the dynamics of the soil profile desiccation at various depths beneath the snow pack as it transitioned from saturated to very dry conditions. Tensiometer data within the plot shows the cessation of drainage out of the root zone by early July, leaving an extended period (3+ months) of drying of the soil profile and an estimate of actual ET (Figure 12). Through monitoring of sap flux and periodic leaf water potential measurements, we tracked the activity of the trees as they responded to changing available moisture in the root zone. Water content, temperature, and soil water potential were measured in six vertical pits across the site. Soil water mass balance was used to estimate ET rates using average VWC from the vertical pits. We found remarkable similarity between independent estimates of ET in the trunk and of water removal from the soil. More than 40% of annual ET takes place during this period where soils <90cm are extremely dry (Figure 13). On an annual basis, soil moisture removed from this shallow layer accounts for only a fraction of the total mass loss. Root zone excavation results show limited root extension into deeper layers. How are the trees accessing this deeper moisture? One possibility is that the trees themselves, or successive generations of trees, have created depressions in the saprolite, through chemical activity, where water can be stored locally. Limited measurements seem to indicate an increase in soil depth beneath the trees (Figure 14).

The sensors were reactive to moisture and temperature variations on multiple timescales. Data show the dynamic response of soil moisture to precipitation, snow melt, and changes in vegetative demand. We demonstrate here the initial two years of a multi-year deployment of soil moisture sensors as a critical integrator of hydrologic/ biotic interaction in a forested catchment as part of a wider effort to document ecosystem response to changing environmental inputs. Sap-flow sensors were responsive to fluctuations in air temperature and solar radiation and values declined along with soil moisture availability. Each tree was instrumented with four sensors and variability was seen around the stem. While the magnitude of total flux may contain considerable uncertainty, the timing is very consistent and can be used to determine when trees are transpiring (Figure 15). Leaf water potential values were measured over a 24 hour period, once per month during the summer drying period and corresponded to changes in available soil water.

Volumetric water content (VWC) was recorded at P301 and Soaproot Saddle using COSMOS, multiple embedded sensors, and during handheld TDR and soil sampling surveys during 2011 (Figure 16). The TDR array observations were the lowest, approximately 3.5 to 6% lower than the COSMOS observations. The embedded sensor networks that use the capacitance sensors (CZT-1, CZT-2 and IC-Transect) observed approximately 1-4% higher VWC than the COSMOS. The COSMOS and the embedded sensor networks effectively observed trends of snow disappearance and soil drainage throughout the summer and fall. All of the *in situ* soil moisture observations responded to precipitation which occurred several times from June to October. VWC of soil samples and Handheld TDR surveys agreed better with the embedded sensor networks than with the COSMOS at P301. However, the soil samples and the Handheld TDR surveys correspond well with the COSMOS at Soaproot Saddle (Figure 16). VWC's of soil samples were more variable than VWC observed with the Handheld TDR, although the magnitude of this variability was not consistent between surveys. VWC observations made by the TDR arrays never corresponded to soil samples or Handheld TDR observations. However, the TDR arrays do have similar seasonal and storm response trends.

VWC is not distributed evenly across the landscape. The distribution of VWC from soil samples and Handheld TDR measurements (Figure 17a) show highly variable soil moisture surrounding the

COSMOS sensor, which is not represented in an area average. Soils at P301 dry out from July to September, then show increase in moisture after rain in October (Figure 17b). These moisture plots show areas that retain moisture. P301 has a small meadow within the plot (SE wet zone on Figure 17c), and is also influenced by a large meadow (Northern wet zone). Rock outcrops and streams also influence the moisture patterns within these plots.

**Water, geochemical cycles, and upscaling of in-situ measurements.** Day of snowcover melt out measured in the Wolverton basin ranged 55 days with the mean being 10 days earlier for the aspect tree and then the north aspect tree (Figure 18). Data from three years of surveys was analyzed for snow depth difference between under canopy and open locations (Figure 19). These surveys indicate greater variation in depth occurs in seasons with less snow suggesting decreased snowpacks will result in greater spatial variability. Similar spatial patterns persist each year with patterns being most pronounced in the very dry 2007 water year and least pronounced in the wettest water year analyzed (2008). Data from the California Cooperative Snow Survey course located in the study area indicate precipitation was below average in 2007, above in 2008, and close to average in 2009. The mean depth for all measurements was 74.5 cm, 191 cm, and 135 cm, respectively, with 51, 24, and 35 percent difference between the under canopy and open measurements. Soil moisture records indicate melt started prior to the snow surveys in 2007 (March 10-27) after the survey in 2008 (April 10-May 15) and close to the time of the surveys in 2009 March 25 – April 18).

Spatial heterogeneity in snow depth, density, and soil moisture infiltration are influenced by orientation to and proximity with tree canopies. Differences between the open and under canopy are most prominent in locations that have high solar incidence during ablation. Conversely, snow lingers in forest gaps that are shaded by large canopies. Density measurements are higher by up to 40% in some under canopy locations suggesting snow melting off canopies and refreezing in the snowpack during the accumulation period.

Spatial interpolation of the percent difference between open and under canopy depth measurements show the largest differences between under canopy and open snowpack on April 1<sup>st</sup> are found in locations with the highest solar insolation following the last major storm of the accumulation period. However, modeled clear-sky irradiance does not fully explain the distribution because the effects of forest structure and canopies are not taken into account. Canopy interception and redistribution of snow and their influence on the energy balance are also important.

Long and short wave radiation plots for south and north aspect trees are presented in Figures 20 and 21. Future work will focus on using established relationships between canopy cover and incoming radiation to predict under canopy ablation to enhance the accuracy of snow cover prediction made in forested areas using Moderate-resolution Imaging Spectroradiometer Snow Covered Area images.

The percent snow cover determined by MODSCAG from peak accumulation and melt out during the 2008 and 2009 water years were compared to ground observations of both forest gaps and under canopies. Ground based measurements indicated that under-canopy melt out of snow-covered area began earlier and ended 1 to 4 weeks after that indicated by satellite observations, which can only view snow in forest gaps. In our study ablation rates, snow cover duration, leaf area index, canopy closure, and Incoming short and long wave radiation were measured on north and southeast facing plots in a subalpine red fir forest. Results from regression analysis yield an  $R^2=0.99$  between modeled and measured short wave radiation and an  $R^2=0.82$  between leaf area index and the difference between open and under canopy thermal infrared radiation. Canopy cover and leaf area index were also found to be good predictors of observed

melt rates and the melt off date of snow under tree canopies. This approach provides a basis for estimating under canopy ablation and, in conjunction with MODSCAG estimates of snow covered area in forest gaps, an accurate prediction of total snow cover in forested areas.

### **Mountain Front Precipitation Accumulation over a 1700 m Elevation Gradient.**

**Figs 22, 23 here**

**Coupled Soil Tree Hydro-Dynamics.** Key scientific findings include: seasonal water content changes, measurements of ET and drainage from the plot, estimates of changing snow depth and soil moisture contents based on canopy cover and interception, and comparison of soil/tree water relationships between two sites with varying species, slope and aspect. Soil-water balance data contributed to a better understanding to watershed- scale water balance. The radial network of shallow MPS-1 sensors show a distinct pattern of shallow soil water depletion over the course of the summer (Figure 24) that is related to both aspect and canopy/root architecture.

Interpretation of the soil matric potential measurements indicate significant spatial variations in root water uptake, likely controlled by presence of roots, with temporal variations partly determined by root water compensation, with larger proportions of root water uptake occurring in the root zone domain with the least water stress, to compensate for reduced root uptake in the water-stressed regions of the root zone domain.

We determined that the majority of the roots and nearly all of the fine roots were in the top 60 cm, with the root density highest from 30-60cm (Figure 25a). The root distribution was axial symmetric around the tree, with the maximum root density at about 2 m radial distance from the tree trunk (Figure 25b). Below 2m, the soil quickly transitioned into saprolite and saprock, which is difficult for tree roots to penetrate, because of its low porosity and density. Figure 26 shows the conceptual model of the subsurface based on the root excavation, coring and geophysical results for both CZT-1 and CZT-2, emphasizing the shallow soil with corresponding low values of soil water storage for CZT-2.

The relative agreement between ET (Evapotranspiration) rates as measured from tree sap flow measurements and estimated from flux tower eddy covariance measurements near CZT-1 and CZT-2 is presented in Figure 27. Though the flux tower measurements are directly computed by summing hourly ET data, the sap flow derived ET was estimated by the ratio of seasonal to annual sap flow, disregarding uncertainty in the absolute sap flow data. Though the foot print of the two types of measurements is very different, the agreement between the relative ET values across the four yearly seasons is very good.

*Analysis of DVP monitoring.* Measurement of soil water content and sap flow for the two monitoring trees during summer 2011 show sap flow (mm/day), in CZT-2 (shallow soil) declining simultaneously with decrease in soil moisture storage changes (Figure 28a), whereas sapflow at CZT-1 continues to remain relatively high despite similar declines in the shallow soil moisture (Figure 28b). The additional DVP measurement results in Figure 28b indicate that CZT-1 is exploring water storage at the larger soil depths, and increasingly so as the shallow soil water becomes unavailable.

Based on DVP measurements, we believe that in addition to deep roots and mycorrhizae water uptake, there is evidence of upward capillary movement from the deeper weathered rock matrix or saprolite/saprock towards the rooting zone. Figure 29 illustrates this point, presenting total soil-water potential (sum of gravitational and matric potential) with corresponding soil-moisture data during August and September, 2011, as determined from tensiometer and ECH<sub>2</sub>O-5TE soil moisture measurements at depths of 120, 150 and 250 cm at the DVP site. The data show periods of both downward gravity and

upward capillary flow, magnitudes can be computed using Darcy's Law from laboratory-measured unsaturated hydraulic conductivity. Noting that soil water moves from high (less negative) to low (more negative) total soil water potential, the data in Figure 29 show that soil water moves downwards below the 150 cm depth in August, but moves upwards across the 250 cm soil profile after August 31, as indicated by the direction of the arrows.

*Critical zone tree (CZT) modeling.* Optimized tree water relationships, as determined from the inverse modeling of the soil-tree domain, are presented in Figure 30. The water retention curve for the tree is in good agreement with literature data, whereas the optimized relative hydraulic conductivity function is shifted when compared with the literature, however their shapes are similar. We note that measurement of tree hydraulic relationships is typically done with small branches or wood cuts, whereas our estimates are based on whole tree effective measurements.

An example of a comparison of measured with simulated data, on which the optimized tree water relationships are based, is presented in Figure 31. As the data show, the numerical modeling was done for an 18-day period only, starting July 15, 2009, and show a fair agreement between measured and simulated sap flow, tree stem water potential and soil water storage measurements. The top panel shows the large reduction in actual ET (green), relative to potential ET (blue), thus indicating significant reduction in tree transpiration as constraint by soil water availability.

**Surface-groundwater interactions.** Results from the constructed meadow pool energy balances are presented in Figure 32. Positive heat fluxes indicate heat coming into the pool and negative fluxes are heat lost from the pool. These data show that both the summer (top panel) and the fall (lower panel) clear sky energy balances are dominated by the incoming shortwave radiation coming into the system and latent heat and back emitted LW radiation leaving the system. These data represent the final stage of analysis for the pool thermal stratification study. A manuscript for this study is near completion.

Groundwater elevations and calculated ET for edge, slope, near stream, and saprock wells in Long Meadow are presented in Figure 33. The ground water elevations have been shifted (190, 150, 100, and 85 cm subtracted from the edge, slope, near stream, and saprock wells, respectively) in order to show the diurnal variation of the levels in the displayed wells on the same plot. All four wells exhibit similar timing of groundwater drawdown and recovery. The edge and saprock wells share similar magnitudes in variation between daily maximum and minimum groundwater elevations. The near stream well exhibits muted variation and the slope well exhibits larger variations as compared to the edge and saprock wells. The calculated ET from the wells show that the edge and saprock wells share similar values of daily evapotranspiration. The meadow slope well tends to have greater ET values than the edge and saprock wells, while the well near the meadow stream is lower than any of the other wells. The similarity in the diurnal behavior and calculated ET of the edge and saprock wells suggests that the meadow edge well is a good indicator of forest ET processes that dictate the behavior of the saprock groundwater. The relatively low groundwater contribution to ET exhibited by the near stream meadow well indicates that the meadow vegetation near the stream is largely utilizing readily available surface water. The large diurnal variation and calculated ET exhibited by the slope well suggests that the diurnal swing in ground water table in this part of the meadow is affected by both forest and meadow ET processes.

ET trends were also investigated in P301 meadow. Some of these results are displayed in Figure 34. The top panel in Figure 34 presents ET as measured by an ET chamber and PET calculated from the meadow met station. Chamber measurements of ET generally fall below the calculated PET. The bottom panel of Figure 34 shows daily values of ET calculated from the saprock and meadow

groundwater monitoring wells and daily PET calculated from the meadow met station. The groundwater contribution to ET calculated from both the saprock well and the meadow well fall below calculated PET. The saprock well exhibits greater groundwater contribution to ET than does the meadow well. The meadow well seems to show behavior similar to that of the near stream well in Long Meadow; the meadow vegetation appears to be utilizing readily available surface water for much of its evapotranspirative demand. The saprock well shows that much more of the evaporative demand at this location is met with groundwater. When compared with daily ET rates measured at the P301 flux tower, ET daily ET signal from the saprock wells is of similar magnitude for much of the summer growing season (Figure 35). This suggests that much of the evaporative demand of the forest is met with groundwater contribution from the saprock.

The trends described between groundwater table behavior, meadow and forest ET are currently being worked into a manuscript.

In order to assess source contribution to the meadow outlet streams, water samples were collected periodically from the streams, meadow and saprock wells, and snow. These samples were analyzed for stable water isotope composition and major ion concentrations. Initial results (not shown) indicate strong linear relationships for calcium-sodium, calcium-magnesium, and sodium-magnesium in both P301 meadow and Long Meadow. The linear relationships suggest that these major cations can be conservative tracers for the meadow systems. We will use these data and results from the analysis of stable water isotope samples in order to conduct end member mixing analysis of the meadow outlet streams. Ultimately, we hope to parse out the seasonality of the different sources to the streams coming out of the meadow systems. These analyses should result in the production of a manuscript.

**Physical Controls on Water and Carbon Exchange and Plant Production.** The low elevation (380 m) tower shows peak photosynthesis in late winter and spring and reduced carbon uptake during summer drought (see Activities Figure 11). The 2020m tower indicates forest photosynthesis is not markedly reduced by either midwinter cold (despite a very heavy snowpack) or late summer drought. Preliminary observations at the 1200m site also show high rates of photosynthesis continuing in late summer and winter. The 2710m tower indicates winter photosynthetic shutdown down at higher elevations. The trees at 2710 m are dormant during the winter, and active photosynthesis is not observed even on warmer days. There is a very sharp phenological threshold between 2020 and 2710 m that roughly coincides with the daytime freezing line and that results in a much shorter growing season up high.

Sap-flow data (Figure 36) show a similar seasonal pattern of canopy gas exchange. In late August, the ecosystem should be experiencing maximum summer drought stress. We find that cooler temperatures in late summer allow more CO<sub>2</sub> uptake, and upper canopy temperatures are cooler than surface temperatures. This confirms the trees at the P301 site do not cease active gas exchange in summer due to drought and suggests the cooler upper canopy mitigates the limitations on productivity of summer drought.

Ongoing measurements are revealing trends in biomass, net primary production (NPP), and carbon turnover rate along the climate gradient (see Activities Table 1). Biomass increases with elevation, peaking at 2020 m and diminishing somewhat above. Aboveground NPP (ANPP) broadly follows this trend, except at the highest site, where ANPP declines disproportionately. The difference between ANPP and biomass drives a shift in carbon turnover time; the biomass at 2710 m turns over at only one quarter the rate observed at the lower sites. This shift in carbon residence time has implications for the ability of these forests to sequester and hold large carbon stocks.

The very sharp reduction in ANPP from 2020 m to 2710 m coincides with the threshold where winter photosynthesis becomes impossible. The 2020 m site, and, to a lesser extent 1,200 m site, exist in a climatological “sweet spot” where photosynthesis continues year round (see Activities section Figure 14). This helps explain the large forest stature, high standing biomass, and high productivity of these ecosystems. We see significant summer drought limitation below this belt (at the 380 m elevation site) and significant cold limitation above the belt (2710 m site). With projected climate warming and drying, we expect a decrease in biomass and NPP at lower elevations, an increase at upper elevations, and unknown changes at the middle elevations.

Some upgrades to the flux towers for the coming year include rebuild the tower at Courtright, rework the power supplies and replace batteries at existing sites, install a high elevation site in order to capture high elevation evapotranspiration, and upgrade the Soaproot and P301 IRGAs which will decrease the many data gaps in the winter due to winter activity. This will reduce data loss during extended cloudy periods.

### **Importance of sub-watershed spatial heterogeneity in ecohydrological modeling for assessing climate change impacts on Sierra mountain catchments.**

Many hydrological models have been used to assess the impact of climate change on ecohydrologic response at watershed scale or larger scales (Null et al., 2010, Miller et al., 2003, Knowles and Cayan, 2002). However, the models tend to have a coarse spatial resolution and thus ignore the fine-scale variation of topography and vegetation structure. Topography and vegetation are key variables for characterizing patterns of snow accumulation and melt (Josh et al, 2009, Musselman et al., 2008) as well as modeling ecologic and hydrologic processes (Zhang and Montgomery, 1994, Laussuer et al., 2006). Moreover, mountain watersheds have high heterogeneity in topography, vegetation over relatively short spatial scales. Therefore, a key challenge in modeling for climate change assessment of mountain watersheds is how to account for high spatial heterogeneities of topography, vegetation in mountain watersheds. In this study, we assess impact of spatial resolution of the RHESSys model input (topography and vegetation) on the model performance (streamflow) and the estimations of the ecohydrologic variables (snow, ET, streamflow, and NPP) in response to climate change and variability of the CZO watersheds (Figure 37).

We test the impact of DEM resolutions on the model streamflow accuracy and estimate of ecohydrologic response to inter-annual climate variability. We used the 1m-LIDAR DEM for deriving the Providence watershed boundaries, and 5m-LIDAR DEM for deriving the Bull watershed boundaries. In addition, the LIDAR DEM was used to estimate the snow-related parameters (elevation, slope, aspect and east-west horizon), and flow-related parameters (flow direction, accumulated area and slope). The model resolution test was conducted with the various DEM resolutions products (5m, 10m, 30m, 90m and 150), which were derived with using a bilinear interpolation scheme in the ArcGIS. The snow parameters were estimated by comparing the model estimate of SWE with measured snow depth at climate stations. The soil parameters were calibrated by comparing the predicted streamflow of each resolution models with measured streamflow. The predictive performance of the model being considered is evaluated using a combination of three objective functions (multiple objectives). The definitions of these objective functions are:



$$\begin{aligned}
R_{eff} &= 1 - \frac{\sum_i (Q_{obs,i} - Q_{sim,i})^2}{\sum_i (Q_{sim,i} - \overline{Q_{obs}})^2} \\
R_{log\,eff} &= 1 - \frac{\sum_i (\log(Q_{obs,i}) - \log(Q_{sim,i}))^2}{\sum_i (\log(Q_{sim,i}) - \log(\overline{Q_{obs}}))^2} \\
PerErr &= \frac{(\overline{Q_{sim}} - \overline{Q_{obs}})}{\overline{Q_{obs}}} \times 100 \\
Accuracy &= R_{eff} \times R_{log\,eff} \times (1 - \left| \frac{PerErr}{100} \right|)
\end{aligned}$$

**Equation 1**

Where  $Q_{obs,i}$  is the observed streamflow and  $Q_{sim,i}$  is the simulated flow at any given time step (i), and  $\overline{Q_{obs}}$  and  $\overline{Q_{sim}}$  are the long-term average of streamflow. Note that the accuracy (equation 1) combines different aspect of flow prediction; high flows ( $R_{eff}$ , Nash-Sutcliffe, 1970), low flows ( $R_{log\,eff}$ ) and total volume error of flows ( $PerErr$ ).

Figure 38 shows that the model accuracy of all the Providence and Bull watersheds declines with coarsening DEM resolutions. In general, there is a clear threshold resolution (30m) above which coarser resolutions can significantly impact streamflow prediction accuracy. Individual watersheds show much greater sensitivity to resolution and in general streamflow estimation for the Bull watersheds was less sensitive to coarsening DEM resolution than for the Providence watersheds.

We also investigated the sensitivity of estimated ecohydrologic responses (summer streamflow, annual streamflow, annual ET and annual NPP) to inter-annual climate variability with various DEM resolutions. In general, results show that model resolution can significantly impact ecohydrologic estimation and their sensitivity to climate. For example, for the D102 watershed, estimates of ET were significantly lower for coarser resolutions. Summer streamflow estimates show an interesting switch between high and low inter-annual variations as resolution increases from 30m to 90m (Figure 39). Finer resolution models estimate an intermediate inter-annual variation in summer streamflow. NPP estimates show the highest rates of NPP for 5m resolution but lowest NPP estimates for the slightly coarser 10m resolution. Only the 5m resolution model shows a significant increase in NPP with annual precipitation. Results highlight model resolution can alter both magnitude and climate sensitivity of eco-hydrologic estimates.

Next steps in this work will test the impact of vegetation parameters (LAI, canopy fraction, rooting depths and litter biomass) on the estimates of ecohydrologic response to climate variability. We have multi-resolution and multi-sensor products of LAI and canopy fraction; LIDAR-LAI and canopy fraction products with various resolution (5m, 10m, 30m, 90m and 150m), Landsat TM- LAI and canopy fraction products with the 30-m resolution. We will compare the model estimates using field-measured litter biomass with the estimates using vegetation dynamics routine in the RHESSys in terms of ecohydrologic response to inter-annual climate variability.

*Strategic sampling microclimate, soil moisture and sapflux for improving ecohydrological predictions.* In snow-dominated mountain systems, climate change alters streamflow generation patterns through changing the timing and magnitude of moisture inputs as precipitation and snowmelt and through changes

in the timing and magnitude of evapotranspiration losses. The net effect of climate change on streamflow generation patterns and associated ecosystem processes ultimately depends on the interaction between changes in inputs and outputs and on vegetation, micro-climate and soil properties. In mountain environments, steep spatial gradients result in substantial variation in atmospheric forcing and vegetation and soil properties over relatively short spatial scales, which necessitate providing finer-scale assessment of climate change impact. Measurements of soil moisture and forest responses to climate are often made at plot scales but are limited in spatial coverage. In this study, we use RHESSys (Regional hydro-ecologic simulation system) combined with spatially intensive monitoring of coupled ecohydrologic variables at the Southern Sierra Critical Zone Observatory (SSCZO), located in the Sierra National Forest, California. Figure 40 shows the conceptual framework for strategically sampling soil moisture and sapflux to assess the impact of inter-annual climate variability on ecohydrologic response. Our general approach involves: 1) physically based model calibration using existing measured snow, soil moisture, sap-flux and streamflow; 2) model estimation of long-term spatial patterns of key hydrologic indicators of soil moisture dynamics; 3) spatial clustering of these indicators to define an index of “hydrologic similarity” that can be mapped spatially and used to define N-distinctive soil moisture/vegetation water clusters across the watershed; 4) optimal locations of additional soil moisture and sap-flow sampling based on clustering analysis; 5) results from additional sampling is then used to refine hydrologic model parameters; and finally, 6) the resulting model will be used to estimate how spatial pattern of soil moisture and vegetation water use is likely to evolve under different climate change scenarios.

We have monitored soil moisture and sapflux in six plots since summer, year 2010 where they are distributed in the Providence watersheds (Figure 41). The measured soil moisture and sapflux showed strong seasonal patterns, while each site showed different temporal patterns (Figure 41). CZT5, CZT6 and CZT7 have higher soil moisture and transpiration than the other sites. CZT7 site has large upslope drainage areas and thus maintains higher soil moisture and transpiration in the summer period than other sites. However, CZT6 also has high summer soil moisture and transpiration, but the site has a relatively small drainage area based on surface topography. Thus, surface topography does not always capture the pattern of subsurface flow. In winter, some sites can maintain high transpiration but other sites are more temperature limited. A key question is whether the model can sufficiently resolve these microclimate patterns. In addition, we collected soil samples to characterize the soil properties of each sample sites. With help from Professor Jan Hopman’s lab in UC Davis, we estimate soil parameters (Table 1). We will use these data to estimate the soil parameters of RHESSys in order to improve the predictions of soil moisture, transpiration and streamflow in the Providence watersheds.

**Table 1: The characterization of soil parameters at the CZT sites**

	Bulk density	Porosity	Ksat (m/day)	Sand (%)	Silt (%)	Clay (%)	$\theta_s$	$\theta_r$	A	n	Soil texture
CZT3	1.4	0.475	26	91	5	4.5	0.4255	0.126	0.024	2.635	Sand
CZT4	1.2625	0.507	6.6	83.5	12	4.5	0.4335	0.1495	0.017	2.47	loamy sand
CZT5	1.3275	0.4685	6.7	81	12.5	6.5	0.401	0.1515	0.016	2.255	loamy sand
CZT6	1.19	0.5145	6.0	76.5	16.5	7	0.436	0.171	0.022	1.97	sandy loam
CZT7	1.3925	0.4455	0.038	62	23.5	15	0.3605	0.086	0.027	1.475	sandy loam
CZT8	1.23	0.5275	15.7	81.5	13.5	5.5	0.392	0.11	0.0135	2.215	loamy sand

Our previous modeling studies highlight the importance of adequate representation of micro-climate patterns as controls on summer moisture deficits and transpiration. To support improvement of micro-climate estimation, we installed eighteen additional microclimate sensors (HOBO) in the summer, year 2011. Figure 6 shows the location of the microclimate sensors. Microclimate sensors measured air temperature and relative humidity at 5-min intervals. Sensor location was selected based on existing the soil moisture and sapflux sampling locations (CZT sites, Figure 41 and 42) and elevation gradients. Figure 43 showed the relationship among microclimate (VPD), soil moisture and sapflux in the summer period. The relationship among microclimate (VPD), soil moisture and transpiration in the summer varied between sites (Figure 43). In the dry sites (CZT3), Transpiration is correlated with soil moisture. In the intermediate site (CZT6), transpiration is highly correlated with VPD. However, in the wet site (CZT7), the transpiration is not correlation with soil moisture and VPD. We expect that the temporal pattern of transpiration at the wet site is correlated with solar radiation.

Next steps in this work will test the improved accuracy of the RHESSys model ecohydrologic predictions (snow, soil moisture, transpiration and streamflow) using estimated spatial microclimate inputs. The model test will be conducted at plot, hillslope and watershed scales and for the different model variables. At patch/plot scale, we will evaluate improvements in model predictions of snow accumulation and melt, soil moisture and transpiration (sapflux) when using refined estimates of microclimate patterns. At the hillslope scale, ET from Eddy covariance flux tower in the P303 watershed can be utilized to evaluate improvements in model estimates of ET. At the watershed scale, streamflow and spatial patterns reflected by strategically located soil moisture and sapflux measurements will be compared with model predictions of soil moisture, transpiration and streamflow, again using our improved interpolation of climate forcing.

*Effect of climate warming on ecohydrologic fluxes in the Providence and Bull catchments.* We use the model to investigate the sensitivity of eco-hydrologic variables to projected climate warming. We consider model estimates of snow, evapotranspiration and streamflow across the two small mountain watersheds (P303 and B203) under future warming scenarios. The P303 watershed is located in the snow-rain transition zone, while the B203 watershed is located in the snow-dominated zone. Table 2 summarizes the basic hydrologic properties of the P303 and the B203 watersheds. To simulate climate warming, this study will apply simple 2 and 4 C° uniform temperature adding to the observed meteorological record based on recent GCM predictions for California Sierras over the next 50-100 years (Cayan et al., 2006). While actual warming scenarios are likely to be substantially more variable in time, we use this simple approach to focus on the direct impact of increasing temperature and avoid the complex and highly uncertain downscaling of climate model output.

**Table 2: Basic hydrologic properties of the P303 and the B203 (Hunsaker, et al., 2011)**

Watershed	P303	B203
Elevation	1730 to 1990m	2185 to 2490m
Aspect	SW	SW
Slope	1.3 to 30.3 (12.73)	0.9 to 24.9(11.38)
Vegetation	Mixed Sierra conifer (Dominant tree species: white fir) LAI distribution:0.3 to 6.2 (3.2)	Mixed Sierra conifer (Dominant tree species: Red fir) LAI distribution: 0.2 to 5(1.6)
Soil	Dominant Soil types: Shaver (66%) Strongly weathered quartz diorite Permeability: Moderately rapid Hydrologic soil group: B	Dominant Soil types: Cagwin(80%) Highly weathered granitic rock Permeability: Rapid Hydrologic soil group: A
Precipitation /Runoff	Precipitation type:Snow-rain transition Mean annual Precipitation (2005 to 2007): 1513mm Runoff ratio(R/P):	Precipitation type: Snow-dominated Mean annual Precipitation (2005 to 2007):1517mm Runoff ratio(R/P):
Temperature	Daily average temperature (°C) of 2004 to 2007 (mean $\pm$ SD): Min: $4.5 \pm 0.8$ Max: $13.0 \pm 1.0$ Mean: $8.6 \pm 0.9$	Daily average temperature (°C) of 2004 to 2007 (mean $\pm$ SD): Min: $3.3 \pm 1.1$ Max: $11.2 \pm 0.7$ Mean: $6.8 \pm 0.8$
Drainage pattern	Wetness index: 4.1 to 13.8(7.2)	Wetness index: 4.1 to 15.9(7.2)

We calibrated RHESSys with measured snow depth and streamflow for two watersheds. In the P303 watershed, the model reproduced the timing of observed snow accumulation and melt but the model tended to underestimate the day of complete snow melt in the dry year (Figure 44). One error might be due to poor prediction of precipitation the phase (snow vs rain). In the B203 watershed, the model reproduced the timing of observed snow accumulation and melt and had better performance than the P303 watershed. After estimating snow-related parameters, we calibrated RHESSys soil drainage parameters to reproduce the observed streamflow (Table 3). The predictive performance of the model being considered was evaluated using a combination of three objective functions (multiple objectives, Equation 1). The model reproduced the measured streamflow of two watersheds (P303 and B203) (Figure 44 and Table 2). The overall accuracy of the streamflow prediction was 0.31 and 0.5 for two watersheds respectively. In the P303 watershed, the model captured the seasonal pattern of observed streamflow, and the model had better performance about low flows than high flows ( $R_{\text{eff}}=0.55$  and  $R_{\text{logef}}=0.71$ ). Poor prediction of peak flow may be due to misrepresentation of variable soil depths within the watershed. The P303 watershed has areas of locally shallow soils (Bales et al., 2011) that can generate the peak flow rapidly in response to snow melt or rainfall events. In our modeling study, however, we assume that soil depth is uniform within the watershed because a detailed soil depth map was not available. The P303 model has also high

percentage error in total annual flow (PerErr=18.3), in 2008. In this simulation, we used the precipitation data in the Upper Providence climate station. However, year 2008 has 25 % difference of annual precipitation between the Upper and Lower Providence stations, although these stations show similar precipitation in other years. Thus, spatial heterogeneity in precipitation accounts for model overestimating of the measured streamflow in the year 2008. Year to year differences in precipitation patterns leads to a significant challenge in developing improved meteorologic inputs.

**Table 3: Calibrated snow-related and soil parameters, and model performance**

Watershed	Snow-related parameters			Soil-related parameters		
	Temperature laps rates (tmax /tmin) (°C/m)	Temperature threshold for rain vs snow (°C)	Temperature melting coefficient (m/°C)	m (m/m)	Ksat_h/Ksat_v (m/day)	GW1/GW2 (/)
P303	0.0063/ -0.0064	-6 to 1	0.005	0.32	264/268	0.266/0
B203	0.0068/ -0.0060	-3 to 3	0.005	0.30	112/288	0.0064/0
Streamflow accuracy measures (equation 1)						
	R <sub>eff</sub>	R <sub>logeff</sub>	PerErr	Accuracy		
P303	0.55	0.71	18.3	0.31		
B203	0.87	0.64	10.5	0.50		

Ksat\_v: vertical saturated hydraulic conductivity; Ksat\_h: horizontal saturated hydraulic conductivity; m: decline coefficient of Ksat with depth; GW1: the percentage of preferential flow from the soil surface to deep groundwater storage; GW2: the linear coefficient of the deep groundwater storage

We used long-term historical climate data and the calibrated model to examine the impact of inter-annual climate variability on four ecohydrologic fluxes (summer streamflow, annual streamflow, annual ET) in two small mountain watersheds. Figure 45 showed that for two watersheds, increasing annual precipitation linearly increased the annual streamflow of two watersheds, but the B203 watershed has higher runoff ratio than the P303 watershed. The higher runoff ratio of the B203 watershed was due to lower vegetation water use (lower LAI) and higher drainage rate of the B203 watershed (Hunsaker et al., 2012 and Table 2). However, the summer (August) flow of the two watersheds had nonlinear relationship with the annual precipitation, while the B203 watershed has higher flow variability than the P303 watershed. The annual ET of the P303 watershed was linearly increased by increased annual precipitation. However, annual ET of B203 was more or less constant with the increased precipitation. Because P303 is a water-limited environment, increased precipitation contributed directly to increased ET. However, because B203 was temperature-limited rather than water-limited, increased annual precipitation did not result in increased annual ET. Figure 45 also showed the effect of climate warming on the relationship among annual precipitation, annual streamflow, summer streamflow, annual moisture deficit, and annual ET for P303 and B203. A 4°C warming scenario did not change the estimated relationship between annual precipitation and other ecohydrologic variables in P303. The warming scenario however did

change the relationship in B203. In B203, climate warming reduced the summer streamflow and increased in the annual Moisture deficit and annual ET, while the annual streamflow did not change.

