Preview of Award 1331726 - annual Project Report

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Using the Susquehanna - Shale Hills CZO to Project from the Geological Past to the Anthropocene Future
PD/PI Name:

- Susan L Brantley, Principal Investigator
- Kenneth J Davis, Co-Principal Investigator
- David M Eissenstat, Co-Principal Investigator
- Li Li, Co-Principal Investigator
- Tess A Russo, Co-Principal Investigator

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Accomplishments

* What are the major goals of the project?

Overall Project: We are learning to earthcast the CZ. To us, earthcasting means developing quantitative models for earth surface evolution that will enable us to project into the future. We plan to do this by creating models to describe fluxes we see today, by testing the models by hindcasting the geologic record, and then using those models to make forecasts. We focus on a 165 km^2 watershed in central PA (Shavers Creek). We have developed an observational model to

measure important aspects of the CZ in this large watershed. Over short timescales and large spatial extents, we are developing an atmosphere-land surface model that couples meteorological and ecological processes with hydrological and biogeochemical processes in regolith using information about i) depth to bedrock; ii) permeability; iii) water uptake by roots; iv) distribution of fractures and macropores. Over long timescales and smaller spatial extents, we are developing models that predict these regolith characteristics. The models that treat these various processes are built on the Penn State Integrated Hydrologic Model (PIHM). With different modules in PIHM we plan to model changes in water, energy, sediment, and solute (WESS) fluxes at various timescales. For the sedimentary rocks underlying our CZO, we use these models to explore how the geological past has impacted the structure of regolith, and, in turn, how this structure contributes toward controlling today's fluxes.

While working on this big picture effort, we have structured our group into 9 teams, identified by 9 driving hypotheses, as described below.

H1 Team Goal: The H1 team is testing the following hypothesis while measuring fracture distributions, using measurements of cosmogenics to assess erosion rates; using boreholes, field observations, and geophysics to predict the structure of porosity and permeability in Shavers Creek watershed and surrounding relevant sites: H1. ***Feedbacks among frost shattering, weathering reactions, and the evolution of topography have resulted in an asymmetric distribution of fractures that in turn controls the observed differences in fluid flow in the subsurface between the sun-facing and shaded sides of catchments within Shale Hills and much of the Susquehanna River Basin.*** *(Kirby, Bierman, DiBiase, West, Brantley, Lin)*

H2 Team Goal: This team is testing the following hypothesis while developing as complete a dataset as possible that allows understanding of the distribution of soil gases, soil moisture, and organic acids and their effects on weathering of regolith in the Shavers Creek watershed: H2. ***The distribution of weathering reactions across a landscape can be described as a function of biotic and abiotic production and consumption of acids (CO_2, DOC) and O_2.*** *(Kaye, Brantley, Eissenstat, Li)*

H3 Team Goal: Team H3 is testing the following hypothesis while developing as complete a dataset as possible that allows understanding of the distribution of tree roots and their effects on water cycling, weathering, fungal distribution, macropores, erosion, and tree throw in the Shavers Creek watershed: H3. ***Trees with deeper roots (oaks) are associated with less frequent tree throw, slower hillslope erosion rates, fewer vertical macropores, faster weathering at depth, and deeper regolith than trees with shallower roots (maples).*** *(Eissenstat, Davis, Kaye, Brantley)*

H4 Team Goal: This team is testing the following hypothesis while developing as complete a dataset as possible that allows understanding of the distribution of regolith and macropores in regolith and their controls on fluid flow among the lithologies within the Shavers Creek watershed. H4. ***Macropores are important in controlling fluid flow and chemistry in soils derived from various lithologies, but the nature and effects of these macropores differ significantly among shale, calcareous shale, and sandstone.*** *(Lin, Duffy, Eissenstat, Davis)*

H5 Team Goal: Team H5 is testing the following hypothesis while developing as complete a dataset as possible that allows understanding of the controls on regolith chemistry and mineralogy using a reactive transport model developed for simulation of regolith formation: H5. ***Greater evapotranspiration on the sunny, north side of Shale Hills means that less water recharges to the stream, explaining why Mg and other cations are less depleted in the regolith on the north compared to the south hillslopes.*** *(Li, Brantley, Kaye, Russo)*

H6 Team Goal: Team H6 is testing the following hypothesis while developing as complete a dataset as possible that allows understanding of the controls on solute concentrations in stream waters of subcatchments within the Shavers Creek watershed, using a reactive transport modelling approach: H6. ***Ions that are released quickly from ion exchange sites (Mg, Na, K) throughout the catchment demonstrate chemostatic behavior (~constant concentration in the stream), whereas Fe, Mn, and DOC concentrations vary with changes in watershed-stream connectivity.*** *(Russo, Brantley, Li, Kaye, Shi, Duffy) Tess Russo is leaving Penn State.*

H7 Team Goal: This team is testing the following hypothesis while developing as complete a dataset as possible that allows understanding of the fluxes of carbon and water in the Shavers Creek watershed using PIHM modelling: H7. ***Land-atmosphere fluxes of carbon (C) and water, ground-water hydrology, and ecosystem change are coupled processes at time scales of months to decades. This coupling varies with the lithology and land use and position on the hillslope****. (Davis, Shi, Eissenstat, Duffy, Lin, Kaye)*

H8 Team Goal: The H8 team is testing the following hypothesis while developing as complete a dataset as possible that allows multi-scale modelling to project physical processes from Shale Hills to Shavers Creek: H8. ***Co-located, intensive, relocatable measurements of soil moisture, tree sap flux, sapwood area, LAI, ground water depth, temperature, ^{18}O and D/H along with a 4-component radiometer, laser precipitation monitor and landscape-level soil moisture (COSMOS) can be assimilated within a multi-scale distributed modeling framework to project physical processes from Shale Hills to Shavers Creek to Young Woman's Creek and Snake Creek watersheds.*** *(Shi, Duffy, Davis, Eissenstat, Lin, Duffy)* Chris Duffy has indicated he would like to have minimal involvement with the CZO other than with respect to PIHM modelling. Instead, Yuning Shi, who has been involved in the CZO since its inception and now works part time on the project, is leading the H8 team in collaboration with Li Li.

H9 Team Goal: The H9 team is spearheading measurements to understand weathering processes in the target catchments and using models to earthcast weathering and other CZ processes into the future while testing the following: H9. ***Increasing atmospheric CO_2 in the future will cause higher temperatures and faster weathering of clays in the catchment, increasing streamwater solute loads.*** *(Brantley, Godderis, Li, Duffy, Davis, Shi)* Pam Sullivan was a postdoctoral student working on this project and she is now an assistant professor at University of Kansas where she is writing up two papers on CZO research. Two seed grants provided data for this team effort. A USGS Seed Grant funded Carleton Bern and the Kent State Seed Grant was used by E. Herndon at Kent State to evaluate the spatial distribution of dissolved and colloidal elements in soils, groundwater, and surface water in the SSHCZO catchment.

* What was accomplished under these goals (you must provide information for at least one of the 4 categories below)?

Major Activities:

As a group, our two biggest achievements for this past year have been the following: i) we now have chosen and begun investigating our third sub-catchment, the Cole Farm site, and ii) we have progressed with our outreach work with the Shavers Creek Environmental Center in helping them (and a class of undergraduate students) design a family hike for their museum that incorporates CZ science. We will get our first data from Cole Farm this summer and this will represent our first data from a heavily impacted (agricultural) site. The site is a private farm and will allow us to compare our pristine sites at Shale Hills (on shale) and Garner Run (on sandstone) to a site impacted by crops, fertilizer, and lack of trees.

Over the last year we also advanced in our use of the PIHM family of models in that we created a new module to describe the creation and evolution of regolith, and to model both vertical and lateral flow in the subsurface. We are initiating the use of these models to compare water flow and regolith formation in the shale watershed (Shale Hills) and the sandstone watershed (Garner Run), and this is elucidating controls on important water, energy, gas, solute and sediment fluxes. As part of these efforts, our geomorphology sub-team has been able to assess the residence times of soils in both the shale and sandstone sub-catchments and is promoting a geological picture of the story of Shaver's creek watershed.

Below we enumerate major activities of each team.

H1. The H1 team completed surface mapping fieldwork in the sandstone subcatchment (Garner Run), in order to assess aspect controls on Pleistocene periglacial processes and their influence on modern surface processes. The surface mapping was supplemented in summer and fall 2016 with shallow geophysical surveys (shallow seismic refraction, ground penetrating radar (GPR), terrain conductivity, and magnetics) as part of new collaborations with J. Hayes (Dickinson College), X. Comas (Florida Atlantic University), and G. Mount (Indiana University of Pennsylvania). In June 2016, the annual Rutgers University Hydrogeophysics Workshop run by L. Slater (Rutgers University) took place in the SSHCZO. Additional key datasets generated from this workshop included an electrical resistivity tomography survey and induced polarization survey in Garner Run. At the University of Vermont, we completed all cosmogenic isotopic measurements from Garner Run, Young Womans Creek, and Hickory Run, analyzed data, and submitted a paper for publication detailing our findings on periglacial boulder fields (Denn et al. submitted). A second submitted paper (Del Vecchio et al., submitted) combines cosmogenic nuclide dating and surface mapping results at Garner Run. Comparison of fracture distributions with geophysical measurements of the Shale Hills catchment is in its final stages, with a manuscript to be submitted June, 2017. We found similar results of a long-lived critical zone at the Hickory Run site with some boulders having exposure ages exceeding half a million years (Denn et al., submitted).

Modeling experiments suggest that periglacial conditions likely contributed to fracturing of the Shale Hills subsurface, priming the development of asymmetric regolith thicknesses and chemical weathering conditions.

H2. The H2 team: 1) published one paper on a study of roots within rock fractures (Hasenmueller et al. 2017), 2) sampled pore fluid over the year in one shale and one sandstone catchment for a comparison study, 3) completed one MS thesis (L. Hill), 4) synthesized results from measurements of soil and foliar nutrient concentrations in 5 shale and 5 sandstone catchments (to extend our efforts within the CZO itself to other areas within central PA), and 5) contributed to locating a new agricultural catchment for research and designing the sampling to occur there.

H3. The H3 team: 1) Continued analysis of the vertical root distribution of trees as affected by shale and sandstone including tree species identification of root distribution by DNA extraction 2) conducted the Tree Workshop and submitted a paper from the workshop (3) contributed to the broader project goals on tracking leaf phenology, litter fall, green leaf chemistry, radial tree growth, and soil moisture in the Shale Hills and Garner Run catchments. This team also contributed to understanding root length density and soil respiration as influenced by topography at the Shale Hills catchment.

H4. The H4 team: 1) published 3 papers related to the Shale Hills catchment in collaboration with other team members (see publication list), 2) established a framework to summarize the dominant controls of macropore/preferential flow across a wide variety of soils and landscapes; 3) continued soil moisture, infiltrometer, EMI and GPR data collections at the Shale Hills and the Gunner Run catchments; 4) developed a field method to detect the occurrence of macropore/preferential flow by integrating different geophysical tools; and 5) utilized the soil moisture data collected from the Ground Hog site for soil moisture analysis.

H5. The H5 team 1) developed a code (RT-FLUX-PIHM) that simulates hydrological and geochemical processes at the watershed scale, 2) used RT-Flux-PIHM to understand the concentration discharge relationships for Cl and Mg at Shale Hills, 3) is developing a reactive transport model for a hillslope catena to understand soil development in Shale Hills.

H6. The H6 team 1) continued stream chemistry data collection at Garner Run and along the main branch of Shavers Creek, 2) installed additional wells in the Valley floor at Garner Run, 3) began monitoring stream discharge and stream water chemistry at the new agricultural site (Cole Farm), and 4) collected Shaver's Creek stream chemistry data before, during, and after a storm event; 5) continues collecting ground water chemistry and interpreting soil chemistry in the Garner Run and Cole Farms sites.

H7. The H7 team 1) continued to maintain the eddy covariance flux data stream from the Shale Hills watershed (forested, shale bedrock), 2) assisted with the installation of a second eddy covariance flux measurement at the Cole Farm site (agricultural watershed, calcareous shale bedrock), 3) ran and evaluated the coupled Flux-PIHM-BiomeBGC

watershed carbon-water-nitrogen modeling system for Shale Hills watershed, 4) continued to work towards a multivariate carbon-water data assimilation system that can be applied to the coupled Flux-PIHM-BiomeBGC modeling system, and can describe, with good accuracy and precision, the coupled carbon-water-nitrogen cycle in complex topography.

H8. The H8 team 1) Conducted stochastic and uncertainty-based Flux-PIHM (Penn State Integrated Hydrologic Model with a land surface module) calibration at Garner Run using the Hornberger-Spear-Young algorithm & Latin hypercube sampling; 2) Compared differences in hydrology between Shale Hills and Garner Run using model-data synthesis to identify lithologic/topographic controls on hydrology (results presented at 2016 Fall AGU); 3) Evaluated effectiveness of boulder map in predicting hydrology at Garner Run; 4) Tested capability of using COSMOS + discharge to constrain the hydrologic model (Flux-PIHM) with synthetic data experiments with a data assimilation system (the ensemble Kalman filter); 5) Compared annual data of COSMOS (areal averaged soil moisture at the shallow soil layer) and GroundHOG (point measurements at different depths) at both Shale Hills and Garner Run (results presented at the Fall 2016 AGU); 6) Analyzed the water budget at three watersheds from <1 to > 100 km^2.

H9. The H9 team completed the following: 1) seed grantee Carleton Bern submitted a paper about movement of fine particles in Shale Hills; 2) seed grantee Lixin Jin submitted a paper about rare earth elements in Shale Hills; 3) Pam Sullivan (who used to be a postdoc here) has almost completed the Earthcasting paper (she reported on it at the CZO Arlington meeting).

Specific Objectives:

Specific Objectives Overall

In our renewal grant, the SSHCZO has been upscaling from a small watershed (Shale Hills) to the entire Shavers Creek catchment (165 km^2). The smaller watershed is pristine and underlain entirely by shale whereas the larger watershed has multiple land uses and is underlain by shale (with and without calcite) and sandstone. To upscale our models, we decided to complete intensive study not only on one first-order pristine shale sub-catchment (Shale Hills), but also on 2 newly chosen sub-catchments: a pristine, sandstone sub-catchment (Garner Run) and a farmed calcareous shale agricultural subcatchment (Cole Farm). We chose the sandstone sub-catchment last year and we now have one year's worth of data. We are currently starting to understand why the sandstone site is so different from the shale site. First, erosion rates are slower, and erosion products (regolith) are not removed rapidly from the sub-catchment except during periglacial periods. We believe that this means that the sandstone site retains much more dust and/or products from overlying weathering units than the shale site. On the other hand, both sub-catchments appear to have two flow zones for loss of water, one near the land surface and one at the top of the water table. We are starting to understand these two flow zones. We also were able to choose and implement the new sub-catchment on a calcareous shale that is farmed. By the end of the summer 2017 we will have our first data from this site,

which meets one of our specific objectives to begin analyzing impacts of farming on water, energy, gas, solute, and sediment fluxes.

Our ongoing modelling efforts are bearing fruit as well: we now have PIHM models running for carbon/water/nitrogen cycling, for stream chemistry, for regolith formation and for landscape evolution. We are using these models to understand Shale Hills sub-catchment and to compare and contrast Shale Hills to Garner run (shale to sandstone). Next year we will use models to understand the new Cole Farm sub-catchment.

All of these efforts were described in our team's paper in Earth Surface Dynamics entitled, "*Designing a suite of measurements to understand the critical zone*."

Specific Objectives Enumerated by Team

H1. In fall 2016, accelerator mass spectrometer measurements for surface and core samples in Garner Run were completed. Along the GroundHOG soil pit transect at Garner Run, we collected and aligned a suite of geophysical surveys in order to interpret spatial variability in regolith thickness, colluvial valley fill thickness, and the thickness of weathered bedrock. Surface cover mapping for Garner Run was completed in summer 2016, and we have begun integrating this dataset with the PIHM hydrologic modeling group. We are moving forward in learning to use geophysical datasets to understand our sub-catchments.

