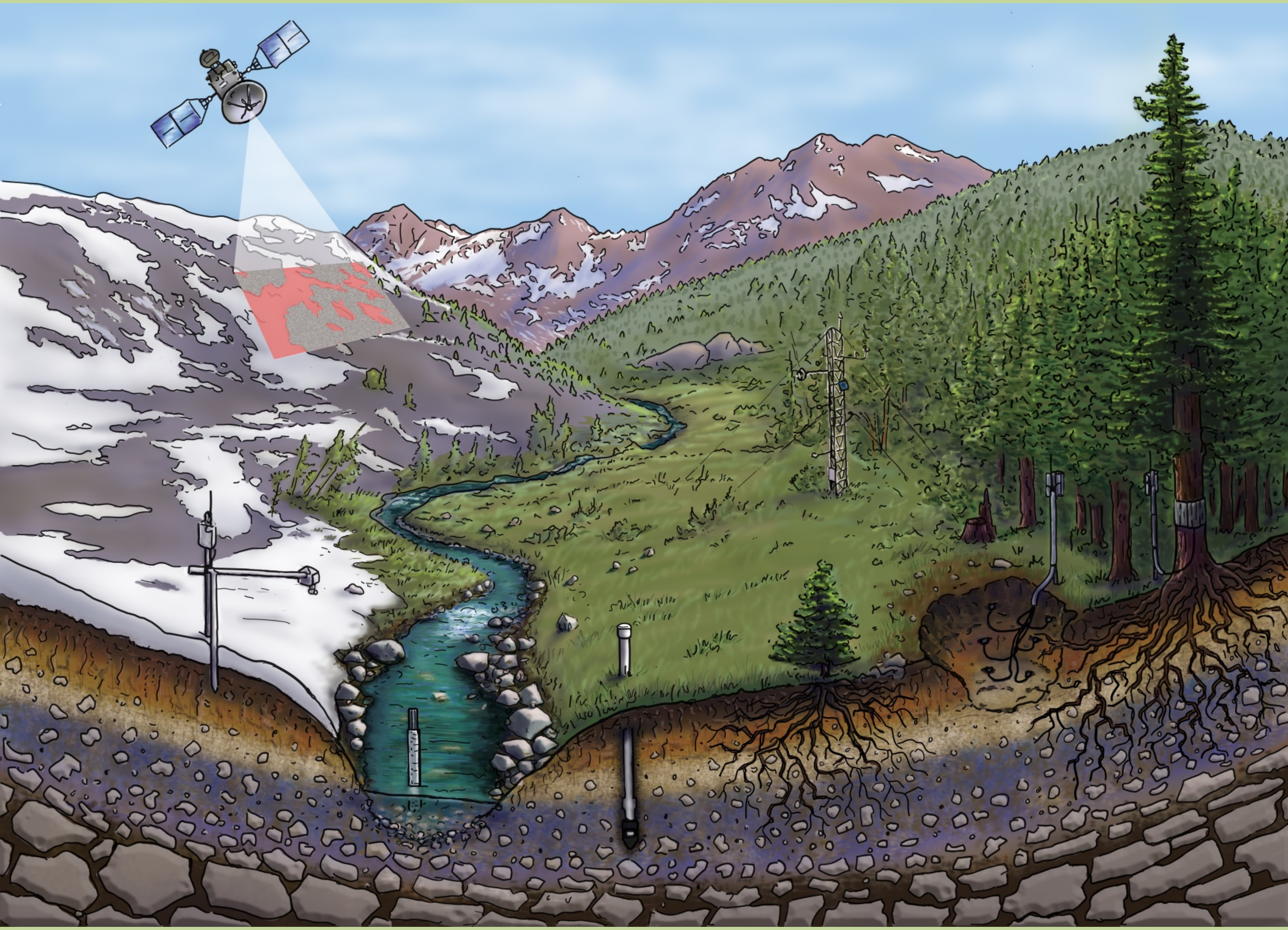
Discoveries in the Critical Zone: Where Life Meets Rock

National Science Foundation
Critical Zone Observatories Network



CZO Discovery Articles National Science Foundation

Table of Contents

Acknowledgements

Many NSF staff members, too numerous to mention individually, assisted in the development and implementation of the CZO network. The CZO program officers and investigators are thanked and congratulated for their creativity and achievements in the coordination and research activities these exciting projects represent.

Articles written by Cheryl Lyn Dybas

Design and Layout by Rachel Bernard

Front Cover Art: Jenny Parks Illustration/SSCZO

Back Cover Art: R. Kindlimann (modified from original)

Critical Zone Observatories

NSF Critical Zone Observatories address pressing scientific questions about geological, physical, chemical, and biological processes and their links in Earth's critical zone.

Introduction: Earth's Critical Zone: Where Life Meets Rock

NSF's Critical Zone Observatories (CZO) Network:
At the Forefront of a New Understanding of Earth's Systems

From Kazakhstan to Kansas, from Canada to Chile, we're witnessing a fast-changing planet. What will it look like in the years, decades and centuries to come?

How far, and in what ways, can Earth's systems be stressed before they undergo transitions to new states—with unforeseen consequences?

Scientists at the National Science Foundation (NSF)'s Critical Zone Observatories (CZOs) are seeking answers. They're working to understand Earth's critical zone - the region between the top of the tree canopy and the base of weathered rock - and its response to climate and land use changes.