Figure 46 presented the climate warming effect on seasonal ecohydrologic fluxes (SWE, ET, and streamflow in the short term (4 years). In the P303, climate warming decreases snow accumulation and accelerated the snowmelt. For 4°C warming, most of precipitation became rain rather than snow. The ET and streamflow responses to warming between 2°C warming and 4°C warming scenarios were insignificant. Warming scenarios lead to earlier peak ET (shifting from April to March) and the magnitude of peak ET to be decreased. The timing of peak streamflow did not change but the magnitude of peak streamflow increased. The warming effect on seasonal ecohydrologic fluxes of B203 is more distinctive than its effect on the fluxes of P303. As well, ET and streamflow response to warming is significantly different between 2°C and 4°C warming. The timing of snow accumulation and melt as well as their magnitudes significantly changed due to increased temperature. The 4°C warming transformed the snow regime of B203 to a pattern of snow accumulation and melt similar to P303 under historical climate. The 2°C warming shifted the timing of peak ET from July to May and the magnitude of peak ET decreased. The 4°C warming caused the magnitude of peak ET similar to historical climate, but shifted the timing of the peak ET from May to March. The warming (2°C and 4°C) shifted the peak streamflow from May to April, and reduced the magnitudes of peak streamflow and summer streamflow. Table 4 showed the change in the mean annual ET of P303 and B203 due to the warming. P303 showed less change in the mean annual ET than B203. The 2°C warming reduced the ET of P303 but increased the ET of B203. However, the 4°C warming caused the ET of P303 similar to one under historical climate, while still increased the ET of B203 but less than the 2°C warming scenario.

**Table 4: Effect of climate warming on the estimate of mean annual ET (mm)**

Change in Mean annual ET (mm)	P303	B203
ET(base)	715	592
ET(2°C)-ET(base)	-14	69
ET(4°C)-ET(base)	-1	48

We explored the spatial structure of seasonal ET in P303 and B203, and how climate warming affected spatial structure of seasonal ET in the two watersheds (Figure 47). Historically, the mean monthly ET in P303 had high ET rate in March, April and May months and after May the ET decreased. However, the mean monthly ET in the B203 increased from March to June, and after June, the ET decreased. The mean monthly ET of P303 showed minimal change with climate warming, while the mean monthly ET of B203 significantly changed with climate warming. In the early growing season, warming increased the monthly ET, while in the late growing season, warming decreased the monthly ET. Interestingly, with a 4°C scenario, the spatial structure ET in B203 became close to the spatial structure of ET of P303 under historical climate. The spatial variance of the monthly ET (measured as coefficient of variance) of P303 historically had a different temporal pattern relative to B203. In P303, the highest variance of the ET occurred in the June and the lowest variance occurred in the March. However, B203 maintained a high variance from March to August relative to P303. March and April months had the highest variance, and May had lowest variance. Climate warming reduced the spatial variance of ET in

P303 throughout the growing season. However, in B203, the climate warming decreased the spatial variance of ET in the early growing season, but increased the variance in the later growing season. Consequently warming scenarios lead to a more similar temporal pattern of ET variance between P303 and B203, although B203 maintains a higher spatial variance of ET in the late growing season.

We explored the spatial pattern of seasonal ET in P303 and B203 under historic and 2 and 4°C warming scenarios (Figure 48). Table 5 showed topographic and vegetation parameters and the correlation between the parameters in the P303 and the B203 watersheds. For both watersheds, elevation is highly correlated with wetness index (Beven and Kirby, 1979) ( $>0.4$ ). In B203, LAI is highly correlated with wetness index (0.48). In March, the ET of P303 was highly correlated with the LAI distribution, but in June and August, the spatial ET was more correlated with wetness index than the LAI. In March, the ET of B203 was weakly correlated with LAI and wetness index. In June and August, the ET pattern shows a greater correlation with LAI and wetness index. For B203, climate warming caused spatial ET in March to be more correlated with LAI and wetness index. Warming increased the contrast between low ET areas and high ET areas, while the warming decreased the area with low ET. In June and August, the spatial pattern of ET changed with climate warming; mean ET decreased, but the spatial variability of ET increased.

**Table 5: Correlation between physiological parameters in the P303 and B203 watersheds**

Parameters (P303/B203)	Elevation	Aspect	Wetness index	LAI
Elevation	1.00/1.00	0.12/-0.10	-0.41/-0.40	-0.14/-0.20
Aspect	0.12/-0.10	1.00/1.00	-0.03/0.08	0.07/-0.2
Wetness index	-0.41/-0.4	-0.03/0.08	1.00/1.00	0.08/0.48
LAI	-0.14/-0.2	0.07/0.08	0.08/0.48	1.00/1.00

We explore the relationship between physiological parameters and seasonal ET by examining the seasonal pattern of the Pearson correlation coefficient (Figure 49). In the P303 watershed, LAI was highly correlated with spatial ET in the early growing season, but in the later growing season, the degree of the correlation decreases and the relationship between LAI and spatial ET became negative. However, wetness index maintain the high correlation relationship to spatial ET throughout the growing season. Elevation and aspect had minor effect on spatial ET. For P303 the correlation coefficient between LAI and spatial ET rapidly decreased in April for the climate warming scenario. The effect of climate warming on the relationship between physiological parameters and spatial ET in P303 was small relative to changes in the B203 watershed. In the B203 watershed, LAI and wetness index were highly correlated with spatial patterns of ET. The 2°C scenario caused the negative relationship between elevation and spatial ET to become stronger in the early growing season (March and April). The 2C warming scenario also led to a higher correlation between LAI with the spatial ET in the early growing season, while the correlation between wetness index and spatial ET stayed constant.

## Erosion and Weathering.

*Landscape evolution.* Work is nearly complete on a manuscript that details a new test of Wahrhaftig's (1965) decades-old hypothesis for the development of “stepped topography” in the southern Sierra Nevada by differential weathering of bare and soil-mantled granite. According to Wahrhaftig's hypothesis, bare granite weathers slower than soil-mantled granite; thus random erosional exposure of bare rock leads to an alternating sequence of steep, slowly weathering bedrock “steps” and gently sloped, but rapidly weathering, soil-mantled “treads.” The hypothesis was tested with (i) terrain analysis, to confirm the existence of the steps and treads, (ii) analysis of air photographs, to identify bare versus soil-mantled terrain, and (iii) cosmogenic nuclides to determine relative erosion rates of bare rock and soil-mantled terrain.

Terrain analysis confirms that the landscape is stepped, consistent with Wahrhaftig's hypothesis (Jessup et al., 2011; Riebe et al., in prep). Yet land cover analysis reveals little difference between the relative abundance of soil and bare rock on both steps and treads; this is inconsistent with Wahrhaftig's hypothesis, which requires bare rock to be concentrated on steps. Moreover, cosmogenic nuclides show that treads are eroding slower than steps, undermining the very foundation of the stepped topography hypothesis. Hence, although erosion rates are indeed faster where soil is present, the differential erosion thus produced does not generate topography in the way envisioned by Wahrhaftig (1965). As a further blow to the hypothesis, a global compilation of cosmogenic-based erosion rates shows that differential erosion due to the presence/absence of soil is not restricted to granitic terrain (Figure 50; after Riebe et al., in prep). Hence, to the extent that such erosion rate differences are responsible for the generation of stepped topography, it should not be restricted to granitic landscapes, in conflict with Wahrhaftig (1965) explanation for the phenomenon. Work on this topic is discussed briefly in Jessup et al. (2011); a full manuscript is forthcoming (Riebe et al., in prep).

*Geophysical and geochemical constraints on weathering and erosion.* Seismic refraction and resistivity surveys were used to estimate regolith thickness and generate representative images of subsurface weathering and water storage potential in the CZO. The geophysical data provide evidence for weathered granite down to an average depth of 25 m (Figure 51; after Holbrook et al., in review). Cosmogenic nuclides show that erosion rates vary from ~75 to 125 m/Ma across the site; hence measured regolith thicknesses correspond to a turnover time of ~400,000 years for the weathering profile as a whole, indicating that weathering measured from regolith at the surface integrates subsurface weathering over late Pleistocene variations in climate (Riebe et al., in prep 2). Hence, to the extent that climate modulates subsurface weathering at the SSCZO, modern surface processes are influenced by a legacy of past conditions.

To estimate how subsurface weathering implied by geophysics corresponds to water holding potential at depth, a rock physics model of seismic velocities was used to infer porosity and how it varies vertically and laterally in the subsurface (Figure 52; Holbrook et al., in review). Analyses suggest that porosity drops from 55% near the surface to zero at the base of weathered rock along one intensively studied transect. Model-predicted porosities are broadly consistent with values measured from both physical and chemical properties of saprolite and rock, suggesting that the analysis of geophysical data provides robust first-order constraints on subsurface weathering and water storage potential across the transect. Results indicate that saprolite is a crucial reservoir of water, potentially accommodating several meters (i.e., volume per unit area) of water (Holbrook et al., in review).



Geochemical measurements indicate that saprolite is also a major source of weathering fluxes, accounting for roughly 50% of the total chemical erosion flux in the headwaters of the SSCZO (Riebe et al., in prep). Chemical erosion in saprolite and soil are significant enough to lead to substantial biases in the buildup of cosmogenic nuclides (Granger and Riebe, accepted). In a new analysis of the importance of these effects, Riebe and Granger (accepted) proposed a method for quantifying these biases from field measurements and showed failure to do so can lead to errors of up to 100% in cosmogenic nuclide studies of landscape erosion rates. Analysis of a global database of weathering (including crucial data from the SSCZO) shows that the correction is strongly correlated with mean annual precipitation, reflecting climatic influence on chemical weathering (Figure 53; Riebe and Granger, *accepted*). Quantifying the correction represents an important revision to the standard practice for inferring denudation rates from cosmogenic nuclides in climatic settings where chemical erosion accounts for a significant fraction of the overall denudation rate.

**Baseline Hydrologic, Sediment and Geochemical Characterization.** Three end-members were determined using EMMA and conservative tracers; near surface runoff, rainstorm runoff, and baseflow (Figure 54). The mean fractional contribution of each end-member varied by site, and the results show that the contribution of near-surface runoff and baseflow were similar, ranging from 0.72 (B203 site) and 0.66 (T003) to 0.27 (P304) and 0.25 (B203), respectively. However, the fractional contribution of flow from rainstorms was much smaller, contributing between 0.063 (D102) and 0.019 (T003). Results displaying temporal variation in fractional contribution of each end-member from water year 2003-2007 are shown in Figure 47.

During periods of snowmelt (April of each year), near-surface runoff provided the greatest contribution to streamflow whereas the opposite occurred during periods of drought (October of each year), where baseflow contributed the most. The relative contribution of rainstorm runoff was lowest for most of the year with the exception of infrequent episodic peaks (Figure 55).

Contributions of near-surface runoff (or snowmelt runoff) and baseflow were highly correlated with streamflow discharge by a linear relationship at both Providence and Bull catchments (Figure 56). The  $R^2$  values were 0.92-0.99 and 0.91-0.97 ( $p < 0.001$ ) for near-surface runoff and baseflow, respectively. The slope varied from 0.53 to 0.83 for near-surface runoff and from 0.20 to 0.46 for baseflow.

All intercepts were negative for near-surface runoff, with a magnitude  $< 7$ , and all positive for baseflow, with a value also  $< 7$ . Those samples collected over four water years from 2004 to 2007 covered different climates and annual precipitation.

By performing a regression between mean end-member contribution and elevation, mean end-member contribution and slope (data not shown), it was determined that no statistically significant correlations were present amongst end-members. This data suggests the relative proportion of rain to snow did not control streamflow pathways across elevation or slope.

**Organic Carbon in Streams.** Water samples for isotopic analysis are being analyzed at UC Merced. Water samples for organic carbon have been analyzed. The results from these samples are going through a rigorous QA/QC process, to ensure that data are correct.

**Novel Isotopes in Streams and Sediments.** Sediment and soil samples are being processed in the laboratory. Water samples from all of the Providence streams are being sampled quarterly. These samples are being shipped for analysis to GFZ-Potsdam, Germany, where project collaborators are doing laboratory analysis

## Soil Nutrient Contents.

*Resin lysimeters fluxes.* Analysis of the resin lysimeters data shows that hotspots in resin-based nitrogen flux appear on a large scale just as they do on a small scale, and that inter-annual variation in soil fluxes is quite high whereas interannual variation in thoroughfall fluxes is low. Interestingly, however, the average N fluxes among watersheds do not differ by much during any given year.

*O horizon data.* Analysis of the O horizon mass and nutrient content data showed hotspots but surprisingly little variation among watershed averages, as was the case for the resin lysimeters, except in the cases of Ca and Mg, which reflected differences previously reported in soils (lower in the Bull than in the Providence watersheds).

*Intensive plot results. O-horizon interflow as a contributing factor for nutrient hotspots within the mineral soil.* Meter sized grids were set up at two locations in the King's River Experimental Watershed (KREW). One grid at each site contained 64 sampling points where 32 of the sampling points had barriers to truncate interstitial flow. The purpose of the barriers was to artificially generate preferential flow paths and we hypothesized that they would create nutrient hot spots in the soil. 16 of the 32 barriers also contained a UniBest® resin capsules. There were also 16 capsules in the O-horizon and 16 control points in the grid. The barriers a 17% higher moisture content 99.7% of the time. After one year there were no significant differences in water extractable nutrient concentrations within the barriers compared to the open soil horizon. The capsules located inside the barriers were not significantly higher than those in the O-horizon with the exception of ammonium-N (Table 6). For nitrate-N and magnesium the capsules outside the barrier were significantly higher (Table 6). Therefore, our hypothesis was not confirmed: although the barriers caused a 17% increase in moisture content, they did not increase nutrient concentrations in the soil except for ammonium-N in the capsules.

A second grid containing 16 sampling point was also established with Western Ag Innovations PRS™ Probes. The probes were placed in sets of two at each sampling point with one set placed vertically with respect to the slope and the other set placed horizontally with respect to the slope. The horizontally placed probes were indented to truncate flow and have higher nutrient concentrations than the vertical samplers. The nutrient concentrations for the probes showed no differences between the horizontal and vertical probes after one year. Hot spots (in the form of extreme outliers) found in the water extractable nutrient concentrations were often located in areas of high total carbon content suggesting organic matter has an influence on hot spot formation. It is believed that nutrient hot spots in the soil can help plants outcompete microbes for nutrients which may mean that there is a positive feedback loop of increasing plant species development, increasing carbon content, and increasing hot spots in the soil.

**Table 6. Average resin capsule data for locations just inside interflow barrier compared with locations with no barriers**

<u>Tower</u>	Ortho-P	NH4-N	NO3-N	Ca	Mg
	μmol/cm <sup>2</sup>	μmol/cm <sup>2</sup>	μmol/cm <sup>2</sup>	μmol/cm <sup>2</sup>	μmol/cm <sup>2</sup>
Barrier	0.41	2.48	1.30	8.48	2.75
No barrier	0.59	0.77	1.91	10.15	4.06
<u>P301</u>	Ortho-P	NH4-N	NO3-N	Ca	Mg

	$\mu\text{mol}/\text{cm}^2$	$\mu\text{mol}/\text{cm}^2$	$\mu\text{mol}/\text{cm}^2$	$\mu\text{mol}/\text{cm}^2$	$\mu\text{mol}/\text{cm}^2$
Barrier	0.43	1.93	2.82	12.17	3.80
No barrier	0.34	1.99	2.84	11.64	3.20
T-Test probabilities					
<i>Tower</i>	0.16	*0.04	*0.06	0.26	*0.05
<i>P301</i>	0.23	0.46	0.49	0.44	0.29

**Nitrogen deposition and fluxes from soil.** Some data from the first three years of sampling are presented here for the Prenart soil vacuum lysimeters. NADP site CA28 data are available at their web site. Drs. Hunsaker and Johnson have started analyzing four years (2004, 2005, 2006, and 2008) of resin lysimeter data from the 150-m grid array (470 points). We are able to look at deposition to the ground and flux into mineral soil at 13 cm depth on an annual basis. As Dr. Johnson has found with his small plot work on N in soils at the SSCZO, the spatial variability for N is high. Locations can be high one year and not the next resulting in “hot spots” that wink in and out over time. The values for N deposition over the four years are consistently higher than expected. Most sampling locations are exceeding critical load levels for the Sierra Nevada (2 kg/ha). N deposition values between 2 to 7 kg/ha alter the lichen community, and values above 17 kg/ha can result in N leaching into stream water and loss of up to 25% of plant fine root biomass. These analyses will continue during 2012.

Soil water concentrations at 13 cm and 26 cm mineral soil depths are taken using a Prenart vacuum lysimeter for the first three years of data collection. Average values are reported with one standard deviation in parenthesis. The minimum detection limit is 0.05 mg/L; however, if a value lower than this was measured it was reported and included in these summaries. Values at or above the minimum detection limit are in bold print.

Table 7 presents an annual average for all sample collection periods (approximately 12/year) by watershed. The majority of values is below the minimum detection limit and therefore can be assumed to have a concentration of zero. Usually (20 out of 24) the N concentrations reported have a higher value at the 13 cm depth than at the 26 cm depth indicating that N is depleted as it moves through the soil column. Only 29% (numbers in italics) of the average values reported here were at or above the 0.05 mg/L detection limit for all depths; the highest value reported is 0.14 mg/L. Nitrate has somewhat higher values (0.05 to 0.14 mg/L) than ammonium (0.05 to 0.10 mg/L) for all watersheds and all years. These soil water concentrations can be converted to flux values, and final results will address fluxes from the atmosphere to the top of the soil, the top of the soil to the 26 cm mineral soil depth, and the soils to the stream waters.

**Table 7. Nitrogen concentrations**

Watershed code	Nitrate soil water concentration, mg/L			Ammonium soil water concentration, mg/L		
	2003	2004	2005	2003	2004	2005
P301						
13 cm	0.06 (0.17)	0.01 (0.03)	0.04 (0.26)	0.03 (0.05)	0.02 (0.04)	0.10 (0.23)
26 cm	0.04 (0.01)	0.00 (0.00)	0.01 (0.02)	0.01 (0.02)	0.01 (0.02)	0.06 (0.17)
P303						
13 cm	0.02 (0.05)	0.05 (0.11)	<i>0.07 (0.21)</i>	0.02 (0.03)	<i>0.02 (0.04)</i>	0.03 (0.06)
26 cm	0.01 (0.03)	0.01 (0.01)	<i>0.10 (0.57)</i>	0.01 (0.03)	<i>0.07 (0.32)</i>	0.01 (0.05)

P304						
13 cm	0.12 (0.35)	0.07 (0.20)	0.05 (0.17)	0.05 (0.08)	0.02 (0.03)	0.02 (0.02)
26 cm	0.03 (0.06)	0.01 (0.03)	0.01 (0.02)	0.02 (0.03)	0.00 (0.00)	0.06 (0.13)
D102						
13 cm	0.14 (0.32)	0.01 (0.01)	0.10 (0.43)	0.05 (0.11)	0.01 (0.02)	0.03 (0.07)
26 cm	0.04 (0.08)	0.02 (0.07)	0.02 (0.05)	0.02 (0.04)	0.02 (0.03)	0.03 (0.05)

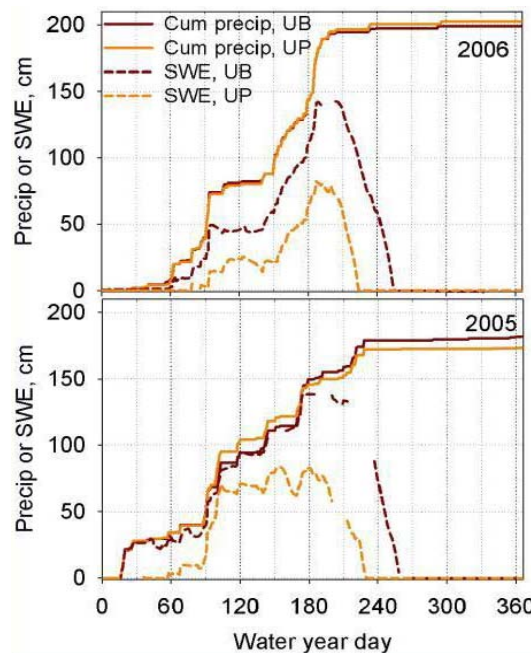
**Current and natural sediment loads.** The range of current variability in sediment loads was established for headwater streams on granitic soils in the southern Sierra Nevada. Seven years of data indicate that the undisturbed watershed and the snow-dominated watersheds produce similar, and sometimes higher, sediment loads for these years as compared to watersheds with active forest management in the lower-elevation rain and snow zone (Hunsaker and Neary 2012).

**Hydrology and meteorology.** Differences in hydrologic response across the rain-snow transition in the southern Sierra Nevada were studied in eight headwater catchments – the Kings River Experimental Watersheds – using continuous precipitation, snowpack, and streamflow measurements (Hunsaker et al, 2012). The annual runoff ratio (discharge divided by precipitation) increased about 0.1 per 300 m of mean catchment elevation over the range 1800-2400 m. Peak discharge lagged peak snow accumulation on the order of 60 days at the higher elevations and 20 to 30 days at the lower elevations. Climate warming that results in a longer growing season and a shift from snow to rain would result in earlier runoff and a lower runoff ratio.

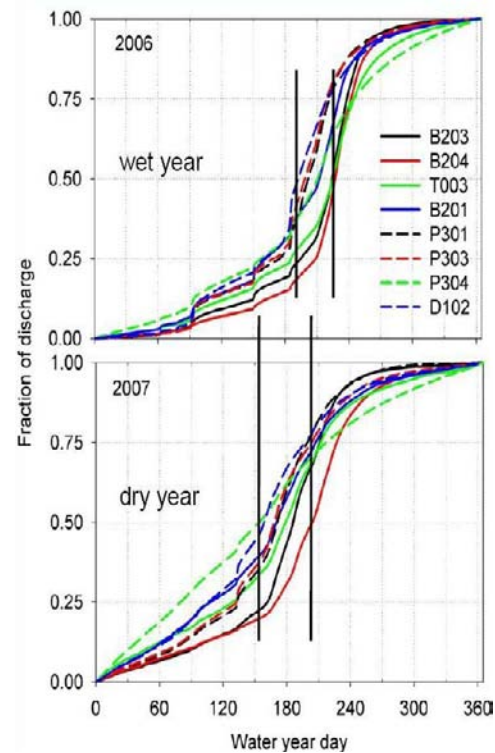
Pathways of streamflow were determined using geochemical tracers for water years 2004-2007 in eight headwater catchments at the Kings River Experimental Watersheds (Liu et al., 2012). Using end-member mixing analysis, the end-members were determined to be near-surface runoff from snowpack and spring rainstorms, fall rainstorm runoff, and baseflow. Baseflow is very responsive to snowmelt and rainstorms, suggesting that baseflow is generated as lateral subsurface flow through macropores.

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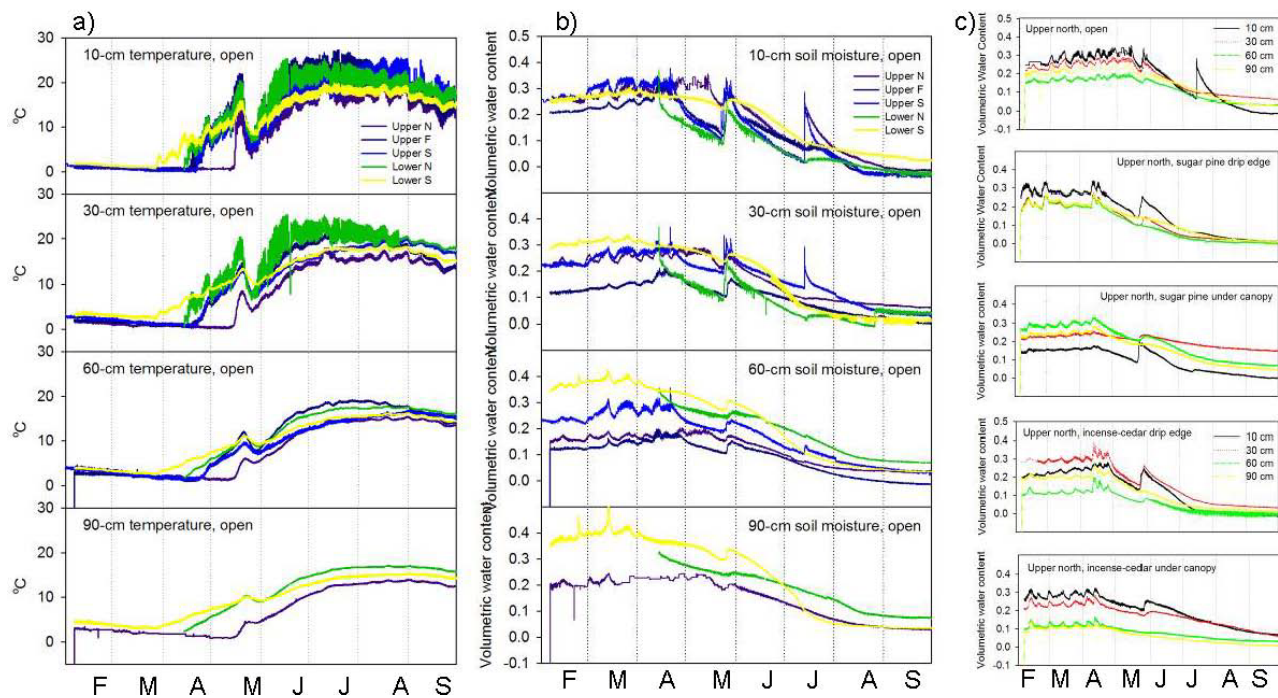
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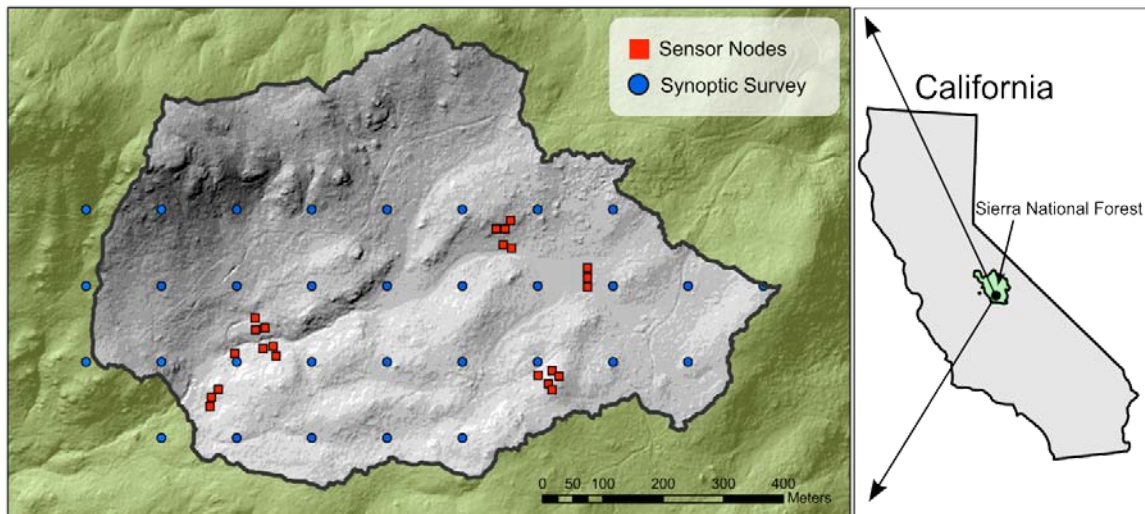
**Figure 1.** Cumulative precipitation and SWE for Bull and Providence watersheds.



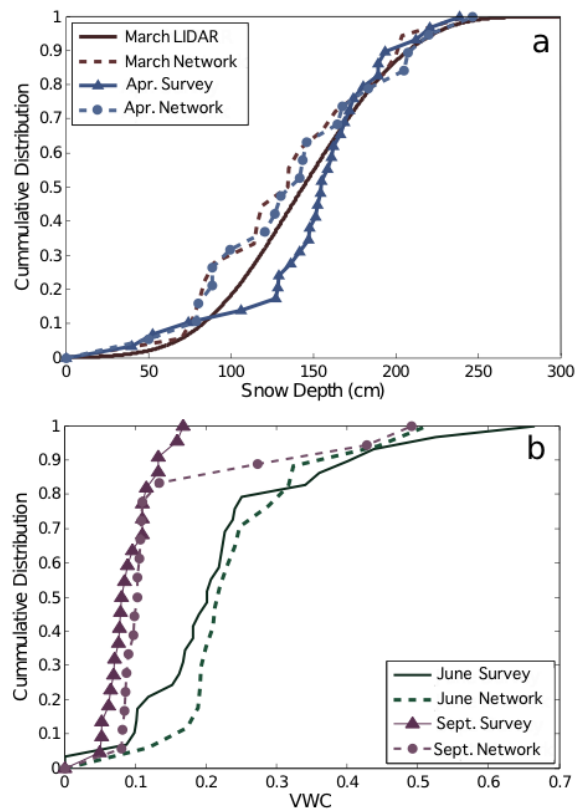
**Figure 2.** Cumulative runoff for the upper (solid lines) and the lower (dashed lines) elevations.



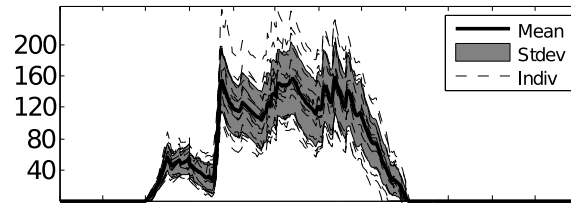
**Figure 3.** Soil temperature (a) and soil moisture (b) data collected 11 instrument nodes at 3 aspects and 2 elevations in 2008. Vertical soil moisture profiles from nodes located at the upper elevation and north facing aspect (c) in 2008.



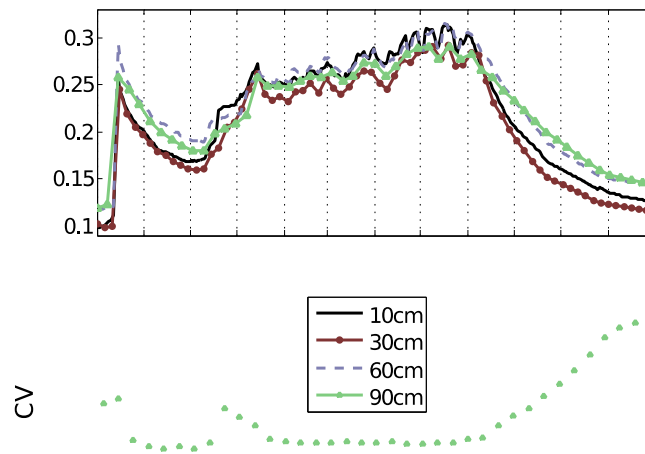
**Figure 4.** Site layout showing location of sensor nodes and synoptic survey sampling points.



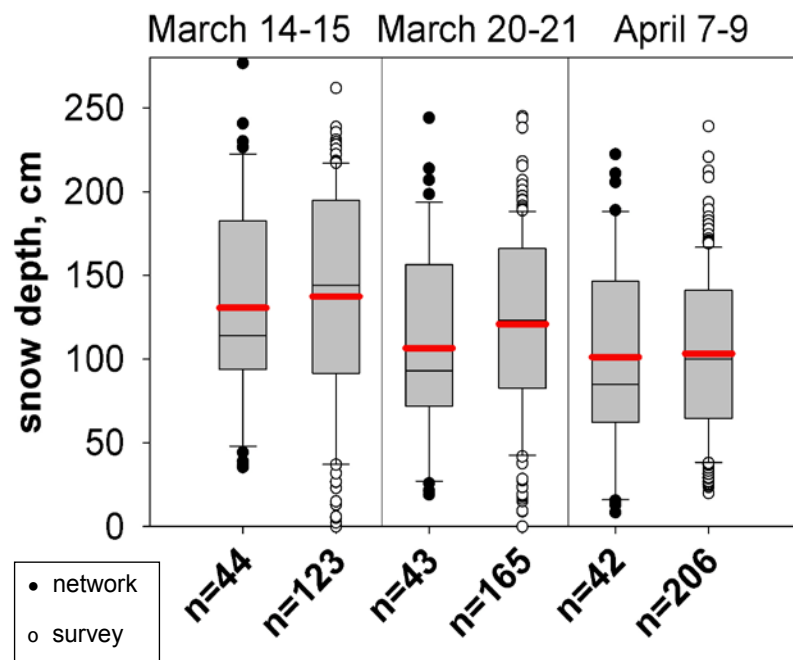
**Figure 5.** Cumulative distribution functions comparing network readings of a) snow depth, and b) soil moisture to those obtained by synoptic and LIDAR surveys.



**Figure 6.** Temporal snowdepth trends October 2009 to October 2010. a) Average snow depth (one standard deviation shown in in gray, individual sensors indicated by dashed lines), b) average snow depth for various canopy covers (open, drip edge, and under canopy), c) Coefficient of variation over time for snow depth and various canopy covers.