H2. The main objectives were to 1) establish our new GroundHOG monitoring scheme at both the shale and sandstone sites and then to repeatedly sample pore chemistry and gas along the GroundHOG catenas, in one shale and one sandstone catchment, 2) expand sampling to other shale and sandstone catchments, 3) expand sampling to a new agricultural catchment on calcareous shale, 4) publish mineralogical, elemental, and SEM analyses of samples from the root-rock interface in shale.

H3. Tree and shrub species were determined for the roots collected from soil pits in Shale Hills and Garner Run catchments as well as in sandstone and shale sites in the Tuscarora State Forest in south central Pennsylvania. Arbuscular and Ectomycorrhizal fungal communities associated with different tree species were also determined at Shale Hills. The team also designed and ran the tree workshop and then wrote and revised the tree workshop paper (almost in press in BioGeosciences Discussions).

H4. The specific objectives of H4 included the goals i) to comprehensively understand the major space-time factors that govern the occurrence and dynamics of macropore/preferential flow; ii) to develop new field methods of detecting and quantifying preferential flow occurrence; and iii) to enhance the comparison of preferential flow patterns across monitoring sites and catchments.

H5. The specific objective of this team was to develop a quantitative model of regolith formation and to relate observations in the CZO to this model.

H6. This team completed a manuscript (Hoagland et al. In Press, Water Resources Research) combining tracer tests, sediment analyses, streamwater, groundwater, spring water, and soil pore water chemistry to describe solute dynamics within Garner Run watershed. The second primary objective was establishing the agricultural study site, including stilling well installation, rating curve measurements, and stream water chemistry measurements.

H7. The team finished testing the response of the carbon stocks and fluxes to environmental forcing (soil temperature, soil moisture, light, soil hydraulic properties, nutrient availability) using the Biome-BGC ecosystem biogeochemistry model, and in the coupled Flux-PIHM-BiomeBGC modeling system, within the Shale Hills watershed.

H8. The team continues to evaluate hydrologic model parameter transferability from Shale Hills to Garner Run; to understand differences in hydrologic processes with different lithology; and to test "must-measure" parameters for hydrologic models using model-data synthesis.

H9. The team is writing the Earthcasting paper, and has submitted the particle transport paper (Bern et al.) and the rare earth element paper (Jin et al.)

Significant Results:

Significant Results Overall

We have now shown that watersheds underlain by sandstone retain their shape and their sediment and regolith for much longer durations than watersheds on shale. This means that the sandstone catchments retain dust and sediment from overlying units for much longer time periods. By comparing and contrasting cosmogenic age dates and observations from our Garner Run sandstone sub-catchment to Hickory Run in northeastern PA, we are starting to pick apart the separate effects of climate change and base level change. We also advanced on developing the ability to model changes in the watersheds over timescales ranging from meteorological to geological as well as testing model output in new sites. For example, landscape variability in terrestrial carbon stocks - low above-ground carbon on the ridge tops, and high at the valley - appears at least partly caused by lateral transport of nitrogen from the ridge top to the valley floor, thus representing the interactions of the nitrogen and water cycles. This is a model-generated hypothesis that needs to be evaluated with additional measurements of the watershed nitrogen cycle.

Significant Results Enumerated by Team

H1. Measurements of cosmogenic ^{10}Be in stream sediments, soils, and surface boulders at Garner Run indicate slow hillslope erosion rates (~6 m/Myr) and integrate over long (40-140 kyr) timescales. Burial ages from analysis of ^{10}Be and ^{26}Al in core samples indicates a >9 m package of colluvial fill that is at least 200-300 kyr old, in agreement with independent estimates based on surface erosion rates and fill volume estimates from

shallow geophysics and coring (Del Vecchio et al. submitted). The presence of well-preserved solifluction lobes and other periglacial landforms in sandstone valleys has previously been attributed to accelerated erosion rates associated with the colder temperatures during the last glacial maximum. We show that although hillslope erosion is likely accelerated during cold periods and transitional warming, this material is preserved for multiple glacial-interglacial cycles in headwater valleys due to coarse grain size.

H2. We discovered that roots growing in shale fractures that were up to 1 m below C horizon soil had similar respiration rates (per g root) as roots growing in soils. Thus, even at depth in the the rock, roots have metabolic rates that are the same as in soil. While there were many types of fracture in this shale, we only found roots in larger fractures that contained silt and clay sized particles. We wondered whether this fine soil-like material had been translocated along root channels from B horizons into the rock fractures, or alternatively whether the material was generated in situ, by roots enhancing weathering of their immediate surroundings. We used mass balance approaches (tau plots) to learn that in situ weathering is the most likely source for the fine material. Thus, "soil" appears to initiate deep below the traditionally identified soil-bedrock interface. We do not yet understand the functional role of deep roots for plants.

H3. Root observations indicated trees on sandstone are somewhat deeper rooted than those on shale. Factors positively correlated with root length density in the Shale Hills catchment included ammonium concentration and soil organic matter content. However, in general, root length density at 0-20 cm did not show a strong dependence on topography at Shale Hills. There was a general pattern of deeper rooting patterns in swales and the valley than at ridgetop and planar midslope. C:N ratios in green leaves have been found to increase as elevation increases in the catchment per species, indicating a decrease in nitrogen concentration. Diverse communities of fungi were observed with limited linkages to tree species root morphology. Root colonization of disturbed nutrient rich hot-spots was strongly shaped by both root morphology and mycorrhizal type.

H4. The H4 team summarized the dominant controls of macropore/preferential flow across various soils and landscapes and developed a framework of six key categories of controls to assess the susceptibility of various soils to preferential flow. We proposed a new method to offset the influence of the number of sensors per site on the detected occurrence frequency of preferential flow using real-time soil moisture data (this enhances the comparison study of preferential flow pattern across CZOs). We compared the difference in preferential flow in Ground HOG transects between Shale Hills and Garner Run catchments. We tested the potential of integrating thermal imaging, repeated GPR scanning, and real-time monitoring to detect the occurrence of preferential flow at Shale Hills and Garner Run.

H5. The team has developed a new code, RT-Flux-PIHM, the first of its kind to simulate hydrogeochemistry with detailed multi-component reactive transport processes at the watershed scale. Two papers have been published about this advance in WRR: one on model development, the other on using the model to understand CQ dynamics.

H6. The apparent controls on C-Q behavior by the hyporheic zone in the sandstone catchment (Garner Run) was compared to the controls on C-Q behavior by the hillslope swale structure in Shale Hills. A paper was published in *Water Resources Research* in the C-Q special issue. The agricultural site was also identified and established within Shaver's Creek watershed. Stream, spring, and groundwater solute chemistry, and stream discharge are now monitored. Solute chemistry is being evaluated with respect to catchment area lithology and land use.

H7. Both the coupled modeling system and the decoupled BiomeBGC modeling have shown that, according to these modeling systems, the interactions between the nitrogen and water cycles is the dominant environmental control on spatial structure in carbon stocks in the Shale Hills watershed. The watershed average biomass pools (above and below ground carbon) and net ecosystem productivity can be optimized in the model for the watershed by using the observed carbon residence time (aboveground biomass divided by above ground net primary productivity), the observed nitrogen deposition rate, and tuning the soil carbon pool decomposition rate. Research to determine the set of observations needed to simulate the spatial variability in carbon cycle stocks and fluxes with precision and accuracy is in progress.

H8. According to the model we are developing for the sandstone watershed, the watershed lithology and soil has larger pores, larger water storage, lower water retention, and more preferential flow. We have developed a model using optimized parameters w/ and w/o utilizing data from a surface boulder map. The latter map helps get parameter estimation closer to physical meaning, and yields a better prediction of the spatial distribution of soil water content; however, the discharge-precipitation relationship can be predicted with or without the boulder data as long as we optimize parameter inputs. We have been also assimilating both COSMOS and discharge observations. These provide good constraints for van Genuchten α and β water retention parameters. The COSMOS shows a positive correlation with the GroundHOG observations, and appears to represent averaged soil moisture in a reasonable fashion. However, the COSMOS data has a longer rainfall response time than point measurements due to their different representativeness.

H9. We have been trying to understand the implications of the Earthcasting models under development by Pam Sullivan. We believe that the earthcasting exercise shows that element cycling by vegetation in Shale Hills may be slowing rather than accelerating weathering rates. We also think we now have an estimate of how much weathering could be accelerated by increasing temperature according to scenarios of climate change based on atmospheric CO2.

Key outcomes or Other achievements:

<u>Overall Key Outcomes or Other Achievements</u>

We have advanced our understanding of the effects of important variables (organic matter content, nitrogen content, precipitation rate, aspect, slope of hillsides, base level, grain

size, root density, etc.) on water, energy, gas, solute, and sediment fluxes in shale and sandstone catchments by developing and beginning to test or explore quantitative models in the PIHM family.

We have discovered that sandstone-underlain catchments retain their shape and sediments for much longer than shale-underlain catchments and thus act like large bowls for accumulation of dust and sediments from overlying units.

We also have discovered that catchments tend to experience both lateral flow and vertical flow of water even in the vadose zone, although the lateral flow is episodic and transient and restricted to layers that saturate because of underlying low-permeability zones. We have produced an important paper describing how to relate vertical and lateral flow of water to reaction fronts in the subsurface and are starting to extrapolate this to some of the other CZOs.

We have also discovered that nitrogen is a key variable in controlling above-and below-ground organic carbon stocks in the watershed and we are exploring this idea with quantitative models.

We have also moved forward on understanding how trees impact water and regolith formation. Trees growing on sandstone appear to have fewer roots and roots that are less dense in the surface layer -- i.e., more evenly distributed with depth -- as compared to trees growing on shale. Our working hypothesis is that because nutrients move more freely in a sandy soil (e.g. sandstone) than in a finer textured soil (e.g. shale), the trees on sandstone do not need to allocate C to as many roots to fully exploit a given volume of soil. In other words, the marginal rate of nutrient return for a given C investment drops off more steeply for roots in sandstone than those in shale because of differences in texture. This key idea is helping us as we move forward to incorporate trees in our models predicting fluxes of water, energy, gas, solutes, and sediments in terrestrial landscapes.

A more generalized observation is that our team is one of the only CZO teams using data assimilation. This is a technique that derives from the meteorology community in which model output is used as if it were data -- and used to help parameterize and improve complex model simulations of weather or climate, etc. This is a standard technique that is in use in meteorological communities and is now being used to help us do hydrologic modelling of our catchments. We are starting to explore how to use data assimilation for other aspects of CZ modelling. One member of our team (Li Li) has submitted a proposal to NSF to explore more ways to use data assimilation at the CZO, in collaboration with Fuqin Zhang in the meteorology department at Penn State.

<u>Key Outcomes or Other Achievements Enumerated by Team</u>

H1. The team 1) Produced 2 papers describing fracture distributions in sandstone/shales in comparison to geophysical surveys (one paper in final prep.); 2) trained 1 postdoc (Nikki West, recently started faculty position at Central Michigan Univ) 3) MS student

Denn has graduated from the University of Vermont. 4) Graduate student Del Vecchio completed her MS degree from Penn State in summer 2017, and is starting a PhD at Penn State with R. DiBiase in fall 2017. Collaborations started in summer 2016 have continued with multiple shallow geophysics field campaigns consisting of teams of PSU graduate students and postdocs, undergraduate students from IUP and Dickinson, and faculty from all three institutions.

H2. The team collected a full growing season of porewater chemistry observation sites along catenas in one shale and one sandstone catchment. We contributed these data to a team publication that used pore water cation concentrations to enhance understanding of concentration-discharge relationships (Hoagland et al. in press). We sampled 8 new sites (4 on shale and 4 on sandstone) for indicators of nutrient limitation to plants and soil microorganisms. These data became the basis for one chapter in a completed MS Thesis (Hill) and a presentation at AGU. We are also working up the soil gas data from the shale site to understand cycling of C and oxygen in the soil.

H3. The team ran the Tree Workshop, and submitted a paper for publication from the workshop (BioGeosciences).

H4. The team published 1 paper related to the Shale Hills catchment and contributed to other published articles (H3 - Gaines et al., 2016, and H4 - Guo & Lin, 2016).

H5. The team has a paper in review describing regolith development on black shale and two papers on CQ relationships in Shale Hills.

H7. The team made a new coupled modeling system, Flux-PIHM-BiomeBGC, available for research. It includes a coupled simulation of groundwater hydrology, biogeochemistry, and surface energy balance. Two manuscripts are drafted, but not yet submitted. This new coupled model is being used to explore our observations about the importance of nitrogen in controlling carbon stocks in the watershed. The eddy covariance flux data record from Shale Hills is continually updated as observations are collected. The Cole Farm flux record is now being processed.

H9. The team helped coordinate and submit a paper on designing a CZO and another paper about the future of the CZO network for the national CZO team. H9 is also working hard to finish the first earthcasting paper for Shale Hills. The team also began monitoring water table depth throughout Shale Hills to relate it to a new idea developed by this team about relating reaction fronts to water flow in the subsurface (an idea published in Brantley et al., 2017; Geomorphology).

* What opportunities for training and professional development has the project provided?

The CZO is used by several classes at Penn State and is visited by faculty and students from several local universities (e.g., Kent State Univ., Lehigh Univ., Univ of Pennsylvania, Indiana Univ of Pennsylvania, Dickinson College, Rutgers Univ.) for research and teaching.

The CZO was also the site of a Hydrogeophysics Field Workshop led by faculty at Rutgers University (see section on personnel) and for a Tree Workshop led by D. Eissenstat and S.L. Brantley (see section on personnel). The field workshop was a terrific opportunity for many students from different schools, nationalities, and ethnicities to work in the "wilds" of Pennsylvania on hydrogeophysics. It was a big success. A proposal was submitted and funded to continue the field workshop every year for the next several years, using the CZO as the field site. The tree workshop was a terrific opportunity for students and faculty from many universities to interact and discuss puzzles related to the interaction of trees with regolith and water in the Earth surface system. A paper has been submitted and is in review in BioGeosciences Discussions.

Training and Professional Development within Each Team is Listed Below

H1. PSU MS graduate student Joanmarie Del Vecchio (advised by R. DiBiase) was mentored in geomorphic mapping using fieldwork, GIS and lidar analysis, and in the interpretation and preparation of rock samples for cosmogenic nuclide analysis. In summer 2016, J. Del Vecchio mentored two undergraduate researchers through the SSHCZO REU program, one of whom presented work at the Fall 2016 GSA Meeting (Silverhart et al., 2016) and will be starting an MS at Penn State with R. DiBiase in Fall 2017. Graduate student Al Denn was mentored at Univ of Vermont by Paul Bierman and mentored a female undergraduate geology student in field work and sample collection.

H2. One graduate student, Lillian Hill (co-advised by J. Kaye and R. Dibiase) was trained in datalogger programming and soil pore chemistry sampling by manual collection and automated sensors. One undergraduate student assisted in these measurements and then conducted independent research comparing nutrient availability on ridgetops and mid slopes. Several other postdocs, graduate students, and undergraduates were trained to sample pore fluid chemistry.

H3. One PhD student successfully passed their candidacy exams in Ecology (Rondy Malik). One PhD student was awarded a NSF GRFP with a proposal on root exudation to be supported by the CZO (Ismaiel Szink).

H4. Two REU students, three undergraduate research assistants, and five visiting scholars were trained to use GPR, EMI, and infiltrometers at the Shale Hills and Gunner Run catchments. A total of 20 graduate students from the Penn State University and the Indiana University of Pennsylvania were trained to conduct time-lapse GPR and EMI at the Shale Hills catchment.

H5. The team graduated a PhD student, Chen Bao, who is now working in industry. Another student, Dacheng Xiao, is working on the hillslope model. Both students have benefitted from monthly SSHCZO seminar and cross-disciplinary discussions. A previous student mentored by this team, Peyman Heidari, is now a professor at Missouri Univ. of Science and Technology.