CZO researchers are peering into this thin veneer of Earth's surface, our living environment – before it goes critical.

Society has long recognized the importance of water, soil, biota, landforms and the network of rivers and streams that makes up watersheds, all part of Earth's critical zone, to human welfare. But only recently have we begun to holistically view the workings of these connected systems.

Water, soil and river geochemistry - and life forms from trees to humans - are interrelated, each influencing the others.

To better comprehend these links, NSF supports research at CZOs in watersheds across the country and beyond.

NSF CZOs are located in the Jemez River Basin in New Mexico and the Santa Catalina Mountains in Arizona; Southern Sierra Nevada Mountains; Christina River Basin on the border of Delaware and Pennsylvania; Susquehanna Shale Hills in Pennsylvania; Boulder Creek in the Colorado Rockies; and Luquillo National Forest in Puerto Rico.

Results from CZO research will help scientists predict how the critical zone orchestrates "ecosystem services" - irreplaceable services, such as fresh water, the environment provides.

In this United Nations International Year of Water Cooperation and into the future, new information is needed about how natural and human systems are linked.

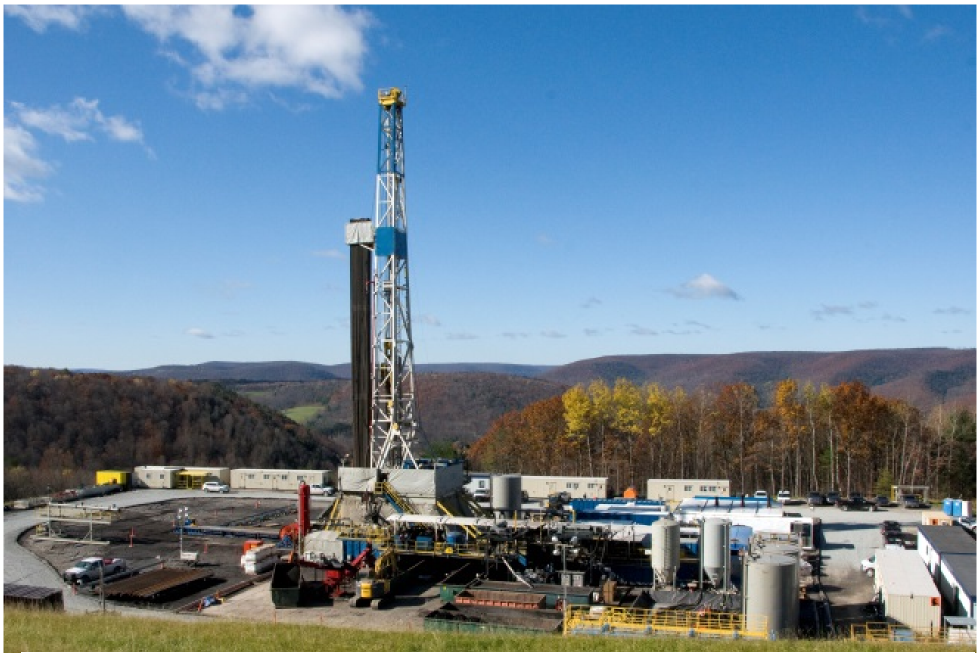
The answers, CZO scientists believe and their discoveries show, lie in a place that's crucial to our planet's habitability – the critical zone.

Wendy Harrison
Director, Division of Earth Sciences
NSF Directorate for Geosciences

Can Marcellus Shale Gas Development and Healthy Waterways Sustainably Coexist?

The Susquehanna Shale Hills CZO is Providing Answers

09 December 2011



Marcellus Shale natural gas drilling is proceeding apace in Pennsylvania.

Amity, Pennsylvania. Epicenter of the natural gas-containing geological formation known as the Marcellus Shale.

Amity lies in Washington County near Anawanna, Pa. Once, Native Americans lived there. They named it Anawanna, or "path of the water," in recognition of its many rivers and streams.

Today Anawanna is but a whisper in tales of the past. But the path of the water for which it's named is making headlines.

The Marcellus Shale Formation underlies some 95,000 square miles of land, from upstate New York in the north to Virginia in the south to Ohio in the west.

The bull's-eye, however, is under Pennsylvania in places like Amity. There the gas-bearing thickness of the shale reaches 350 feet; it thins to less than 50 feet in other areas.

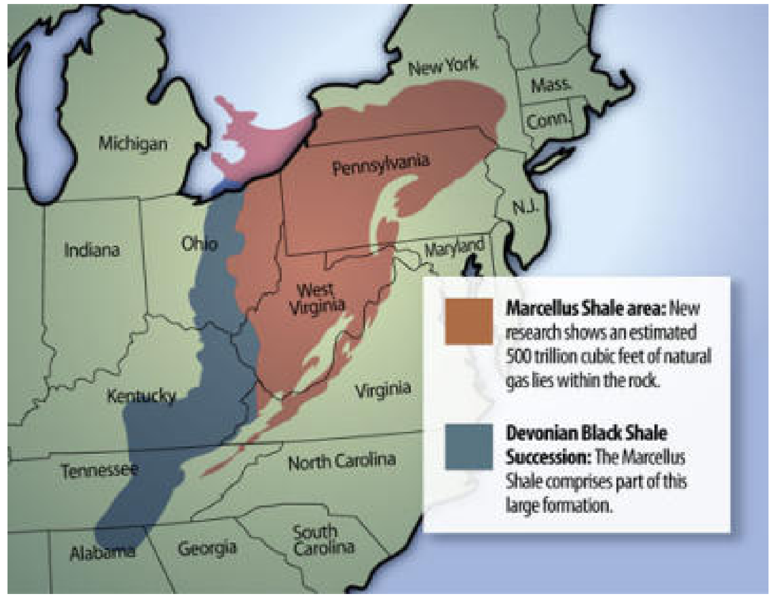
The Marcellus Shale gas reservoir may contain nearly 500 trillion cubic feet of technically-recoverable gas. At current use rates, that volume could meet the U.S. demand for natural gas for more than 20 years.