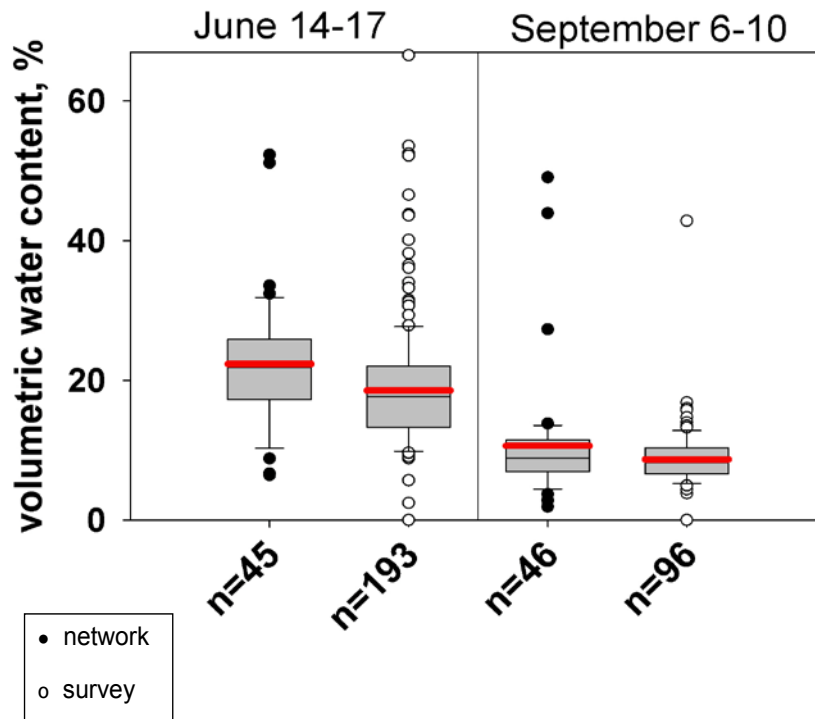


**Figure 7.** Temporal VWC behavior October 2009 to October 2010. a) Average soil moisutre across various solid depths, b) VWC coefficient of variation at various soil depths.

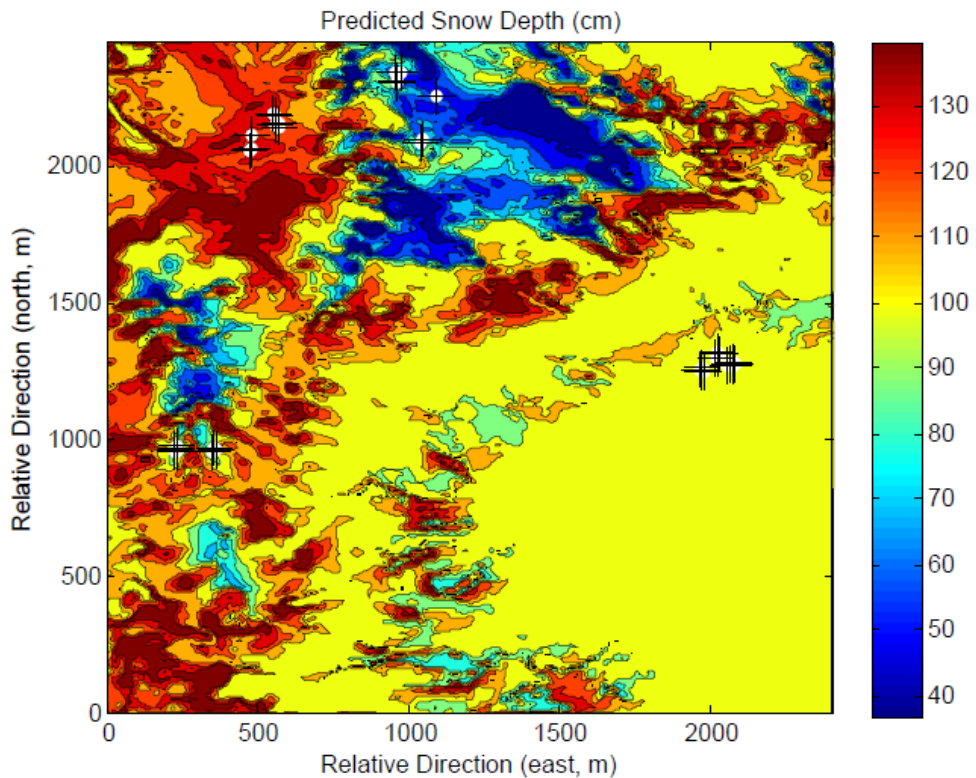


**Figure 8.** Snow depth observations made by the ground-based instrument cluster and survey observations. The horizontal black line in each box represents the median snow depth value, while the red line indicates the sample mean. Three separate surveys occurred, indicated by the dates above each network/survey pair. Sample sizes are indicated on the x-axis.

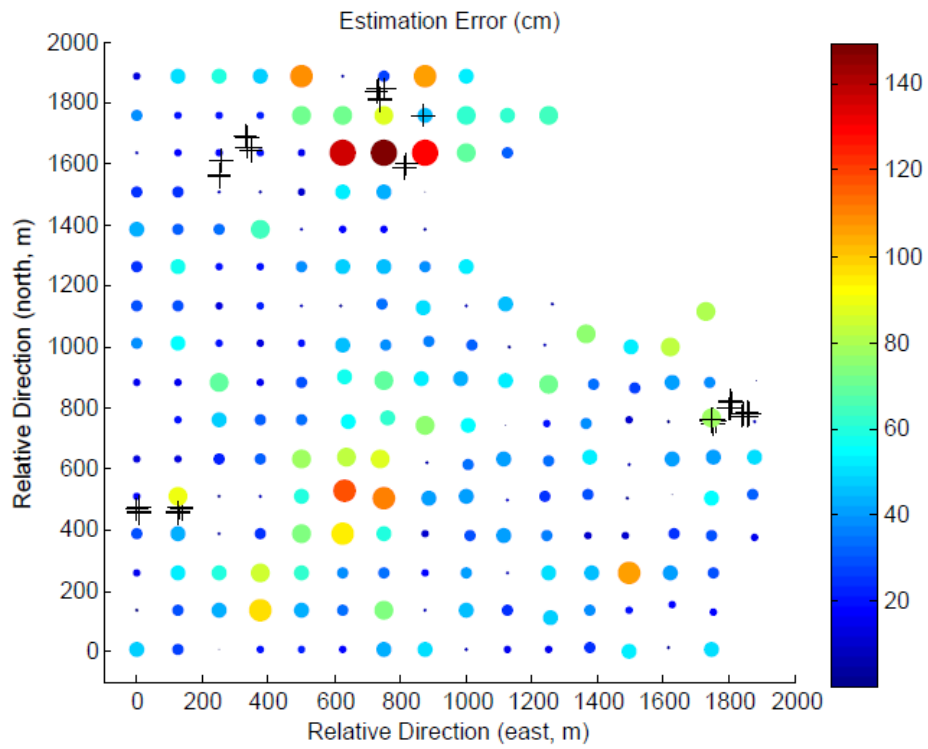




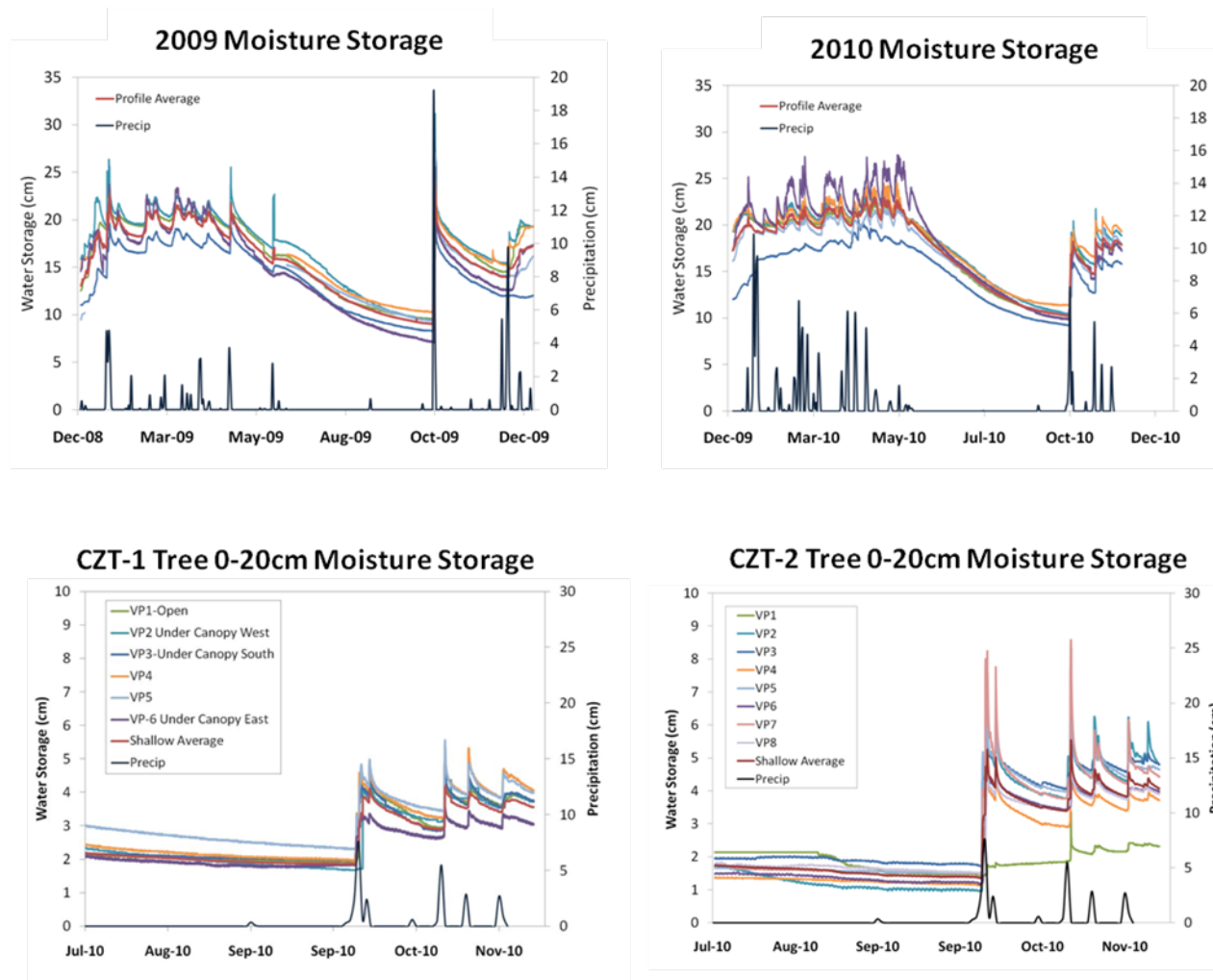
**Figure 9.** Soil moisture observations made by the ground-based instrument cluster and survey observations. Instrument cluster observations are from 10-cm probe, survey observations are from integrating over top 20 cm of soil. The horizontal black line in each box represents the median soil moisture value, while the red line indicates the sample mean. Two separate surveys occurred, indicated by the dates above each network/survey pair. Sample sizes are indicated on the x-axis.



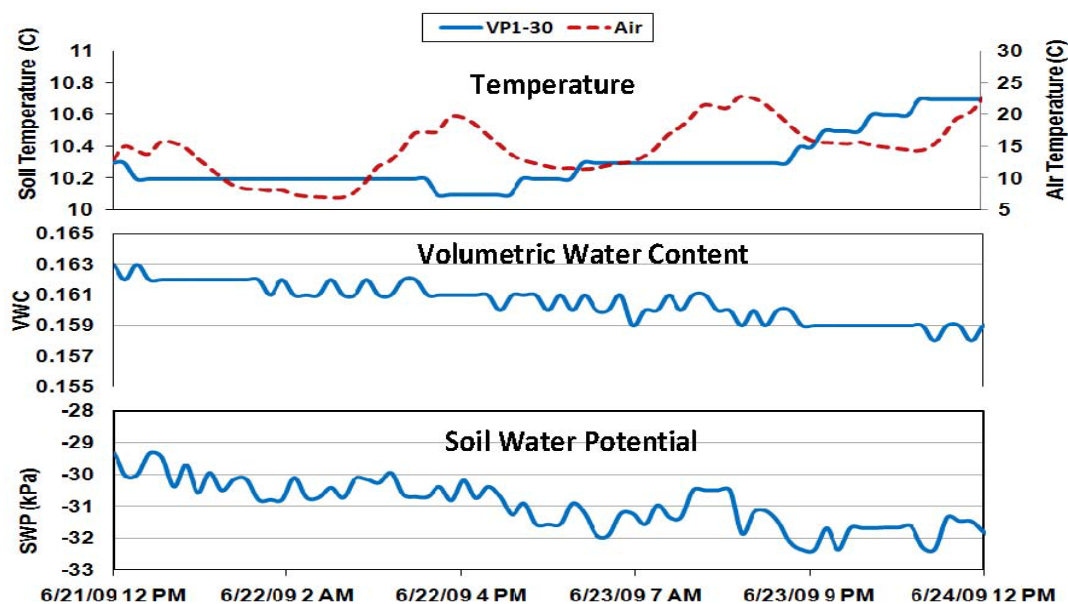
**Figure 10.** Predicted snow depth based on Gaussian process model. The sensor network locations are indicated with black crosses. Red indicates deep snow and blue is shallow snow.

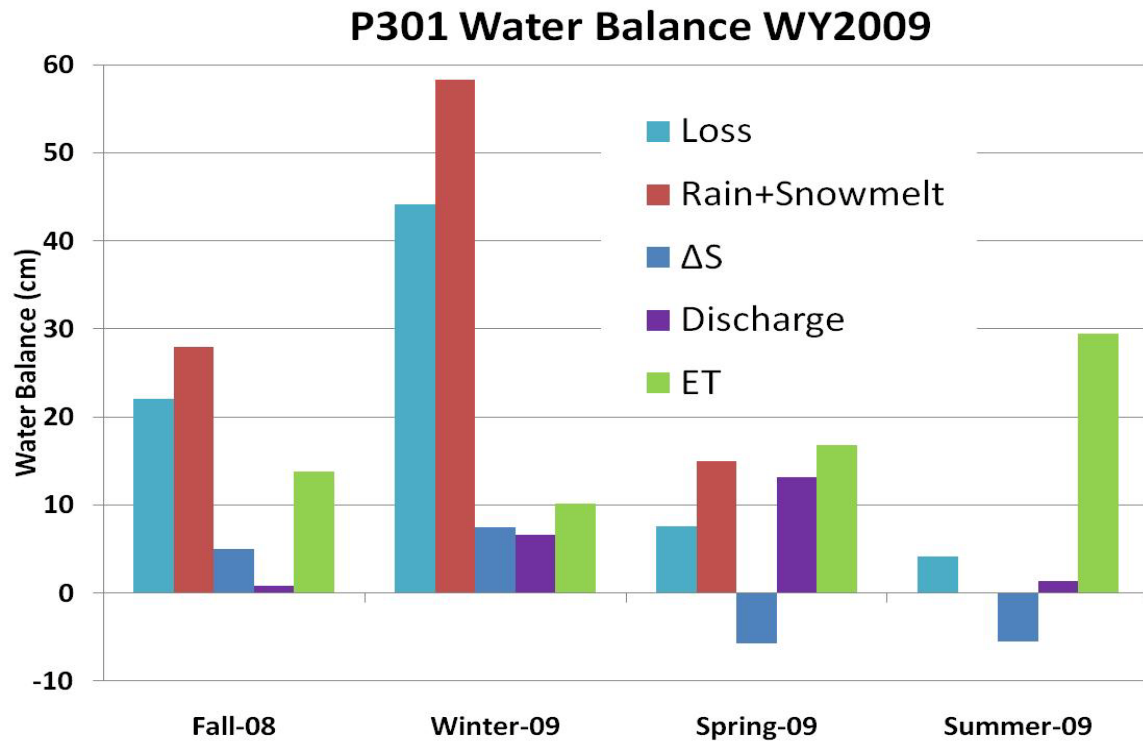


**Figure 11.** Estimation error of predicted snow depth based on Gaussian process model. The sensor network locations are indicated with black crosses. Big-red circles indicate locations with high error and small-blue indicate locations with low prediction error.

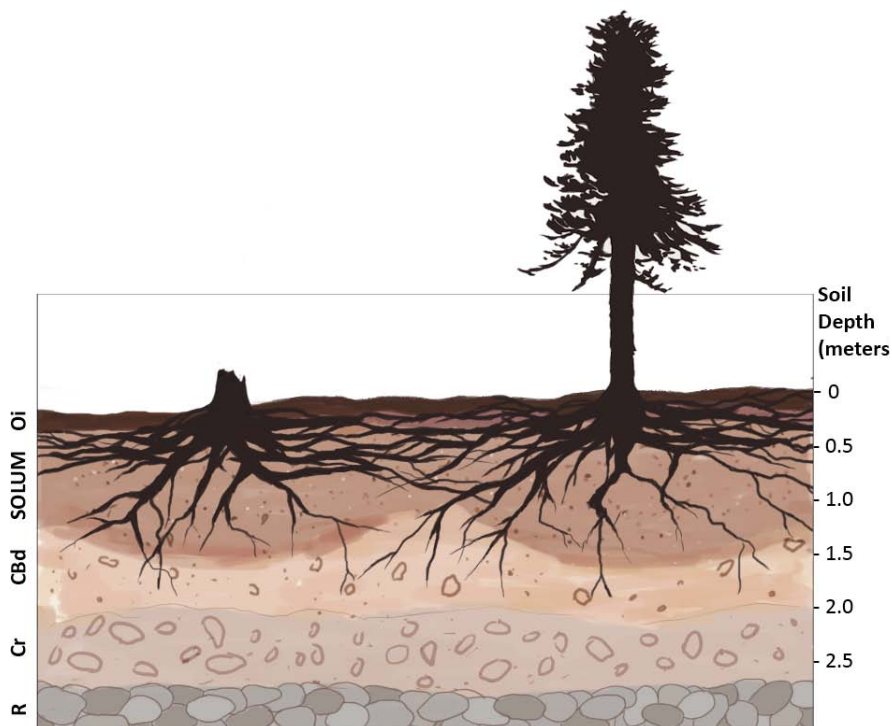


**Figure 12.** Water content, temperature and soil water potential measured in six vertical pits across the site. Measurements are shown at multiple scales, for a 2-year period (above) and a shorter, 3-day time frame (below).

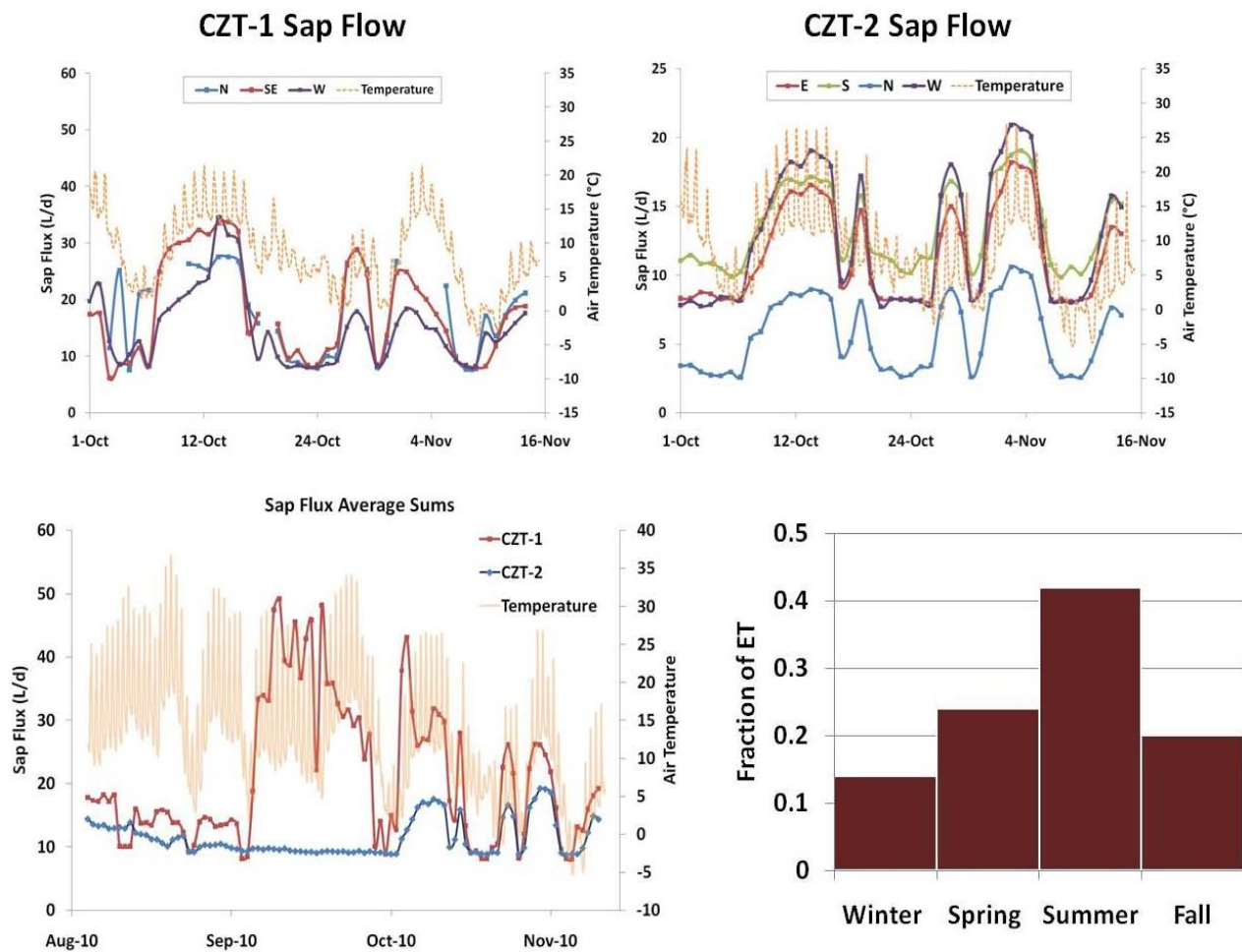




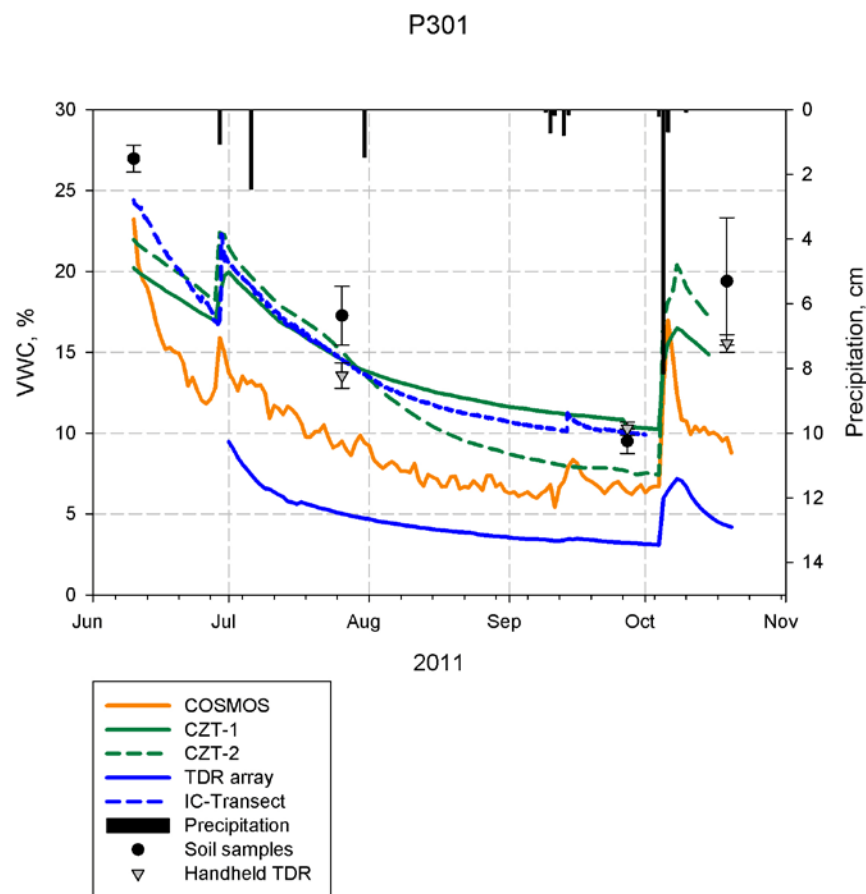
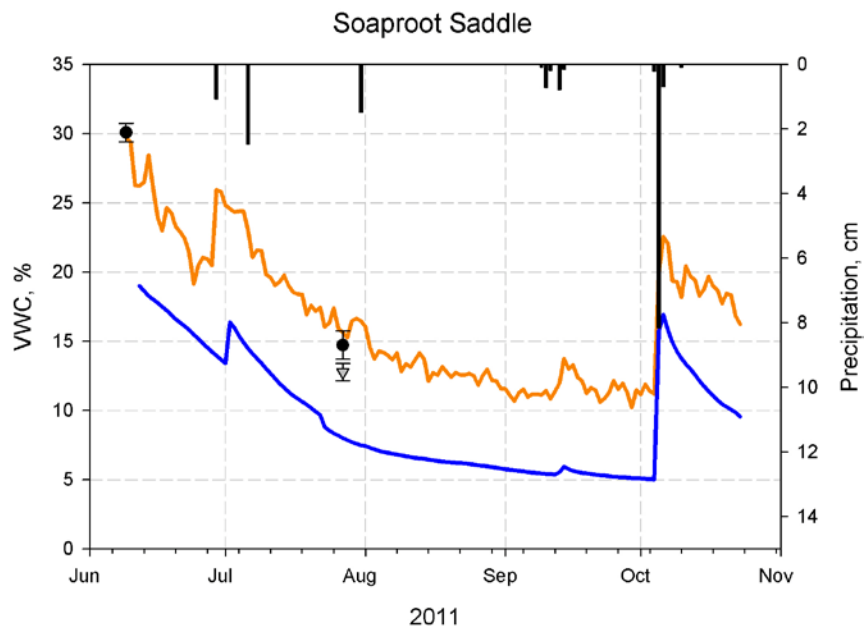
**Figure 13.** Water balance based on CZT-1 and water balance instrument cluster data for WY 2009.



**Figure 14.** Schematic layout of the excavated tree with inferred root architecture. Diagram shows root density decreasing with depth and the potential for soil depth to be influenced by the tree directly beneath the footprint.

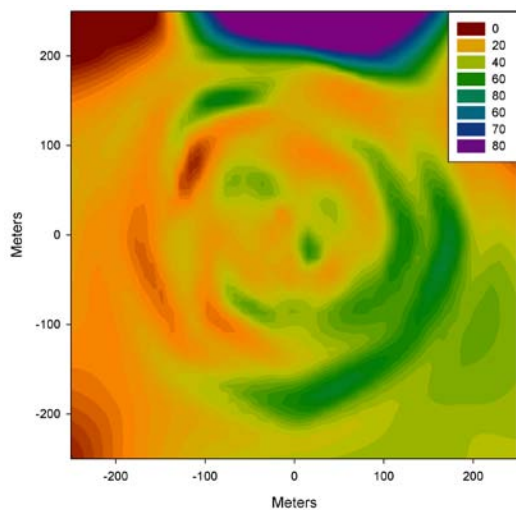


**Figure 15.** Sapflow sensors at both sites showing response to air temperature. Also shown is the near cessation of sap flow at CZT-2 in fall 2010 due to thin soils and lack of available soil water. Seasonal timing of sap flow can be estimated as a fraction of annual ET taken from the water balance.

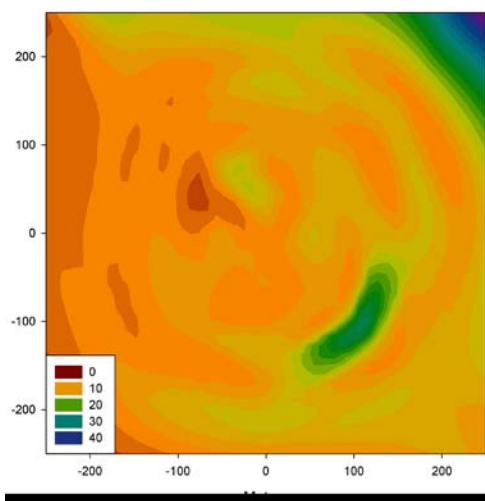


**Figure 16.(a) P301, (b) Soaproot Saddle.** Soil moisture near within the footprint of the P301 Tower COSMOS sensor (Orange), VWC associated with CZTrees (Green), VWC from Instrument Cluster (Blue-dash), VWC from tower soil moisture transect (Blue-solid). Handheld TDR and soil samples during surveys are shown with standard deviation bars.

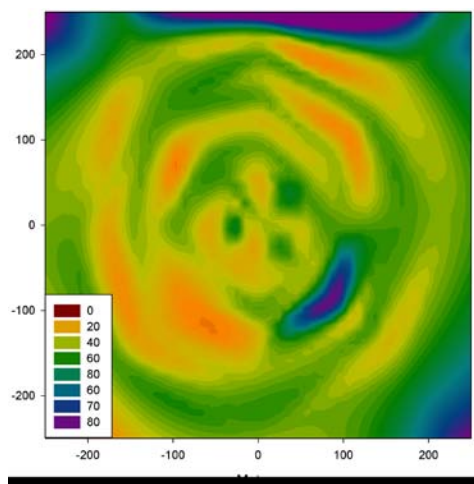




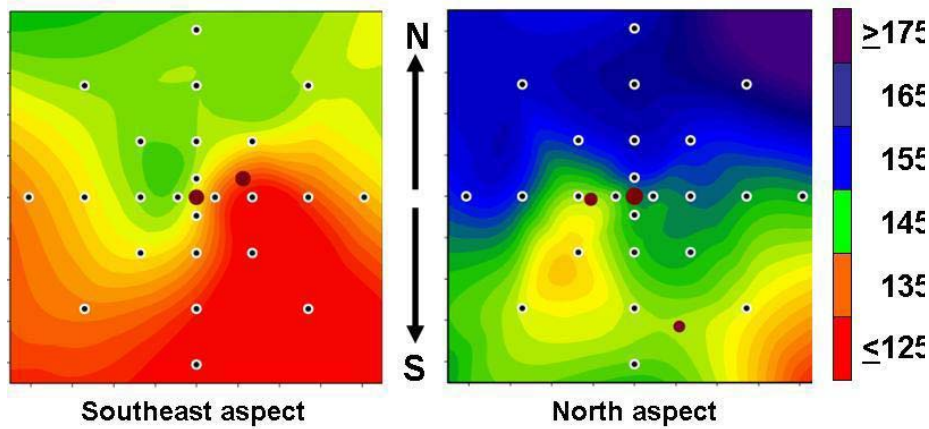
**Figure 17a.** July 28 handheld-TDR soil moisture



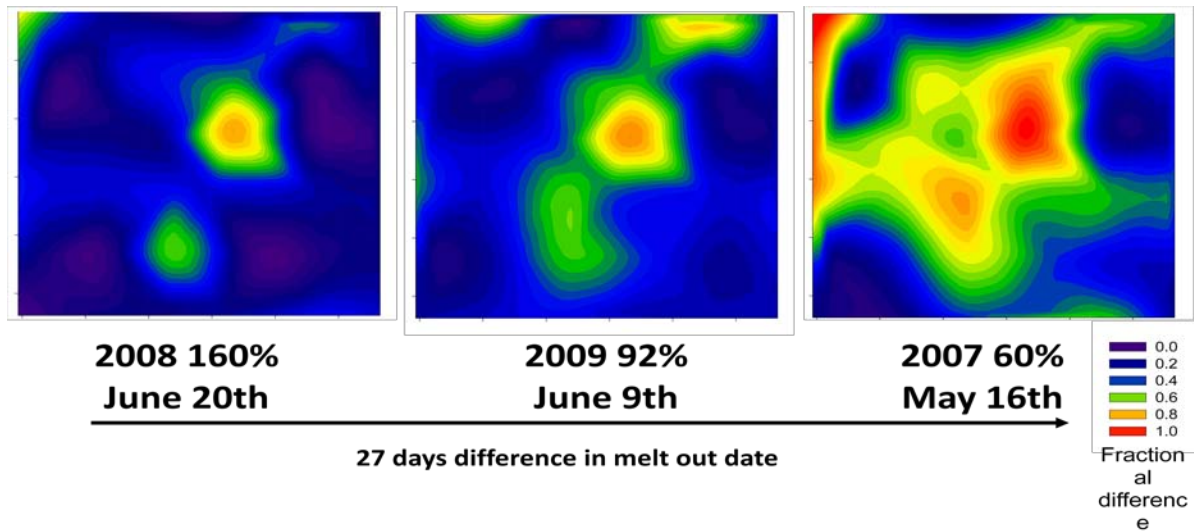
**Figure 17b.** September 28 handheld-TDR soil moisture



**Figure 17c.** October 19 handheld-TDR soil moisture



**Figure 18.**Day of snowcover melt out around a Southeast aspect tree and a North aspect tree.



**Figure 19.**Percent difference between snow depth measured under canopy and in the open for 2007-2009. Percent difference between under canopy and open depth are arranged for comparison with 75 year mean snow course depths to demonstrate a progression to earlier and more variable melt dates.