H6. Undergraduates (Lacroce and Walker) worked as field assistants to the watershed coordinator. Four REU students hosted by Russo and Brantley in summer 2016 were trained in collecting and analyzing stream samples. Each student presented his/her results as posters at the CUAHSI Biennial meeting in Shepherdstown, WV. A graduate student co-advised by Russo and Brantley submitted her work on C-Q at the sandstone catchment to *Water Resources Research*,

which will serve as one chapter of her dissertation (Beth Hoagland). A second graduate student, also co-advised by Russo and Brantley (Callum Wayland), has given several presentations on his progress and plans at the agricultural site at Penn State, and a poster at the National All-Hands CZO meeting in Arlington, VA in June 2017. A third graduate student (Virginia Marcon) has been working on understanding and relating groundwater and soil chemistry in Garner run catchment.

H7. Doctoral student He passed her comprehensive exam in January 2017, and is working on the second part of her dissertation. Her doctoral committee includes three members of the CZO team (Davis, Eissenstat, Shi), a global climate scientist, and a watershed hydrologist.

H8. A graduate student Dacheng Xiao (co-advised by L. Li and Y. Shi) was trained to systematically perform model sensitivity analysis and synthesize field observations for hydrologic modeling. Xiao also be trained in scientifically writing.

H9. The earthcasting work has been under the supervision of Pam Sullivan, who postdoc'ed here and then moved to Univ of Kansas to join their faculty. Brantley continues to mentor Sullivan in a department where there have been some issues. Sullivan worked with Brantley to publish one paper (Sullivan PL, Ma L, West N, Jin L, Karwan DL, Noireaux J, Steinhoefel G, Gaines KP, Eissenstat DM, Gaillardet J, Derry LA, Meek K, Hynek S, Brantley SL. CZ-tope at Susquehanna Shale Hills CZO: Synthesizing multiple isotope proxies to elucidate Critical Zone processes across timescales in a temperate forested landscape. Chemical Geology 2016;445:103-119.) Similarly, another team mebmer and ex-postdoc at Shale Hills, Lixin Jin, is now a faculty member at Univ of TX El Paso and Brantley has also been mentoring her. Jin just submitted a paper about Shale Hills rare earth elements.

* How have the results been disseminated to communities of interest?

H1. Key results of the geomorphic mapping, cosmogenic dating, and geophysical surveying have been presented at national meetings (GSA and AGU). In spring 2017, J. Del Vecchio worked with an outdoor education class taught through PSU at the Shavers Creek Environmental Center to develop a field-integrated iPad app to share the results with the public. In May 2017, R. DiBiase hosted the 6th annual Amtrak Club geomorphology meeting at PSU, which included a talk and poster session featuring student posters from the SSHCZO and a field trip to Garner Run with 30 faculty and students from regional universities. Papers have also been submitted (see Products).

H2. The H2 team leader (J. Kaye) has been participating in the Soil Microbiology cross CZO Working group to disseminate and learn CZO approaches. He attended a working group meeting in Toronto during the reporting period. Team members gave several talks on campus and at other venues. Two publications and several conference talks (Hill et al. 2016 AGU) disseminated results to the scientific community.

H3. Work on vertical root distribution was disseminated at the ESA Annual Meeting (2016) and the AGU Annual Fall Meeting. Work at the Shale Hills CZO was also disseminated at a DOE PI meeting associated with a DOE grant at the site. Work presented included how soil respiration

and root length density are affected by topography and in coupling of Biome BGC with PHIM. Work on root and mycorrhizal fungal biology was also disseminated at meetings with the general public (e.g. Master Gardeners; Private Land Owners). The H3 team also organized and hosted the Tree Workshop and is currently revising a paper in press for BioGeosciences on the impact of trees on the CZ.

H4. H4 produced 1 publication (Geoderma), contributed to 2 publications (Vadose Zone Journal and Tree Physiology), and 8 presentations (AGU Fall Meeting and 3rd International Conference on Hydropedology).

H5. The team has been actively advocating the use of models to understand complex systems and general principles across CZOs. Specifically, i) The team, together with Russo and Hoagland (H6 team), is actively involved in a Cross-CZO C-Q relationship workshop; ii) Li has developed an online reactive transport modeling (RTM) course that has been and will be used to teach graduate students across CZOs. The online course has been taught twice in Spring 2016 and 2017. With further refinement, Li plans to make all course materials public next year so that anyone who is interested in using RTM can access it without the limit of time and space. To the best of the team's knowledge, this is the first RTM online course, which has the potential for teaching the next generation of scientist RTM tools for CZO work; iii) Li also led a forward-looking manuscript "Expanding the role of reactive transport models in Critical Zone Processes", which is published in early 2017. This manuscript comes out of an RTM workshop (together with Kate Maher and Alexis Navarre-Sitchler) in 2014. iv) Li organized an AGU session "Modeling the Critical Zone: Integrating processes and data across disciplines and across scales" together with Harry Vereecken (Bonn University, Germany), Lejo Flores (Boise State University), and Sally Thompson (Eel river CZO) in December 2016; v) Li also organized a session on "Novel Developments and Data-Integration in Complex Biogeochemical and Hydrological Process Models" with Christof Meile (U. Georgia) in the biennial Computational Methods in Water Resources (CMWR) conference in June 2016 in Toronto, Canada.

H6. Team members gave talks on campus and at the National All-Hands meeting in Arlington, VA.

H7. The team has presented research results at the CZO All-Hands meeting and as contributions to the team colloquium series. A poster was presented at the North American Carbon Program All-Investigators' Meeting in March of 2017 and at Penn State's 20th Environmental Chemistry and Microbiology Student Symposium. Two manuscripts will be submitted shortly. The Shale Hills eddy covariance flux tower has been registered as part of the AmeriFlux network, a broadly used, continental-scale network of eddy covariance flux towers. It has also been registered as a ground validation site for EcoStress, a NASA Earth Venture satellite system to be launched in 2019, and intended to monitor ecosystem physiological status from space at high spatial and temporal resolution.

H8. Team members gave talks on campus and at other venues (e.g. 2016 AGU Fall Meeting).

H9. Pam Sullivan has given several talks on Earthcasting and is completing the paper on this topic in collaboration with Susan Brantley. Brantley gave several invited talks on weathering and

erosion and water flow, including at the Binghamton Geomorphology meeting, at the Gilbert Club after AGU, at Univ of Wyoming, and other venues. She will give an invited talk at the Catchment Gordon Conference at Bates College in June.

* What do you plan to do during the next reporting period to accomplish the goals?

Overall:

During the very successful All Hands meeting in May 2017, the graduate students put together a series of posters that brought together datasets from the CZO for synthesis. As a result of this activity, several synthesis papers will be started this year to pull together the different datasets. These papers will highlight some of our emerging ideas:

In humid temperate climates, water is mostly taken up by trees from the upper 30 cm of soil. Nutrients are foraged by trees from hot spots by using either their roots or associated fungi depending upon whether the trees have thin roots that host arbuscular mycorrhizal fungi or thick roots that host ecomycorrhizal fungi respectively.

The critical zone acts as a capacitor for atmospheric pollutants deposited at the land surface: N, S, Mn, Pb, and a few other metals have been deposited from different human activities over different time periods and now are leaving the CZ after different time lags.

CO2 concentrations in the soil atmopshere are influenced mostly by moisture variations across the landscape; in contrast, aboveground C patterns are governed by N deposition and transport.

The shaded sides of east-west trending shale catchments in PA are steeper than the sunny sides because of faster freeze-thaw cycling, especially during hte periglacial period. This cycling drives more efficent downslope soil transport.

The deepest of the nested reaction fronts under the valley of the CZO, oxidative dissolution of pyrite, weakens the rock, accelerates stream incision, and leads to a cascade of shallower reactions that remove solutes and particles from the catchment.

Specific:

H1. Roman DiBiase is leading a group paper on shallow geophysical surveying in Garner Run. This paper includes students and faculty from Rutgers University (i.e. from the Hydrogeophysics Field Workshop form summer 2016). Al Denn and others are submitting a paper synthesizing work from Young Womans Creek in summer 2017.

The 82nd Field Conference of Pennsylvania Geologists is being held in State College, PA in fall 2017, and will focus heavily on the work that has been done at the CZO. There will be over 200 participants spanning academia, government, and industry visiting the CZO field site.

Roman DiBiase recruited a MS student (Perri Silverhart, former REU student within the CZO) to PSU to work on geomorphology of Cole Farm agricultural site, in order to distinguish between anthropogenic and periglacial drivers of colluvial valley aggradation.

H2. Having established pore chemistry monitoring at shale and sandstone forested catenas, the H2 team will emphasize adding a catena in an agricultural catchment on calcareous shale. We will sample all three sites to build a record of differences in pore chemistry between the shale, sandstone, and calcareous shale catchments. We have accumulated a significant dataset from several landscape positions and two lithologies that show variation in CO2/O2 ratios , but we have yet to identify mechanisms that control that variation. Thus, an important upcoming analysis is focused on understanding patterns in existing soil pore gas ratios (CO2/O2). We will seek to publish two papers, one on this ratio analysis, and a second on nutrient cation variability across shale and sandstone catchments.

H3. The team contributed to one paper describing root functions within rock fractures. They are revising a synthesis paper on the influence of trees on building and plumbing the critical zone. The team will also publish work on tree species composition of roots in relation to soil depth along the catenas in sandstone and shale and submit at least two papers associated with the influence of topography on root respiration and root length density. They will help the broader research efforts by continuing to monitor soil moisture, sap flux, litter fall, LAI and tree diameter growth. New work will continue to follow root dynamics (root birth, death and standing crop) using minirhizotrons. The team will also contribute one paper in collaboration with other hypothesis groups on the soil-plant-atmosphere continuum in regards to soil moisture, sap flux and eddy covariance measures of evapotranspiration. They will also initiate studies to examine the influence of lithology, tree species and soil depth on root exudation and factors controlling wood decomposition. Additional living leaves will be collected throughout the catchment to determine green leaf chemistry with respect to physical leaf traits such as specific leaf area (SLA). The tree team is starting to work with the model-development team to create a root-water module for the PIHM suite of models.

H4. More soil moisture and GPR/EMI data are to be collected in the field and more papers are planned for publication in the next reporting period. We will refine the field method of detecting macropore/preferential flow by coupling thermal imaging and time-lapse GPR scanning and upscale preferential flow patterns from site-scale to hillslope-/catchment-scale.

H5. Continued model development of regolith formation. 1D ridgetop simulations will be run to model regolith formation at Shale Hills, and if time permits, for the sandstone and calcareous shale lithologies. Hillslope catena models will be developed for simulation of shale, and if time permits, for the sandstone and calcareous shale lithologies.

H6. The team will support installation of GroundHOG instruments at the agricultural site, which will provide necessary pore water and soil moisture data for modeling fluid and solute transport within the catchment. The current graduate student working on H6 will develop conceptual and quantitative hydrologic models for the agricultural site, and begin using field data and remote sensing products to develop a scaled up model characterizing C-Q behavior in the greater

Shaver's Creek watershed. The team will also assist the cross-CZO postdoctoral researcher conducting hydrologic studies across the network.

H7. Research work will be expanded to include further model-data comparison (nitrogen cycle, soil respiration, carbon stock uncertainty assessment) and, if warranted, additional field data collection to refine our understanding of the carbon-water-nutrient interactions within the Shale Hills watershed. We will use spatially distributed soil respiration measurements to evaluate further BiomeBGCs parameterizations of the soil carbon cycle across the watershed. We will attempt to evaluate the nitrogen cycle processes suggested by our coupled modeling system with field nitrogen cycle observations. We will complete a model sensitivity study that will prioritize observations needed to simulate the watershed carbon and nitrogen cycles at Shale Hills. This work moves us towards the objective of a data assimilation system for coupled watershed hydrology and biogeochemistry. This work will ultimately result in an improved understanding of the impact of topography and soil properties on carbon-water-nutrient cycling across the earth's landscape, especially in low-order watersheds.

H8. Based on the understanding of water, energy, sediment, and solute fluxes at Shale Hills and Garner Run, the strategy of simulating Shaver's Creek with less intensive measurements will be evaluated. The data assimilation experiments will be performed to understand the impact of soil properties on hydrologic processes and to identify the effectiveness of using different observations to constrain model parameters.

H9. The main goal for H9 in the next time period is to get the earthcasting paper submitted and published. A secondary goal is to start to pull together a paper describing timelags of inputs to catchments, including lead, nitrogen, carbon, manganese, sulfur, etc. This work is still in the planning and discussing stage.

Supporting Files

	Filename	Description	Uploaded By	Uploaded On
(Download)	Annual CZO Meeting Susquehanna Shale Hills Poster 2017.pdf	CZO All-Hands Poster 2017	Susan Brantley	06/13/2017
(Download)	ShaleHillsReviewComments_EmilyElliott.pdf	Review Report from Professor Emily Elliott, University of Pittsburgh	Susan Brantley	06/13/2017
(Download)	ShaversCreekWatershed_DataFlow.pdf	Shaver's Creek Watershed	Susan Brantley	06/13/2017

Filename	Description	Uploaded By	Uploaded On
	and DataFlow		
(Download) CZO Budget Analysis_Year 5.pdf	Budget Analysis and Projection for Year 5	Susan Brantley	06/16/2017

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Products

Books

Book Chapters

Inventions

Journals or Juried Conference Papers

- Baldwin, C., Naithani, K.J., and Lin, H (2017). Combined soil-terrain stratification for characterizing catchment-scale soil moisture variation. *Geoderma*. 285 . Status = PUBLISHED; Acknowledgment of Federal Support = Yes ; Peer Reviewed = Yes ; DOI: 10.1016/j.geoderma.2016.09.031
- Bao, Chen, Yuning Shi, Li Li, Christopher Duffy (2017). Understanding Hydrogeochemical Processes at the Watershed Scale: 1. Development of RT-Flux-PIHM. *Water Resources Research*. 53 . Status = PUBLISHED; Acknowledgment of Federal Support = Yes ; Peer Reviewed = Yes ; DOI: 10.1002/2016WR018934
- Bern, Carleton R. and Yesavage, Tiffany (2017). Geochemical modeling of small mineral particle losses from sedimentary rock-derived soils. *Geochimica et Cosmochimica Acta*. . Status = SUBMITTED; Acknowledgment of Federal Support = Yes ; Peer Reviewed = Yes
- Brantley Susan L., Marina Lebedeva, Victor Balashov, Kamini Singha, Pamela L. Sullivan, Gary Stinchcomb (2017). Relating chemical reaction fronts to hillslope drainage. *Geomorphology Special Issue*. 277 . Status = PUBLISHED; Acknowledgment of Federal Support = Yes ; Peer Reviewed = Yes ; DOI: 10.1016/j.geomorph.2016.09.027
- Brantley, S. L., Eissenstat, D. M., Marshall, J. A., Godsey, S. E., Balogh-Brunstad, Z., Karwan, D. L., Papuga, S. A., Roering, J., Dawson, T. E., Evaristo, J., Chadwick, O., McDonnell, J. J., and Weathers, K. C. (2017). Reviews and syntheses: On the roles trees play in building and plumbing the Critical Zone. *Biogeosciences Discussions*. 1. Status = PUBLISHED; Acknowledgment of Federal Support = Yes ; Peer Reviewed = Yes ; DOI: 10.5194/bg-2017-61
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- Chen W, Koide RT, Eissenstat DM. (2017). Root morphology and mycorrhizal type strongly influence root production in nutrient hot spots of mixed forests. *Journal of Ecology*. . Status = PUBLISHED; Acknowledgment of Federal Support = Yes ; Peer Reviewed = Yes ; DOI: 10.1111/1365-2745.12800
- Del Vecchio, J., DiBiase, R.A., Denn, A.R., and Bierman, P.R. (2017). A record of coupled hillslope and channel response to Pleistocene periglacial erosion in a sandstone headwater valley, central Pennsylvania. *Geological Society of America Bulletin*. . Status = SUBMITTED; Acknowledgment of Federal Support = Yes ; Peer Reviewed = Yes
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- West, N. and Kirby, E. (2017). Lithologic, climatic, and baselevel influence on the evolution of hilltop curvature in first-order watersheds in the central Appalachians. *Earth Surface Processes and Landforms*. . Status = SUBMITTED; Acknowledgment of Federal Support = Yes ; Peer Reviewed = Yes
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- Yu, Xuan; Christopher Duffy; Yu Zhang; Gopal Bhatt; Yuning Shi (2016). Virtual experiments guide calibration strategies for a real-world watershed application of coupled surface-subsurface modeling .. *Journal of Hydrologic Engineering*. 21 (11), . Status = PUBLISHED; Acknowledgment of Federal Support = Yes ; Peer Reviewed = Yes ; DOI: 10.1061/(ASCE)HE.1943-5584.0001431