The shale's proximity to the heavily populated mid-Atlantic and Northeast makes its development economically advantageous. Already, more than 4,000 shale gas wells have been drilled in Pennsylvania.

But the Marcellus Shale has a bête noire. With such rapid development, gas exploitation is creating environmental challenges for Pennsylvania - and beyond.

Retrieving the Marcellus Shale's gas requires a process known as hydraulic fracturing, hydrofracking or simply fracking.

Fracking involves the use of large quantities of water, three to eight million gallons per well, mixed with additives, to break down the rocks and free up the gas. Some 10 to as much as 40 percent of this fluid returns to the surface as "flowback water" as the gas flows into a wellhead.



Marcellus Shale underlies the U.S. East Coast region from New York to Virginia.

Once a well is in production and connected to a pipeline, it generates what's known as produced water. "Flowback and produced water," says Susan Brantley, a geoscientist at Penn State University, "contain fluid that was injected from surface reservoirs - and 'formation water' that was in the shale before drilling."

Enter the bête noire.

These flowback fluids carry high concentrations of salts, and of metals, radionuclides and methane. "Such chemicals," says Brantley, "can affect surface and groundwater quality if released to the environment without adequate treatment."

The rapid pace of Marcellus Shale drilling has outstripped Pennsylvania's ability to document pre-drilling water quality, even with some 580 organizations focused on monitoring the state's watersheds. More than 300 are community-based groups that take part in volunteer stream monitoring.

Geoscientist Susan Brantley of Penn State doing field work in the Marcellus Shale region.

Pennsylvania has more miles of stream per unit land area than any other state in the U.S. "It's overwhelming to keep track of," says Brantley. "These community organizations have identified a need for scientific and technical assistance to carry out accurate stream assessments."

Working through the National Science Foundation's (NSF) Susquehanna Shale Hills Critical Zone Observatory (CZO), one of six such observatories in the continental U.S. and Puerto Rico, Brantley studies the "critical zone" where water, atmosphere, ecosystems and soils interact.

Now, with a grant from NSF's Science, Engineering and Education for Sustainability (SEES) Research Coordination Networks (RCN) activity, Brantley is developing a Marcellus Shale Research Network.

The network will identify groups in Pennsylvania that are collecting water data in the Marcellus Shale region; create links among these organizations to meld the resulting data; and organize a water database through the NSF-funded Consortium of Universities for the Advancement of Hydrologic Sciences.

The database will be used to establish background concentrations of chemicals in streams and rivers, and ultimately to assess changes throughout the Marcellus Shale area.

The results, Brantley hopes, will help community groups evaluate hydrogeochemical data. The network will use geographic information systems that incorporate population and economic data to consider the potential for public health risks.

"An outcome of the NSF investment in the Susquehanna Shale Hills Critical Zone Observatory has been a better interpretation of the chemistry and flow of groundwater in shale," says Enriqueta Barrera, program director in NSF's Division of Earth Sciences, which funds the CZOs.

"The SEES-RCN project will use this information in assembling data collected by watershed associations, government agencies, and water scientists to further

Hundreds of streams and rivers large and small flow through the Marcellus Shale Formation.

knowledge on the effect of hydrofracking on groundwater properties."