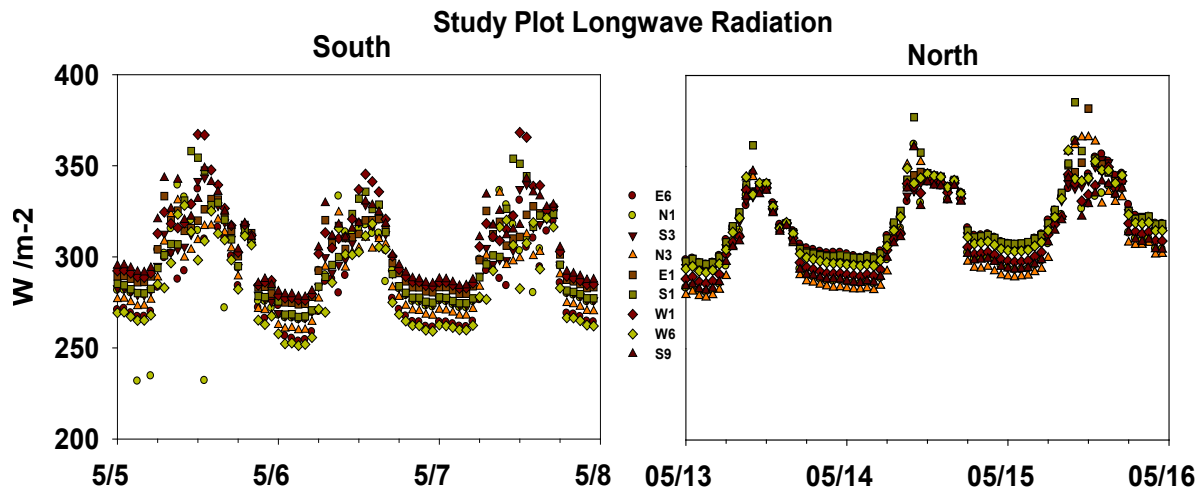


Figure 20. Longwave radiation plot for south and north aspect tree for 6 days during May 2010.

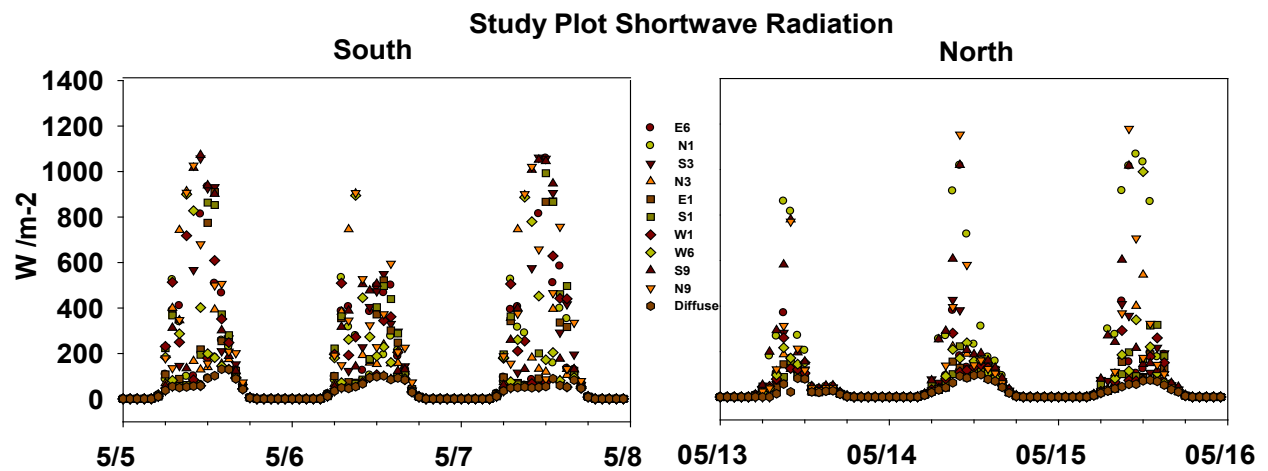
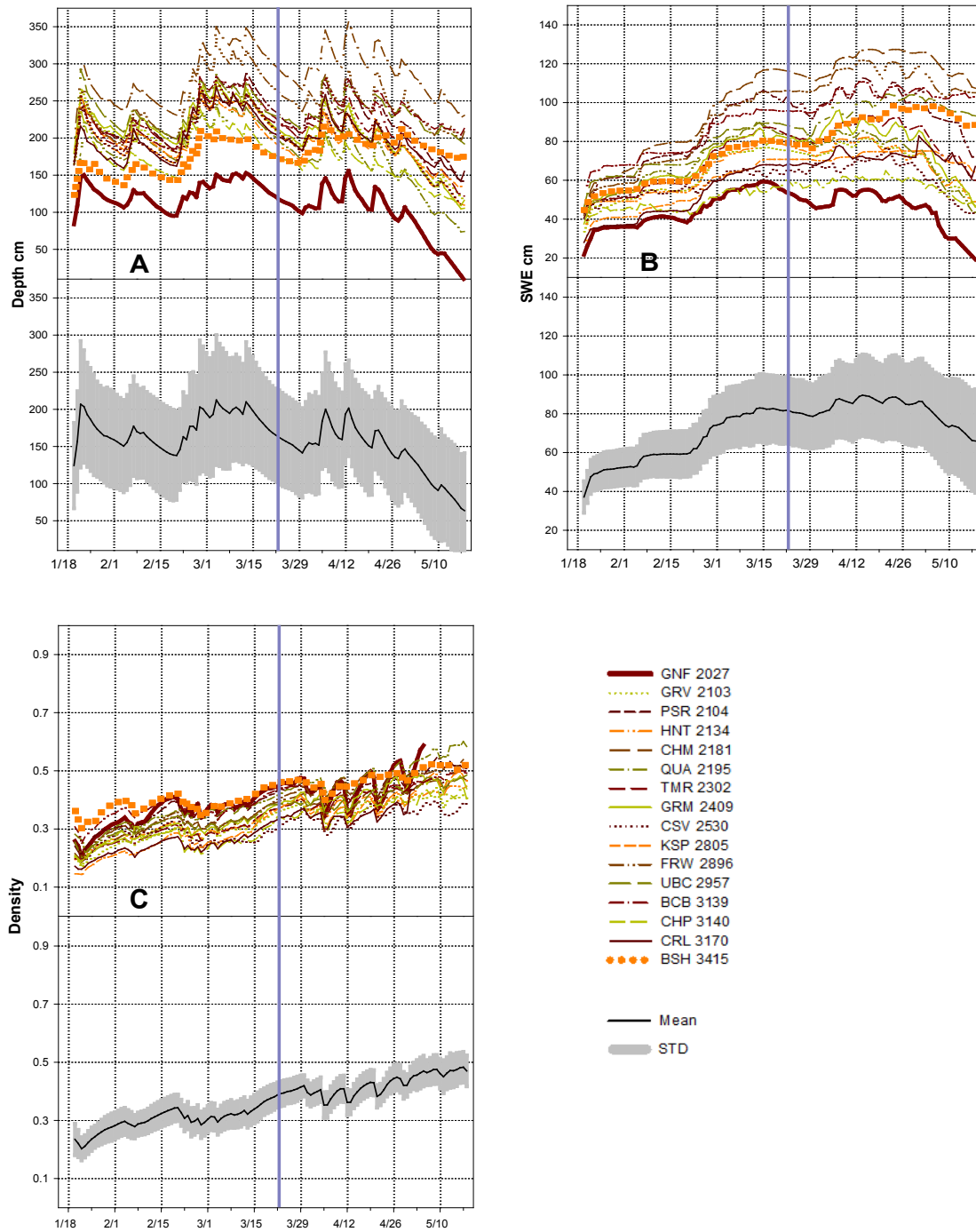
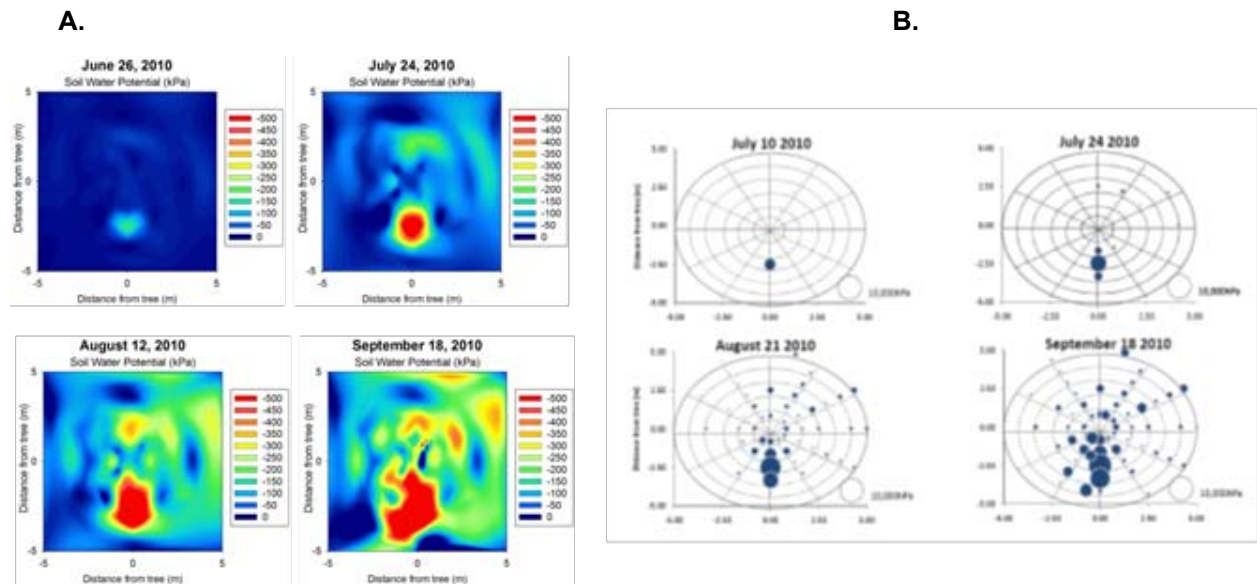


Figure 21. Shortwave radiation plot for south and north aspect tree for 6 days in May 2010.

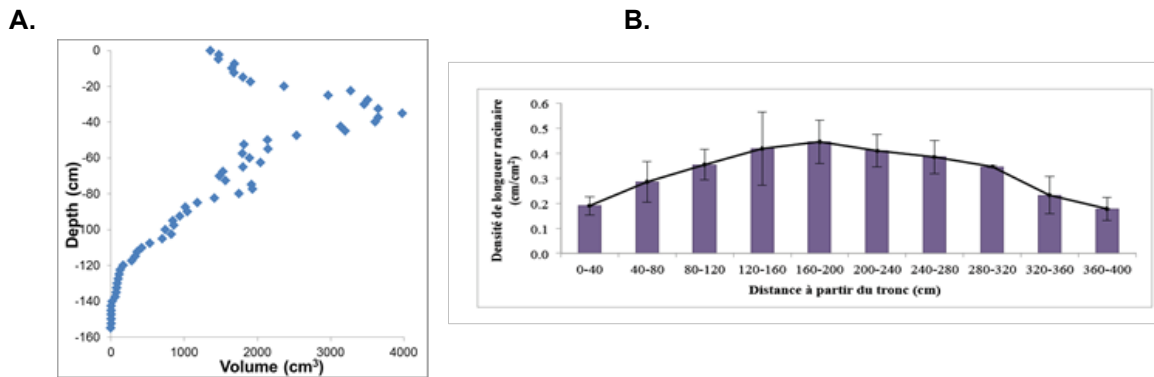
**Figure 22.** LiDAR derived snow depths for 2010 water year accumulation period in the Kaweah watershed Southern Sierra Nevada, red outline. Mean snow depths for each 1 meter elevation band on a 1700 m elevation gradient upper left. Snow depths between 2050 and 3300 m demonstrate a strong correlation ( $r^2.97$ ) with elevation. Elevations below 2050 m and over 3300 m are less well correlated and have higher coefficients of variation of snow depth within each elevation, shown as dark and light shaded blue in lower right digital elevation map.



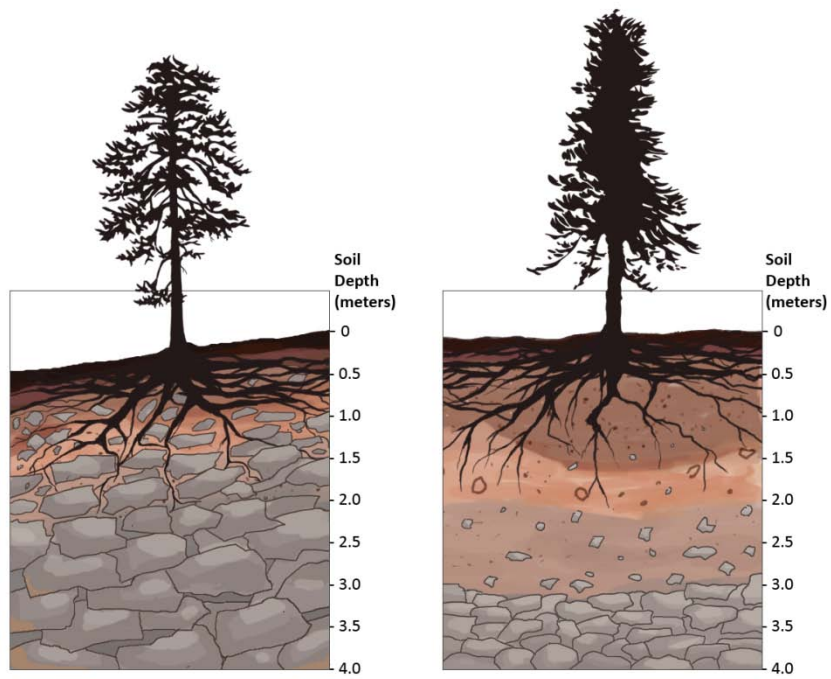
**Figure 23.** Snow depth (A) water equivalent (B) and density (C) for all west slope snow pillow-depth sensor instrument suites located within one degree latitude of study area, data for, highest and lowest elevation stations are plotted in bold. Lower panels show mean in black and 2 standard deviations in grey, blue bar shows LiDAR acquisition dates. No significant elevation trends are evident in these data a small range of 5 to 18% in snow density is seen throughout the season justifying the conversion of depth to water equivalence for the acquisition dates.



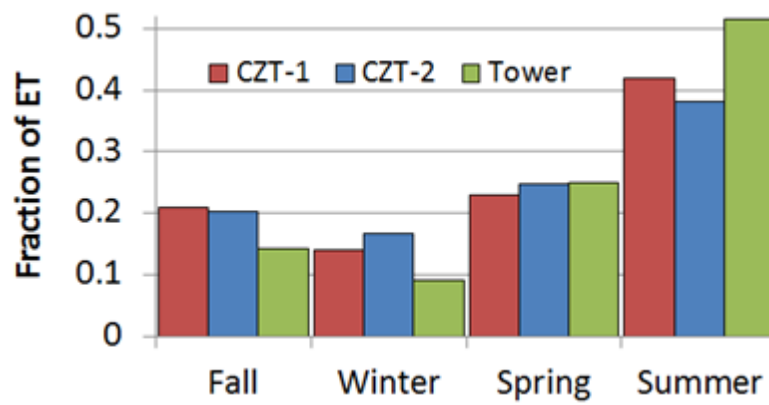
**Figure 24.** (A) Spatial distribution soil matric potential by at four measurement times during the 2010 summer period, and (B) as determined from the 72 30-cm deep MPS soil water matric potential sensors. Size of circle represents magnitude of matric potential measurement.



**Figure 25.**(A) Vertical and lateral (B) distribution of tree roots from the excavated tree.

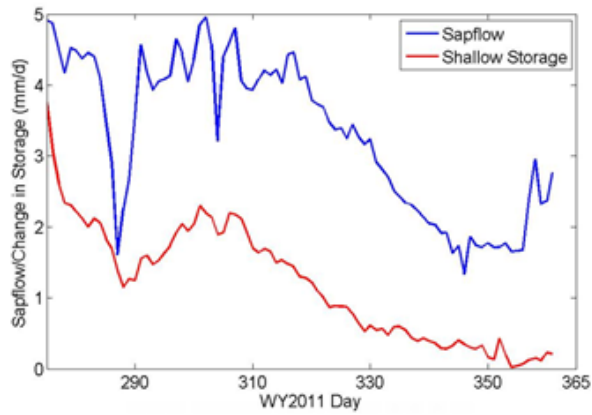


**Figure 26.** Conceptual model of the subsurface for CZT-2 (left) and CZT-1 (right).

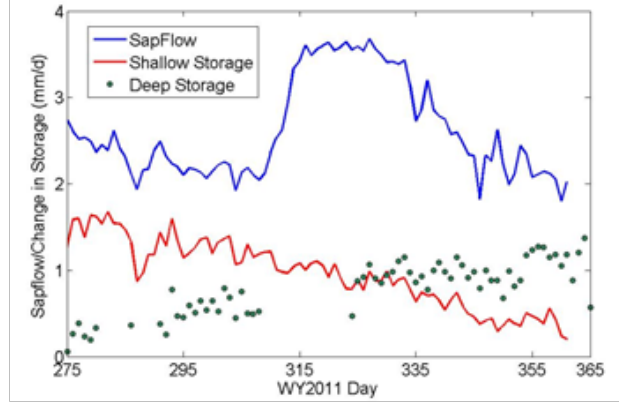


**Figure 27.** Partitioning of seasonal ET, using both sap flow and flux tower measurements.

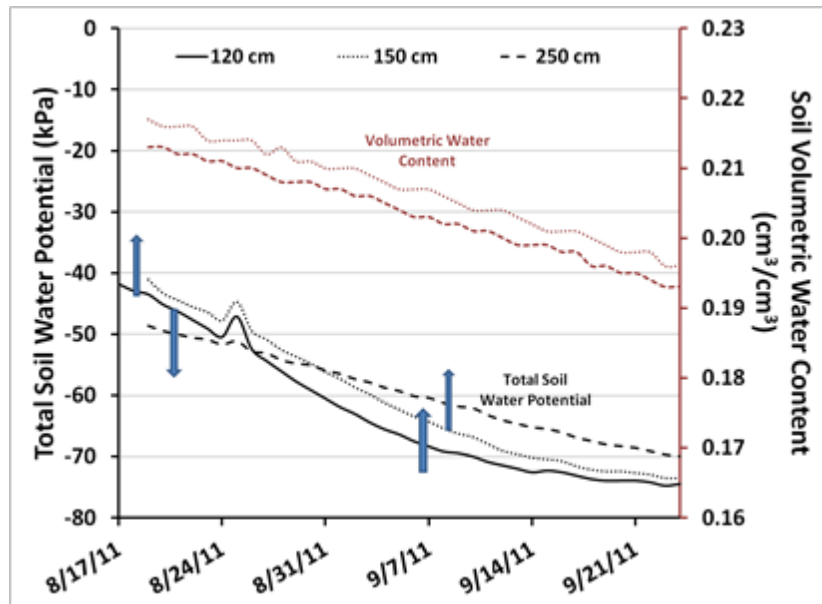
A.



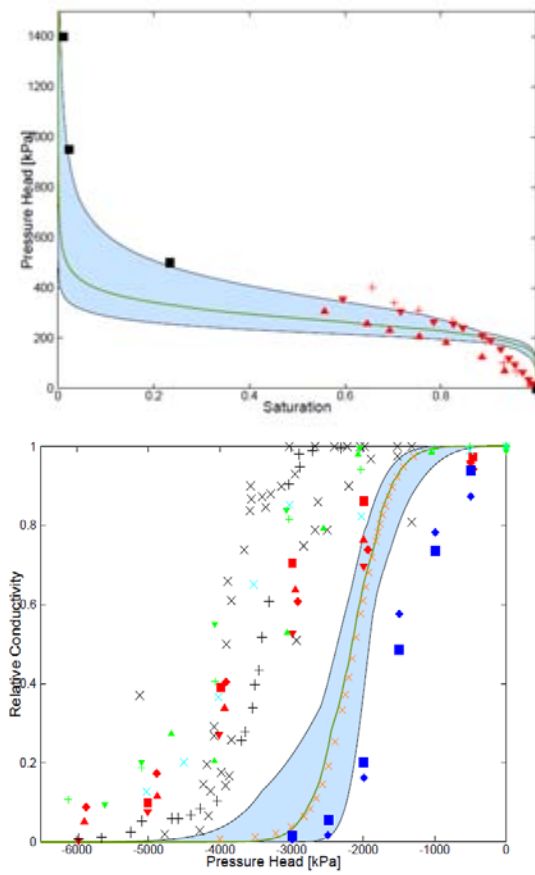
B.



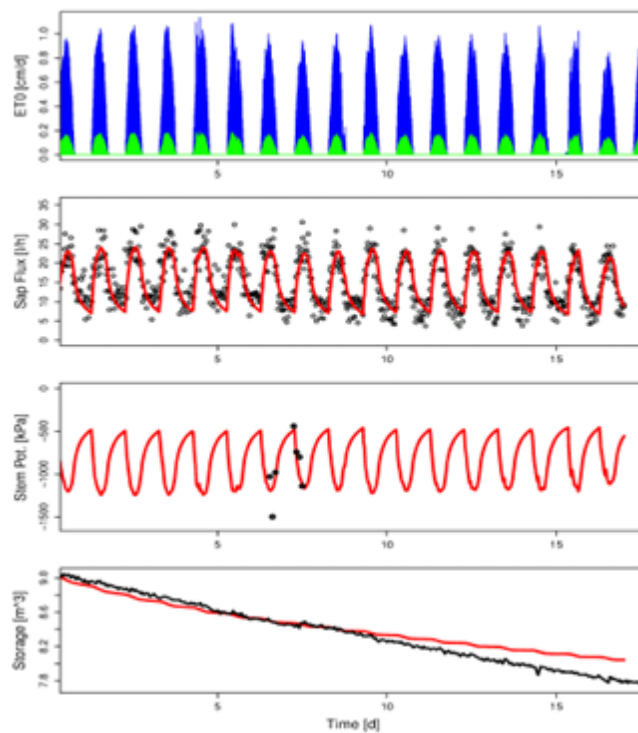
**Figure 28.** Changes in soil moisture storage and sap flow (mm/day) from CZT-2 (A) and CZT-1 (B), starting July 1. Deeper sensors at CZT-1 show the source of moisture switching to deeper soil moisture storage.



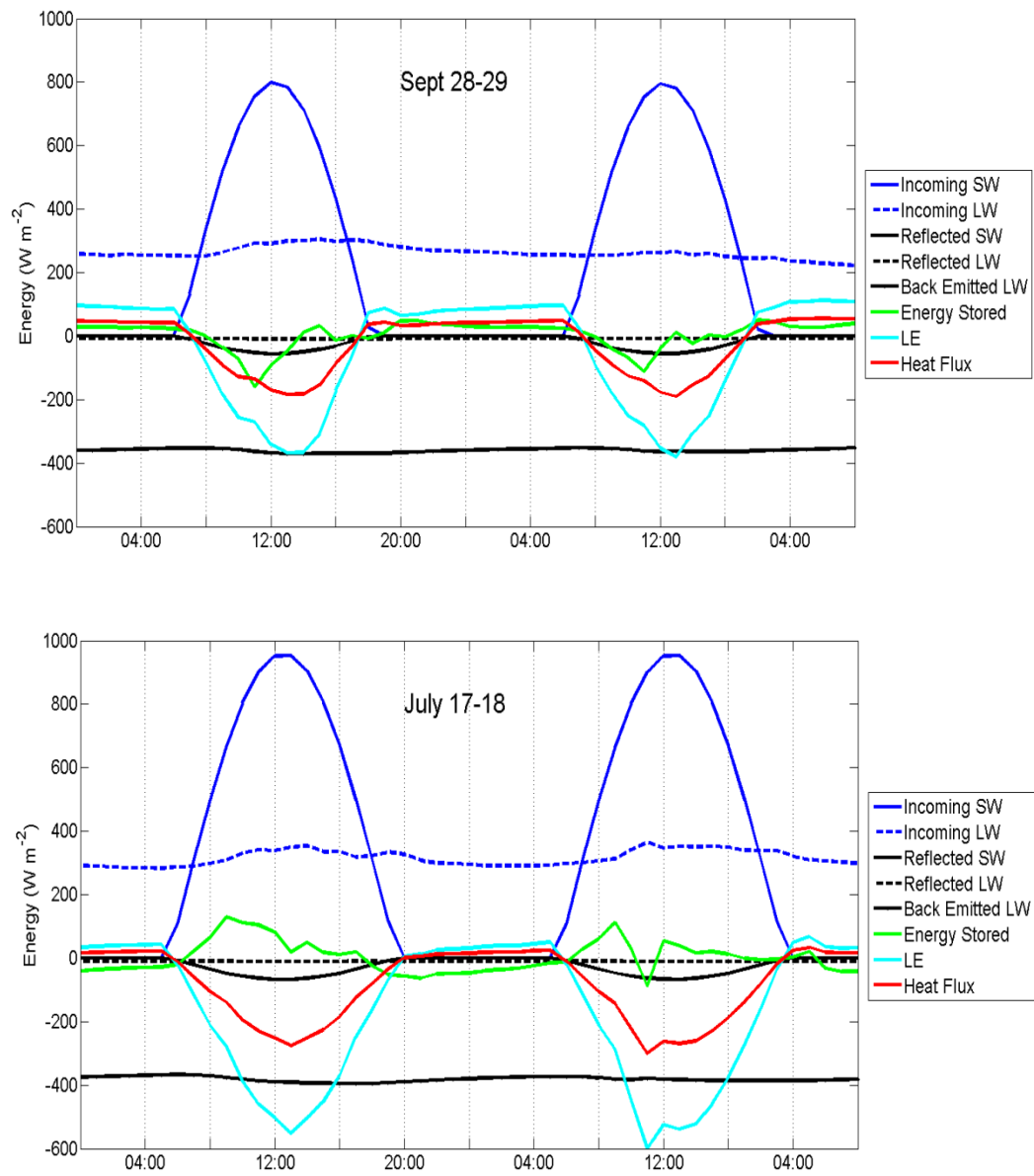
**Figure 29.** Soil water potential and soil moisture trends during August and September, 2010, at the DVP location. Arrows indicate direction of soil water movement. For example, because the total soil water potential at 150 cm (dotted line) is less negative than the corresponding value at 120 cm (continuous line), soil water moves from 150 to 120 cm (upwards) throughout the monitoring period.



**Figure 30.**Optimized tree water retention (top) and unsaturated hydraulic conductivity (bottom) functions, compared with literature data.

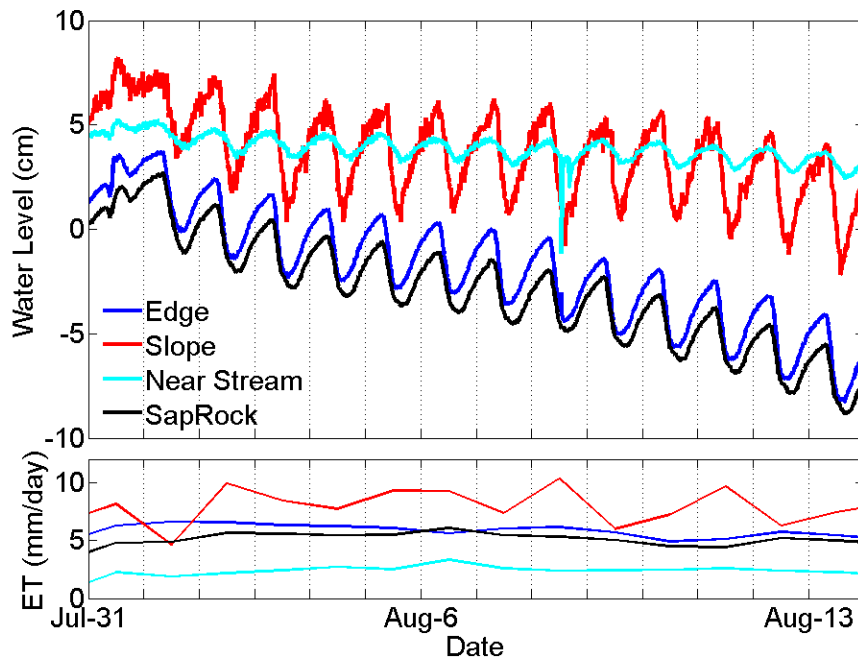


**Figure 31.**Comparison of measured with simulated soil water and tree trunk data.

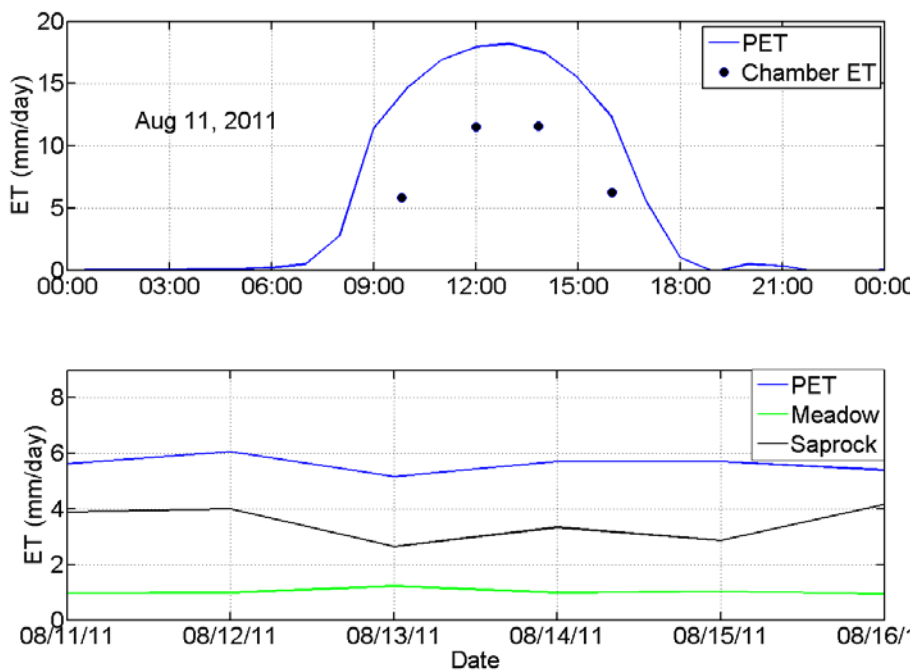


**Figure 32.** Constructed meadow pool energy balance for the summer (top panel) and the fall (lower panel). Energy stored is determined by change in pool temperatures, LE is the latent heat flux, and Heat Flux is the sensible heat flux.

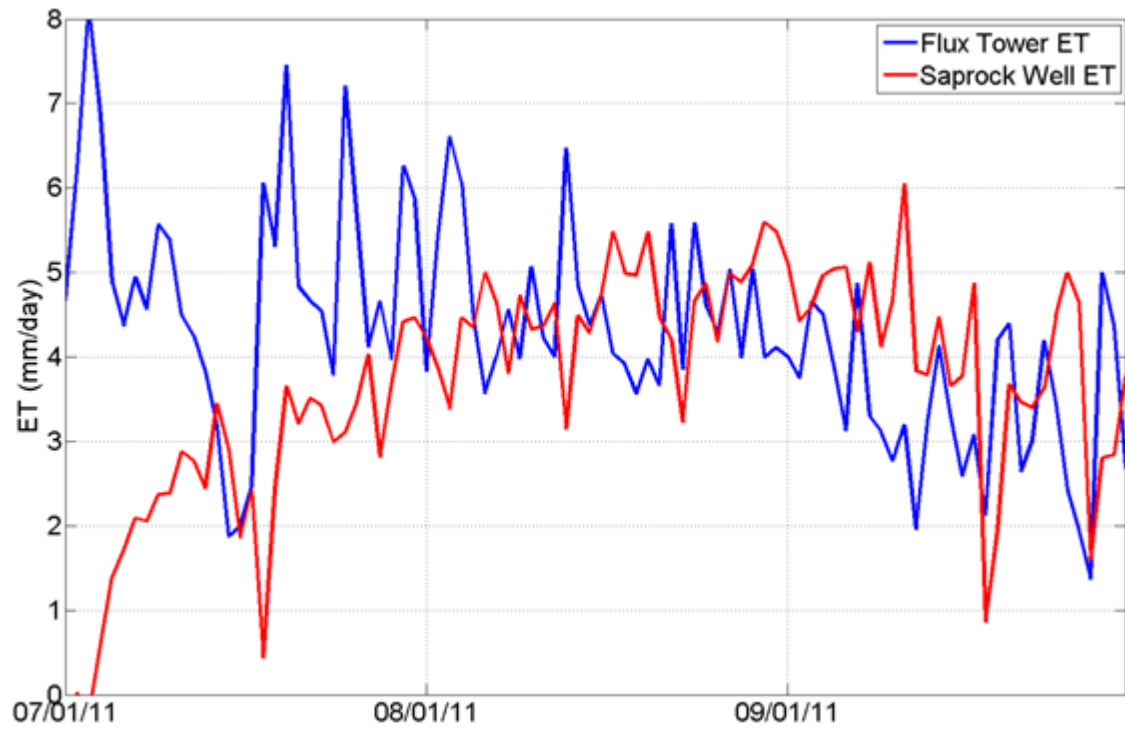




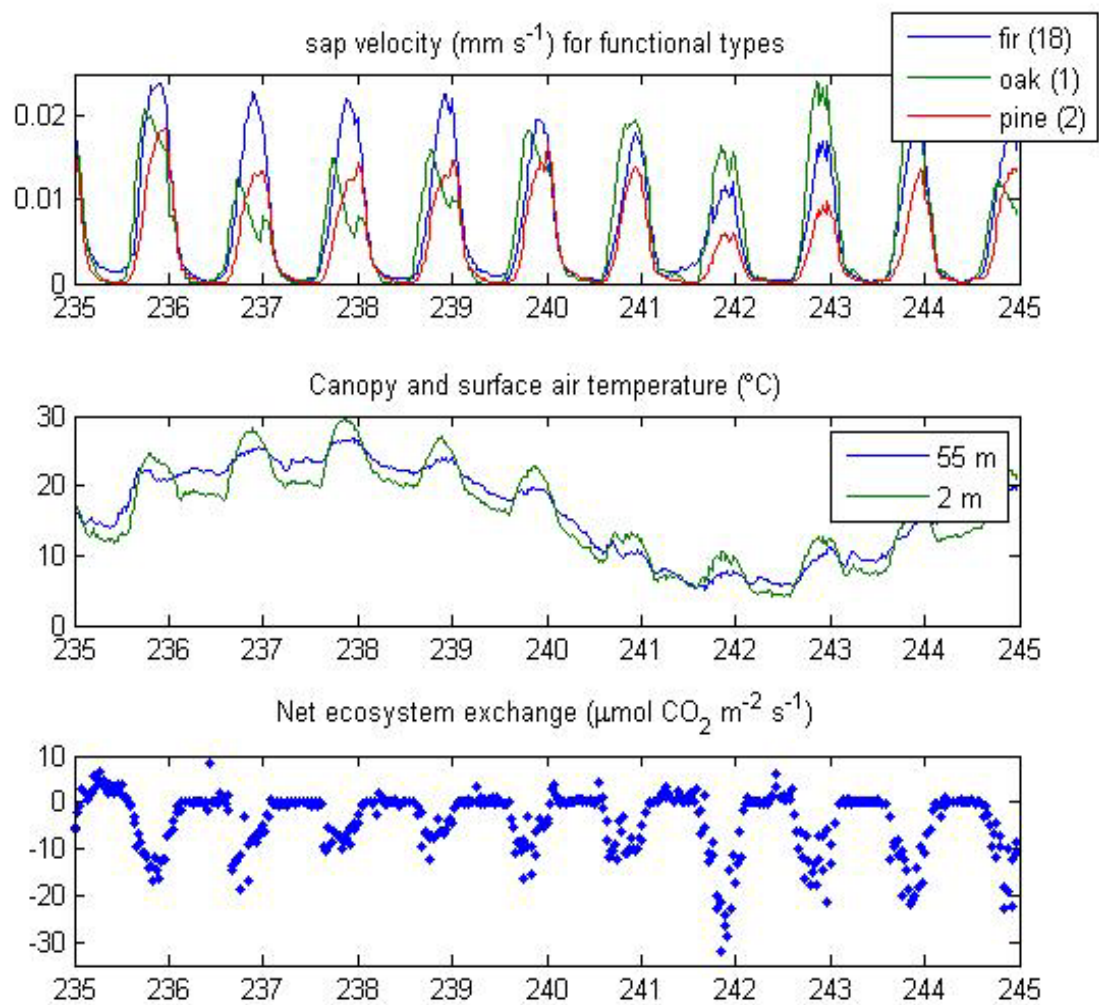
**Figure 33.** Comparable groundwater elevations for edge, slope, and saprock wells (Top panel) and calculated groundwater contribution to ET for near stream, slope, edged, and saprock wells (lower panel).