Licenses

Other Conference Presentations / Papers

- Lin, H. and Guo, L. (2016). *A framework for estimating the occurrence frequency and dominant controls of preferential flow across diverse soil landscape*. 2016 Fall Meeting, American Geophysical Union. San Francisco, CA. Status = PUBLISHED; Acknowledgement of Federal Support = Yes
- Cai, Z., Xiao, D., Shi, Y., and Li, L. (2016). *Assimilating the cosmic-ray soil moisture observing system measurements for understand watershed hydrodynamics*. 2016 Fall Meeting, American Geophysical Union. San Francisco, CA. Status = PUBLISHED; Acknowledgement of Federal Support = Yes
- Zhang, C., D. Xiao, Y. Shi, and L. Li (2016). *Assimilating the cosmic-ray soil moisture observing system measurements to understand watershed hydrodynamics*. AGU Fall Meeting. San Francisco, CA.. Status = PUBLISHED; Acknowledgement of Federal Support = Yes
- Mount, G., Guo, L., Comas, X., DiBiase, R., Hayes, J.L., Del Vecchio, J., Forsythe, B., Brantley, S.L., and Lin, H. (2016). *Characterizing Subsurface Lithology and Hydrological Processes at the Susquehanna Shale Hills CZO Using Multi-scale Near-surface Geophysical Measurements*. 2016 Fall Meeting, American Geophysical Union. San Francisco, CA. Status = PUBLISHED; Acknowledgement of Federal Support = Yes
- Del Vecchio, J., Denn, A., DiBiase, R., and Bierman, P. (2016). *Colluvial signatures of Pleistocene sediment production in central Pennsylvania*. 2016 Fall Meeting, American Geophysical Union. San Francisco, CA. Status = PUBLISHED; Acknowledgement of Federal Support = Yes
- Szink, I., Adams, T.S., Orr, A.S., Ruppel, M., Donnelly, S., Brazil, L.I., and Eissenstat, D.M. (2016). *Comparing Rooting Depth and Niche Partitioning Between Shale and Sandstone Derived Soils in Central Pennsylvania Mixed Forests*. 2016 Fall Meeting,

American Geophysical Union. San Francisco, CA. Status = PUBLISHED; Acknowledgement of Federal Support = Yes

- Zarif, F., Slater, L.D., Brantley, S.L., Robinson, J., and Kessouri, P. (2016). *Electrical Resistivity Imaging is Consistent with Shallow Interflow within the Garner Run subcatchment of the Susquehanna Shale Hills CZO*. 2016 Fall Meeting, American Geophysical Union. San Francisco, CA. Status = PUBLISHED; Acknowledgement of Federal Support = Yes
- Silverhart, P., Zhi, W., Xiao, D., Del Vecchio, J., DiBiase, R., and Li, L. (2016). *Evaluating the Importance of Regolith Heterogenity on Catchment Hydrology in Garner Run, Susquehanna Shale Hills Critical Zone Observatory, Pennsylvania, USA*. 2016 Geological Society of America Fall Meeting. Denver, CO. Status = PUBLISHED; Acknowledgement of Federal Support = Yes
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- Zhang, Y., Slingerland, R.L., Duffy, C., Gu, X., Lin, H., and West, N. (2016). *Geomorphic equilibrium and the spatial variation of the geomorphic diffusivity at the Susquehanna Shale Hills Critical Zone Observatory*. 2016 Fall Meeting, American Geophysical Union. San Francisco, CA. Status = PUBLISHED; Acknowledgement of Federal Support = Yes
- Lin, H. (2016). *Hot Spots and Hot Moments: Linking Hydropedology and Biogeochemistry in the Critical Zone (Invited)*. 2016 Fall Meeting, American Geophysical Union. San Francisco, CA. Status = PUBLISHED; Acknowledgement of Federal Support = Yes
- Li, L., Bao, C., Sullivan, P.L., Brantley, S.L., Shi, Y., and Duffy, C. (2016). *Hydrogeochemical Synchrony Drives Chemostatic Behavior in Stream Chemistry (Invited)*. 2016 Fall Meeting, American Geophysical Union. San Francisco, CA. Status = PUBLISHED; Acknowledgement of Federal Support = Yes
- Chen W, Koide RT, Eissenstat DM (2016). *Identity of host tree species may not control community composition of ecto- and arbuscular mycorrhizal fungi.*. Ecological Society of American Annual Meeting. Ft. Lauderdale, FL., 7-12 August. Status = PUBLISHED; Acknowledgement of Federal Support = Yes
- Iavorivska, L., and Boyer, E.W. (2016). *Inputs of Organic Carbon to Watersheds via Atmospheric Deposition: Variation Across Spatial and Temperal Scales*. 2016 Fall Meeting, American Geophysical Union. San Francisco, CA. Status = PUBLISHED; Acknowledgement of Federal Support = Yes
- Griffiths, Z.G., Davis, K.J., and He, Y. (2016). *Investigating the Effects of Soil Moisture on Net Ecosystem Exchange in Shale Hills*. 2016 Fall Meeting, American Geophysical Union. San Francisco, CA. Status = PUBLISHED; Acknowledgement of Federal Support = Yes
- Gu, X., Rempe, D., and Brantley, S.L. (2016). *Investigating the mechanisms of shale porosity development to understand hydrologic controls on hillslope scale weathering in a comparison across CZOs*. 2016 Fall Meeting, American Geophysical Union. San Francisco, CA. Status = PUBLISHED; Acknowledgement of Federal Support = Yes

- Matthew Bardo, Maya Bokunewicz, Susan Brantley, Lachlan Campbell, Matthew Carroll, Zachiah Cook, John Donoughe, Maria Duiker, Brandon Forsythe, Ava Fritz, Hannah Good, Kristen Lenze, Aaron Li, Emily Lieb, Kacy Mann, Lena Nyblade, Yvonne Pickering, Maria Rodriguez Hertz, Ethan Rowland, Eugene Ruocchio, Bryn Schoonover, Kathryn Thomas, Jennifer Zan Williams (2017). *MONITORING, COLLECTING, AND ANALYZING THE WATER QUALITY DATA OF STREAMS IN CENTRAL PENNSYLVANIA*. 2017 GSA Joint Section Meeting, Northeastern (52nd) and North-Central (51st), 19–21 March 2017. Pittsburgh, Pennsylvania, USA. Status = PUBLISHED; Acknowledgement of Federal Support = Yes
- West, N., Kirby, E., Nyblade, A., and Brantley, S.L. (2016). *Microclimate Controls on the Evolution of Critical Zone Architecture in the Susquehanna Shale Hills Critical Zone Observatory*. 2016 Fall Meeting, American Geophysical Union. San Francisco, CA. Status = PUBLISHED; Acknowledgement of Federal Support = Yes
- Bern, C. and Yesavage, T. (2016). *Modeling Small Mineral Particle Losses along Slopes of the Susquehanna Shale Hills Critical Zone Observatory*. 2016 Geological Society of America Fall Meeting. Denver, CO. Status = PUBLISHED; Acknowledgement of Federal Support = Yes
- Weitzman, J.N. and Kaye, J.P. (2016). *N Budget and Topographic Controls on N2O in a Shale Watershed with High Atmospheric N Deposition*. 2016 Fall Meeting, American Geophysical Union. San Francisco, CA. Status = PUBLISHED; Acknowledgement of Federal Support = Yes
- He, Yuting, Davis, Kenneth, Shi, Yuning, Eissenstat, David, Kaye, Jason, and Kaye, Margot (2017). *Observing and Simulating Spatial Variations of Forest Carbon Fluxes and Stocks in Complex Terrain*. Joint North American Carbon Program and AmeriFlux Principal Investigators' Meeting. North Bethesda, MD, March 27 – 30. Status = PUBLISHED; Acknowledgement of Federal Support = Yes
- Denn, A. and Bierman, P.R. (2016). *Old Rocks, New Data: Cosmogenic 10Be Analysis of a Relict Periglacial Boulder Field, Hickory Run State Park, Pennsylvania*. 2016 Geological Society of America Fall Meeting. Denver, CO. Status = PUBLISHED; Acknowledgement of Federal Support = Yes
- Eissenstat, D.M., Chen, W., Cheng, L., Liu, B., Koide, R.T., and Guo, D. (2016). *Plant Functional Traits Associated with Mycorrhizal Root Foraging in Arbuscular Mycorrhizal and Ectomycorrhizal Trees*. 2016 Fall Meeting, American Geophysical Union. San Francisco, CA. Status = PUBLISHED; Acknowledgement of Federal Support = Yes
- Sullivan, P.L., Hynek, S., Gu, X., and Brantley, S.L. (2016). *Pyrite Dissolution Leads Watershed Geomorphological Evolution*. 2016 Geological Society of America Fall Meeting. Denver, CO. Status = PUBLISHED; Acknowledgement of Federal Support = Yes
- Steinhoefel, G., Fantle, M.S., and Brantley, S.L. (2017). *Quantifying shale weathering by Li isotopes at the Susquehanna Shale Hills Critical Zone Observatory*. European Geosciences Union General Assembly 2017. Vienna, Austria. Status = PUBLISHED; Acknowledgement of Federal Support = Yes
- DiBiase, R., Del Vecchio, J., Mount, G., Hayes, J.L., Comas, X., Guo, L., Lin, H., Zarif, F., Forsythe, B., and Brantley, S.L. (2016). *Quantifying the spatial variability in critical zone architecture through surface mapping and near-surface geophysics (Invited)*. 2016

Fall Meeting, American Geophysical Union. San Francisco, CA. Status = PUBLISHED; Acknowledgement of Federal Support = Yes

- Hill, L.Z., Kaye, J.P., and Brantley, S.L. (2016). *Soil CO2 and O2 concentrations in shale and sandstone catchments of central Pennsylania*. 2016 Fall Meeting, American Geophysical Union. San Francisco, CA. Status = PUBLISHED; Acknowledgement of Federal Support = Yes
- Del Vecchio, J., Martin, C., Mount, G.J., Hayes, J., Comas, X., and DiBiase, R. (2016). *Surface and Subsurface Characteristics of Periglacial Landscape Modification in Central Pennsylvania*. 2016 Geological Society of America Fall Meeting. Denver, CO. Status = PUBLISHED; Acknowledgement of Federal Support = Yes
- Dykhoff, S., Williams, J., Brazil, L., Pollack, J., Brantley, S. (2016). *TeenShale Network: Combining Hands-on Field Experience with Data-Driven Hydrology Education Tools*. 2016 CUAHSI Biennial Symposium. Shepherdstown, WV. Status = PUBLISHED; Acknowledgement of Federal Support = Yes
- Duggan-Haas, D., Smith, L., White, T., Ross, R.M., and Derry, L.A. (2016). *The Shale Hills Critical Zone Observatory Virtual Fieldwork Experience: Using Virtual Fieldwork to Catalyze Actual Field Work in K-16 Classes (Invited)*. 2016 Geological Society of America Fall Meeting. Denver, CO. Status = PUBLISHED; Acknowledgement of Federal Support = Yes
- Guo, L and Lin, H. (2016). *Three Principles of Water Flow in Soils*. 2016 Fall Meeting, American Geophysical Union. San Francisco, CA. Status = PUBLISHED; Acknowledgement of Federal Support = Yes
- Orr A, Adams TS, Eissenstat DM, Kaye JP (2016). *Topographic Controls on Belowground Carbon Allocation in a Small, Temperate Watershed*. Ecological Society of American Annual Meeting. Ft. Lauderdale, FL., 7-12 August. Status = PUBLISHED; Acknowledgement of Federal Support = Yes
- Li, L., Bao, C., Shi, Y., Duffy, C., and Brantley, S.L. (2016). *Understanding Hydrogeochemical Processes at the Watershed Scale Using RT-Flux-PIHM*. 2016 Fall Meeting, American Geophysical Union. San Francisco, CA. Status = PUBLISHED; Acknowledgement of Federal Support = Yes
- Xiao, D., Shi, Y., and Li, L. (2016). *Understanding controls of hydrologic processes across two monolithological catchments using model-data integration*. 2016 Fall Meeting, American Geophysical Union. San Francisco, CA. Status = PUBLISHED; Acknowledgement of Federal Support = Yes
- Jin, L., Ortiz, A., Ogrinc, N., Kaye, J., Ma, L., Hasenmueller, E.A., Sullivan, P.L., and Brantley, S.L. (2017). *Understanding inorganic carbon dynamics in natural and human-impacted critical zones*. American Chemical Society 253rd annual meeting San Francisco, CA.. San Francisco, CA.. Status = PUBLISHED; Acknowledgement of Federal Support = Yes
- Duffy, C., Thomas, E., Bhatt, G., Holmes, G., Boyer, E.W., and Sullivan, P. (2016). *Using Isotopic Age of Water as a Constraint on Model Identification at the Critical Zone Observatory (Invited)*. 2016 Fall Meeting, American Geophysical Union. San Francisco, CA. Status = PUBLISHED; Acknowledgement of Federal Support = Yes

- Brantley, S.L., Wendt, A., and Sowers, T.A. (2016). *Using Stream Chemistry Measurements by Scientists and Nonscientists to Assess Leakage from Oil and Gas Wells in Pennsylvania*. 2016 Fall Meeting, American Geophysical Union. San Francisco, CA. Status = PUBLISHED; Acknowledgement of Federal Support = Yes
- Shi, Y., Eissenstat, D.M., Davis, K.J., and He, Y. (2016). *Using a spatially-distributed hydrologic biogeochemistry model to study the spatial variation of carbon processes in a Critical Zone Observatory*. 2016 Fall Meeting, American Geophysical Union. San Francisco, CA. Status = PUBLISHED; Acknowledgement of Federal Support = Yes
- Brubaker, Kristen M. (2016). *Using leaf-on and leaf-off airborne LiDAR to model vegetation structure and above-ground carbon storage in the critical zone*. ForestSAT 2016: a bridge between forest sciences, remote sensing and geo-spatial applications. Santiago, Chile, November 17 2016. Status = PUBLISHED; Acknowledgement of Federal Support = Yes

Other Products

- *Educational aids or Curricula.*

  Online course PNG 550: Reactive Transport in the Subsurface

  ### Overview

  This course targets graduate students from various disciplines that work with chemical and physical processes in natural subsurface. This includes, for example, petroleum and natural gas engineering, geosciences, environmental engineering, agricultural engineering, civil engineering, chemical engineering, and applied mathematics. The course teaches fundamental concepts that are important in understanding subsurface reactive transport processes, as well as their quantitative representation and application. Covered topics include, for example, (bio)geochemical thermodynamics and kinetics, contaminant transport, and reactive transport coupling. Depending on the students' interests, the course will discuss the applications of the principles in understanding and quantifying chemical weathering processes, environmental (bio)remediation, geological carbon sequestration, and reservoir souring.

  The course will be taught through a combination of lectures that discuss general principles and reactive transport equations, and exercises with a series of example files. The students will learn to set up models, as well as to visualize and interpret the modeling output. The example files will be tailored to the students' interests every year.

  ### Learning Outcomes

  1. Understand the mathematical representation of various types of (bio)geochemical reactions;
  2. Understand general principles governing the coupling among reactions, flow, and transport processes;
  3. Understand the importance of different processes under different conditions;

4. Develop computational skills to simulate coupled flow, transport, and reactions using a reactive transport modeling code (for example, CrunchFlow);
5. Develop the ability to communicate and collaborate within interdisciplinary teams.

Learning Environment

This website provides the primary instructional materials for the course. The menu on the top of the page links you to course orientation, syllabus, lessons, Canvas system, and other supporting materials. Canvas - Penn State's course management system, is used to support the delivery of this course as well as it provides the primary communications, calendaring, discussion, and submission tools for the course.