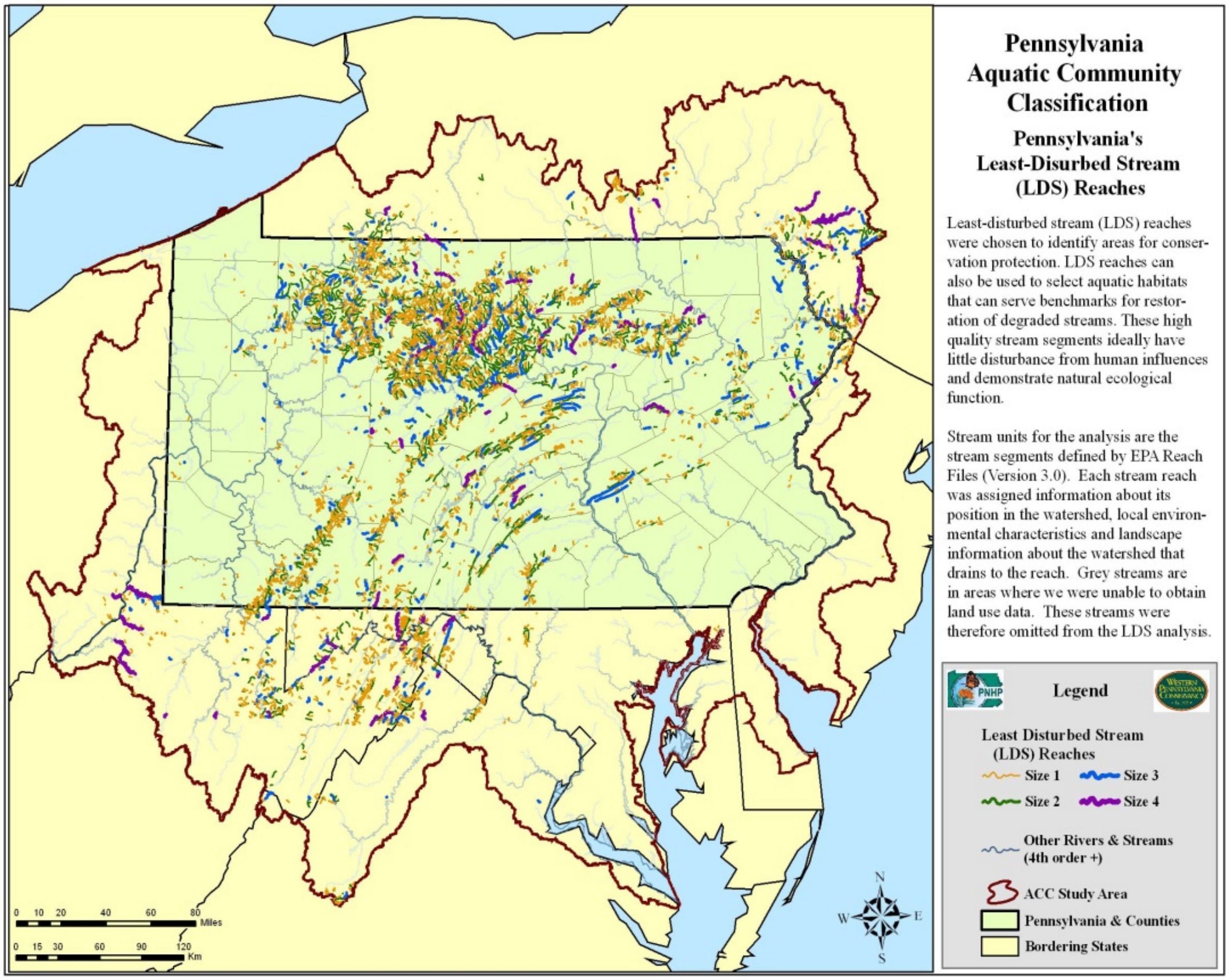
The Marcellus Shale RCN, says Brantley, "is designed to act as an 'honest broker' that collates datasets and teaches ways of synthesizing the data into useful knowledge. The approach stresses that volunteer data acts as a 'canary in a coal mine' to inform agencies about when and where they need to intensify water quality monitoring."

Of particular concern are concentrations of salts such as barium and strontium, high in some discharges as a result of the mixing of gas drilling fluids with naturally-occurring barium-strontium-containing waters.

"Barium can cause gastrointestinal problems and muscular weakness," says Brantley, "when people are exposed to it at levels above the EPA drinking water standards, even for relatively short periods of time.

"Animals [such as cows, pigs, sheep] that drink barium-laced waters over longer periods sustain damage to kidneys and have decreases in body weight, and may die of the effects."

A temporary freshwater impoundment to be used for fracking, or hydraulic fracturing.



Many of Pennsylvania's streams are unpolluted havens for aquatic life, including trout.

The waterways of Pennsylvania have recorded many important human activities in the history of the U. S., Brantley says. "It's expected that they will record the development of the Marcellus Shale gas as well."

The rise and fall of coal mining is found in concentrations of dissolved sulfates in the state's rivers. Pennsylvania's air, water and soils retain the signature of the steel industry, and of coal-burning over the last century, in their low-level manganese contamination.

Documenting the effects of shale gas extraction, says Brantley, requires extensive water sampling and a database of long-term records.

In the past, monitoring sometimes didn't begin until after effects were noticed. But times are changing. "In the future," says Brantley, "monitoring networks of all kinds will need to include citizen scientists to keep costs down, and research scientists will need to learn to use such networks to the best outcome."