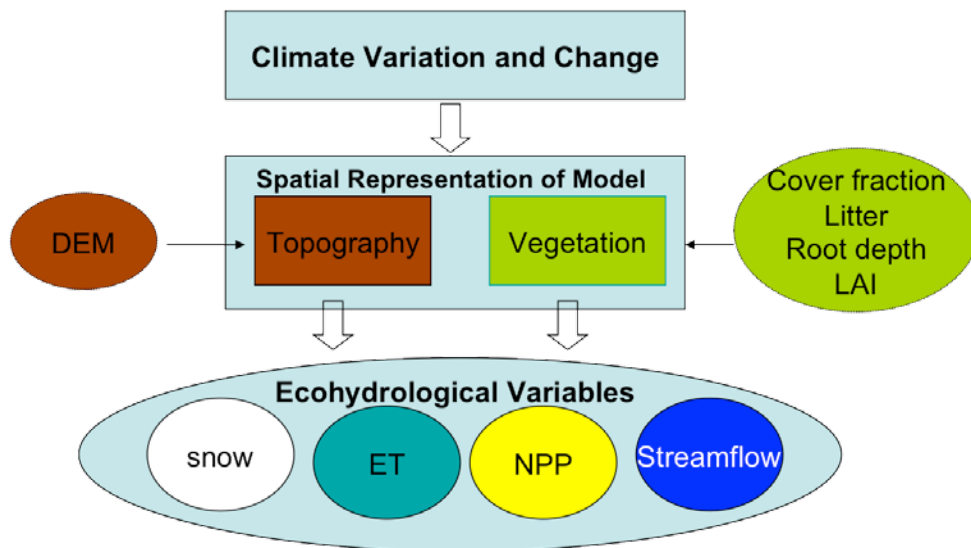
**Figure 34.** Comparison of chamber measured ET and PET (top panel) and ET calculated from meadow and saprock wells and PET (lower panel).



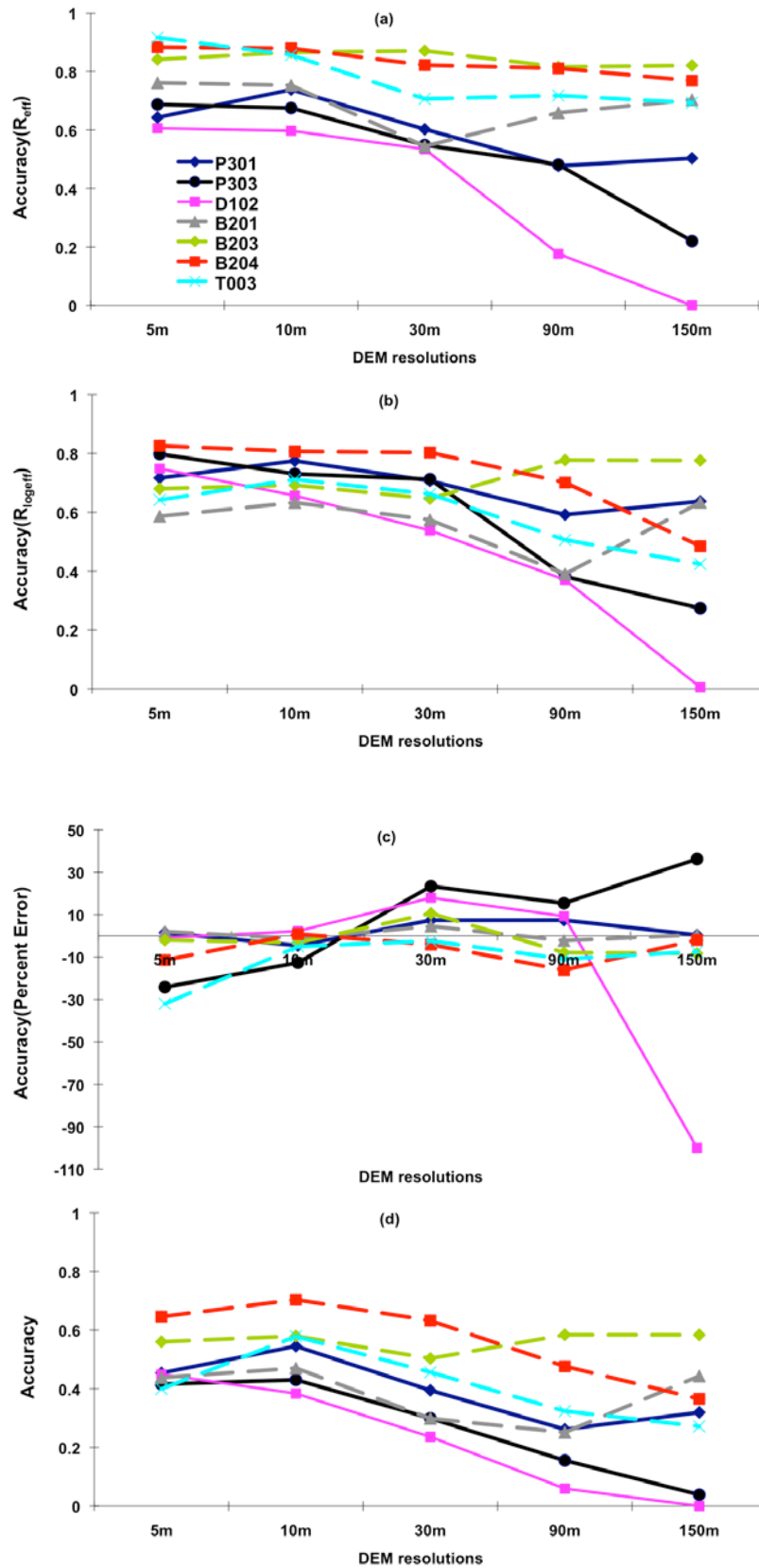
**Figure 35.** ET as measured at the P301 Flux tower and as the average of calculated values from the three saprock wells.



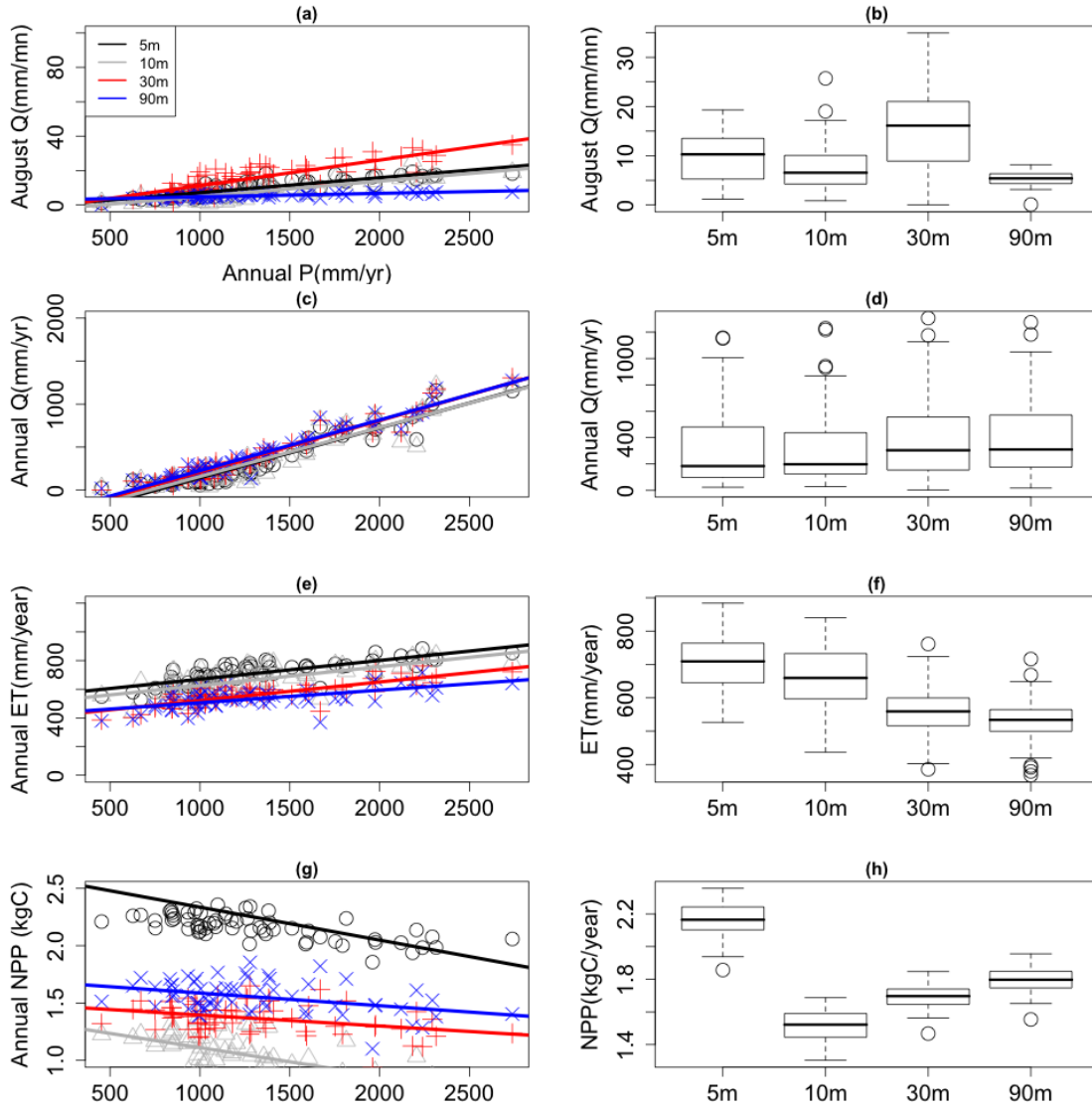
**Figure 36.** Sap flow compared to canopy top air temperature and carbon flux for late August 2010.



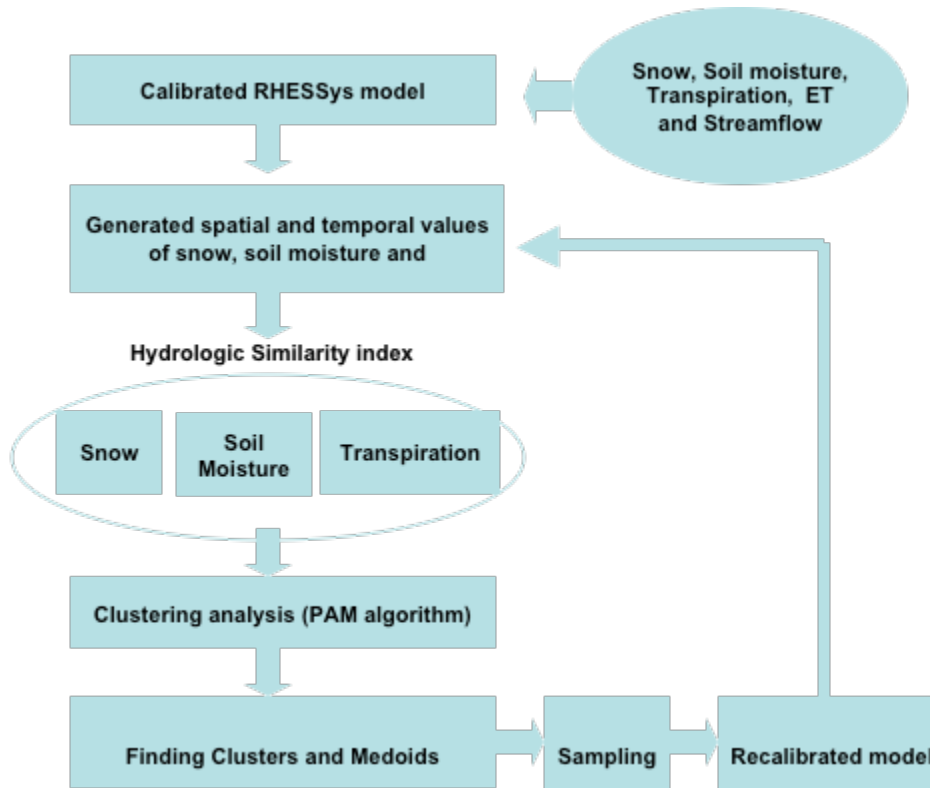
**Figure 37.** The conceptual framework for testing the impact of topographic and vegetation parameters on ecohydrologic prediction to climate variability



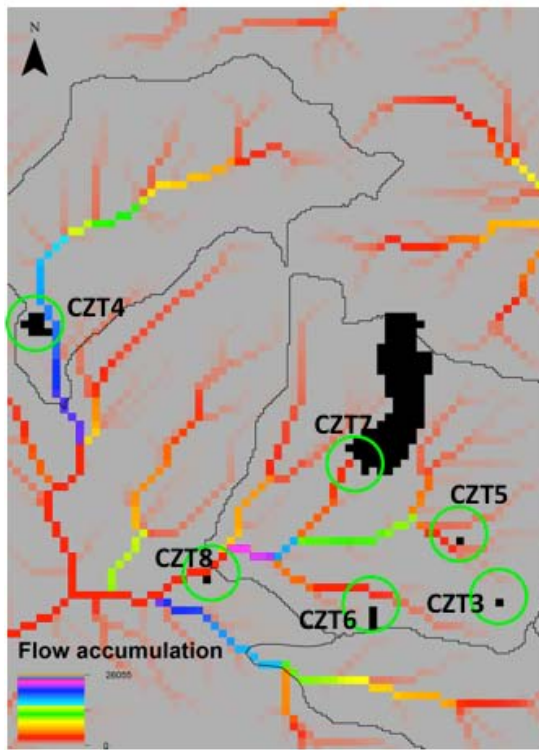
**Figure 38.** Effect of the DEM resolution on the model streamflow accuracy of CZO watersheds: (a) using  $R_{eff}$ , (b) using  $R_{logeff}$ , (c) Percent Error and (d) combined accuracy measure.



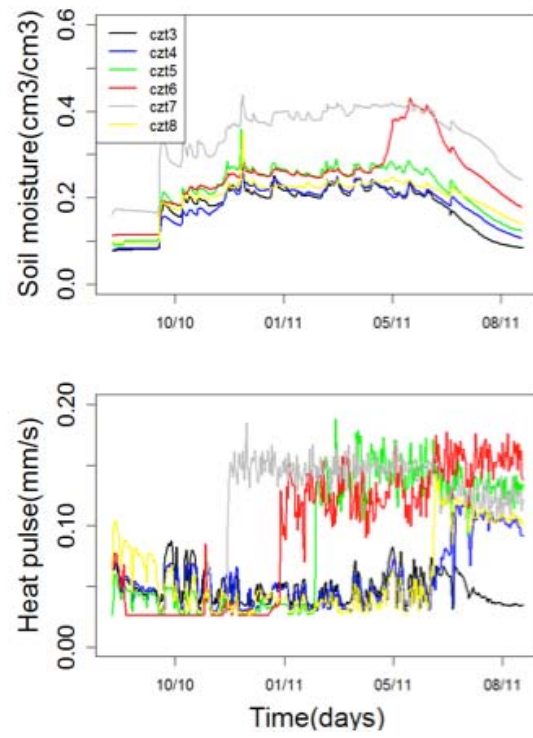
**Figure 39.** The sensitivity of estimated ecohydrologic response to climate variability with different DEM resolution for the D102 watershed.



**Figure 40.** The conceptual framework of strategic sampling design approach for soil moisture and vegetation water use in this study.



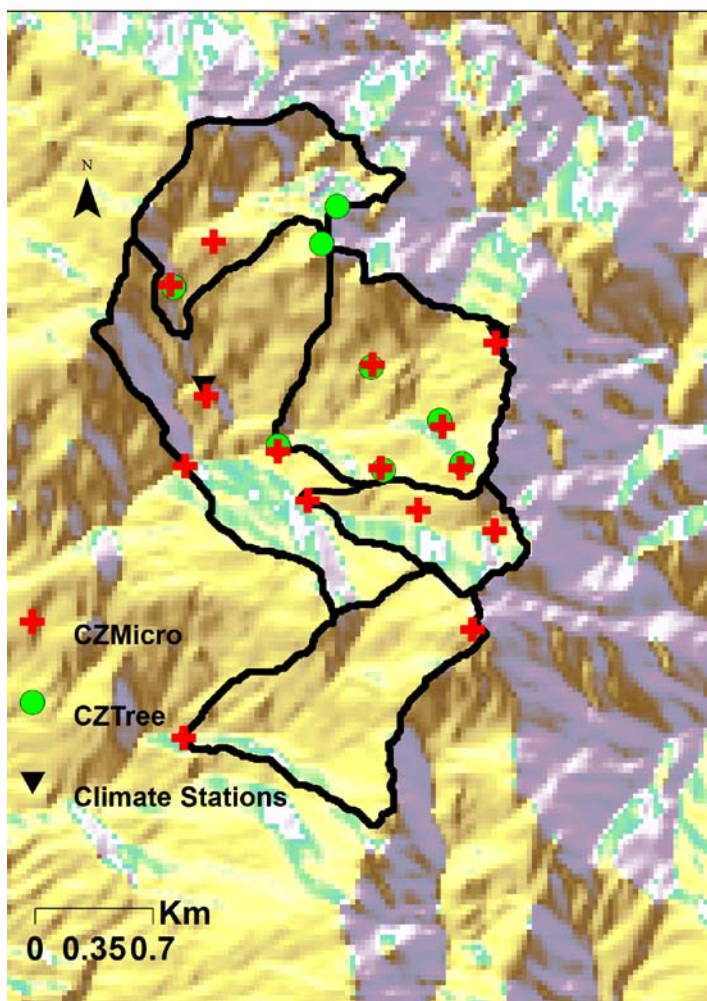
(a)



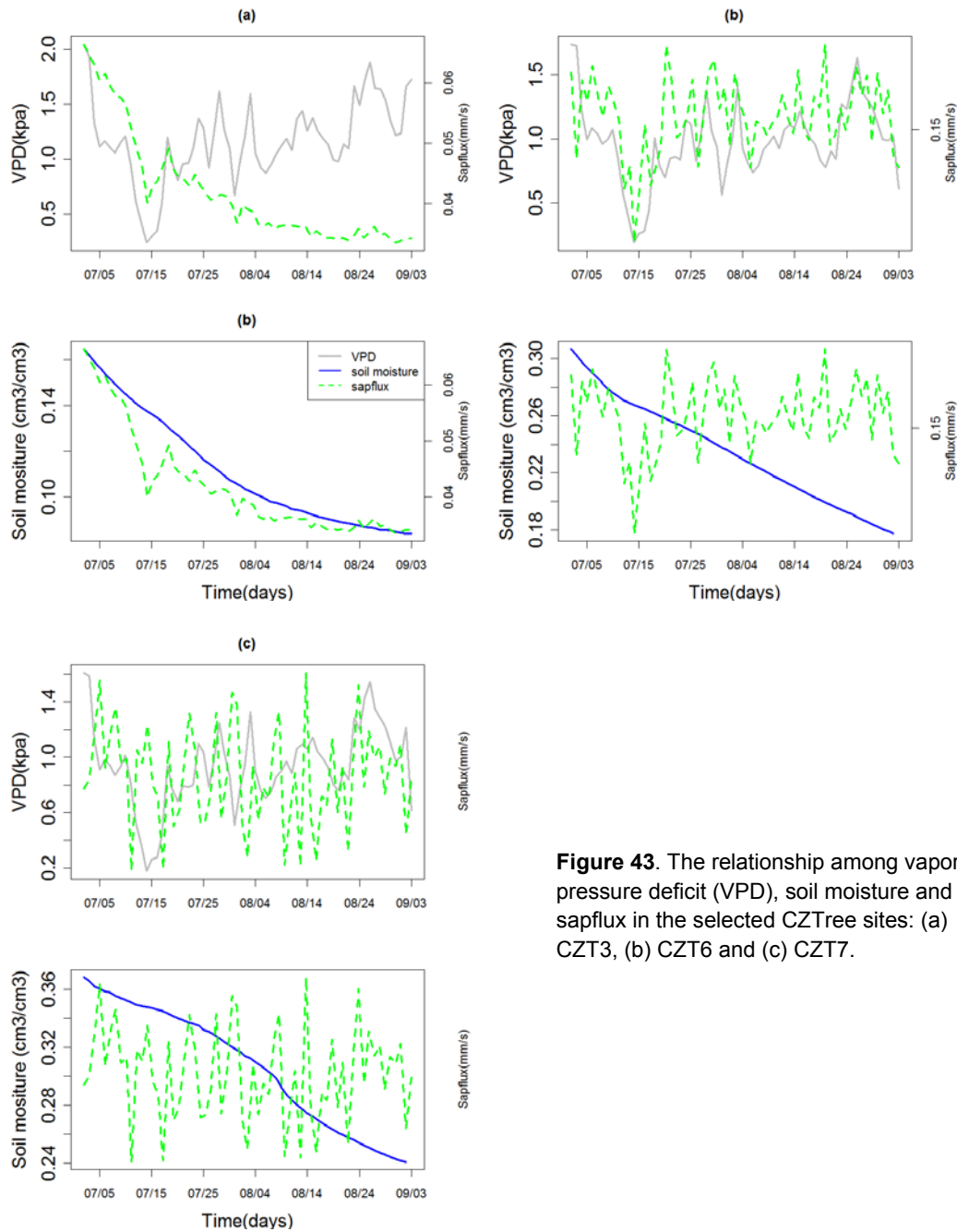
(b)

**Figure 41.** The location of CZT sites and collected soil moisture and sapflux data: (a) the upslope area of each CZT site and (b) the time series of collected soil moisture and sapflux data at the CZT sites

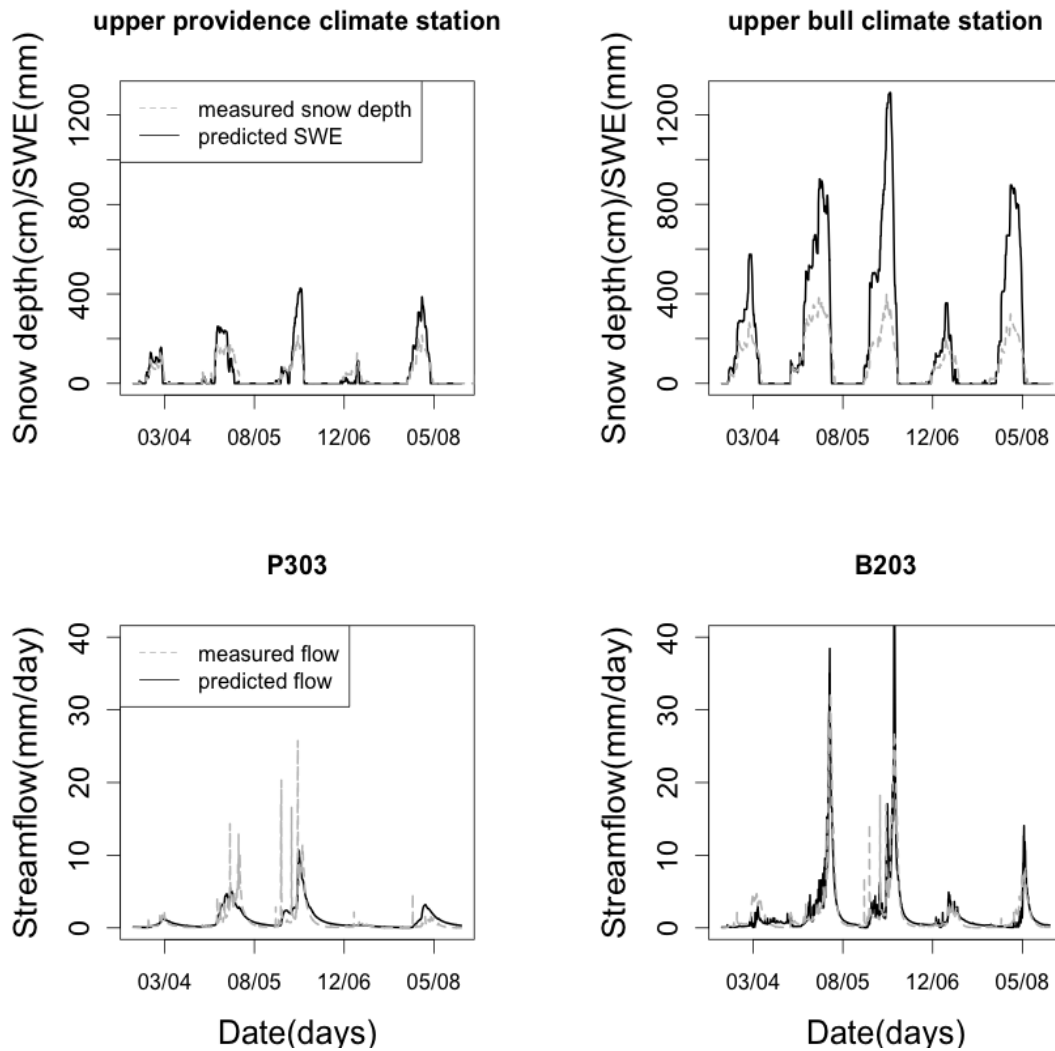




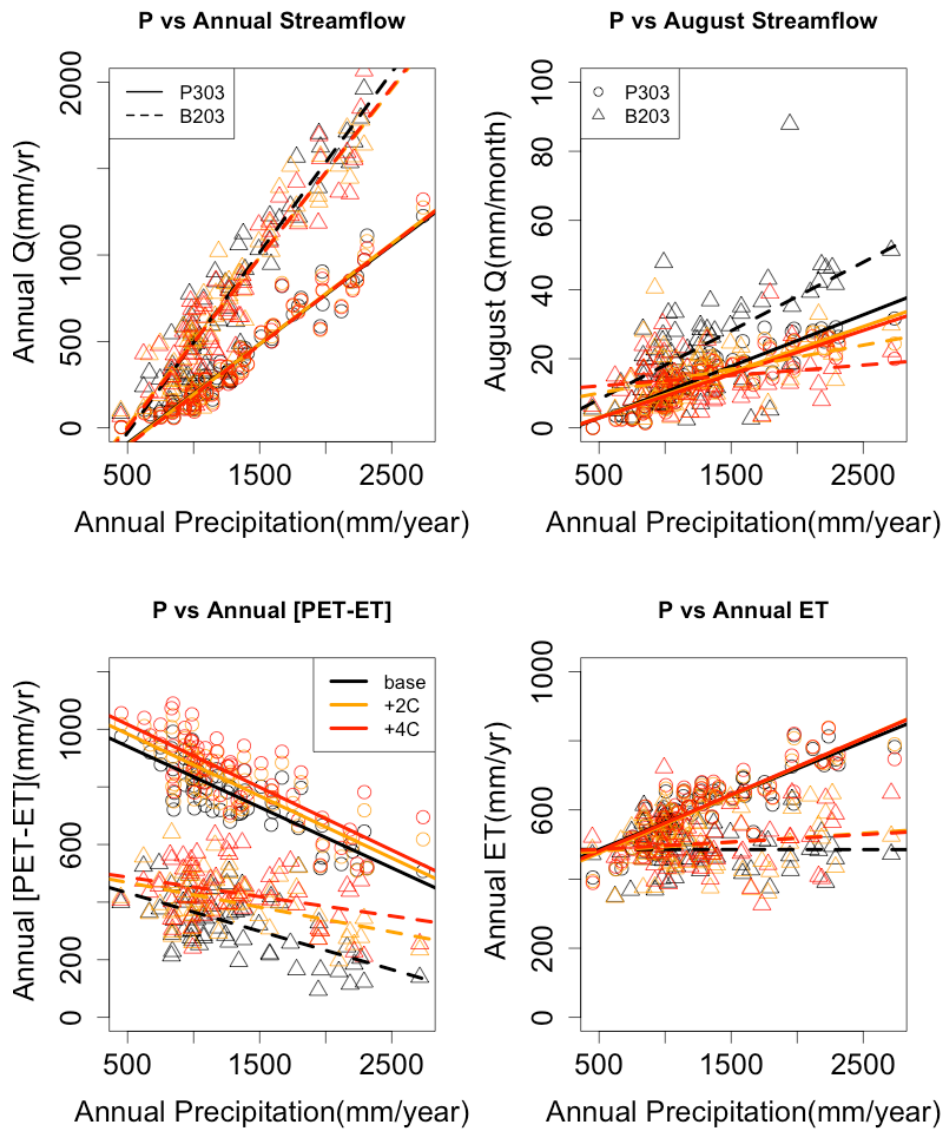
**Figure 42.** The location of microclimate, soil moisture and sapflux sensor: CZMicro(microclimate), CZTree( soil moisture and sapflux), Climate Stations (upper and lower providence meteorological station)



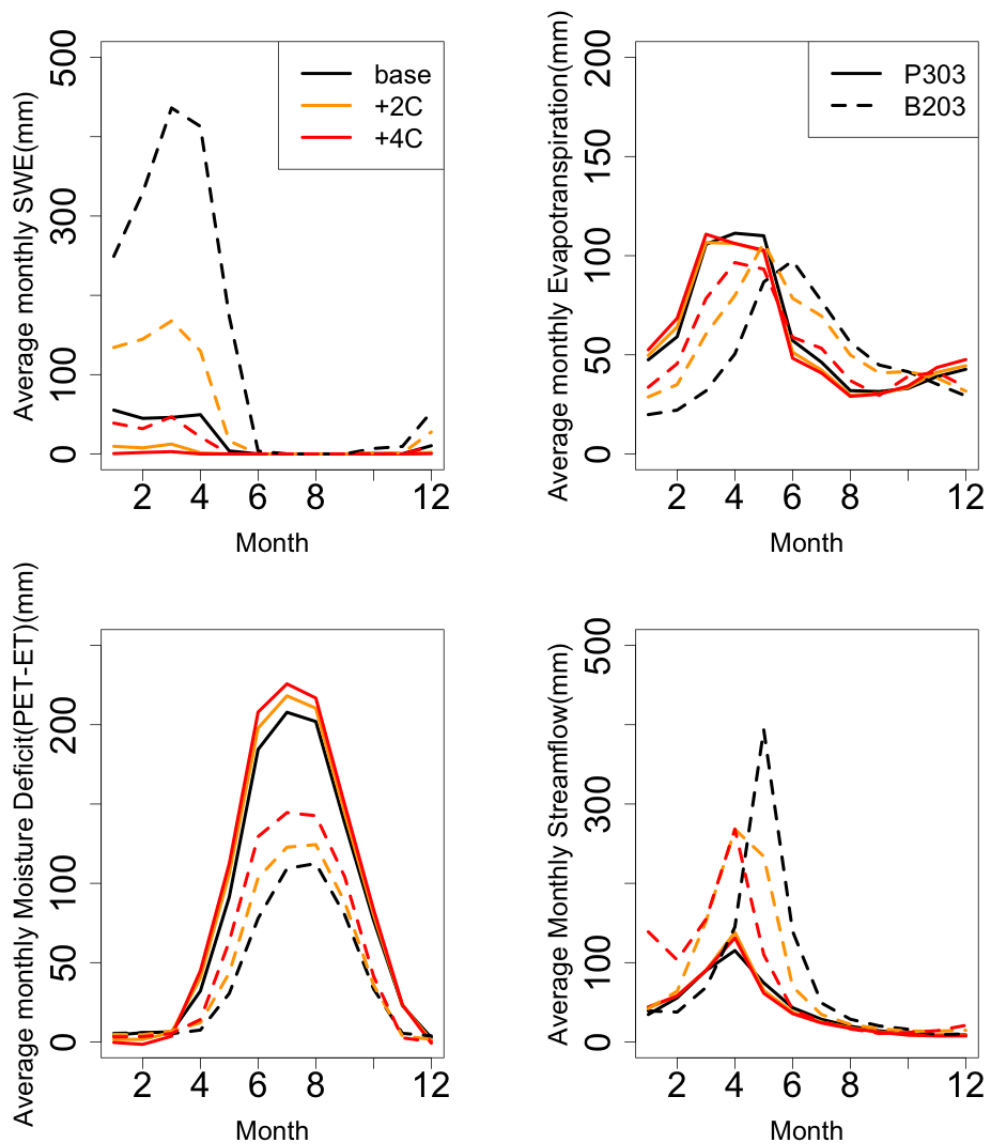
**Figure 43.** The relationship among vapor pressure deficit (VPD), soil moisture and sapflux in the selected CZTree sites: (a) CZT3, (b) CZT6 and (c) CZT7.