Other Publications

Patents

Technologies or Techniques

- Data Manager/Cyberspecialist continued to import CZO data into locally-hosted MS SQL Server database, linked to local CZO data portal web site (http://www.czo.psu.edu/data_overview.html). Instrument map on this site was maintained, including adding new instrumentation and data collection sites. The addition of an agricultural sampling site is currently underway. PHP scripts were written to download data via web from this database (e.g., http://www.czo.psu.edu/data_surfflux.html).

  Data Manager/Cyberspecialist has uploaded a number of new and/or updated datasets of the following: Land/Atmosphere Fluxes, Soil Gas and Porewater Concentrations, Discharge, Stage, and Water Chemistry, Surface and Groundwater Chemistry, Precipitation and other Meteorology, Ground Penetrating Radar, Colloidal Suspensions, Vegetation (Shrub) Transects, Soil Moisture, Soil Temperature, Soil Electrical Conductivity, Soil Dielectric, Soil Respiration. These new datasets and pre-existing ones are accessible via http://criticalzone.org/shale-hills/data/datasets and http://www.czo.psu.edu/data_overview.html. Time series and other datasets have been imported into locally-hosted SQL Server database, and access pages (e.g.,http://www.czo.psu.edu/data_surfflux.html) created.

  Data Manager/Cyberspecialist continued to populate and maintain locally-hosted MS SQL Server database for storage and archiving of local CZO data. Currently there is approximately 206 Gigabytes of data in the database amongst over 100 data tables. It is assumed this database will be maintained beyond the project.

Thesis/Dissertations

- Del Vecchio, J.. *A record of coupled hillslope and channel response to Pleistocene periglacial erosion in a sandstone headwater valley, central Pennsylvania*. (2017). The Pennsylvania State University. Acknowledgement of Federal Support = Yes
- Arvy Adira. *Assessing the Subsurface Geology of Garner Run Through the Relationship Between Seismic Velocity and Layer Density (Senior Thesis, Geosciences)*. (2015). The Pennsylvania State University. Acknowledgement of Federal Support = No
- Denn, A.. *DETECTING LANDSCAPE RESPONSE TO PERTURBATIONS BY CLIMATE AND BASE LEVEL IN CENTRAL PENNSYLVANIA USING IN-SITU 10Be AND 26Al*. (2017). The University of Vermont. Acknowledgement of Federal Support = Yes
- Molly R Cain. *Elucidating the Effects of Reservoir Filling on Watershed Hydrodynamics and Shallow Groundwater Chemistry in a Previously Impounded Lake (Senior Thesis, Geosciences)*. (2015). The Pennsylvania State University. Acknowledgement of Federal Support = Yes
- Katie P. Gaines. *FOREST ECOHYDROLOGY IN A CENTRAL PENNSYLVANIA CATCHMENT: A STABLE ISOTOPE APPROACH (PhD Dissertation, Ecology)*. (2015). The Pennsylvania State University. Acknowledgement of Federal Support = Yes
- Zhang, Y. *FULLY-COUPLED HYDROLOGICAL AND MORPHOLOGICAL PROCESSES FOR MODELING LANDSCAPE EVOLUTION*. (2016). The Pennsylvania State University. Acknowledgement of Federal Support = Yes
- Matthew Kenney. *Isotopic data sonification: Shale Hills Critical Zone Observatory (Master of Fine Arts, Arts and Architecture)*. (2015). The Pennsylvania State University. Acknowledgement of Federal Support = Yes
- Hill, L.Z.. *Lithological controls on soil properties of temperate forest ecosystems in central Pennsylvania*. (2017). The Pennsylvania State University. Acknowledgement of Federal Support = Yes
- Eric Wang. *Seismic Refraction for Subsurface Analysis of Garner Run (Senior Thesis, Geosciences)*. (2015). The Pennsylvania State University. Acknowledgement of Federal Support = No
- Sara Macdonald. *Thick soil formation on Orthoquartzite since the Wisconsinan in Huntingdon County (Senior Thesis, Geosciences)*. (2015). The Pennsylvania State University. Acknowledgement of Federal Support = Yes
- Bao, Chen. *UNDERSTANDING HYDROLOGICAL AND GEOCHEMICAL CONTROLS ON SOLUTE CONCENTRATIONS AT LARGE SCALE*. (2016). The Pennsylvania State University. Acknowledgement of Federal Support = Yes
- Weitzman, Julie. *VARIATION IN SOIL NITROGEN RETENTION ACROSS LAND USES, LANDSCAPES, AND LANDFORMS IN CENTRAL PENNSYLVANIA*. (2016). The Pennsylvania State University. Acknowledgement of Federal Support = Yes

Websites

- *Susquehanna Shale Hills CZO*
  http://www.czo.psu.edu/data_overview.html

CZO datasets are a powerful resource for developing and testing Earth system models. CZOs produce a large volume of data from a wide range of physical, chemical, and biological disciplines as well as spatial and temporal scales. This "flood" of disparate observational data partly reflects a new generation of integrated measurements. For example, most CZOs are using LIDAR imagery, copious isotopic samples, and low-cost sensors; others are also using eddy correlation and embedded sensor networks.

This research site, the focus of National Science Foundation-supported research since the 1970s, has comprehensive datasets on distributed water budgets (1970-75), has served as a model test bed for hydrological response (1998-present), and is augmented here by new geochemical, geomorphological, ecological, lidar, and soils datasets, all available to the research community.

- *Susquehanna Shale Hills Critical Zone Observatory*
  http://criticalzone.org/shale-hills/

  Our website presence within the Critical Zone Observatory Network, delivers to the public our research emphasis and project design, observations, team members, manuscripts and conference presentations, as well as our activities and events.

Supporting Files

	Filename	Description	Uploaded By	Uploaded On
(Download)	EarthChemSubmissions_20170613.pdf	Listing of datasets registered with DOIs and available for discovery in the EarthChem Library	Susan Brantley	06/15/2017
(Download)	CZO Management Plan_2016-17_submitted.pdf	Updated Management Plan	Susan Brantley	06/16/2017

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Participants/Organizations

What individuals have worked on the project?

Name	Most Senior Project Role	Nearest Person Month Worked
Brantley, Susan	PD/PI	1
Davis, Kenneth	Co PD/PI	1
Eissenstat, David	Co PD/PI	1
Li, Li	Co PD/PI	1
Russo, Tess	Co PD/PI	1

Name	Most Senior Project Role	Nearest Person Month Worked
Bern, Carleton	Co-Investigator	1
Bierman, Paul	Co-Investigator	1
Brubaker, Kristen	Co-Investigator	1
Comas, Xavier	Co-Investigator	0
Dere, Ashlee	Co-Investigator	1
DiBiase, Roman	Co-Investigator	1
Gaines, Katie	Co-Investigator	0
Hasenmueller, Elizabeth	Co-Investigator	0
Hayes, Jorden	Co-Investigator	0
Karwan, Diana	Co-Investigator	0
Kaye, Jason	Co-Investigator	1
Kaye, Margot	Co-Investigator	0
Keating, Kristina	Co-Investigator	0
Kirby, Eric	Co-Investigator	0
Lin, Henry	Co-Investigator	1
Liu, Wenjing	Co-Investigator	0
Long, Robert	Co-Investigator	0
Mount, Greg	Co-Investigator	1
Nyquist, Jon	Co-Investigator	0
Perdrial, Julia	Co-Investigator	0
Pett Ridge, Julie	Co-Investigator	0
Richter, Dan	Co-Investigator	0
Singha, Kamini	Co-Investigator	0
Slater, Lee	Co-Investigator	0
Stottlemyer, Aaron	Co-Investigator	0
Sullivan, Pamela	Co-Investigator	0
West, Nicole	Co-Investigator	1
Donnelly, Siobhan	K-12 Teacher	0
Dykhoff, Sharon	K-12 Teacher	0
Smith, Lauren	K-12 Teacher	0
Clarke, Brian	Postdoctoral (scholar, fellow or other postdoctoral position)	0
Guo, Li	Postdoctoral (scholar, fellow or other postdoctoral position)	3
Adams, Tom	Technician	0
Neal, Andrew	Staff Scientist (doctoral level)	0

Name	Most Senior Project Role	Nearest Person Month Worked
Shi, Yuning	Staff Scientist (doctoral level)	3
Bao, Chen	Graduate Student (research assistant)	0
Chen, Weile	Graduate Student (research assistant)	1
Del Vecchio, Joanmarie	Graduate Student (research assistant)	6
Denn, Alison	Graduate Student (research assistant)	6
Douglas, Baldwin	Graduate Student (research assistant)	0
Gu, Xin	Graduate Student (research assistant)	1
He, Yuting	Graduate Student (research assistant)	6
Heidari, Peyman	Graduate Student (research assistant)	1
Hill, Lillian	Graduate Student (research assistant)	3
Hoagland, Beth	Graduate Student (research assistant)	6
Hopkins, Isaac	Graduate Student (research assistant)	0
Iavorivska, Lidiia	Graduate Student (research assistant)	0
Jiang, Fei	Graduate Student (research assistant)	0
King, Elizabeth	Graduate Student (research assistant)	1
Orr, Alexandra	Graduate Student (research assistant)	1
Osterman, Gordon	Graduate Student (research assistant)	1
Reed, Warren	Graduate Student (research assistant)	3
Szink, Ismaiel	Graduate Student (research assistant)	6
Wade, Anna	Graduate Student (research assistant)	0
Weitzman, Julie	Graduate Student (research assistant)	1
Wu, Yuan	Graduate Student (research assistant)	1
Xiao, Dacheng	Graduate Student (research assistant)	6
Xu, Neil	Graduate Student (research assistant)	0
Zarif, Fardous	Graduate Student (research assistant)	1
Zhang, Yu	Graduate Student (research assistant)	0
Arthur, Dan	Non-Student Research Assistant	0
Brazil, Liza	Non-Student Research Assistant	0
Forsythe, Brandon	Non-Student Research Assistant	12
Harper, Jeremy	Non-Student Research Assistant	1
Williams, Jennifer	Non-Student Research Assistant	12
Duggan, Patrick	Undergraduate Student	1
Forgeng, Michael	Undergraduate Student	1
Pecce, Julian	Undergraduate Student	1
Seidel, Aaron	Undergraduate Student	1

Name	Most Senior Project Role	Nearest Person Month Worked
Potter, Joshua	Consultant	1
Bicknell, Kelsey	Research Experience for Undergraduates (REU) Participant	0
Blackman, Taylor	Research Experience for Undergraduates (REU) Participant	0
Christhilf, Jennifer	Research Experience for Undergraduates (REU) Participant	0
Grankee, Sarah	Research Experience for Undergraduates (REU) Participant	0
Heyer, Bryan	Research Experience for Undergraduates (REU) Participant	0
Lad, Uma	Research Experience for Undergraduates (REU) Participant	0
Martin, Conner	Research Experience for Undergraduates (REU) Participant	0
Redmon, Meagan	Research Experience for Undergraduates (REU) Participant	0
Ruppel, Margaret	Research Experience for Undergraduates (REU) Participant	0
Ryan, Sophie	Research Experience for Undergraduates (REU) Participant	0
Schwyter, Anna	Research Experience for Undergraduates (REU) Participant	0
Shaw, Meaghan	Research Experience for Undergraduates (REU) Participant	0
Silverhart, Perri	Research Experience for Undergraduates (REU) Participant	0
Wahab, Leila	Research Experience for Undergraduates (REU) Participant	0

Full details of individuals who have worked on the project:

Susan L Brantley
Email: brantley@essc.psu.edu
Most Senior Project Role: PD/PI
Nearest Person Month Worked: 1

Contribution to the Project: Supervises the project

Funding Support: receives salary on the project

International Collaboration: No
International Travel: No

Kenneth J Davis
Email: kjd10@psu.edu
Most Senior Project Role: Co PD/PI
Nearest Person Month Worked: 1

Contribution to the Project: supervises eddy co-variance aspects of project; sits on steering committee

Funding Support: n/a

International Collaboration: No
International Travel: No

David M Eissenstat
Email: dme9@psu.edu
Most Senior Project Role: Co PD/PI
Nearest Person Month Worked: 1

Contribution to the Project: supervises tree research, sits on steering committee

Funding Support: Penn State and this award

International Collaboration: No
International Travel: No

Li Li
Email: lili@engr.psu.edu
Most Senior Project Role: Co PD/PI
Nearest Person Month Worked: 1

Contribution to the Project: supervises reactive transport modelling

Funding Support: Penn State and this award

International Collaboration: No
International Travel: No

Tess A Russo
Email: russo@psu.edu
Most Senior Project Role: Co PD/PI
Nearest Person Month Worked: 1

Contribution to the Project: supervises hydrologic synthesis, sits on steering committee

Funding Support: Penn State and this award

International Collaboration: No
International Travel: No

Carleton Bern
Email: cbern@usgs.gov
Most Senior Project Role: Co-Investigator
Nearest Person Month Worked: 1

Contribution to the Project: Advancing the understanding of colloidal transport

Funding Support: USGS

International Collaboration: No
International Travel: No

Paul Bierman
Email: pbierman@uvm.edu
Most Senior Project Role: Co-Investigator
Nearest Person Month Worked: 1

Contribution to the Project: Geomorphologist/Geochemist - works on Hypothesis 1

Funding Support: University of Vermont and NSF

International Collaboration: No
International Travel: No

Kristen Brubaker
Email: brubaker@hws.edu
Most Senior Project Role: Co-Investigator
Nearest Person Month Worked: 1

Contribution to the Project: Contributes to H3

Funding Support: Hobart & William Smith Colleges

International Collaboration: No
International Travel: No

Xavier Comas
Email: xcomas@fau.edu
Most Senior Project Role: Co-Investigator
Nearest Person Month Worked: 0

Contribution to the Project: Hydrogeophysics Specialist

Funding Support: NSF

International Collaboration: No
International Travel: No

Ashlee Dere
Email: ald271@psu.edu
Most Senior Project Role: Co-Investigator
Nearest Person Month Worked: 1

Contribution to the Project: shale weathering along transect sites

Funding Support: University of Nebraska, Omaha

International Collaboration: No
International Travel: No

Roman DiBiase
Email: rad22@psu.edu
Most Senior Project Role: Co-Investigator
Nearest Person Month Worked: 1

Contribution to the Project: Coordinator of geomorphological soils analysis

Funding Support: Penn State and NSF

International Collaboration: No
International Travel: No

Katie Gaines
Email: kpgaines@psu.edu
Most Senior Project Role: Co-Investigator
Nearest Person Month Worked: 0

Contribution to the Project: works on tree physiology

Funding Support: CZO

International Collaboration: No
International Travel: No

Elizabeth Hasenmueller
Email: hasenmuellerea@slu.edu
Most Senior Project Role: Co-Investigator
Nearest Person Month Worked: 0

Contribution to the Project: Hydrochemist - works on Hypothesis 2

Funding Support: St. Louis University

International Collaboration: No
International Travel: No

Jorden Hayes
Email: hayesjo@dickinson.edu
Most Senior Project Role: Co-Investigator
Nearest Person Month Worked: 0

Contribution to the Project: New member of advisory board, hydrogeophysics specialist

Funding Support: Dickinson College

International Collaboration: No
International Travel: No

Diana Karwan
Email: dlkarwan@umn.edu
Most Senior Project Role: Co-Investigator
Nearest Person Month Worked: 0

Contribution to the Project: Cross-CZO Investigator

Funding Support: NSF

International Collaboration: No
International Travel: No

Jason Kaye
Email: jpk12@psu.edu
Most Senior Project Role: Co-Investigator
Nearest Person Month Worked: 1

Contribution to the Project: Soil Biogeochemist - works on Hypotheses 2, 3, 5, and 6

Funding Support: Penn State and NSF

International Collaboration: No
International Travel: No

Margot Kaye
Email: mwk12@psu.edu
Most Senior Project Role: Co-Investigator
Nearest Person Month Worked: 0

Contribution to the Project: Contributes to H3

Funding Support: Penn State

International Collaboration: No
International Travel: No

Kristina Keating
Email: kmkeat@andromeda.rutgers.edu
Most Senior Project Role: Co-Investigator
Nearest Person Month Worked: 0

Contribution to the Project: Contributing collaborator, hydrogeophysics field workshop