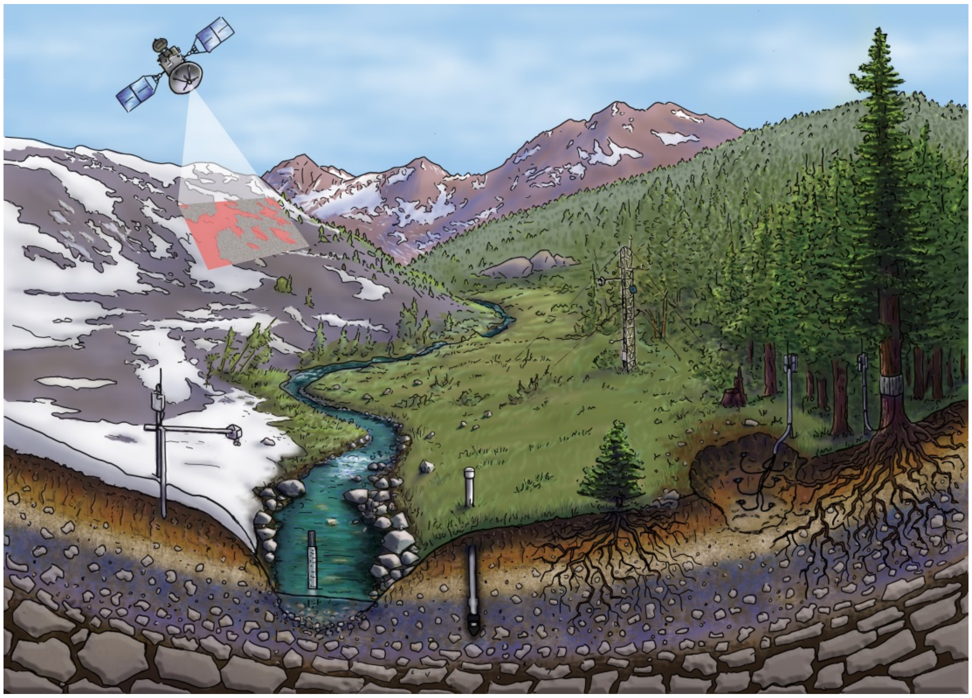
Can we have natural gas development and clean waterways?

The Marcellus Shale Research Network will provide much-needed answers, says Barrera. "Successfully developing new energy resources while maintaining healthy ecosystems," she says, "is the very heart of sustainability."

A Tree Stands in the Sierra Nevada

A coniferous view of the link between snowmelt and water supplies in the U.S. West

07 August 2012



Research at NSF's Southern Sierra CZO links snowmelt with downstream water supplies.

White fir, ponderosa pine, Jeffrey pine. Sugar pine, incense cedar, red fir. The conifers of the headwater ecosystems of California's Sierra Nevada.

If trees could talk, what tales they might tell. Tales of the health of the forests, of the winter snows that fall on their branches, and of how much water they transpire to the atmosphere.

Now, one tree may be poised to do just that, or at least to offer new insights into a place called the critical zone: the region where rock meets life between the tip of the forest canopy and the base of weathered rock.

The Critical Zone Tree, the white fir is called. It's a scientific totem pole that stands tall in the forest of the Southern Sierra Critical Zone Observatory (CZO).

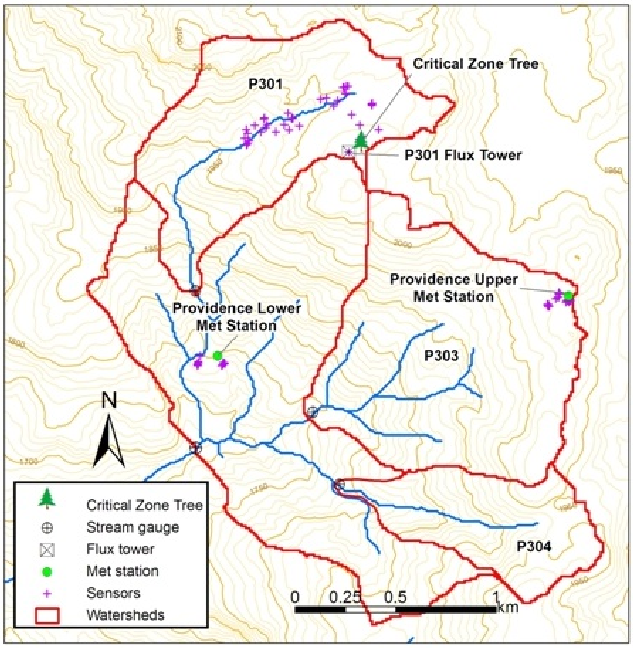
The Southern Sierra CZO is one of six such observatories supported by the National Science Foundation (NSF). Scientists there recently found that winter snow from Sierra blizzards foretells how much water will be at the bases of the mountains during summer.

That's important for people downstream who toil in California's multi-billion-dollar agricultural industry and depend on water from Sierra snowmelt. The water is the source of more than 60 percent of California's supply.

Without torrents of melting snow cascading across hillsides, wildflowers won't bloom, and the birds and bees that need the flowers' nectar can't thrive.

But more and more, the rivers are running dry, running late or running early.

"NSF's CZOs are providing scientists with new knowledge of the critical zone and its response to climate and land-use change," says Enriqueta Barrera, program director in NSF's Division of Earth Sciences, which funds the network of six CZOs.



Location of the Critical Zone Tree, a white fir among ponderosa pines and other conifers.

"They're the first systems-based observatories dedicated to understanding how Earth's surface processes are coupled," says Barrera. "The results will help us predict how the critical zone will affect the ecosystem services on which society depends."

The water cycle, the breakdown of rocks and eventual formation of soil, the evolution of rivers and valleys, patterns of plant growth, and landforms we see all result from processes that take place in the critical zone.

"The CZOs are fostering an investigation of the critical zone as a holistic system," says Barrera.

NSF's CZOs are located in watersheds in the southern Sierra Nevada, Boulder Creek in the Colorado Rockies, Susquehanna Shale Hills in Pennsylvania, Christina River Basin on the border of Delaware and Pennsylvania, Luquillo riparian zone in Puerto Rico, and the Jemez River and Santa Catalina Mountains in New Mexico and Arizona.