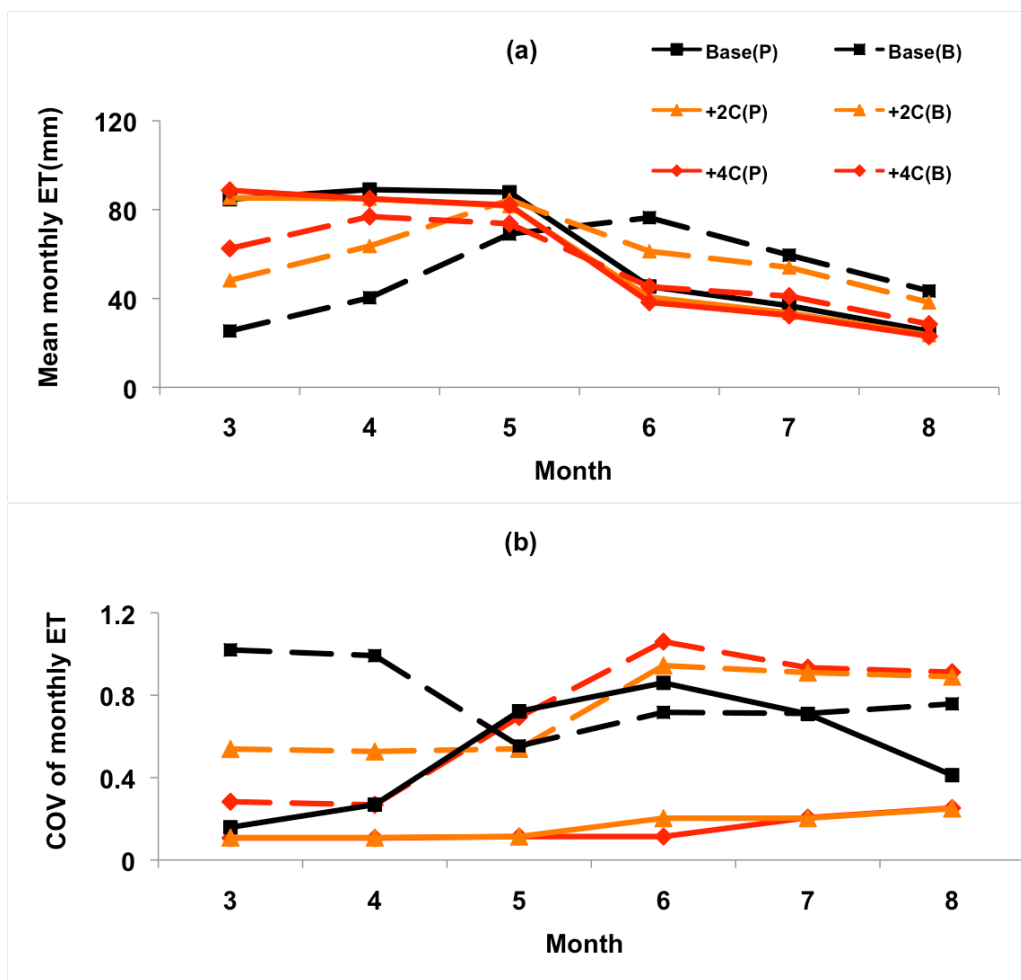
**Figure 44.** Model evaluation: (upper left), Comparison of observed snow depth with predicted SWE at the upper providence climate station, (upper right) Comparison of observed snow depth with predicted SWE at the upper bull climate station, (lower, left) Comparison of observed streamflow with predicted streamflow at the P303 gauging station data, and (lower right) Comparison of observed streamflow with predicted streamflow at the B203 gauging station.



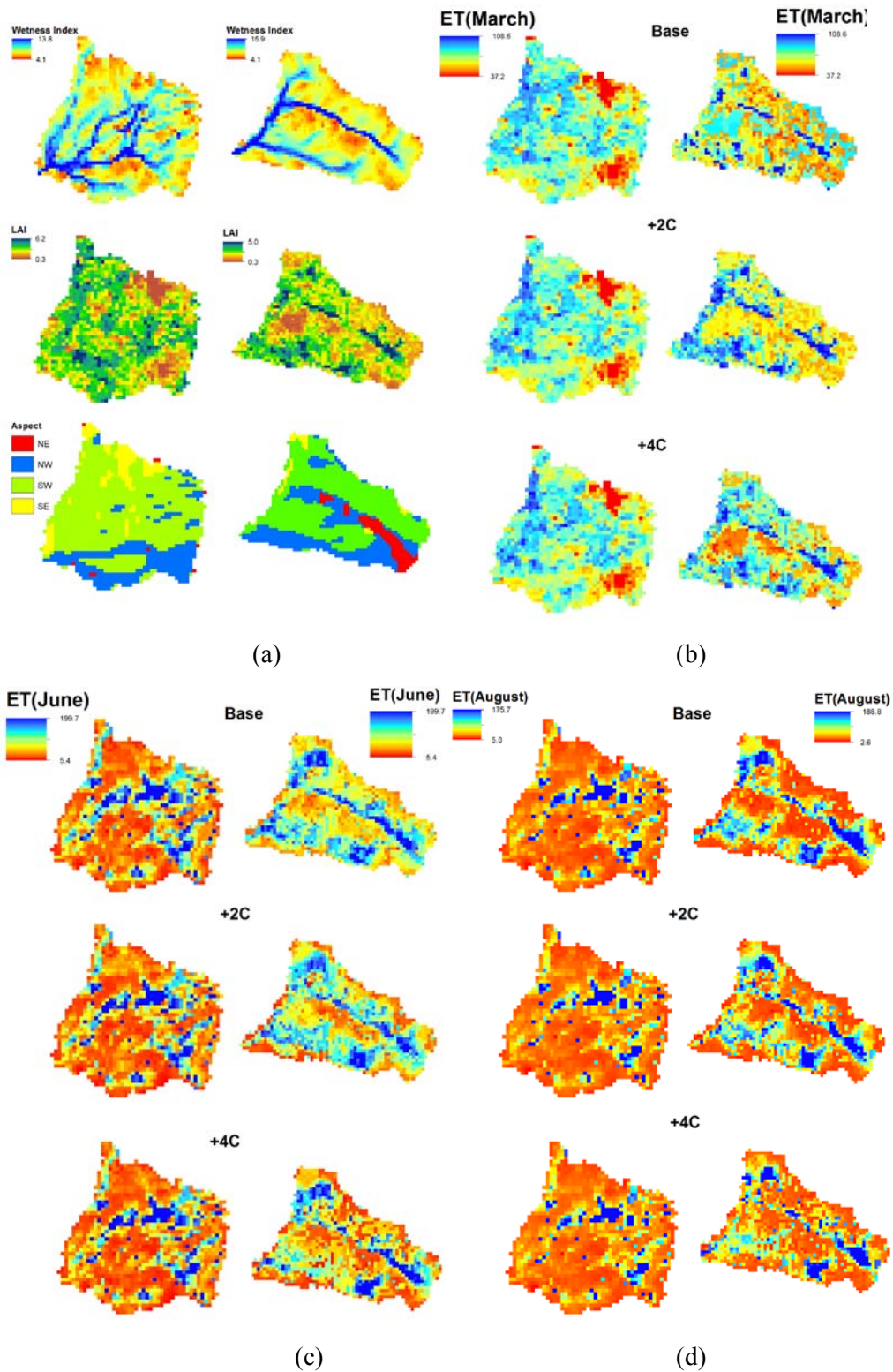
**Figure 45.** The relationship among annual precipitation, annual streamflow, August streamflow, annual ET and annual Moisture deficit (PET-ET) of the P303 and the B203 watersheds during climate warming scenarios



**Figure 46.** Climate-warming effect on seasonal watershed scale fluxes of P303 and B203

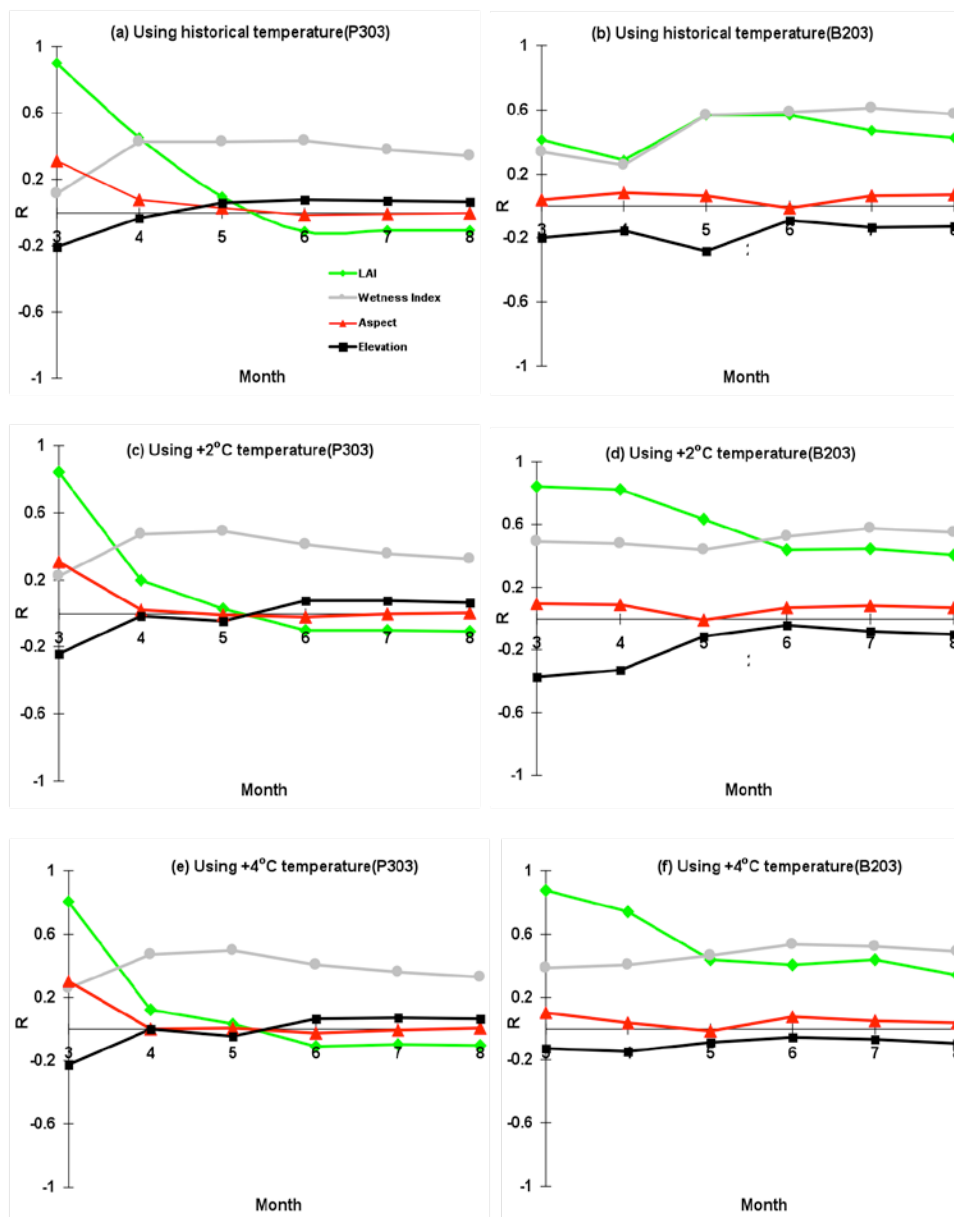


**Figure 47.** Seasonal change of spatial mean and coefficient of variance of ET for the P303 and the B203 watersheds with climate warming: (solid line)- P303 and (dotted line) –B203



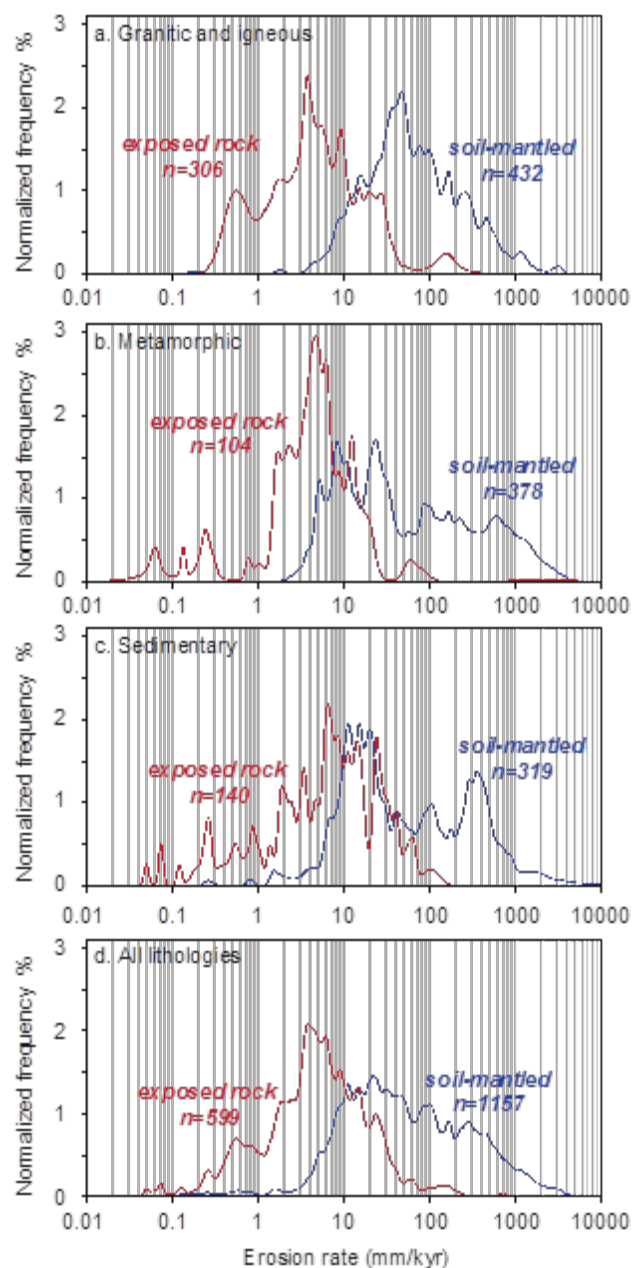
**Figure 48.** The effect of climate warming on spatial pattern of ET for the P303 and B203 watersheds: (a) physiological parameters, (b) March, (c) May and (d) August.



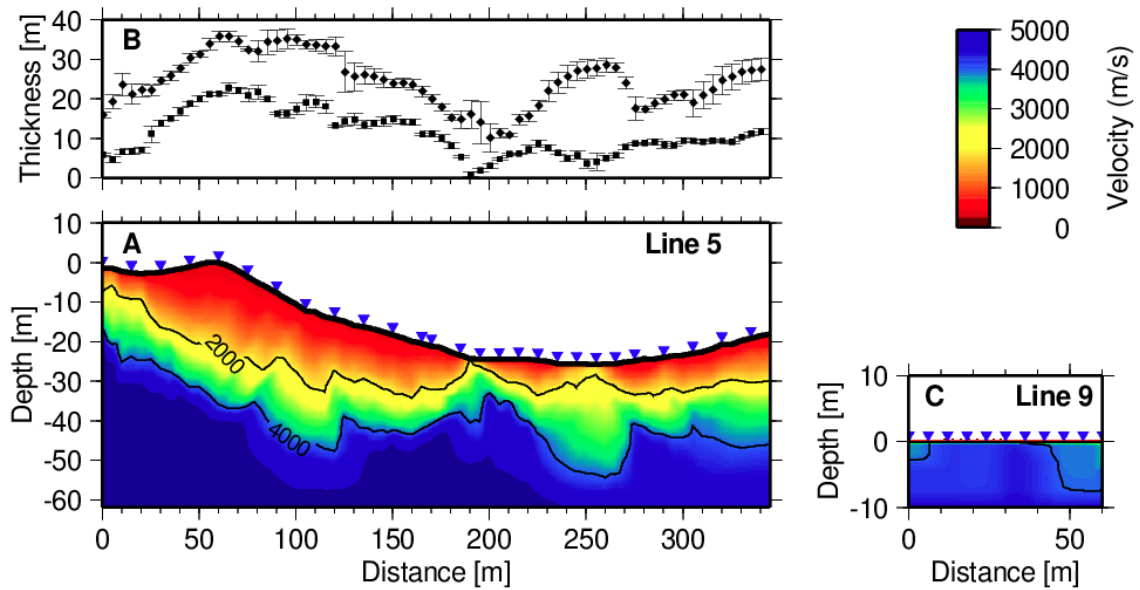


**Figure 49.** The relationship between physiological parameters and spatial ET (expressed as Pearson correlation coefficient ( $R$ )).

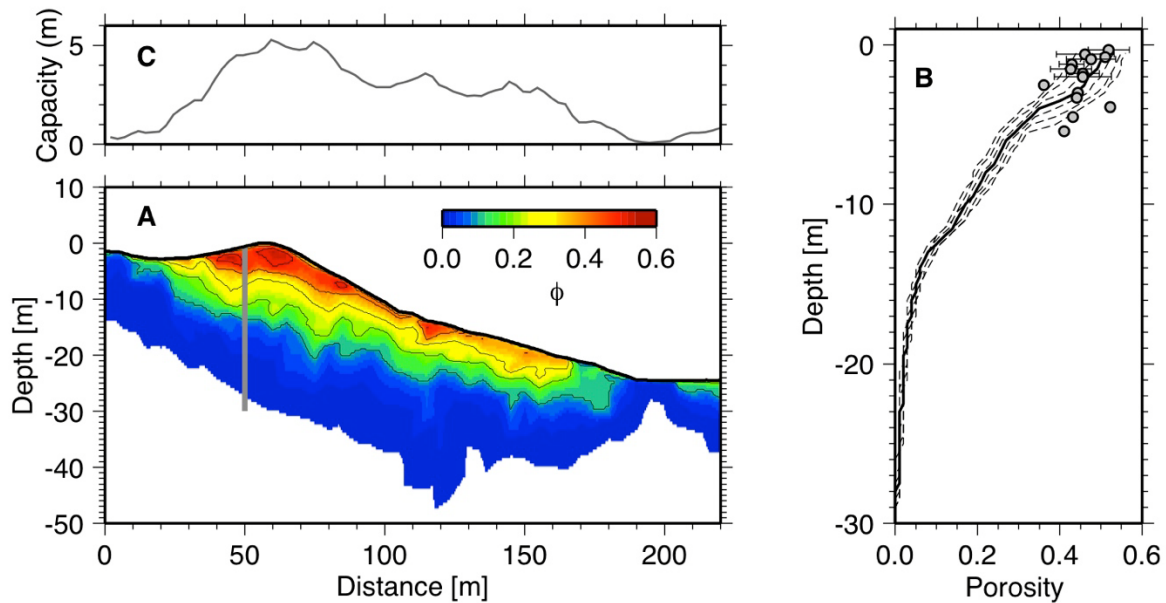




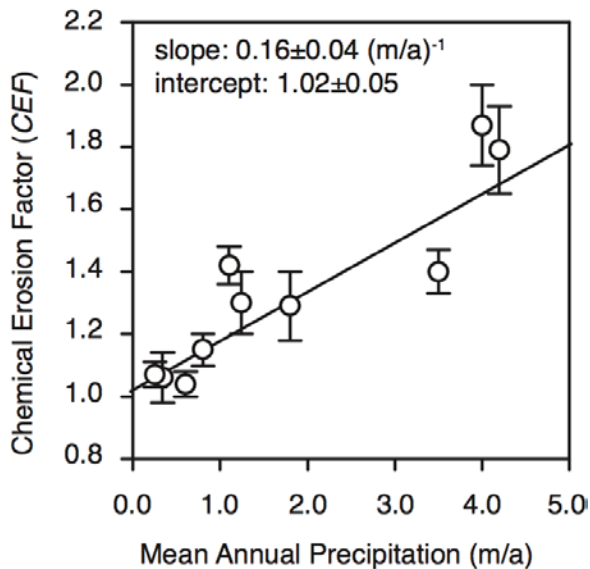
**Figure 50.** Probability distributions of erosion rates of exposed (red) and soil-mantled rock (blue) based on a global compilation of cosmogenic-nuclide data ( $n=1756$ ) for different lithologic groupings including: (a) granitic and igneous; (b) metamorphic; (c) sedimentary; and (d) all lithologies combined, including volcanic landscapes not plotted separately due to a paucity of examples (after Riebe et al., in prep 1). Density traces reflect the normalized sum of data points at each erosion rate, with published uncertainties to distribute each point according to the normal distribution. In each case, erosion rates of exposed rock plot markedly lower than erosion rates of soil-mantled terrain. Hence, differential erosion according to the presence/absence of soil could plausibly manifest itself as changes in relief in other landscapes besides granite.

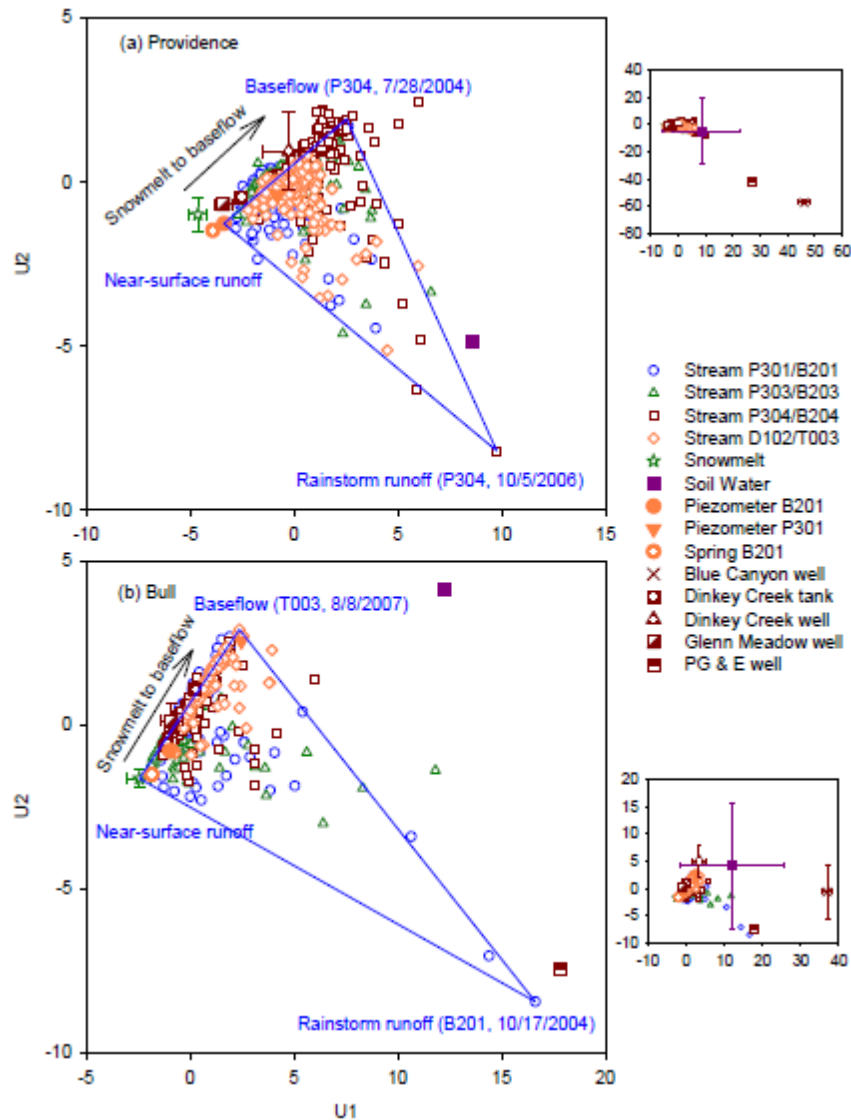


**Figure 51.** (A) Velocity model of a transect spanning a forested slope and swampy meadow in the headwaters of the CZO based on inversion of first-arrival travel times. (B) Depth from the surface to the 2000 m/s and 4000 m/s contours. Error bars reflect variations observed in a Monte Carlo ensemble of solutions that result from a range of starting models. Depth to the 4000 m/s contour varies from 10 to 35 m (average 23 m) and is highest at the crest of the forested slope, under CZT-1, a heavily instrumented white fir. In contrast, under the swampy meadow, depth to the 4000 m/s contour is shallowest and most variable, ranging from ~10 to 30 m over just 60 m of horizontal distance. (C) Velocity model of Line 9 from inversion of first-arrival travel times. Velocities of 4000 m/s at the surface on Line 9, acquired on an extensive granite outcrop, enable interpretation of 4000 m/s velocities (blue shades) on Line 5 as coherent bedrock at depth. After Holbrook et al., in review.

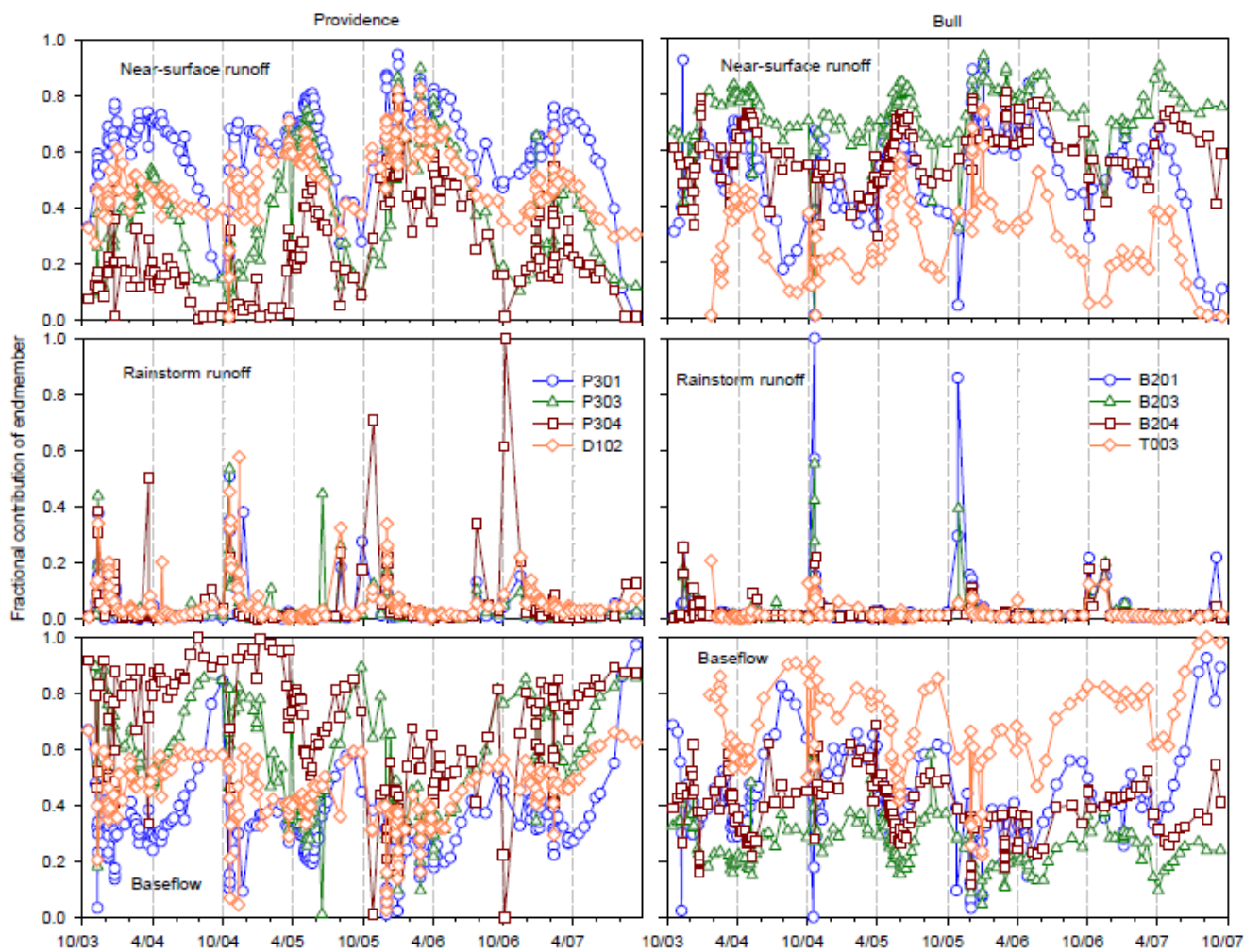


**Figure 52.** Line 5: (A) Porosity model on southern portion of Line 5, calculated from seismic velocities using a rock physics model, and assuming dry porosity and a composition of 50% feldspar, 25% quartz, and 25% clay. Porosity is contoured every 0.1 (10%). White region at base shows area where porosity is predicted to be zero (i.e., at the bedrock-regolith interface). Note that this is a minimum porosity for that composition; if pore space is saturated, higher porosities would be needed to match seismic velocities. (B) Predicted porosity-depth profiles at the location of the gray line in figure A, near the white fir CZT-1. The solid line shows the predicted porosity for the composition assumed in part A; dashed lines show sensitivity of porosity calculation to variation in composition over a range of 25-50% quartz, 10-65% feldspar, and 0-65% clay. Points mark porosities ( $\pm$  standard deviations where available) measured from volumetric samples of saprolite (see text); the broad agreement between modeled and measured porosities suggests the Herz-Mindlin analysis provides realistic estimates of water storage potential in the CZ. (C) Total water storage capacity of the subsurface, in meters of water, calculated by integrating porosity profiles with depth at all positions across the model. At the top of the hill near CZT-1, the subsurface could hold  $\sim 5$  m of water if fully saturated; on average, over the entire profile, the water holding capacity is  $\sim 3$  m. After Holbrook et al. (*in review*).

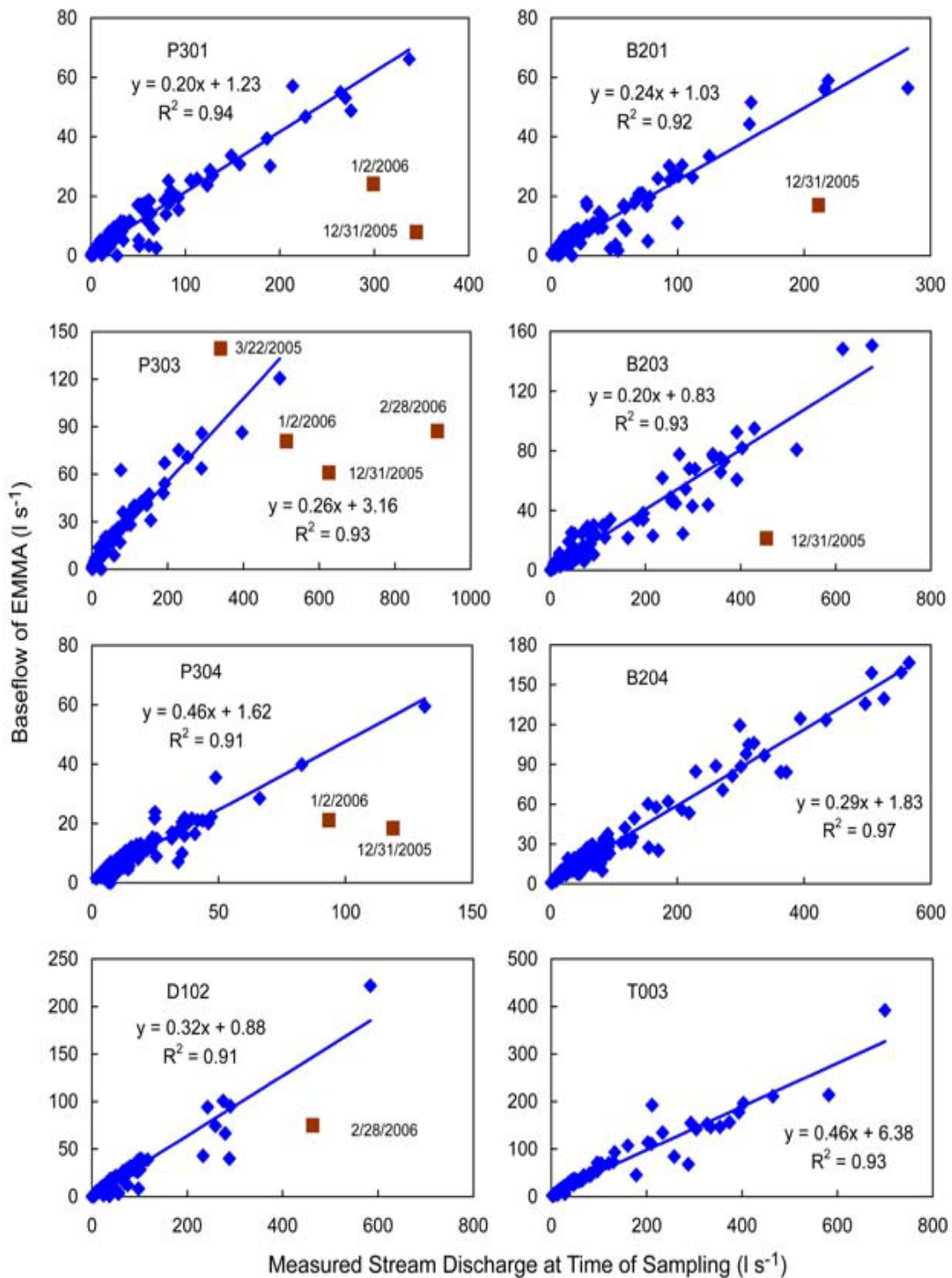




**Figure 54.** End-member mixing diagrams for Providence (a) and Bull (b) catchments. The majority of sample points lie within the triangles. Each corner of the triangle is a representative end-member (Near-surface runoff, Baseflow, and Rainstorm runoff). The arrow shows the change in distribution of samples from snowmelt to baseflow. Inset diagrams show all samples points including outliers.