Funding Support: Rutgers

International Collaboration: No
International Travel: No

Eric Kirby
Email: eric.kirby@geo.oregonstate.edu
Most Senior Project Role: Co-Investigator
Nearest Person Month Worked: 0

Contribution to the Project: Geomorphologist - works on Hypothesis 1

Funding Support: Oregon State University

International Collaboration: No
International Travel: No

Henry Lin
Email: hul3@psu.edu
Most Senior Project Role: Co-Investigator
Nearest Person Month Worked: 1

Contribution to the Project: Hydorpedologist - works on Hypotheses 1, 4, 7, and 8

Funding Support: Penn State and NSF

International Collaboration: No
International Travel: No

Wenjing Liu
Email: wul26@psu.edu
Most Senior Project Role: Co-Investigator
Nearest Person Month Worked: 0

Contribution to the Project: collaborative investigator

Funding Support: Chinese Academy of Sciences

International Collaboration: No
International Travel: No

Robert Long
Email: rlong@fs.fed.us
Most Senior Project Role: Co-Investigator
Nearest Person Month Worked: 0

Contribution to the Project: collaborating investigator

Funding Support: US Forest Service

International Collaboration: No
International Travel: No

Greg Mount
Email: Gregory.Mount@iup.edu
Most Senior Project Role: Co-Investigator
Nearest Person Month Worked: 1

Contribution to the Project: Hydrogeophysical specialist, collaborator

Funding Support: IUP

International Collaboration: No
International Travel: No

Jon Nyquist
Email: nyq@temple.edu
Most Senior Project Role: Co-Investigator
Nearest Person Month Worked: 0

Contribution to the Project: collaborating investigator

Funding Support: Temple

International Collaboration: No
International Travel: No

Julia Perdrial
Email: Julia.Perdrial@uvm.edu
Most Senior Project Role: Co-Investigator
Nearest Person Month Worked: 0

Contribution to the Project: contributing collaborator

Funding Support: University of Vermont

International Collaboration: No
International Travel: No

Julie Pett Ridge
Email: julie.pett-ridge@oregonstate.edu
Most Senior Project Role: Co-Investigator
Nearest Person Month Worked: 0

Contribution to the Project: Contributing collaborator

Funding Support: Oregon State

International Collaboration: No
International Travel: No

Dan Richter
Email: drichter@duke.edu
Most Senior Project Role: Co-Investigator
Nearest Person Month Worked: 0

Contribution to the Project: contributing collaborator

Funding Support: Duke

International Collaboration: No
International Travel: No

Kamini Singha
Email: ksingha@mines.edu
Most Senior Project Role: Co-Investigator
Nearest Person Month Worked: 0

Contribution to the Project: Hydrogeologist - works on Hypothesis 1

Funding Support: Colorado School of Mines

International Collaboration: No
International Travel: No

Lee Slater
Email: lslater@andromeda.rutgers.edu
Most Senior Project Role: Co-Investigator
Nearest Person Month Worked: 0

Contribution to the Project: Collaborative investigator

Funding Support: Rutgers University

International Collaboration: No
International Travel: No

Aaron Stottlemyer
Email: ads175@psu.edu
Most Senior Project Role: Co-Investigator
Nearest Person Month Worked: 0

Contribution to the Project: collaborative investigations

Funding Support: Penn State

International Collaboration: No
International Travel: No

Pamela Sullivan
Email: pls21@psu.edu
Most Senior Project Role: Co-Investigator
Nearest Person Month Worked: 0

Contribution to the Project: Hydrochemist - works on Hypotheses 6 and 9

Funding Support: The University of Kansas

International Collaboration: No
International Travel: No

Nicole West
Email: nxw157@psu.edu
Most Senior Project Role: Co-Investigator
Nearest Person Month Worked: 1

Contribution to the Project: geomorphologist - works on Hypothesis 1

Funding Support: Central Michigan University

International Collaboration: No
International Travel: No

Siobhan Donnelly
Email: siobhan@clccharter.org
Most Senior Project Role: K-12 Teacher
Nearest Person Month Worked: 0

Contribution to the Project: Contributed to H3

Funding Support: NSF and CLC Charter School

International Collaboration: No
International Travel: No

Sharon Dykhoff
Email: srd224@psu.edu
Most Senior Project Role: K-12 Teacher
Nearest Person Month Worked: 0

Contribution to the Project: Contributed to H9

Funding Support: NSF and Dominion Christian School

International Collaboration: No
International Travel: No

Lauren Smith
Email: smith.lauren1030@gmail.com
Most Senior Project Role: K-12 Teacher
Nearest Person Month Worked: 0

Contribution to the Project: CZO National Office

Funding Support: REU/RET for CZO from NSF

International Collaboration: No
International Travel: No

Brian Clarke
Email: bac43@psu.edu
Most Senior Project Role: Postdoctoral (scholar, fellow or other postdoctoral position)
Nearest Person Month Worked: 0

Contribution to the Project: Geomorphologist - worked on Hypothesis 1

Funding Support: unknown

International Collaboration: No
International Travel: No

Li Guo
Email: lug163@psu.edu
Most Senior Project Role: Postdoctoral (scholar, fellow or other postdoctoral position)
Nearest Person Month Worked: 3

Contribution to the Project: Contributes to H4

Funding Support: NSF

International Collaboration: No
International Travel: No

Tom Adams
Email: tsa3@psu.edu
Most Senior Project Role: Technician
Nearest Person Month Worked: 0

Contribution to the Project: Contributes to H3

Funding Support: Penn State and DOE

International Collaboration: No
International Travel: No

Andrew Neal
Email: aln16@psu.edu
Most Senior Project Role: Staff Scientist (doctoral level)
Nearest Person Month Worked: 0

Contribution to the Project: Watershed Specialist

Funding Support: unknown

International Collaboration: No
International Travel: No

Yuning Shi
Email: yshi@psu.edu
Most Senior Project Role: Staff Scientist (doctoral level)
Nearest Person Month Worked: 3

Contribution to the Project: Hydrologist - works on Hypothesis 7 and 8

Funding Support: CZO, Lehigh University

International Collaboration: No
International Travel: No

Chen Bao
Email: cub200@psu.edu
Most Senior Project Role: Graduate Student (research assistant)
Nearest Person Month Worked: 0

Contribution to the Project: works on Hypothesis 5

Funding Support: unknown

International Collaboration: No
International Travel: No

Weile Chen
Email: wuc139@psu.edu
Most Senior Project Role: Graduate Student (research assistant)
Nearest Person Month Worked: 1

Contribution to the Project: collaborative research

Funding Support: DOE

International Collaboration: No
International Travel: No

Joanmarie Del Vecchio
Email: jzd5570@psu.edu
Most Senior Project Role: Graduate Student (research assistant)
Nearest Person Month Worked: 6

Contribution to the Project: MS student in geomorphology working on H1

Funding Support: CZO

International Collaboration: No
International Travel: No

Alison Denn
Email: adenn@uvm.edu
Most Senior Project Role: Graduate Student (research assistant)
Nearest Person Month Worked: 6

Contribution to the Project: contributing to H1

Funding Support: CZO

International Collaboration: No
International Travel: No

Baldwin Douglas
Email: dcb5006@psu.edu
Most Senior Project Role: Graduate Student (research assistant)
Nearest Person Month Worked: 0

Contribution to the Project: collaborative investigations

Funding Support: Penn State

International Collaboration: No
International Travel: No

Xin Gu
Email: xug102@psu.edu
Most Senior Project Role: Graduate Student (research assistant)
Nearest Person Month Worked: 1

Contribution to the Project: collaborative research

Funding Support: Penn State

International Collaboration: No
International Travel: No

Yuting He
Email: yzh120@psu.edu
Most Senior Project Role: Graduate Student (research assistant)
Nearest Person Month Worked: 6

Contribution to the Project: works on PIHM and Biome-BGC

Funding Support: CZO

International Collaboration: No
International Travel: No

Peyman Heidari
Email: heidarip@mst.edu
Most Senior Project Role: Graduate Student (research assistant)
Nearest Person Month Worked: 1

Contribution to the Project: collaborator on reactive transport modeling

Funding Support: Missouri University of Science and Technology

International Collaboration: No
International Travel: No

Lillian Hill
Email: lzh157@psu.edu
Most Senior Project Role: Graduate Student (research assistant)
Nearest Person Month Worked: 3

Contribution to the Project: contributing to H2

Funding Support: CZO

International Collaboration: No
International Travel: No

Beth Hoagland
Email: neh137@psu.edu
Most Senior Project Role: Graduate Student (research assistant)
Nearest Person Month Worked: 6

Contribution to the Project: contributing to H6

Funding Support: CZO

International Collaboration: No
International Travel: No

Isaac Hopkins
Email: ieh105@psu.edu
Most Senior Project Role: Graduate Student (research assistant)
Nearest Person Month Worked: 0

Contribution to the Project: works on Hypothesis 4

Funding Support: unknown

International Collaboration: No
International Travel: No

Lidiia Iavorivska
Email: lui100@psu.edu
Most Senior Project Role: Graduate Student (research assistant)
Nearest Person Month Worked: 0

Contribution to the Project: collaborative research

Funding Support: Penn State

International Collaboration: No
International Travel: No

Fei Jiang
Email: ffj5012@psu.edu
Most Senior Project Role: Graduate Student (research assistant)
Nearest Person Month Worked: 0

Contribution to the Project: collaborative research

Funding Support: Penn State

International Collaboration: No
International Travel: No

Elizabeth King
Email: eking@coas.oregonstate.edu
Most Senior Project Role: Graduate Student (research assistant)
Nearest Person Month Worked: 1

Contribution to the Project: Contributing collaborator

Funding Support: Oregon State

International Collaboration: No
International Travel: No

Alexandra Orr
Email: aso124@psu.edu
Most Senior Project Role: Graduate Student (research assistant)
Nearest Person Month Worked: 1

Contribution to the Project: collaborative investigations

Funding Support: Penn State

International Collaboration: No
International Travel: No

Gordon Osterman
Email: gko4@rutgers.edu
Most Senior Project Role: Graduate Student (research assistant)
Nearest Person Month Worked: 1

Contribution to the Project: groundwater geophysics

Funding Support: Rutgers

International Collaboration: No
International Travel: No

Warren Reed
Email: wpr5005@psu.edu
Most Senior Project Role: Graduate Student (research assistant)
Nearest Person Month Worked: 3

Contribution to the Project: Contributes to H3

Funding Support: Penn State

International Collaboration: No
International Travel: No

Ismaiel Szink
Email: ips5062@PSU.EDU
Most Senior Project Role: Graduate Student (research assistant)
Nearest Person Month Worked: 6

Contribution to the Project: Contributes to H3

Funding Support: Penn State and NSF

International Collaboration: No
International Travel: No

Anna Wade
Email: anna.wade@duke.edu
Most Senior Project Role: Graduate Student (research assistant)
Nearest Person Month Worked: 0

Contribution to the Project: collaborating student working with postdoc to learn hydrology sampling techniques in the CZO.

Funding Support: Duke University

International Collaboration: No
International Travel: No

Julie Weitzman
Email: jnw142@psu.edu
Most Senior Project Role: Graduate Student (research assistant)
Nearest Person Month Worked: 1

Contribution to the Project: works on Hypothesis 2

Funding Support: CZO and NSF

International Collaboration: No
International Travel: No

Yuan Wu
Email: yxw5312@psu.edu
Most Senior Project Role: Graduate Student (research assistant)
Nearest Person Month Worked: 1

Contribution to the Project: Contributes to H4

Funding Support: Penn State and NSF

International Collaboration: No
International Travel: No

Dacheng Xiao
Email: dzx102@psu.edu
Most Senior Project Role: Graduate Student (research assistant)
Nearest Person Month Worked: 6

Contribution to the Project: contributing to H8

Funding Support: CZO

International Collaboration: No
International Travel: No

Neil Xu
Email: hxx5055@psu.edu
Most Senior Project Role: Graduate Student (research assistant)
Nearest Person Month Worked: 0

Contribution to the Project: Contributes to H4

Funding Support: Penn State

International Collaboration: No
International Travel: No

Fardous Zarif
Email: fardous zarif
Most Senior Project Role: Graduate Student (research assistant)
Nearest Person Month Worked: 1

Contribution to the Project: collaborator on geophysical methods, specifically electrical resistivity surveys

Funding Support: Rutgers University

International Collaboration: No
International Travel: No

Yu Zhang
Email: yzz130@psu.edu
Most Senior Project Role: Graduate Student (research assistant)
Nearest Person Month Worked: 0

Contribution to the Project: works on PIHM-sed

Funding Support: CZO, Duke University

International Collaboration: No
International Travel: No

Dan Arthur
Email: dka12@psu.edu
Most Senior Project Role: Non-Student Research Assistant
Nearest Person Month Worked: 0

Contribution to the Project: Data Manager / Cyberspecialist

Funding Support: CZO, USDA Pasture Laboratory

International Collaboration: No
International Travel: No

Liza I Brazil
Email: lib5105@psu.edu
Most Senior Project Role: Non-Student Research Assistant
Nearest Person Month Worked: 0

Contribution to the Project: Contributed to H3

Funding Support: CUSHSI

International Collaboration: No
International Travel: No

Brandon Forsythe
Email: brf11@psu.edu
Most Senior Project Role: Non-Student Research Assistant
Nearest Person Month Worked: 12

Contribution to the Project: watershed coordinator

Funding Support: CZO

International Collaboration: No
International Travel: No

Jeremy Harper
Email: jph217@psu.edu
Most Senior Project Role: Non-Student Research Assistant
Nearest Person Month Worked: 1

Contribution to the Project: field assistant

Funding Support: CZO

International Collaboration: No
International Travel: No

Jennifer Williams
Email: jzw126@psu.edu
Most Senior Project Role: Non-Student Research Assistant
Nearest Person Month Worked: 12

Contribution to the Project: Program, Outreach, and Sample Coordinator

Funding Support: CZO

International Collaboration: No
International Travel: No

Patrick Duggan
Email: pcd5063@psu.edu
Most Senior Project Role: Undergraduate Student
Nearest Person Month Worked: 1

Contribution to the Project: Contribute to H6

Funding Support: Unknown

International Collaboration: No
International Travel: No

Michael Forgeng
Email: mjf5807@psu.edu
Most Senior Project Role: Undergraduate Student
Nearest Person Month Worked: 1

Contribution to the Project: undergraduate field assistant

Funding Support: CZO

International Collaboration: No
International Travel: No

Julian Pecce
Email: jzp5336@psu.edu
Most Senior Project Role: Undergraduate Student
Nearest Person Month Worked: 1

Contribution to the Project: Contributes to H4

Funding Support: NSF and Penn State

International Collaboration: No
International Travel: No

Aaron Seidel
Email: A.D.Seidel@iup.edu
Most Senior Project Role: Undergraduate Student
Nearest Person Month Worked: 1

Contribution to the Project: collaborating contributor

Funding Support: Indiana University of Pennsylvania

International Collaboration: No
International Travel: No

Joshua Potter
Email: jep189@psu.edu
Most Senior Project Role: Consultant
Nearest Person Month Worked: 1

Contribution to the Project: collaborative outreach

Funding Support: Penn State

International Collaboration: No
International Travel: No

Kelsey Bicknell
Email: kbicknell@unm.edu
Most Senior Project Role: Research Experience for Undergraduates (REU) Participant
Nearest Person Month Worked: 0

Contribution to the Project: Contributed to H6

Funding Support: NSF

International Collaboration: No
International Travel: No
Year of schooling completed: Sophomore
Home Institution: University of New Mexico
Government fiscal year(s) was this REU participant supported: 2015

Taylor Blackman
Email: tnb5149@psu.edu
Most Senior Project Role: Research Experience for Undergraduates (REU) Participant
Nearest Person Month Worked: 0

Contribution to the Project: worked with Tim White

Funding Support: REU/RET for CZO from NSF

International Collaboration: No
International Travel: No
Year of schooling completed: Junior
Home Institution: Penn State University
Government fiscal year(s) was this REU participant supported: 2016

Jennifer Christhilf
Email: jc18@umbc.edu
Most Senior Project Role: Research Experience for Undergraduates (REU) Participant
Nearest Person Month Worked: 0