At the Southern Sierra CZO, "we investigate how the water cycle drives critical zone processes," says lead scientist Roger Bales of the University of California, Merced. "Research focuses on water balance, nutrient cycling and weathering across the rain-snow transition line."

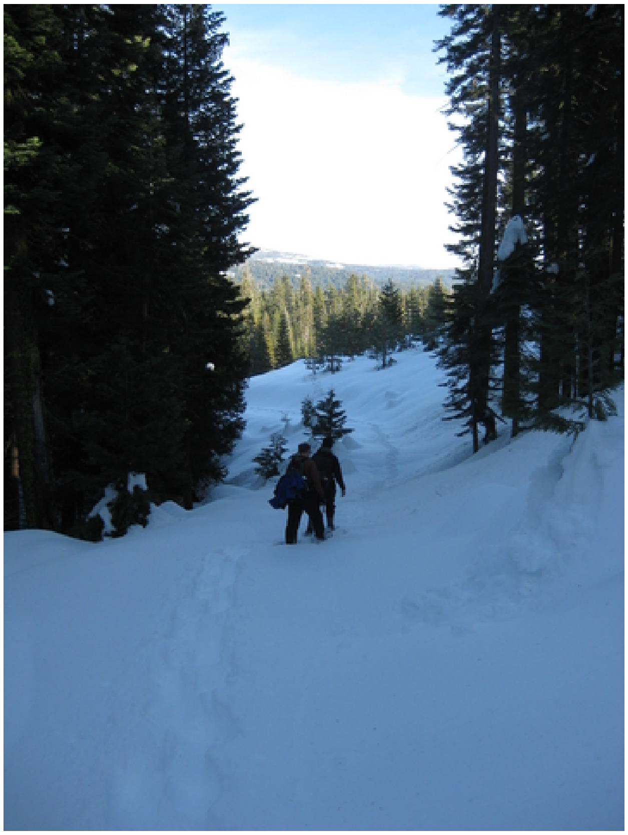
Society has long recognized the importance of water, soil, landforms and rivers to human welfare, says Bales, "but has only recently begun to look at their workings as a coupled system."

Water, vegetation and geochemistry are all interrelated, Bales and other scientists have found, with feedbacks from each influencing the others. But how are they interrelated?

Enter the Critical Zone Tree--or trees. "In actuality," says Bales, "there are several of them."

The white fir and its coniferous relatives observe Sierra forests from the headwaters of the Providence Creek Basin. The trees and forest floor around them are covered with instruments that measure soil moisture, temperature, snow depth, solar radiation, sap

Listening to a tree's heartbeat: A sap-flux meter monitors a Critical Zone Tree.



Scientists snowshoe to the NSF CZO site in the mountain forests of the Sierra Nevada.

flow and snowmelt patterns.

Beneath them are crisscrossing streams that course through a series of meadows. These rivers and creeks fan out across the mountains, carrying water across hill and dale - water that eventually sustains California's food-producing Central Valley.

The Critical Zone Tree(s) play a starring role in the Southern Sierra CZO story. They've become frontrunners for a series of wireless sensors that dot the forest like wildflowers in spring, transforming scientists' understanding of the mountain water cycle.

The sensor network tracks snowpack depth, water storage in soil, and stream flow and water use by vegetation - information that's important for the wise use of water in the arid mountain west.

"This type of wireless sensor network will revolutionize the way we understand our most important source of water in California - and far beyond," says Bales.

Natural resource managers often lack accurate estimates of precipitation, and of the loss of water from the soil from direct evaporation and by transpiration from the surfaces of plants in the mountains. Therefore, they struggle to know how much water to retain in reservoirs, how much to release - and when.

In a future that holds even more uncertainty, the Southern Sierra CZO wireless sensor network will provide water officials with a way to better predict snowmelt runoff.

"This observation system is our window into the future of water availability in the southern Sierras," says Wendy Harrison, Director of NSF's Division of Earth Sciences.

Climate warming means that more rain and less snow will fall in the Sierras and plant growth will change accordingly. How long will we be able to rely on the Sierra snowpack as a "water tower"?

Science-in-the-snow: Downloading data from instruments placed on Critical Zone Trees.

"An understanding of 'water balance,' made possible by the CZO, is what's needed to predict how whole-scale changes in vegetation cover will affect the future amount and timing of water availability in this region," says Harrison.

Scientists at the Southern Sierra CZO are finding answers by teasing apart the interconnected strands of critical zone processes. They're asking questions such as: How do variations in landscapes affect the way soil moisture, water use by vegetation, and stream flow respond to snowmelt and rainfall?

Bales and colleagues have found that small temperature differences between rain- and snow-dominated Sierra watersheds result in significantly different timing of runoff in the region's coniferous forests.

For every one degree Celsius increase in long-term average temperature, the scientists believe, runoff will happen seven to 10 days earlier in some locations.

"We've also found that across a range of elevations, forests transpire water year-round," says Bales, "with much higher water use than previously predicted."

The results highlight a new link between climate and the deeper subsurface beneath trees.

Getting to the root of water availability, it turns out, may fall in the domain of not one Critical Zone Tree, but across--and under--a whole forest of them.