**Figure 55.** Temporal variation in fractional contribution of end-members for Providence and Bull sites. Data here shown here include water years 2003-2007.



**Figure 56.** Correlation between the contribution of baseflow (by flow rate) determined by EMMA using geochemical tracers and stream flow discharge at each catchment.

## Activities

**Background.** The Southern Sierra Critical Zone Observatory (CZO) was established in 2007 as a community platform for research on critical-zone processes, and is based on a strategic partnership between the University of California and the Pacific Southwest Research Station (PSW) of the U.S. Forest Service. The CZO is co-located with PSW's Kings River Experimental Watersheds (KREW), a watershed-level, integrated ecosystem project established in 2002 for long-term research to inform forest management.

The conceptual science model for the CZO is built around bi-directional links between landscape/climate variability and water/material fluxes across the rain-snow transition. Ongoing research focuses on water balance, nutrient cycling and weathering across the rain-snow transition; soil moisture is an integrating variable. Science questions currently being addressed include:

- How does landscape variability control how soil moisture, evapotranspiration and streamflow respond to snowmelt and rainfall?
- How is soil moisture linked to topographic variability, soil formation and weathering rates?
- What physiological mechanisms are controlling how vegetation distribution and function vary with climate?
- How do vegetation attributes influence cycling of water, energy, CO<sub>2</sub>?
- What is the link between soil heterogeneity, water fluxes and nutrient availability?

The Southern Sierra CZO is located at elevations 1750-2100 m, across the rain-snow transition, in a productive mixed-conifer forest, with extended measurement nodes at elevations 400-2700 m. The main CZO site includes 3 headwater catchments with a dominant southwest aspect (37.068°N, 119.191°W) (Figures 1-4).

Soils within the watersheds developed from residuum and colluvium of granite, granodiorite, and quartz diorite parent material. Soils are weakly developed as a result of the parent material's resistance to chemical weathering and cool temperatures. Upper-elevation soils are at the lower extent of late Pleistocene glaciations. Shaver and Gerle-Cagwin soil families dominate the watershed. Soils are gravely sand to loamy sand, with a sand fraction of about 0.75. Soils are shallow (< 50 cm) in parts of the watershed with low tree density and many rock outcrops. Soils in more gently sloping terrain with linear or convex hillslopes are moderately deep; and landforms with the deepest soils (>150 cm) supporting a high tree density.

The area has a high forest density, with canopy closures up to 90%. In May 2012, PSW has begun thinning treatments in two of the three headwater catchments of the CZO, to inform forest managers about impacts of thinning on ecosystem services. They have plans to perform controlled burns the following summer. Five more nearby, similar headwater catchments are part of this USFS research. The area has limited recreational use, e.g., hunting and OHV use.

CZO research is carried out by students, faculty, staff and postdoctoral researchers from nine campuses, plus other collaborators who are making use of our data for comparative studies with other locations. There is both a wide range of disciplinary focus and critical-zone time scales represented in these investigations, from the response of the seasonal water cycle to perturbations, to the formation of soils to the weathering of the Sierra Nevada. There is also a high degree of integration between investigators. The main institutions with faculty students/postdocs doing research focused at the CZO



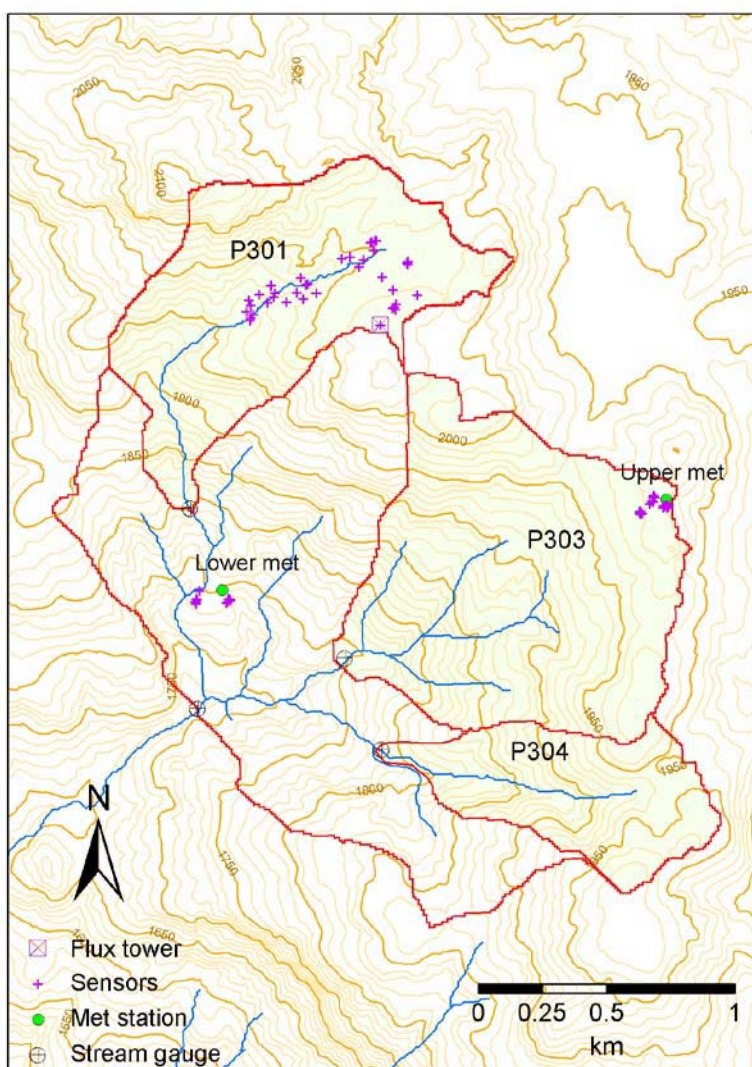
include: UC Merced, UC Davis, UC Berkeley, UC Santa Barbara, UC Irvine, UCLA, U. Nevada Reno, U. Colorado, U. Wyoming.

Research activities include: i) measurements of water, carbon, and nutrient cycle fluxes and states, ii) measurements of weathering over annual and longer time scales, and iii) hydrologic and biogeochemical modeling. It is planned to initiate further studies of critical zone form, formation and structure.

**Core CZO measurements, data management and integration.** Core activities provide common data to investigators and help integrate the research of the multiple scientists involved. There is also a vigorous outreach and education component. The PI supervises 2.5 staff (field hydrologist, data manager, outreach and communications scientist) and coordinates with the KREW PI to provide essential infrastructure and

communications for the CZO. The CZO field hydrologist works closely with the KREW field staff to maintain a core measurement program, and coordinate field campaigns involving the various CZO researchers. The CZO data manager works closely with the PI and other scientists to archive, serve, and carry out quality control on data. The outreach and communications scientist, co-supervised by the Co-PI in charge of education and outreach (M. Conklin), assists with project management, engages in hands-on outreach with both stakeholders and K-12 audiences, and is active in communicating CZO results to multiple audiences.

The water-balance instrument cluster at the main CZO site, the Providence catchments, is in its fourth water year of operation (Figure 1). The instrument cluster includes over 380 individual sensors, placed around 13 trees, in three meadow transects, at three aspects and different elevations. The sensors in P301 form a wireless sensor network (WSN). An eddy-covariance flux tower is in P301, with three additional towers forming an elevation transect. Towers are at the San Joaquin Experimental Range (SJER) (420 m), Soaproot Saddle (1080 m), Providence (1950 m), and Shorthair Creek (2670 m). The elevation gradient on the west side of the Sierra characterizes the change in precipitation (from rain to snow-dominated) and ecosystem types which are specific to different elevation bands.



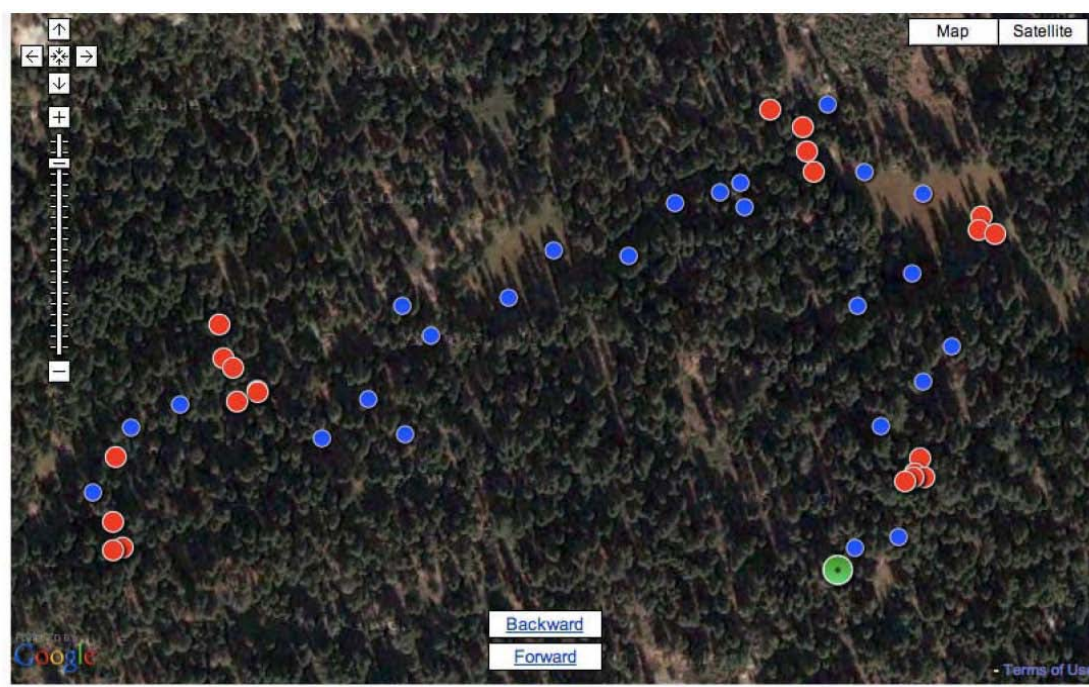
**Figure 1.** Instrument cluster design at KREW CZO site. Instrument node locations, strategically placed to capture variability in elevation, aspect and vegetation properties.

completing the instrument cluster design. The instrument cluster includes over 380 individual sensors, placed around 13 trees, in three meadow transects, at three aspects and different elevations. The sensors in P301 form a wireless sensor network (WSN). An eddy-covariance flux tower is in P301, with three additional towers forming an elevation transect. Towers are at the San Joaquin Experimental Range (SJER) (420 m), Soaproot Saddle (1080 m), Providence (1950 m), and Shorthair Creek (2670 m). The elevation gradient on the west side of the Sierra characterizes the change in precipitation (from rain to snow-dominated) and ecosystem types which are specific to different elevation bands.



The water-balance instrumentation is producing consistent data, which are archived in our digital library, subjected to quality-control procedures, and made available to our CZO team and the broader community. The Wolverton baseline instrument cluster also continues to produce quality data. Data are currently being processed to Level 2 (outliers removed, formatted, calibrated) for publishing at the national CZO site. Our digital library and data catalog are updated at least semi-annually. Level 3 data are also being produced (e.g. gaps filled, averaged hourly and daily). The SSCZO website is updated at least monthly, or more often as developments warrant.

The DUST wireless sensor network and EME Systems dataloggers have continued to operate in the P301 ground-based water-balance instrumentation (Figure 2). The DUST wireless network is distributed, self-assembling, and self-healing, meaning that if links in the network go down unexpectedly, alternative links form to ensure data will continually transmit. The WSN currently consists of 60 radio motes, and links over 250 of the sensors to a central data hub. All of our systems use solar power.

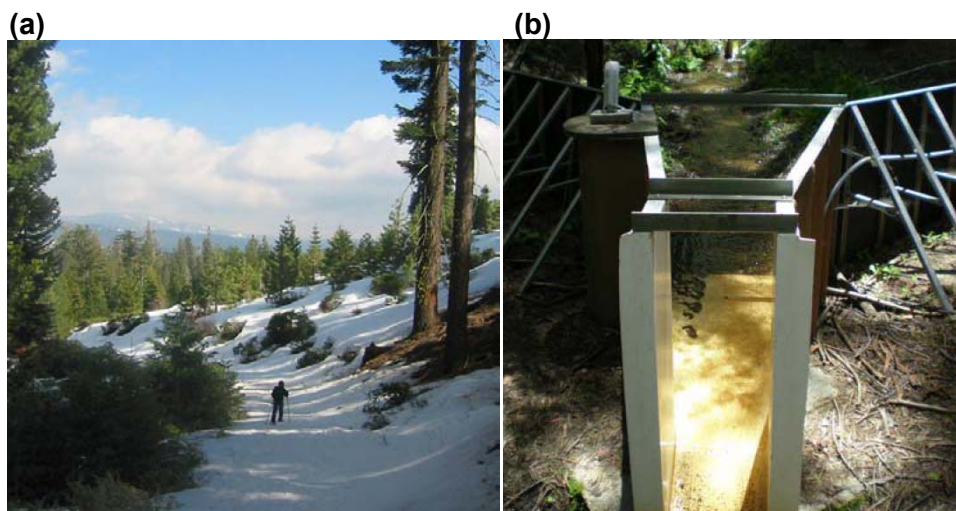


**Figure 2.** Locations of DUST wireless network radios. The green dot indicates the mother computer, the red dots indicate sensors, and the blue dots indicate hopper radios.

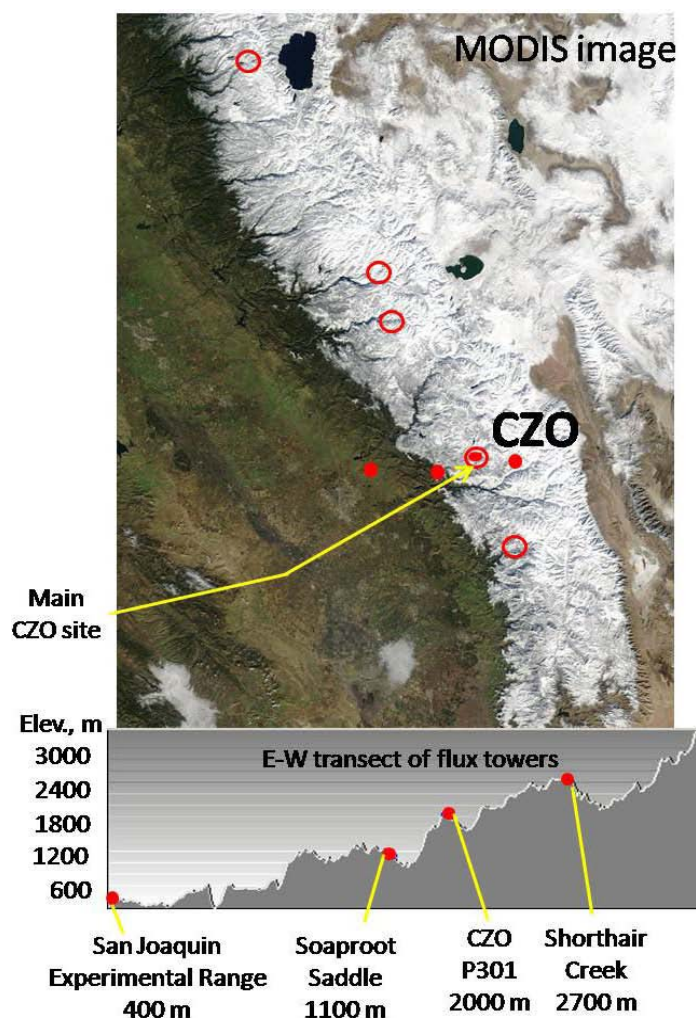
The wireless nature of the systems permits for data to be sampled at a large scale, and subsequently to be piped to a central location, aggregated for easy collection, and transmitted off site via cellular modem. This would not have been possible with conventional wired setups. The infrastructure for the WSN was set in 2009 to test communications for a robust network. An above-average snowpack and higher than average winds caused some damage to the interim infrastructure and identified weak points in the deployment. The WSN has since undergone reinforcement and installation as more permanent infrastructure. We are currently experimenting with wireless Ethernet technology that can connect multiple locations over distances of 30km. This will allow us to incorporate data from other sites within the Providence basin to the central communication hub.

**Core KREW measurements and data management.** Streamflow, meteorological, turbidity, and sediment measurements and data analysis have continued. Collaboration between USFS and SSCZO personnel is ongoing and will continue in the production of the series of manuscripts discussed in the Workplan, which is appended to this description of activities. The SSCZO is working with KREW in

order to combat USFS budget cuts that have led to a loss of personnel and a reduction in KREW field activities. Turbidity measurements have ceased for WY 2011, due to staffing and USFS budgetary cuts.



**Figure 3.** a) Road into CZO in early spring. b). Looking upstream of a typical stream



**Figure 4.** East-west topographic transect of flux towers, from 400 m to 2700 m elevation. Flux tower sites are throughout the Southern Sierra Nevada.

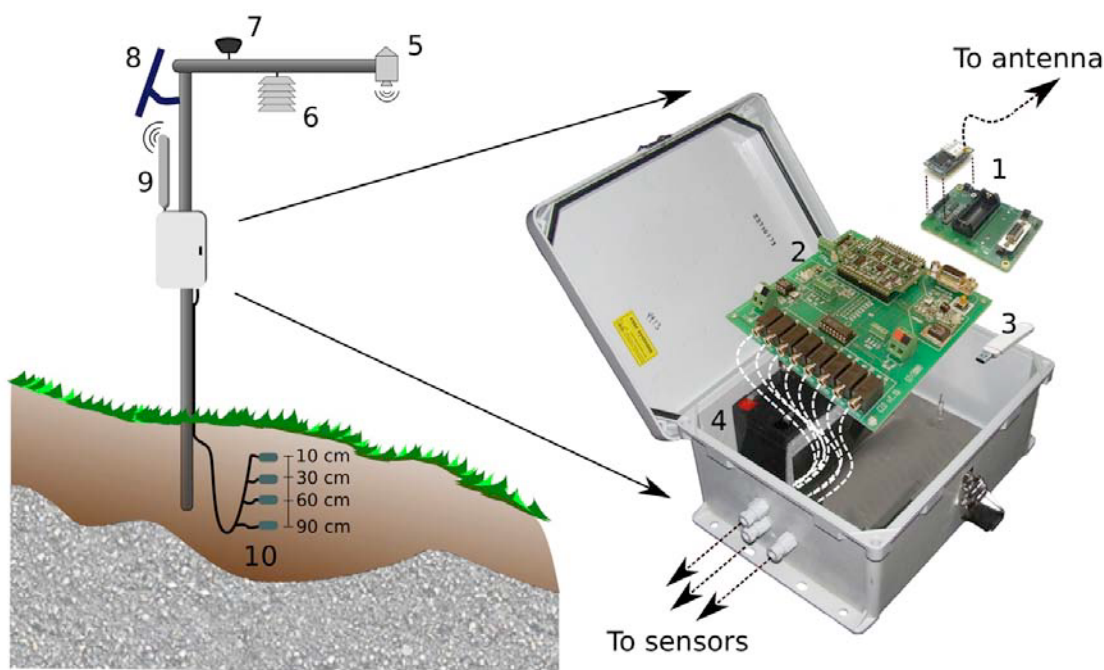
See Figures 3 (a) and (b) for a typical stream control section in CZO/KREW catchments.

Airborne LiDAR was flown for the broader CZO installations, including Providence, Bull, Teakettle, Tokopah, and Wolverton catchments, as well as the San Joaquin Experimental Range (SJER), Soaproot Saddle, and Shorthair flux tower sights (Figure 4). Bull and Teakettle, not shown on Figure 4, are intermediate between the main CZO site (Providence) and the Shorthair Creek tower. Bull and Teakettle are part of the KREW project and provide additional locations for higher elevation SSCZO monitoring. Flights were conducted mid-March 2010 near peak snow accumulation and again in the summer 2010 when snow was melted. LiDAR data will provide spatial distribution of snow depth, leaf area index, canopy structure, and a high resolution digital elevation map. DEM data are available now; and canopy data are being processed for distribution in fall. New watershed boundaries were delineated



for the Providence basin, and will be field-validated this summer.

**Wireless sensor network.** We are in the process of making significant improvement to our wireless sensor network hardware. The network is made up of *sensor-nodes* (Figure 5, radio, data logger, and sensors), and *repeater-nodes* (only radio for network redundancy). We are moving towards emphasizing the real-time aspect of the network, and are equipping each network node with its own *IPv6* address, a unique identifier which will allow us to develop seamless interfaces to each individual sensor in the field. This will make data dissemination significantly easier, and will permit for non-technical users to gain direct access to the data via easy to use web services. The new hardware will also be rated for significantly higher environmental exposures, and will require an order of magnitude less power. We have also developed the ability to connect this latest generation of wireless hardware to the Campbell Scientific line of products, which are currently the de-facto standard for environmental measurements. This will permit a massive portion of the scientific community to benefit from wireless sensor network technology by upgrading their existing line of data loggers through a simple open-source attachment.



**Figure 5.** Sensor node architecture: (1) mote, (2) custom data-logger to interface the sensor array, (3) on-site memory storage, (4) 12V battery, (5) snow-depth sensor, (6) humidity and temperature sensor, (7) solar radiation sensor, (8) 10W solar panel, (9) external 8dBi antenna, (10) four soil moisture, temperature, and matric potential sensors at varying depths.

All of the sensor-nodes are now equipped with *Sensirion* humidity and temperature sensors (Figure 5). From a hydrologic perspective, humidity will be an important indicator of the snow-rain transition zone; the readings will also permit us to study the effects of RH on 2.4 GHz low-powered radio communications, a significant issue which has not been studied for general WSN deployments.

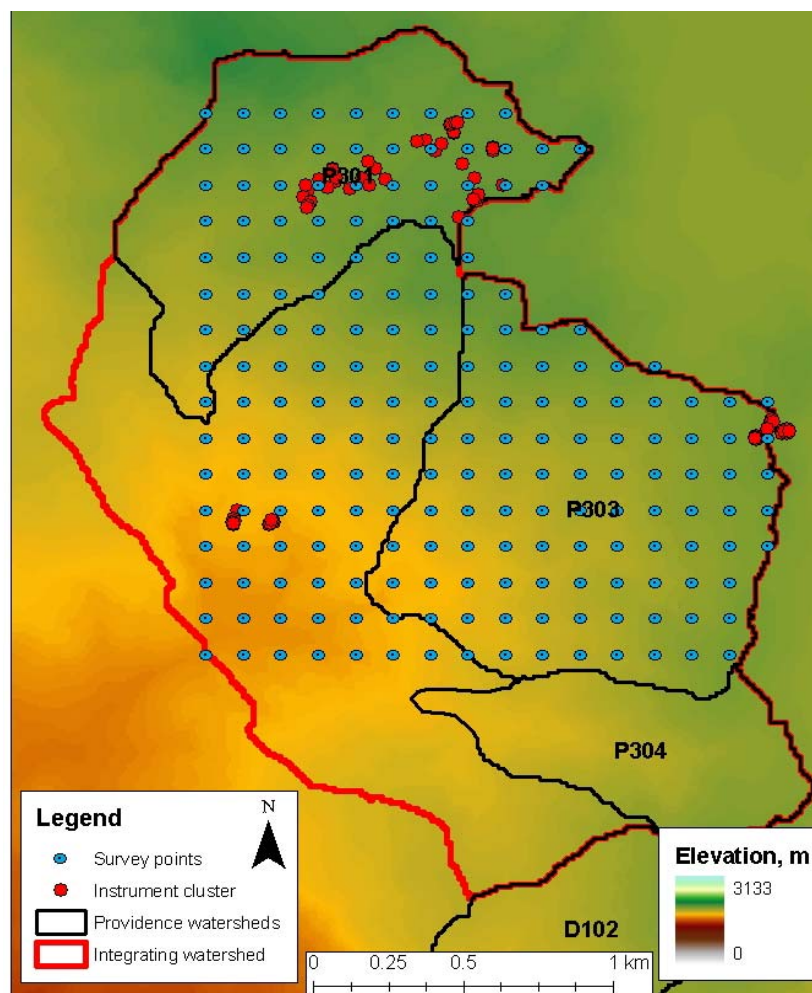
**Snow and soil processes.** LiDAR flights at Providence occurred in WY 2010 for both snow on and snow off conditions. These data are currently being used to create new watershed boundaries for the basin, with field validation occurring in summer 2012. High-resolution GPS and total station surveys of all equipment is scheduled to occur in summer 2012, to better fit the LiDAR accuracy. The LiDAR data are also being used to verify snow depth observations made by the water balance instrument cluster. Basin-

wide snow depth estimates will be modeled using the 50 site water balance instrument cluster and compared with the LiDAR observations. Cross-CZO snow depth and LiDAR data are being analyzed.

The WY2011 snow survey of Providence basin occurred on March 13-16. The main survey consisted of 206 gridded snow depth measurement locations throughout the basin (Figure 6). A subset of sample locations were analyzed for snow density using a federal sampler, five snow pits were analyzed for snow density and snow-water nutrient analysis, and several intense high density snow depth sampling grids. The high intensity sampling grids were in locations with high predicted snow depth variability

based on the WY2010 observations and modeling.

Two soil moisture surveys were completed in the Providence basin in 2010; after snow melt (June 14-17) and after the summer dry period (September 6-10). Shallow soil moisture measurements were taken at the same grid locations used in the snow survey. Representative soil samples were taken for laboratory analysis. The multi-parameter synoptic soil survey consisted of measurements of soil volumetric water content across a grid of over 200 points (this grid coincided with the synoptic snow survey conducted in April 2010), tree trunk moisture, and leaf water potential measurements were taken at a subset of the grid points. Soil moisture surveys for WY2011 have been planned for the beginning of



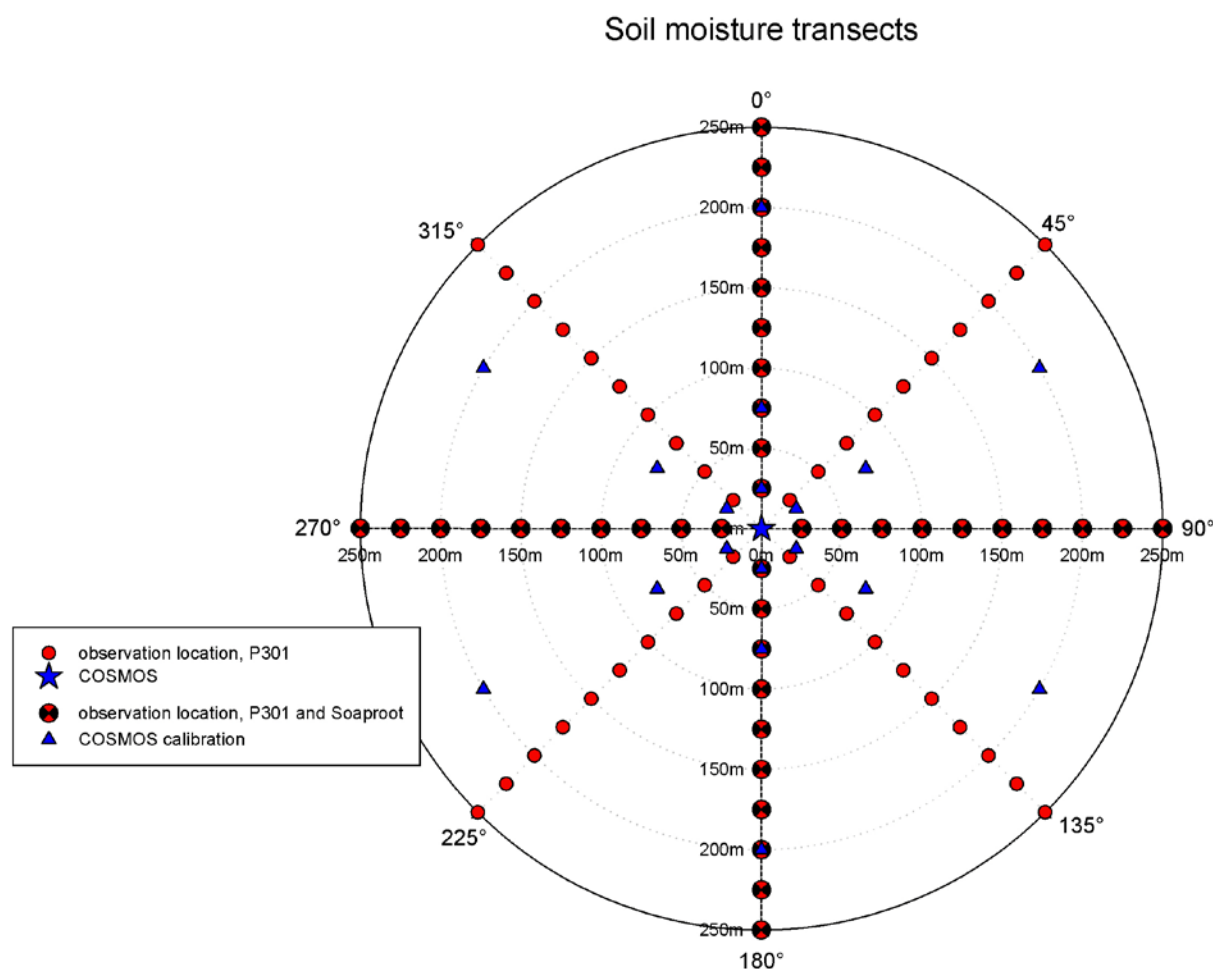
**Figure 6.** Snow and soil survey locations, with ground-based instrument cluster.

summer, mid-summer, and pre-winter. The beginning of the summer soil survey has been completed on June 27-28, for a partial coverage of the upper Providence basin. Ninety-eight sample points were observed before the survey was interrupted by an unexpected rain event. Observations were made using two handheld volumetric water content tools, used to measure moisture content of the upper 20cm of soil. Twenty representative soil samples were taken for laboratory analysis at a subset of these sample locations. These observations will be compared with instrument cluster observations and model predictions of basin soil moisture.

Based on discussions from the SSCZO team and participants at the March 2011 CZO All Hands meeting, we have started to address a lack of understanding of deep vadose zone processes and how they relate to basin scale water balances. We have started a monitoring effort, the Deep Vadose zone Project

(DVP) to instrument and make observations deeper than 1 m based on the desire for deep soil monitoring. We successfully augured down to 4m next to CZTree-1 and instrumented the pit with matric potential sensors at 1m intervals. Additionally, the deeper vadose zone monitoring will utilize measurements of volumetric water content (Decagon 5-TM) and soil water potential (Decagon MPS-1 and tensiometers) to determine the soil water status at depths of 150, 200, and 250 cm. The 5-TM and MPS-1 sensors will be used determine water fluxes and the soil water status at depth throughout the year. Our basin-wide soil depth observations have previously been limited to 1m. On June 27<sup>th</sup> we started auguring and probing throughout the basin on the 125-m grid used in the snow and soil surveys (Figure 6). This will provide much needed data to improve our soil depth model, and better inform us of the critical zone processes that occur below 1m depth.

We installed two Cosmic-ray soil moisture observation systems (COSMOS) at our Soaproot Saddle and P301 flux tower sites on June 9-10. The COSMOS installation is part of collaboration with University of Arizona. Soil samples were collected for laboratory analysis and calibration of the sensors. These sensors report hourly averages of volumetric water content for approximately 0.28 km<sup>2</sup> surrounding the flux towers. We installed a soil monitoring transect in conjunction with each tower. This transect includes observations of shallow volumetric water content along with matric potential measurements to a maximum depth of 2 m. These soil monitoring transects were installed at the tree low-elevation flux



**Figure 7.** Soil moisture surveys that occurred in July, September and October using hand-held TDR and soil sampling. COSMOS calibration sampling occurred at the installation in July.

tower locations during summer 2011. Soil moisture monitoring and sampling occurred within the footprint of the COSMOS sensors for better calibration throughout the soil drying period (Figure 7). Soil moisture surveys that occurred in July, September and October using hand-held TDR and soil sampling. Hourly COSMOS data for the Soaproot Saddle and P301 tower site are currently available online via the University of Arizona website: <http://cosmos.hwr.arizona.edu/Probes/probemap.php>.