Contribution to the Project: working on H3

Funding Support: REU/RET for CZO from NSF

International Collaboration: No
International Travel: No
Year of schooling completed: Sophomore
Home Institution: University of Maryland, Baltimore County
Government fiscal year(s) was this REU participant supported: 2016

Sarah Grankee
Email: sbg12013@mymail.pomona.edu
Most Senior Project Role: Research Experience for Undergraduates (REU) Participant
Nearest Person Month Worked: 0

Contribution to the Project: Contributed to H1

Funding Support: NSF

International Collaboration: No
International Travel: No
Year of schooling completed: Sophomore
Home Institution: Pomona College
Government fiscal year(s) was this REU participant supported: 2015

Bryan Heyer
Email: bheyer@usciences.edu
Most Senior Project Role: Research Experience for Undergraduates (REU) Participant
Nearest Person Month Worked: 0

Contribution to the Project: working on H6

Funding Support: REU/RET for CZO from NSF

International Collaboration: No
International Travel: No
Year of schooling completed: Sophomore
Home Institution: University of the Sciences in Philadelphia
Government fiscal year(s) was this REU participant supported: 2016

Uma Lad
Email: ulad@smu.edu
Most Senior Project Role: Research Experience for Undergraduates (REU) Participant
Nearest Person Month Worked: 0

Contribution to the Project: working on H9

Funding Support: REU/RET for CZO from NSF

International Collaboration: No
International Travel: No
Year of schooling completed: Junior
Home Institution: Southern Methodist University
Government fiscal year(s) was this REU participant supported: 2016

Conner Martin
Email: conmart95@gmail.com
Most Senior Project Role: Research Experience for Undergraduates (REU) Participant
Nearest Person Month Worked: 0

Contribution to the Project: worked on H1

Funding Support: REU/RET for CZO from NSF

International Collaboration: No
International Travel: No
Year of schooling completed: Junior
Home Institution: University of Pittsburgh
Government fiscal year(s) was this REU participant supported: 2016

Meagan Redmon
Email: redmonm16@hanover.edu
Most Senior Project Role: Research Experience for Undergraduates (REU) Participant
Nearest Person Month Worked: 0

Contribution to the Project: Contributed to H4

Funding Support: NSF

International Collaboration: No
International Travel: No
Year of schooling completed: Junior
Home Institution: Hanover College
Government fiscal year(s) was this REU participant supported: 2015

Margaret E. Ruppel
Email: ruppelm@wittenberg.edu
Most Senior Project Role: Research Experience for Undergraduates (REU) Participant
Nearest Person Month Worked: 0

Contribution to the Project: Contributed to H3

Funding Support: NSF

International Collaboration: No
International Travel: No
Year of schooling completed: Junior
Home Institution: Wittenberg University
Government fiscal year(s) was this REU participant supported: 2015

Sophie Ryan
Email: sophie.ryan@uvm.edu
Most Senior Project Role: Research Experience for Undergraduates (REU) Participant
Nearest Person Month Worked: 0

Contribution to the Project: worked on H6

Funding Support: REU/RET for CZO from NSF

International Collaboration: No
International Travel: No
Year of schooling completed: Sophomore
Home Institution: University of Vermont
Government fiscal year(s) was this REU participant supported: 2016

Anna Schwyter
Email: axs5408@psu.edu
Most Senior Project Role: Research Experience for Undergraduates (REU) Participant
Nearest Person Month Worked: 0

Contribution to the Project: Contributed to H4

Funding Support: NSF

International Collaboration: No
International Travel: No
Year of schooling completed: Junior

Home Institution: Penn State University
Government fiscal year(s) was this REU participant supported: 2015

Meaghan Shaw
Email: meshaw@smu.edu
Most Senior Project Role: Research Experience for Undergraduates (REU) Participant
Nearest Person Month Worked: 0

Contribution to the Project: Contributed to H6

Funding Support: NSF

International Collaboration: No
International Travel: No
Year of schooling completed: Junior
Home Institution: Southern Methodist University
Government fiscal year(s) was this REU participant supported: 2015

Perri Silverhart
Email: psilverhart@middlebury.edu
Most Senior Project Role: Research Experience for Undergraduates (REU) Participant
Nearest Person Month Worked: 0

Contribution to the Project: worked on H1

Funding Support: REU/RET for CZO from NSF

International Collaboration: No
International Travel: No
Year of schooling completed: Junior
Home Institution: Middlebury College
Government fiscal year(s) was this REU participant supported: 2016

Leila Wahab
Email: lmw8@rice.edu
Most Senior Project Role: Research Experience for Undergraduates (REU) Participant
Nearest Person Month Worked: 0

Contribution to the Project: worked on H6

Funding Support: REU/RET for CZO from NSF

International Collaboration: No
International Travel: No
Year of schooling completed: Sophomore
Home Institution: Rice University
Government fiscal year(s) was this REU participant supported: 2016

What other organizations have been involved as partners?

Name	Type of Partner Organization	Location
Beijing Normal University	Academic Institution	Beijing, China
Brown University	Academic Institution	Providence, RI
Missouri University of Science and Technology	Academic Institution	Rolla, MO
Ninxia University	Academic Institution	Ningxia, China
Oregon State University	Academic Institution	Corvallis, Oregon
Princeton University	Academic Institution	Princeton, NJ
Rutgers University	Academic Institution	New Brunswick, New Jersey
Saint Louis University	Academic Institution	Saint Louis, MO
State College Area School District	School or School Systems	State College, PA
Technical Univ. of Munich	Academic Institution	Munich, Germany
Temple University	Academic Institution	Philadelphia, PA
UMass-Amherst	Academic Institution	Amherst, MA
CTEMPS	Academic Institution	University of Nevada, Reno
USDA Forest Service	State or Local Government	Corvallis, OR.
USDA-NRCS-NSSC	State or Local Government	Newtown Square, PA
Univ of Kansas	Academic Institution	Lawrence, Kansas
University of Guelph, Canada	Academic Institution	Guelph, ON, Canada
University of Nebraska Omaha	Academic Institution	Omaha, NE
University of Texas @ El Paso	Academic Institution	El Paso, TX
University of Toulouse, France	Academic Institution	Toulouse, France
Chinese Academy of Sciences	Academic Institution	Beijing, China
Colgate University	Academic Institution	Hamilton, NY
Dickinson College	Academic Institution	Carlisle, Pennsylvania
Hollidaysburg Area High School	School or School Systems	Hollidaysburg, PA
Horbart & William Smith Colleges	Academic Institution	Geneva, New York
Indiana University of Pennsylvania	Academic Institution	Indiana, Pennsylvania
Kent State University	Academic Institution	Kent, Ohio

Full details of organizations that have been involved as partners:

Beijing Normal University

Organization Type: Academic Institution
Organization Location: Beijing, China

Partner's Contribution to the Project:
Collaborative Research

More Detail on Partner and Contribution:

Brown University

Organization Type: Academic Institution
Organization Location: Providence, RI

Partner's Contribution to the Project:
Collaborative Research

More Detail on Partner and Contribution:

CTEMPS

Organization Type: Academic Institution
Organization Location: University of Nevada, Reno

Partner's Contribution to the Project:
Facilities
Collaborative Research

More Detail on Partner and Contribution:

Chinese Academy of Sciences

Organization Type: Academic Institution
Organization Location: Beijing, China

Partner's Contribution to the Project:
Collaborative Research

More Detail on Partner and Contribution:

Colgate University

Organization Type: Academic Institution
Organization Location: Hamilton, NY

Partner's Contribution to the Project:
Collaborative Research

More Detail on Partner and Contribution:

Dickinson College

Organization Type: Academic Institution
Organization Location: Carlisle, Pennsylvania

Partner's Contribution to the Project:
Collaborative Research

More Detail on Partner and Contribution:

Hollidaysburg Area High School

Organization Type: School or School Systems
Organization Location: Hollidaysburg, PA

Partner's Contribution to the Project:
Collaborative Research

More Detail on Partner and Contribution:

Horbart & William Smith Colleges

Organization Type: Academic Institution
Organization Location: Geneva, New York

Partner's Contribution to the Project:
Collaborative Research

More Detail on Partner and Contribution:

Indiana University of Pennsylvania

Organization Type: Academic Institution
Organization Location: Indiana, Pennsylvania

Partner's Contribution to the Project:
Collaborative Research

More Detail on Partner and Contribution:

Kent State University

Organization Type: Academic Institution
Organization Location: Kent, Ohio

Partner's Contribution to the Project:
Collaborative Research

More Detail on Partner and Contribution:

Missouri University of Science and Technology

Organization Type: Academic Institution
Organization Location: Rolla, MO

Partner's Contribution to the Project:
Collaborative Research

More Detail on Partner and Contribution:

Ninxia University

Organization Type: Academic Institution
Organization Location: Ningxia, China

Partner's Contribution to the Project:
Collaborative Research

More Detail on Partner and Contribution:

Oregon State University

Organization Type: Academic Institution
Organization Location: Corvallis, Oregon

Partner's Contribution to the Project:
Collaborative Research

More Detail on Partner and Contribution:

Princeton University

Organization Type: Academic Institution
Organization Location: Princeton, NJ

Partner's Contribution to the Project:
Collaborative Research

More Detail on Partner and Contribution:

Rutgers University

Organization Type: Academic Institution
Organization Location: New Brunswick, New Jersey

Partner's Contribution to the Project:
Collaborative Research

More Detail on Partner and Contribution:

Saint Louis University

Organization Type: Academic Institution
Organization Location: Saint Louis, MO

Partner's Contribution to the Project:
Collaborative Research

More Detail on Partner and Contribution:

State College Area School District

Organization Type: School or School Systems
Organization Location: State College, PA

Partner's Contribution to the Project:
Collaborative Research

More Detail on Partner and Contribution:

Technical Univ. of Munich

Organization Type: Academic Institution
Organization Location: Munich, Germany

Partner's Contribution to the Project:
Collaborative Research

More Detail on Partner and Contribution:

Temple University

Organization Type: Academic Institution
Organization Location: Philadelphia, PA

Partner's Contribution to the Project:
Collaborative Research

More Detail on Partner and Contribution:

UMass-Amherst

Organization Type: Academic Institution
Organization Location: Amherst, MA

Partner's Contribution to the Project:
Collaborative Research

More Detail on Partner and Contribution:

USDA Forest Service

Organization Type: State or Local Government
Organization Location: Corvallis, OR.

Partner's Contribution to the Project:
Collaborative Research

More Detail on Partner and Contribution:
USDA-NRCS-NSSC

Organization Type: State or Local Government
Organization Location: Newtown Square, PA

Partner's Contribution to the Project:
Collaborative Research

More Detail on Partner and Contribution:
Univ of Kansas

Organization Type: Academic Institution
Organization Location: Lawrence, Kansas

Partner's Contribution to the Project:
Collaborative Research

More Detail on Partner and Contribution:
University of Guelph, Canada

Organization Type: Academic Institution
Organization Location: Guelph, ON, Canada

Partner's Contribution to the Project:
Collaborative Research

More Detail on Partner and Contribution:
University of Nebraska Omaha

Organization Type: Academic Institution
Organization Location: Omaha, NE

Partner's Contribution to the Project:
Collaborative Research

More Detail on Partner and Contribution:

University of Texas @ El Paso

Organization Type: Academic Institution
Organization Location: El Paso, TX

Partner's Contribution to the Project:
Collaborative Research

More Detail on Partner and Contribution:

University of Toulouse, France

Organization Type: Academic Institution
Organization Location: Toulouse, France

Partner's Contribution to the Project:
Collaborative Research

More Detail on Partner and Contribution:

What other collaborators or contacts have been involved?

We hosted the 3-day CZ Science Workshop "Exploring Four Critical Puzzles about Trees, Water, and Soil: A Vision for Research" which included 29 participants (14 female and 3 minority) from 15 institutions across the United States and Canada. The agenda included 12 oral presentations, 4 posters, and a field trip through the CZO. The cross-disciplinary working group, 16 junior scientists and 13 senior scientists, distilled four puzzlers into nine working hypotheses. Post-workshop, 13 participants contributed to the discussion paper "Reviews and syntheses: On the roles trees play in building and plumbing the Critical Zone" submitted to Biogeosciences Discussions, an interactive open-access journal of the European Geosciences Union.

Rutgers Hydrogeophysics Field Workshop returns to the CZO from June 28-30th and will host more than 25 students and faculty (30% female) from Rutgers, Indiana University of Pennsylvania, Lancaster University - UK, Rice University, Passaic County Community College, Hudson County Community College, and Penn State . The team gathered to learn how to run a hydrogeophysical field campaign using multiple gephysical tools in the same field locations, Shale Hills catena and Garner Run catena, to elucidate subsurface observations. Of specific interest this year, collecting overlapping transects of seismic refraction, GPR, and resistivity along the Garner Run valley floor. Resulting from the 2016 campaign, the proposal "GP-EXTRA: A geoscience pathway field experience in near-surface geophysics to promote recruitment and retention of transitional students in quantitative geosciences" was successfully funded and will expose 24 freshman and sophomore level undergraduate underrepresented minority students to state-of-the-art geophysical equipment, an active field research laboratory, experts in near-surface geophysics, critical zone science, and potential geoscience career paths in a 2-week applied field experience.

Impacts

What is the impact on the development of the principal discipline(s) of the project?

Overall:

Our published paper in Earth Surface Processes and Landforms is the first such publication that describes the thought process behind designing a critical zone observatory. In this paper we have published a first order answer to the question, what must we measure to be able to quantitatively model the CZ? In addition, our ideas about nested reaction fronts, interflow versus groundwater flow, and the importance of aspect on controlling rates of weathering and erosion are starting to permeate into the greater earth surface science community. We have pushed the importance of oxidation as one of the first reactions (if not the first) at depth in the CZ, and this idea is being picked up in many threads around the community (riverine cycling, global models, chemical-physical coupling, etc.). We have created one of the 3 most popular models for regolith formation, i.e., the chemical weathering reactive transport model of regolith formation.

Finally, the PIHM suite of models is being used at several CZOs and by nonCZO scientists in the US and abroad. It has been used as well for modelling for the Chesapeake Bay consortium.

Impacts for each hypothesis:

H1. By determining the age of a thick colluvial deposit at Garner Run, we will help constrain the relative efficiency of periglacial versus temperate hillslope erosion and sediment transport, and evaluate the timescales of sediment storage in upland valleys important for assessing models of Appalachian landscape evolution.

H2. Testing a simple and robust pore chemistry monitoring approach, emphasizing comparisons among catenas, could lead to a widely applied strategy to compare pore chemistry across the CZ.

H3. Coordinating with H2 and H9, the team analyzed vegetation in the sandstone site and compared it to the shale site, and examined root length density at the shale site for understanding water uptake and other biotic interactions in regolith.

H4. We have developed a framework for systems understanding the major controls of macropore/preferential flow across soils and landscapes that can be used to guide the prediction of the susceptibility of various soils to macroproe/preferential flow. This is a significant contribution to hydropedology and soil hydrology. We have refined the method of using a soil moisture sensor network to detect the occurrence frequency of macropore/preferential flow, which reduces the uncertainty in the detected preferential flow frequency and improves cross-site comparison This provides an opportunity to recognize the general mechanisms of macropore/preferential flow occurrence and dynamics across CZOs.

H5. RT-Flux-PIHM is the first numerical model capable of modeling hydrological, land surface interactions, and multi-component reactive transport all together. This provides a powerful tool to explore complex process coupling not only for SSHCZO, but also for other CZOs. It can be used for X-CZO model data comparison to derive general principles.

H6. This team has collected stream chemistry and discharge data, and has integrated physical and chemical measurements to locate and characterize groundwater – streamwater interactions. Over the next year the team will demonstrate how to upscale using nested sub-catchments, geophysical observations, synoptic and long timescale monitoring, and modelling.

H7. We are determining the degree to which knowledge of topography, lithology, and soil physical properties are needed to understand watershed carbon-nitrogen-water cycling. We will also identify the observational networks required to characterize carbon stock and fluxes in complex topography.