See web-version for video:
"Snowfall and snowmelt in the Sierras beneath the Critical Zone Tree"
http://www.nsf.gov/discoveries/disc_summ.jsp?cntn_id=125091&org=NSF

Science on the Graveyard Shift

Discovering what gets buried and how

31 October 2012

Graveyards are excellent research sites; their soil lies undisturbed.

Into the graveyard

By dark of night in an old graveyard, things rustle. At least, if that cemetery is at London Grove Friends Meeting in Kennett Square, Pa.

Look between the oldest markers, or under a gnarled oak tree that's been guarding the graveyard since the time of William Penn in 1682. You'll find not a ghost, but a scientist, probing the dirt for the secrets it might reveal.

"These soils have been undisturbed for centuries, if at all, and hold the key to understanding how humans have altered the landscape," says geoscientist Anthony Aufdenkampe of the National Science Foundation's (NSF) Christina River Basin Critical Zone Observatory (CZO) on the border of Delaware and Pennsylvania.

To discover answers, Aufdenkampe, who is also affiliated with Pennsylvania's Stroud Water Research Center, is in graveyards taking samples at noon and at midnight. "We do a lot of storm-chasing to follow erosion," says Aufdenkampe, "so we're often out at the 'witching hour.'"

The Christina River Basin CZO is one of six NSF CZOs in watersheds across the nation.

In addition to the Christina River Basin site, CZOs are located in the Southern Sierra Nevada, Boulder Creek in the Colorado Rockies, Susquehanna Shale Hills in Pennsylvania, Luquillo riparian zone in Puerto Rico, and the Jemez River and Santa Catalina Mountains in New Mexico and Arizona.

They're providing us with a new understanding of the critical zone--the region

The Christina River flows through three states: Pennsylvania, Maryland and Delaware.

Anthony Aufdenkampe and Rolf Aalto, to right of tree, inspect an ancient oak in a cemetery in London Grove, Pa.

between the top of the forest canopy and the base of unweathered rock: Our living environment - and its response to climate and land-use changes.

Marked by rotting soil

It all starts with bedrock and with rotting soil.

To scientists, this putrid rock, as the Greeks called it, is known as saprolite. It's the first stage of the continuous transformation of rock to fertile soils, says Aufdenkampe, and needs thousands to millions of years of mixing by water, plants, microbes, worms and other organisms.

But its journey doesn't end there.

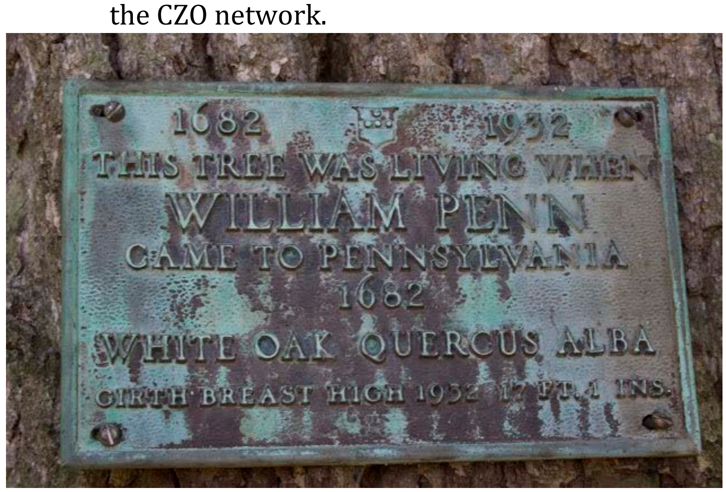
For centuries, researchers thought that these building blocks of life stayed close to home -that the molecules in a falling leaf didn't travel far before meeting their ultimate fates. They returned to the atmosphere as greenhouse gas, or became incorporated into the soil.

Now, scientists at the Christina River Basin CZO believe otherwise.

They're testing the idea that erosion and mixing of soil minerals with carbon in fresh plant remains - and subsequent burial downslope or downstream - is the key to what happens to the carbon, and to the greenhouse gases it forms.

Aufdenkampe and colleagues published results of a study comparing carbon transport in the Christina River Basin watershed and others around the world in the February, 2011, issue of the journal *Frontiers in Ecology and the Environment*.

"Society has long recognized the importance of water, soil, vegetation and land forms to human welfare, but only recently have we begun to holistically probe the workings of these coupled systems in projects like the CZOs," says Wendy Harrison, Director of NSF's Division of Earth Sciences, which funds the CZO network.



This "Penn Oak," or white oak, was standing when William Penn arrived in Pennsylvania in 1682.

Map of the Christina River Basin

"This new way of doing science will allow us to predict how an entire watershed will respond to land use and climate change."

Scientists once believed that they could understand whether a forest or a field was storing greenhouse gases by studying small research plots alone.

"Now we know that we need to look carefully at all the forms of carbon that leave a plot and flow downhill and downstream," says Aufdenkampe. "We need to follow the carbon and the soil from saprolite to the sea."

Twists and turns of the Christina River

Sippunk, Tasswaijres, Minquess Kill. The Christina River has been known by these names and many others.

It's a tributary of the Delaware River; its 35 miles flow through southeastern Pennsylvania, northeastern Maryland, and into Delaware. From Franklin Township, Pa., to Wilmington, Del., the Christina River and its tributaries drain an area of 565 square miles.

Its streams supply 100 million gallons of water each day for more than half a million people in three states.