**Water, geochemical cycles, and upscaling of in-situ measurements.** Measurements from the Wolverton basin and the Teakettle Experimental Forest in the Red Fir zone of the southern Sierra Nevada (2,300-2,600 m elevation) were used to evaluate our hypothesis that topography and vegetation cover are the most important variables affecting snowmelt and soil moisture. The global variables of slope, aspect, and topography influence large scale patterns of snow and soil moisture but vegetation also has a significant influence on the small scale distribution of both. The forest canopy has multiple effects on the accumulation and ablation of snow resulting in a heterogeneous snow cover and the subsequent soil moisture. Snow, as opposed to rain, represents > 90% of the annual precipitation received by these ecosystems and demonstrates a clear seasonal signal in vadose-zone recharge. Our strategy is to combine synoptic surveys and instrumental data from both sites to describe these processes across broad temporal and spatial scales.

Day of snowcover melt out was measured around a north aspect and a southeast aspect tree in the Wolverton baseline watershed in 2007-2009. Using a 500x500 m grid, 270 depths were collected within the basin. Synoptic snow surveys were also conducted in the Wolverton basin within 4 days of April 1st from 2007-2009 using a 600x600 m area. In addition, depth and density were measured at 36 grid points, four times, once in each cardinal direction, under the canopy of the nearest mature Red Fir tree, and 3-4 times in the closest canopy gap. Radiation measurements of incoming short and longwave radiation were made in 2010 over three days using paired radiometer arrays placed on previously studied north and south facing plots in patterns radiating out from tree stems.

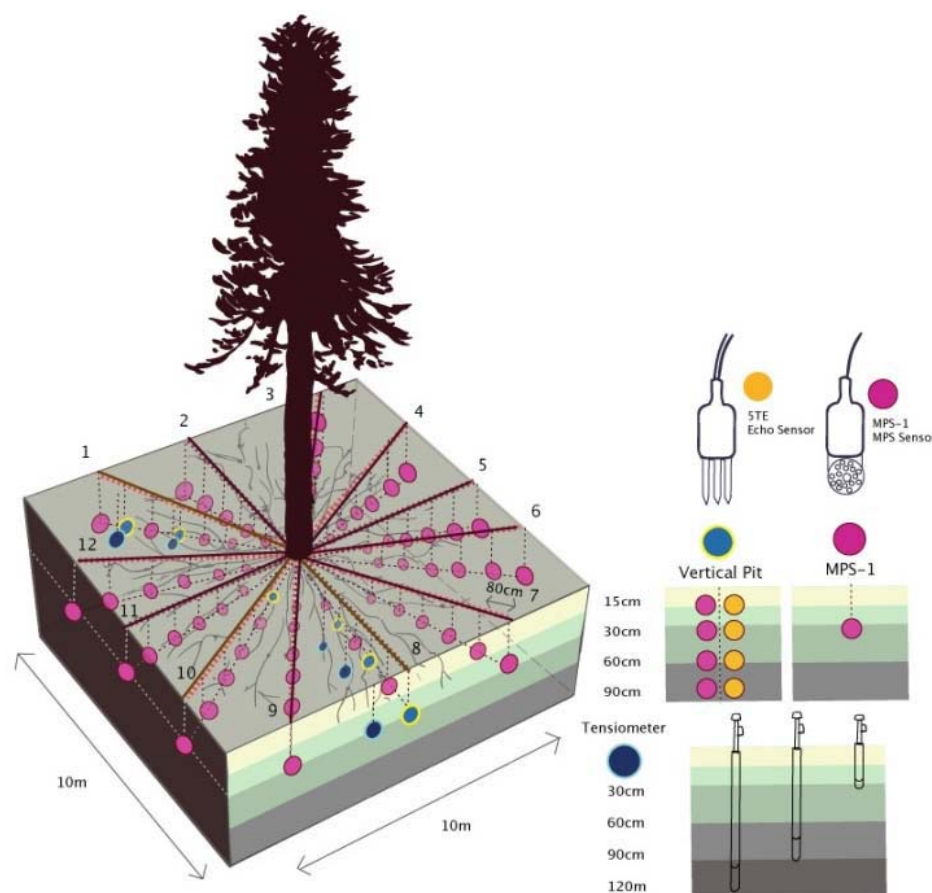
**Coupled Soil Tree Hydro-Dynamics.** Efforts at UC Davis have been primarily directed toward the coupling of canopy processes with subsurface water dynamics. We made significant contributions toward partitioning tree available water into different soil compartments using a combination of monitoring and modeling activities. Using tree root excavation and portable LiDAR measurements, it was determined that root activities are generally limited to the top 1.5 m leaving a significant deep soil moisture storage reservoir available in the late summer and fall. Using annual water balance calculations and near surface soil moisture measurements, we estimate that about one-third of forest transpiration comes for this deeper soil moisture store.

We have focused our efforts the soil water budget and soil-tree water interactions through intensive monitoring of water dynamics of the root zone, trunk and canopy of selected trees in the SSCZO watershed, and most recently below the rooting zone. A hydrodynamics model was developed to couple acquired data with computer simulations, to seek (1) improved understanding of the coupled soil-tree-atmosphere system, including water dynamics and its coupling between root zone and tree trunk and canopy, (2) to quantify relations between atmospheric forcing and tree root water uptake as controlled by soil water stress, and (3) to confirm the significance of deep soil water storage available for root water uptake in extended periods of no precipitation in the summer and fall.

In order to refine the results achieved to date, we have chosen to continue efforts in the following focus areas:

1. Characterization of the deep vadose zone, including measurements to estimate deep soil water storage and fluxes, and to improve understanding of weathering and pedogenesis processes;
2. Continued development of multi-scale observations and monitoring sensor networks using innovative sensor technologies, to support model testing efforts;
3. Coupling of above-ground with below-ground critical zone processes, and to further integrate data streams with relevant models for hypothesis testing; and
4. Continued investigation of hillslope-scale interactions between the atmosphere and the subsurface through integration of piezometer and deep vadose measurements to test relevant hydrological processes (depth to bedrock, deep vadose zone, lateral flow) .

Instrument deployments were completed for both CZT-1 (Figure 8) and CZT-2 (Figure 9) in August 2010. Combined, the two instrumented trees sites include approximately 300 sensors to monitor temporal and spatial variations in soil moisture, soil water potential and temperature, sapflow and tree temperature and moisture content.

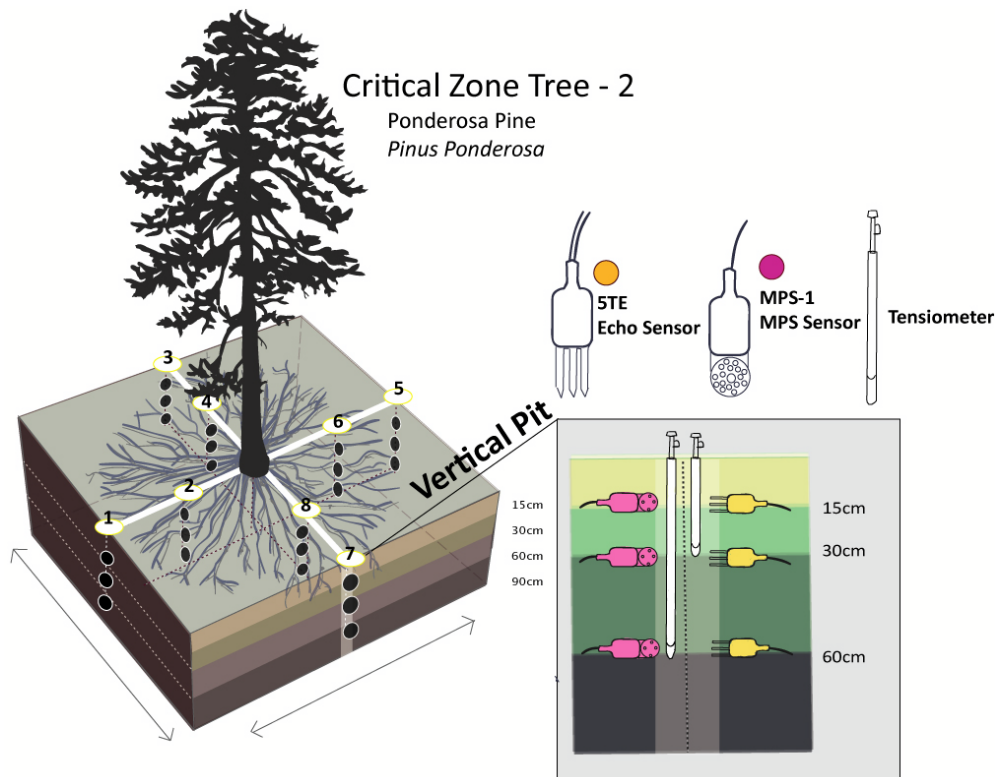


**Figure 7.** Layout CZT-1 including location of Echo-5TE, MPS, vertical soil moisture/temperature pits, and tensiometers.

Measurements on the intensively instrumented white fir (*Abies concolor*) tree (CZT-1) include soil moisture, temperature, and soil matric potential with both (MPS) sensors and tensiometers for over 40 months. In addition, data of sap flux sensors and time domain reflectometry (TDR) for stem water content measurements show responses to fluctuations in air temperature and solar radiation. The instrumentation of CZT-2 was deployed in and around a ponderosa pine (*Pinus ponderosa*). The CZT-1 site with its flat topography, deep soil and dense canopy



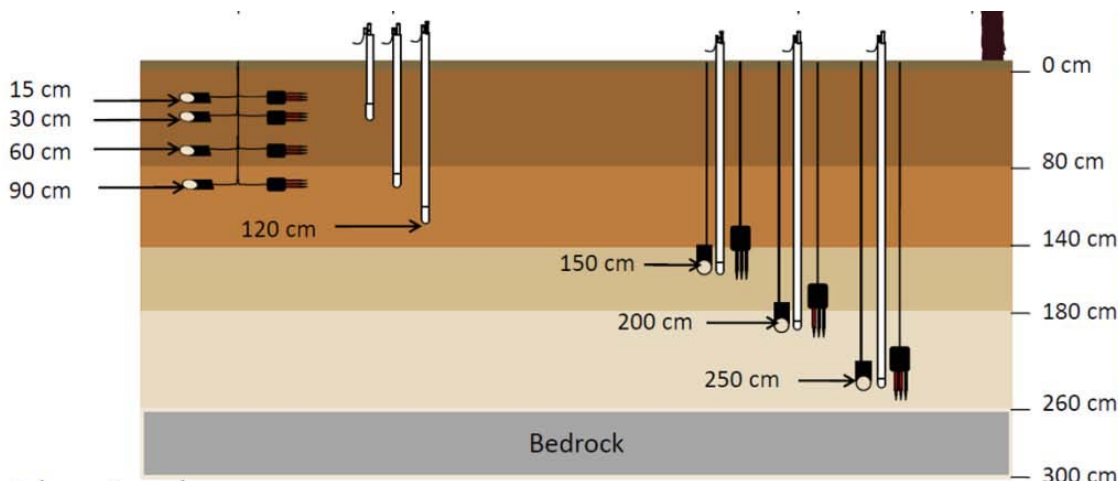
cover, complements the CZT-2 site with its shallow, sloping and exposed soil, thereby representing watershed variability.



**Figure 8.** Layout CZT-2 including location of Echo-5TE, MPS, locations, vertical soil moisture/temperature pits, and tensiometers.

In September of 2010 we excavated the roots of a white fir adjacent to CZT-1 using pressurized air to remove the soil around the roots down to 2 m. Terrestrial LiDAR was used to scan the exposed roots and provide a 3-D model of the root system. The analysis underway will provide the opportunity to generate a detailed map of root architecture in combination with soil characterization measurements.

*Deep vadose zone project (DVP).* In the late summer of 2011 we installed a new network of deep



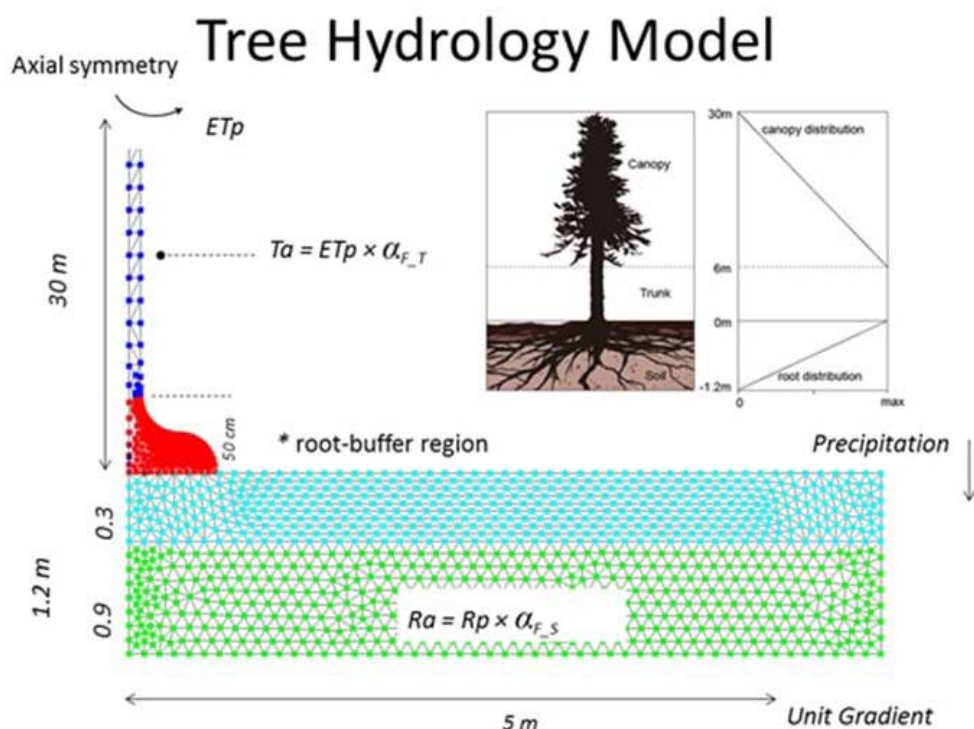
**Figure 9.** Instrumentation at DVP near CTZ-1.



instrumented holes and neutron access pipes (DVP) near the CZT-1 cite (Figure 9). At this specific location, the soil was deeper than had previously been estimated from measurements at CZT-1. Coring results were supported by geophysical survey data near CZT-1.

**Critical Zone Tree (CZT) modeling.** By way of numerical flow modeling, the overall goal is to identify the physical processes that control spatial and temporal changes in water flow in the coupled soil-tree-atmosphere domain. The requirements for this model are to (a) simulate time series of tree sap flow and stem water potential, soil water content and matric potential, and (b) to couple collected data with numerical flow simulations, allowing estimation of tree water relationships (water retention and unsaturated hydraulic conductivity functions). We continued to develop a coupled numerical simulation model of the soil/tree/atmosphere continuum at CZT-1 (Figure 10). This model is driven by spatially distributed potential evaporation in the canopy and includes reduction functions of potential ET and root water uptake as determined by leaf and soil water potential, respectively. In order to estimate deep soil water contributions to tree ET, the soil domain was extended to 5 m depth. Estimation of the tree water relationships was done using inverse modeling, minimizing residuals between measured and simulated soil and tree variables. The model is coupled with the root architecture model derived from excavated tree root data, allowing accurate description of spatial variations in root water uptake so that compensation mechanisms by roots can be understood. Finally, tree-scale modeling will be scaled up at the watershed scale using relationships developed with ET measurements taken at the adjacent P301 flux tower.

**Surface-groundwater interactions.** We improved our understanding of the drivers of thermal stratification of meadow pools by constructing an energy balance for LP-33 pool. We used incoming shortwave radiation calculated from assumed top of the atmosphere radiation, incoming longwave (LW)



**Figure 10.** Coupled Tree soil model using the HYDRUS model.

radiation calculated from air temperature and emissivity, reflected SW and LW as a function of assumed respective albedos, back emitted LW calculated from the pool surface temperature, and an assumed

Bowen Ratio to complete the energy balance.

Ground water elevation and depth specific pressure head continued to be monitored in the 24 wells and piezometers in the P301 meadow and the 31 wells and piezometers in Long Meadow. Ground water elevations were analyzed for seasonal trends and daily evapotranspiration (ET) signals. Water samples were collected from the monitoring wells and analyzed for stable water isotope composition and major ion concentrations.

Salt dilution tracer tests were conducted at the two meadow stream locations in P301 meadow. The tests were used in conjunction with 15 minute interval stage measurements to build a rating curve for each location. Water samples were collected periodically from each stream location and analyzed for stable water isotope composition and major ion concentrations.

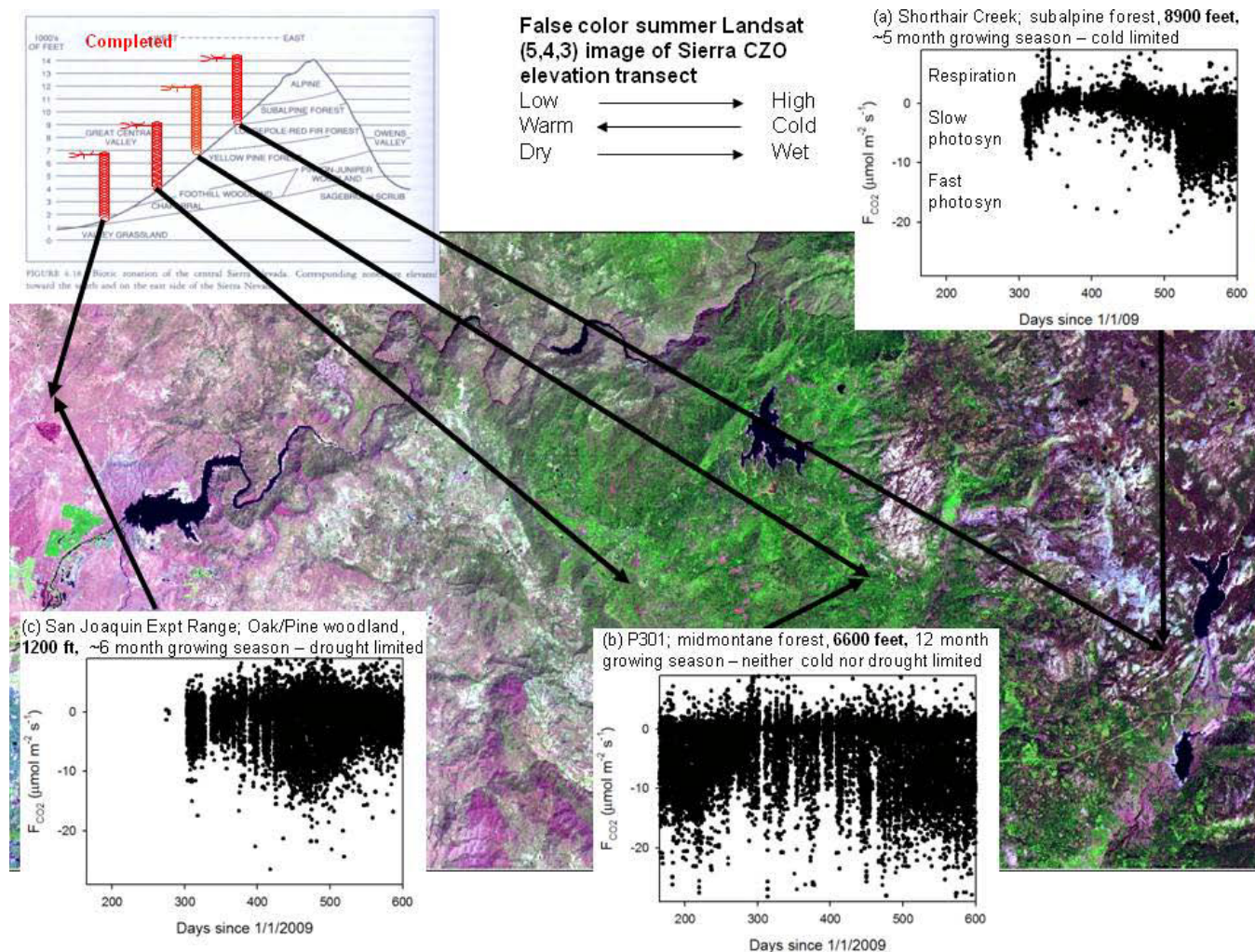
We deployed a mobile meteorological station for 1-3 week intervals in P301 and Long Meadow. The data from the station was used to calculate PET for the meadows during the respective time interval and compared to data from met stations located near to the meadows but in the forest vegetation.

**Physical controls on water and carbon exchange and plant production.** We are using the climate gradient of four eddy covariance towers to understand the mechanistic interactions between climate, soil development, species distribution, biotic production, and hydrological balance (Figure 11, Table 1). Our main activities during the last year were: i) the installation and operation of the Soaproot Saddle eddy-covariance tower at 1200 m, which completes the transect, ii) the year-round operation of the three original flux towers, and iii) the establishment of additional in-situ measurements, including plant primary production and sap flow.

**Table 1.** Climate and forest properties at the four primary sites. Climate data are annual means from PRISM (2000-2009) or from tower data when available.

Site	Precip., mm	T, °C	Hypothesized climate limitations	Biomass, tC/ha	Tree NPP, tC/ha/yr
Oak woodland (382 m)	506	18.2	Severe summer drought	18.6	0.4**
Yellow pine (1204 m)	794	13.2	Summer drought	60.5	3.6**
Mixed conifer (2017 m)	922	10.8	Neither drought nor cold	95.3	6.3
Lodgepole (2709 m)	1064	4.3	Severe winter cold	83.4	1.5**

\*\*Preliminary estimates from less than one year of data



**Figure 11.** False color Landsat image with locations of the four completed eddy covariance towers. Plots of seasonal CO<sub>2</sub> uptake at each of the completed towers are included. Winter occurred from Day of Study 330 to 520, and summer from day of study 540 onwards. Data points are 30-minute covariances, with negative fluxes indicating daytime net CO<sub>2</sub> uptake (photosynthesis) and near zero or positive fluxes indicating net respiratory CO<sub>2</sub> uptake (either at night or during periods when photosynthesis was dormant).

The towers transmit a subset of observations hourly, which allows us to keep an eye on system function. The complete data set is collected manually every month and transferred to UCI via the internet. These data are then processed and posted on the digital library at UCM. The P301 tower has been collecting data for 3 years; the SJER and Shorthair towers have been collecting data for 2 years; the Soaproot Saddle tower has been collecting data for 12 months. The tower sites were also surveyed and instrumented to measure individual tree productivity and water use. One hectare plots were mapped within the footprint of each tower. Dendrometer bands and biomass collection traps are measured every 1-2 months to obtain aboveground NPP. Sap flow sensors measure transpiration on 12-20 trees at the upper three tower sites. Finally, an additional set of plots was established at 120 m elevation intervals between the tower sites to provide finer resolution information on production and species composition variation with elevation.

Some upgrades to the flux towers for the coming year include rebuild the tower at Courtright, rework the power supplies and replace batteries at existing sites, install a high elevation site in order to capture high elevation evapotranspiration, and upgrade the Soaproot and P301 IRGAs which will

decrease the many data gaps in the winter due to winter activity. This will reduce data loss during extended cloudy periods.

### **Importance of sub-watershed spatial heterogeneity in ecohydrological modeling for assessing climate change impacts on Sierra mountain catchments.**

*Effect of spatial resolution of DEM on ecohydrologic predictions and its sensitivity to climate variability.* Eco-hydrologic models are key tools used to generalize results from intensively instrumented plot studies to broader spatial scales and to project future watershed behavior. The Sierra CZO provided an opportunity to examine the usefulness of fine-scale spatial data for calibrating and refining models of coupled eco-hydrologic processes. We applied RHESys (Regional hydro-ecologic simulation system) to all Sierra CZO watersheds. We examined impact of DEM resolution on accuracy of streamflow prediction and the sensitivity of estimates ecohydrologic response (snow, streamflow, evapotranspiration (ET) and net primary productivity (NPP)) to climate variability. The model accuracy (streamflow) of the Providence and Bull watersheds declines with coarsening DEM resolutions. The streamflow estimation for the Bull watersheds was less sensitive to coarsening DEM resolution than the Providence watersheds. In addition, DEM resolution significantly impacts ecohydrologic estimation and their sensitivity to inter-annual climate variability.

*Strategic sampling microclimate, soil moisture and sapflux for improving ecohydrological predictions.* We also developed a strategy for field data collection that is explicitly directed at evaluating and improving model estimates of spatial heterogeneity in ecohydrologic processes including soil moisture and transpiration. Our measurements of soil moisture and sapflux showed strong seasonal pattern, within variation in the timing of onset of these seasonal trajectories differing across locations. Our previous modeling studies highlight the importance of adequate representation of micro-climate patterns as controls on summer moisture deficits and transpiration for the Sierra CZO sites. To support improved representation of micro-climate forcing patterns in models, we have collected additional air temperature and relative humidity in the Providence watersheds using eighteen the microclimate sensors (HOBO) since summer, year 2011. Each site shows a different temporal relationship among vapor pressure deficit (VPD), soil moisture and sapflux in summer. In the dry sites, transpiration is limited by available soil moisture. In the intermediate sites, the transpiration is highly correlated with VPD. However, in the wet sites, the transpiration is not correlation with soil moisture and VPD. We expect that the temporal pattern of transpiration at the wet sites is correlated with solar radiation. We will use these data to constrain parameters of the RHESys, and to refine the climate inputs in order to improve the predictions of soil moisture, transpiration and streamflow in the Providence watersheds.

*Effect of climate warming on ecohydrologic fluxes in the Providence and Bull catchments.* We used RHESys to compare the ecohydrologic response to projected climate warming between a snow-rain transition watershed (P303) and a snow-dominated watershed (B203). We applied simple warming scenarios (2 and 4°C). Model projections of streamflow changes are generally consistent with previous work in the Western US that show earlier snow melt and center-of-mass of hydrograph shifts to earlier in the year. The B203 watershed has larger change in the inter-annual and seasonal ecohydrologic fluxes to climate warming than the P303 watershed. In this paper we also examine how controls on the spatial-temporal pattern of vegetation water use differ across this rain-to-snow transition. We found that for both watersheds, growing seasonal ET (March to August) has high correlation with LAI (vegetation biomass) and wetness index (flow drainage pattern). Warming scenarios reduce the annual ET in the P303 watershed while warming increased the annual ET in the B203 watershed. Moreover, 4°C warming transform ecohydrologic patterns in the B203 watershed to behave like the P303 watershed under

historical climate including; 1) the snow regime, 2) the timing of peak streamflow, 3) the spatial structure (mean and COV) of seasonal ET, and 4) the relationship between LAI and seasonal ET.

**Erosion and weathering.** The first phase of geochemical analyses of regolith and rock samples from the CZO is now complete and data reduction is underway, with one publication now in press. Results are shedding light on the degree of chemical weathering in saprolite and soil and how it varies across the CZO catchments. In an expansion of this work, the sampling of bulk geochemistry of regolith and bedrock has pushed beyond the confines of the CZO catchments, with the goal of quantifying the role of dust in regulating the geochemistry of granitic soils in the surrounding landscape. Another aim in this expansion is to improve understanding of factors that influence the presence/absence of soil and vegetation; there is some suggestion from preliminary results that the notable bimodality in soil and vegetative cover may be regulated in part by nutrient concentrations in underlying bedrock. Work is continuing on this question, as part of a new master's thesis project at the University of Wyoming.

The first phase of analyses of cosmogenic nuclides in stream sediment is nearly complete and is providing the basis a broad analysis of landscape evolution in the CZO and surrounding landscape. In an expansion of the cosmogenic-based sediment tracing work, preliminary sampling was completed for analysis of (U-Th)/He ages in apatite from bedrock in the region. The goal is to use the bedrock ages to constrain the source elevations of stream sediment, which is ultimately generated from rock on slopes and thus carries a geochemical fingerprint of its origins in the form of U, Th, and He concentrations in apatite crystals.

Work is continuing on geophysical characterization of the near surface (<40 m depth) for constraints on weathering and water storage potential at depth. The near surface geophysical work expanded from its initially limited to scope in the previous year to new locations within the CZO and also to new methods. Previously, only seismic velocity structure had been investigated. In fall 2011, the work was expanded to include resistivity, thus providing new constraints on critical zone architecture.

**Baseline hydrologic, sediment and geochemical characterization.** In February 2012a manuscript was accepted examining geochemical controls of streamflow pathways in the 8 KREW catchments, including the 3 CZO catchments. The manuscript addressed 3 main questions including; i) what are the end-members contributing to streamflow in these catchments, ii) did these end-members vary with elevation, and iii) can these results give any insight into predicting streamflow when using hydrologic models?

Between 2003 and 2007, bi-weekly stream water samples were collected at the watershed gauging stations using ISCO samplers. In addition, soil water (13-26 cm depth), piezometer water (~1.5 m depth), snowmelt, spring water, and deep groundwater (drinking well) samples were collected from nearby sites and at various times prior to 2009. Analysis of samples included major ions ( $\text{Ca}^{2+}$ ,  $\text{Mg}^{2+}$ ,  $\text{Na}^+$ ,  $\text{K}^+$ ) and anions ( $\text{Cl}^-$  and  $\text{SO}_4^{2-}$ ). By means of statistical methods, end-members were determined by isolating conservative tracers and using end-member mixing analysis (EMMA). The fractional contribution and correlation with topography of each end-member was also determined.

**Organic carbon in streams.** Sampling for organic carbon in the KREW streams that commenced in April 2009 continued until April 2010. Samples were collected monthly at the KREW gauging stations; sampling has coincided with the bi-weekly major ion sampling conducted by the Forest Service KREW field team. Along with the organic carbon samples, water isotope samples have been collected. The collected organic carbon samples have been sent to Elizabeth Boyer at Pennsylvania State University for analysis. Isotope samples were processed at UC Merced.



**Novel isotopes in streams and sediments.** Novel stable isotopes (Si, Mg, Li, Rb, and others) are being sampled across the landscape surface (vegetation, rock, soil, water), with the objective to link these isotope compositions to weathering processes. We sample bedrock, plant litter, soils, soil waters and river waters for analysis of major cations, anions, and isotopic compositions. This sampling will focus around the Providence Creek watershed, where quantified long-term soil weathering and erosion rates have already been studied (Dixon et al 2009).

**Soil Nutrient Contents.** In addition to the two papers already published, we submitted a third paper on nutrient hotspots to Soil Science in March 2011 (Johnson et al., in review). This paper summarizes the results of the first year data described in the previous report. See the publication list for details. Year three samples were pulled and soil cores were extracted and analyzed for nutrient concentrations. Year four collectors were established, including experiments where O horizon runoff barriers were placed. In addition to hotspot investigations on the intensive plots, Johnson has been analyzing resin lysimeters and O horizon data collected by C. Hunsaker, Johnson, and helpers over the past 8 years.

**Nitrogen deposition and fluxes from soil.** KREW research was designed to evaluate a nitrogen budget and fluxes both before and after forest restoration treatments. This research was established in 2002 before the SSCZO began, however, synergy with CZO research has enhanced it. Nitrogen (N) as nitrate and ammonium is measured in precipitation (both rain and snowmelt), stream water, shallow soil water, and the flux from ground to shallow mineral soil (26 cm). More details than we present here can be found in the KREW Research Study Plan at [www.fs.fed.us/psw/programs/snrc/water/kingsriver](http://www.fs.fed.us/psw/programs/snrc/water/kingsriver).

One Prenart vacuum lysimeter is located in each of the four Providence watersheds; each Prenart has 6 tips that sample at the 13 cm mineral soil depth and 6 tips that sample at the 26 cm mineral soil depth. Enough water can be collected every two weeks during the wet season (November through June) for chemistry analyses of these waters. The Prenart lysimeters provide an indication of temporal variability during the wet season at these intensively monitored locations. Co-located with the vacuum lysimeters are bulk (wet and dry deposition) snowmelt samplers (6 under the forest canopy, 1 open); these samples are collected at the same frequency as the Prenart samples. A large array (150-m grid spacing between sample points) of resin lysimeters are deployed across the watersheds to get the annual spatial variability of N at ground level and at the 13 cm mineral soil depth: P301 has 44 sampling points, P303 has 60, P304 has 39, and D102 has 54. The chemistry of incoming precipitation is measured by an Aerochem sampler (CA28) located at watershed P301 that is part of the National Atmospheric Deposition Network (NADP); this sampler provides a weekly composite water sample. All of these measurements started in 2002 except the Aerochem which started in 2007. Aerochem measurements are continuing, but the other measurements were ended in 2009 pending the implementation of the forest thinning and underburning treatments. KREW has collected seven years of extensive N data to evaluate N deposition to the forest soil and N flux into the shallow mineral soils.

A subset of the resin lysimeters are co-located near the 87 quantitative soil pits for which Johnson et al. reported nutrient analyses in 2010 (*Geoderma* 160).

**Current and natural sediment loads.** The Forest Service maintains eight sediment basins in the Kings River Experimental Watersheds that allow annual sediment loads to be measured and characterized. Other landscape characteristics are measured to help determine the source of stream sediments.

**Hydrology and meteorology.** The Forest Service maintains 10 instrumented streams in the Kings River Experimental Watersheds and four meteorology sites with 15-minute data from October of 2002 to present. These data are quality assured and daily values are posted to the Forest Service's public

databases for streamflow and precipitation data (<http://lterweb.forestry.oregonstate.edu/climhy>). These data are also provided to the SSCZO database. The initial years of data have been analyzed and the first publication completed (Hunsaker et al., 2012). While most of the SSCZO team focuses on the lower elevation site at Providence (rain-snow transition), some researchers are also working at the high elevation (snow dominated) site at Bull.

**Photo credits.** Figure 3: Ryan Lucas.