This work moves us towards the objective of a data assimilation system for coupled watershed hydrology and biogeochemistry. This work will ultimately result in an improved understanding of the impact of topography and soil properties on carbon-water-nutrient cycling across the earth's landscape, especially in low-order watersheds.

H8. Team H8 will provide insight into hydrologic model upscaling and parameter transferability, and provide guidance of watershed observational system design.

H9. By publishing a paper (next year) on the use of WITCH to understand porewater chemistry, we will demonstrate how aspect can control weathering in temperate climates. This paper will have significant impact on our understanding of the rates of weathering and how to earthcast surface processes into the future.

What is the impact on other disciplines?

Overall: We have a good track record and organizational plan for development of our integrated CZ model that will be used in many ancillary disciplines:

PIHM: Duffy et al. Completed
Flux-PIHM: Shi et al. Completed
RT-PIHM: Chen Bao and Li Li Completed
Flux-PIHM-BGC: Ken Davis and Yuning Shi In Progress
Flux-PIHM-WITCH: P. Sullivan and Y. Godderis In Progress
PIHM-LE: R. Slingerland and Y. Zhang Paper submitted

Impacts described per each hypothesis:

H1. We have begun developing the use of combined GPR, seismic, and resistivity surveys for geomorphology and this use of these geophysical techniques in this way will be useful for soil science and for characterizing the architecture of the critical zone.

H2. Ecological experimental designs could be impacted if the team's catena monitoring approach proves successful in illuminating key drivers of ecosystem dynamics from a few carefully located sampling points. Evidence that this impact is occurring comes from the Hoagland et al. 2017 paper in which pore water chemistry data from this team led to a new interpretation of Q-C relationships for hydrologists.

H3. Work for H3 helped bring aspects of Critical Zone science to the ecological, horticultural and forest management communities. Eissenstat gave talks to conference for Master Gardeners and for Forest Land Owners.

- Eissenstat, David M. Tree Roots - How They Grow & Interact. 2017 Forest Landowners Conference, Altoona, PA. 23-24 March 2017.
- Eissenstat, David M. On the roots and mycorrhizas of woody plants. 2017 Gardenwise Conference, York, PA 11 March 2017.

H4. We have demonstrated the unique strength (deep time, deep depth, and deep coupling) of the CZ concept in exploring and understanding Earth surface processes. We have tested and improved the application of geophysical tools in characterizing subsurface CZ architectures and CZ functions. We have summarized recent achievements in hydropedology and identified opportunities to advance this field and highlighted the potential contribution of hydropedology to propel CZ science.

H5. The RT-FLUX-PIHM model is cross-disciplinary in its capability of integrating processes important for different disciplines (hydrology and geochemistry). The hillslope regolith model will be integrating hydrology, geochemistry, and geomorphology.

H7. The development of the PIHM family of models has initiated collaboration across all of the disciplines of our CZO project. Our work has also introduced the concept of biogeochemical data assimilation to fields not typically used to utilizing these tools in their research. We hope that the results of this work will also enable high-resolution, high-fidelity simulation of the impacts of climate, environmental chemistry, and land use changes on watershed carbon, nitrogen and water cycles. Our work may inform new treatment of the role of topography in regional to global scale simulations of the terrestrial carbon cycle, such as earth systems models used for climate projections.

H8. The method of land surface hydrologic observation system design developed for H8 can be expanded to other fields (e.g., biochemistry, geochemistry).

H9. Our team has been the first to publish papers in Earthcasting, and our soon-to-be-submitted earthcasting paper that uses aspect as a way to probe future impact of climate will extend this effort and be noticed by many sub-fields within CZ science.

What is the impact on the development of human resources?

During this year, 26 faculty, 41 graduate students, and ~ 100 undergraduate students have been working or studying at the Susquehanna Shale Hills CZO. The site is acting as a mecca for

surrounding institutions and faculty and students in teaching and learning about the critical zone. Specifically, the site hosted 38 Penn State WeatherCampers (highschool students), the Critical Zone Teachers Workshop, a Math Modelling Workshop (hosted by Lee Kump and Rudy Slingerland), an 8-member delegation from the Chinese Geological Survey and the China Univeristy of Geosciences, PSU Forestry 475 - Principles of Forest Soils Management, PSU Geoscience 483 - Environmental Geophysics, PSU Geoscience 203 - Physical Processes in Geology, PSU ERM 435 - Limnology, Kent State GEOL 4/5/72065 - Watershed Hydrology, PSU RPTM 425 - Principles of Interpretive Materials, and PSU RPTM 430 - Environmental Education Methods and Materials. Research continues with collaborators from University of Nebraska-Omaha, University of Queensland-AU, Indiana University-Pennsylvania, Dickinson College, Florida Atlantic University, and Temple Univeristy. Cross-CZO investigations are underway with Oregon State University (Mo isotopes in riverine systems), Cornell Univeristy (Hg sequestration in soils), and University of Nebraska-Omaha (erosion rates). During this reporting period, three M.S. degrees were successfully defended and 25 total papers have been submitted, are under review, are accepted, or published.

The PA Geologic Survey has selected Shale Hills CZO for the featured tour of 2017 Fall field conference, which will take place Oct 5th - 7th.

Roman DiBiase, co-investigator, hosted the Amtrak Club Annual Conference at Penn State and the CZO with theme "Propagation of climate and tectonic signals through landscapes." The 47 participants came from sixteen academic institutions and the National Science Foundation and the agenda included 10 oral presentations, 21 poster presentations, and an afternoon in the CZO.

Emma Hauser, University of Kansas graduate student, has received CZO SAVI funds to investigate how the ratio of nutrients provided annually via organic matter decay vs. annual vegetation nutrient demand varies across different lithologies, soil development, and across multiple CZOs (Calhoun and Catalina-Jemez). Hauser has visited Shale Hills, collected representative leaf-litter samples from multiple plots across the catchment and is using soil and rock geochemical data available on our website to guide research interpretations.

The CZO seminar series this year included the following presentations, open to anyone on campus at Penn State and broadcast by webinar to our seed-grantees and co-investigators at other institutions:

September 9th: Susan L. Brantley, Distinguished Professor of Geosciences and Lead-PI, will present the "***State of the CZO***"; October 14th: Discussion of Cole Farm Ag Site instrumentation with entire team; November 11th: Roman DiBiase and Greg Mount on "***Multi-scale Critical Zone architecture at Garner Run revealed from near-surface geophysics***"; December 9th: Alison Denn, MS Candidate at the University of Vermont, who will present "***Need a rate? Want a date? ^{10}Be measurements of regolith at the SSHCZO and beyond***"; January 13th: Yuting He, Yuning Shi, Li Li, and Jason Kaye will present "***Nitrogen cycling & modeling in the CZO***"; February 10th: Callum Wayman, Tess Russo, Jason Kaye, and others will present "***Agricultural Research in the CZO***"; March 27th: Dacheng Xiao, PhD Candidate Energy and Mineral Engineering, wil present "***Understanding the lithology control of hydrologic processes across the Shale Hills and the Garner Run using model-data integration***"; April 24th: Dan

Shapich and Brandon Forsythe will present "***Data Flow & Management and Field Season Preparations***"; May 11th-12th: SSHCZO All-Hands – AGU style mini-symposium, May 11th included 5 oral presentations, the CZO field trip with Emily Elliott, 8 faculty, and 18 students/postdocs, and concluded with featured seminar by Emily Elliott @ 4:00pm "***Exploring AIR-WATER-ECOSYSTEM interactions of reactive nitrogen using stable isotope geochemistry***"; May 12th included 5 student/postdoc oral presentations, 15 poster presentations, brainstorming for renewal, and networking. The program planner is available http://criticalzone.org/shale-hills/research/annual-activities-shale-hills/. This year's meeting included 40 participants from the following institutions: Delta-Phase Electronics (Peter DeBarber), Cary Institute (Julie Weitzman), Hobart & William Smith Colleges (Kristen Brubaker), Indiana University of Pennsylvania (Greg Mount), University of Pittsburgh (Emily Elliott), Institute of Earth Environment at Chinese Academy of Sciences (Zhao Jin), Wageningen University & Research (Marijn van der Meij), University of North Carolina - Chapel Hill (Jon Duncan), Middlebury College (Perri Silverhart), and Penn State University (all others).

One graduate student is participating in CUAHSI's National Water Center Innovators Program - Summer Institute "Forecasting the Water Resources of the Nation."

What is the impact on physical resources that form infrastructure?

Overall: Instrumentation of the agricultural subcatchment has begun. Hydrologic sampling of Shaver's Creek and Cole Farm has been ongoing since fall 2016.

We have now established the GroundHOG sampling scheme (soil moisture, soil gas, soil porewater across a catena) at three sites. These installations are robust for long time periods and can be used to quantify soil pore chemistry for other projects and over long time scales.

In one shale and one sandstone catchment, soil moisture sensors were installed at multiple depths in pits at ridgetop, midslope, and valley floor positions. These will allow continuous monitoring of soil moisture. Dendrobands and sap flux sensor were placed on trees around one pit at Shale Hills and Garner Run. As part of a project funded by DOE, we also place 250 minirhizotron tubes throughout the catchment at Shale Hills. This team helped install a stilling well at the new agricultural site and supported siting and installation of the GroundHOG monitoring sites. The team has assisted with the establishment of an eddy covariance measurement system at Cole Farm.

What is the impact on institutional resources that form infrastructure?

The CZO research was leveraged to acquire a DOE grant (Eissenstat, Kaye, Shi, Davis, Lin, & Duffy) aimed at assessing the influence of topography on belowground carbon fluxes, and modeling these processes in the Shale Hills CZO with a coupled Earth system and hydrological model. The Shale Hills observatory was also used to assess species variation in mycorrhizal root foraging by a Ph.D. student (Weile Chen) working in the Eissenstat lab and funded by NSF BIO Directorate, IOS program.

We have begun working with some agricultural scientists at Penn State to help them start a study of switch grass and nutrient mobility at our farmed site.

What is the impact on information resources that form infrastructure?

A "Precepts for Collaboration" guide to best practices for collaborative science at the SSHCZO was adopted by the CZO team and remains a living document for the team and collaborators.

The tree survey at Shale Hills is available on line (measure DBH on all trees >20cm, record mortality, record recruitment, correct species)

A user manual is being developed for RT-FLUX-PIHM.

Eddy covariance flux data from Shale Hills and Cole Farm are available to the research community. Shale Hills has been incorporated into the AmeriFlux network, and the EcoStress validation site network.

Three new datasets (Shaver's Creek Watershed Stream Chemistry, 2014, 2015, 2016) have been submitted to the EarthChem library and assigned DOIs, all with public release dates of September 2018, bringing the total EarthChem library contributions from SSHCZO to thirty-six.

Data Manager/Cyberspecialist continued to import CZO data into locally-hosted MS SQL Server database, linked to local CZO data portal web site (http://www.czo.psu.edu/data_overview.html). Instrument map on this site was maintained, including adding new instrumentation and data collection sites. The addition of an agricultural sampling site is currently underway. PHP scripts were written to download data via web from this database (e.g., http://www.czo.psu.edu/data_surfflux.html).

Data Manager/Cyberspecialist has uploaded a number of new and/or updated datasets of the following: Land/Atmosphere Fluxes, Soil Gas and Porewater Concentrations, Discharge, Stage, and Water Chemistry, Surface and Groundwater Chemistry, Precipitation and other Meteorology, Ground Penetrating Radar, Colloidal Suspensions, Vegetation (Shrub) Transects, Soil Moisture, Soil Temperature, Soil Electrical Conductivity, Soil Dielectric, Soil Respiration. These new datasets and pre-existing ones are accessible via http://criticalzone.org/shale-hills/data/datasets and http://www.czo.psu.edu/data_overview.html. Time series and other datasets have been imported into locally-hosted SQL Server database, and access pages (e.g.,http://www.czo.psu.edu/data_surfflux.html) created.

Data Manager/Cyberspecialist continued to populate and maintain locally-hosted MS SQL Server database for storage and archiving of local CZO data. Currently there is approximately 206 Gigabytes of data in the database amongst over 100 data tables. It is assumed this database will be maintained beyond the project.

What is the impact on technology transfer?

Watershed coordinator Brandon Forsythe is working with Michael Piasecki (CCNY) to test a new data logger for watershed monitoring.

What is the impact on society beyond science and technology?

The TeenShale water quality outreach project trained 15 high school participants in authentic field research in collaboration with Penn State experts. Participants use scientific instruments to measure stream depth and velocity and water quality indicators such as stream temperature, pH, dissolved oxygen, and electrical conductivity. As an inquiry-based project, all aspects from the evolution from ideas and data gathering, to data analysis, comparisons with big data, and science communication are addressed. New this year, the students presented at NE/NC GSA Joint Section Meeting in Pittsburgh in the Undergraduate Poster Session as well as the Annual Shale Network Workshop. This year's cohort included four seniors, who have participated their entire high school career. A blog post "*Making the connection - from the classroom to the field*" is available in Adventures in the Critical Zone (http://criticalzone.org/national/blogs/post/making-the-connection-from-the-classroom-to-the-field/) and a manuscript is in preparation.

The CZO student team continues collaborations with Shaver's Creek and 17 Spring Semester SEED (Student Engagement & Experiential Discovery) students within the Recreation, Park, and Tourism Management Program at Penn State. These students use Shaver's Creek as a classroom for a semester long experiential journey of outdoor leadership and environmental interpretation course. Building upon current infrastructure in and around Shaver’s Creek Environmental Center, SEED students are designing a walking trail with points of interest focused on Critical Zone processes or instrumentation deployed within the Penn State Forest. The final product will be delivered to the public as an iBeacon designed walking tour with stops along the trail which highlight the geology, soils, hydrology, forest ecology, and the carbon/water cycle as observed in central Pennsylvania. Discussions are ongoing with respect to the Discovery Room display and outdoor experience to be included in the newly renovated space, currently under major expansion.

At least two huge societal problems are related to ongoing work at our CZO. Specifically, many members of the public are worried about hydraulic fracturing and whether the injection of fracking fluids could enter groundwater resources. Will fracking harm groundwater? This can be rephrased as, what is the depth of the critical zone? We are actively working to understand how to model and predict the dept of flow of water in the subsurface.

In a second example, the US is seeking a geologic site to safely dispose radioactive waste. This disposal site must sequester the waste from groundwater, must not be eroded or weathered away, must not be easily fractured to allow inlet of new groundwater, and must be safe from human intrusion. All of these societally relevant questions are essentially CZ questions. Will a geologic repository be eroded before the radwaste decays adequately? This can be rephrased as, what is the rate of weathering and erosion in this locality? All of the work we do at the Susquehanna Shale Hills CZO is aimed at understanding these types of questions, although our target area is one watershed in central PA.

Changes/Problems

Changes in approach and reason for change

As we have previously noted, we decided not to begin studying a pristine calcareous-shale subcatchment as we had originally planned in our proposal. This is simply because we are stretched very thin because we are running 3 subcatchments (Shale Hills, Garner Run, Cole Farm) and monitoring the entire Shavers creek watershed. Furthermore, we previously noted that Chris Duffy is no longer working with the CZO and so we decided to not do the outreach modelling effort for Snake Creek with SUNY Binghamton. This decision was also precipitated by the fact that Joe Graney (Binghamton) was too busy to interact with us and come to our All Hands meetings. (This was reported on a previous report). We also previously reported that we decided not to keep giving out seed grants because the grantees were not publishing with the money. In this final year, we may revisit this idea if one of our grantees needs money to finish a paper.

Actual or Anticipated problems or delays and actions or plans to resolve them

Tess Russo has decided to leave Penn State. She has two students on the project, Callum Wayland and Beth Hoagland, and S. Brantley and Li Li will be supervising them to completion. They have been making fine progress. We believe we will be able to complete all work Dr. Russo had begun.

Changes that have a significant impact on expenditures

A few of our wells are starting to cave in and we are seeking to open them up, which may cost us funding. We are exploring how to do this. We have also found an old well into the sandstone ridge that we are trying to open back up as well, and this may cost money.

Significant changes in use or care of human subjects

Nothing to report.

Significant changes in use or care of vertebrate animals

Nothing to report.

Significant changes in use or care of biohazards

Nothing to report.