The first European settlements in Delaware sprang up near the confluence of the Christina and Delaware rivers. Trees lining the banks of the rivers, and across the land, were felled. In their place came farms and factories.

How has the region's human history affected rivers and streams that now course through forests and farms, suburbs and cities? And how has this centuries-old legacy changed the carbon cycle in the Christina River Basin watershed?

To find out, Aufdenkampe picks up a shovel. As he digs through fallen leaves and several feet of dirt on a streambank flanked by gravestones, stripes of soil begin to emerge.

In their center is something dark and moist. Perfectly preserved, it's a part of the bank buried hundreds of years ago by erosion caused by colonial forefathers.

Kyungsoo Yoo and Rolf Aalto inspect a post-colonial floodplain deposit. Once carbon is buried in such a floodplain, it's locked away for thousands of years.

Anthony Aufdenkampe (right), and Rolf Aalto, shown at London Grove Friends Meeting cemetery.

"They usually have one of three fates," Aufdenkampe says, "a return to the skies as a greenhouse gas, incorporation into the tissues of living organisms, or burial in soils and sediments."

From dust to dust

Where do scientists look for clues to those ultimate fates? They dig into soils and scour waterways, with a stop along the way near a local cemetery or two.

"Soils under ancient trees and in old cemeteries provide a geochemical reference that we can use to estimate human-caused erosion elsewhere on the landscape," says Aufdenkampe.

People inevitably leave their mark on the land, he says. But will the carbon buried by 400 years of human activities give up the ghost and move on, or will it rest in peace?

"In the future," Aufdenkampe asks, "will what's in the soil return to haunt us all?"

Scientists at the Christina River CZO hope to discover how this sediment - and that above and below it - was deposited, and where waterways may carry it next, if anywhere.

"How are humans affecting the carbon cycle in a watershed like the Christina River Basin?" asks Aufdenkampe. "How far afield does what happens here go? Does it reach the Delaware, the Atlantic or beyond?"

Research at the CZO takes a "whole watershed" approach to discovering where carbon and other elements end up.

See web-version for full photo gallery:
"Scientists in a Graveyard"
http://www.nsf.gov/discoveries/disc_summ.jsp?cntn_id=125882&org=NSF

High-Peak Creeks, Forest Fires and Landscape Erosion: Could They Be Linked?

Colorado's Boulder Creek watershed: where rushing streams, raging blazes and the Rockies meet

14 January 2013

Research in Gordon Gulch, Colo., part of NSF's Boulder Creek Critical Zone Observatory.

Fire and water. One scorches the other, only to be drowned in return. Could their effects on a watershed be related?

Scientists conducting research in Colorado's Rocky Mountains at the National Science Foundation (NSF) Boulder Creek Critical Zone Observatory (CZO) are finding out.

Boulder Creek is a 31-mile-long stream draining the Rocky Mountains to the west of Boulder, Colo., as well as the city itself and surrounding plains.

At the Boulder Creek CZO, scientists see fire and water as being closely tied to the landscape--and to what's below that landscape in the subsurface environment.

"Ultimately, it's the landscape that controls where fires are most likely," says scientist Suzanne Anderson of the University of Colorado at Boulder, Director of the Boulder Creek CZO.

"It all begins with the presence of the mountains," she says, "with the landscape beneath the forests and streams."

The Colorado Front Range, whose mountains Boulder Creek plummets down, are the stage upon which fire, water and forests are set.

Take the Fourmile Canyon Fire of September, 2010. It burned 6,400 acres, destroyed 169 homes and caused more than $217 million in damages.

The wildfire raged through the Boulder Creek watershed's rugged terrain. The resulting deforestation, CZO scientists have found, left the area at risk of flooding and erosion, including debris flows from the fire.

Bird's eye view: Boulder Creek and the Rocky Mountains from the skies above.

NSF's Critical Zone Observatories: where rock meets water meets life

The Boulder Creek CZO is one of six NSF CZOs in watersheds across the nation.

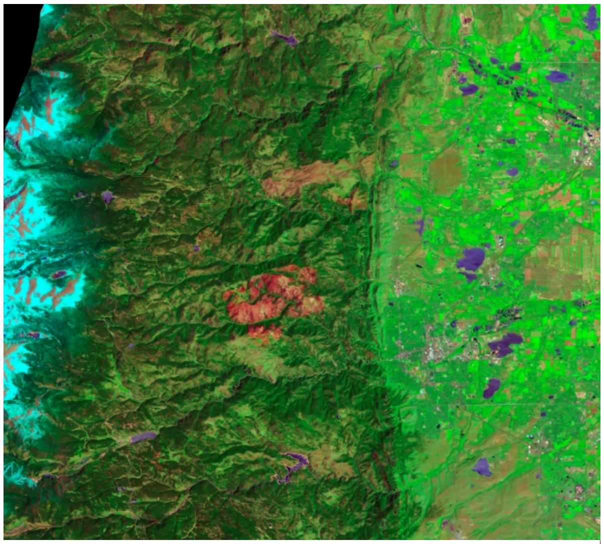
In addition to the Boulder Creek site, CZOs are located in the Southern Sierra Nevada, Christina River Basin on the border of Delaware and Pennsylvania, Susquehanna Shale Hills in Pennsylvania, Luquillo riparian zone in Puerto Rico, and the Jemez River and Santa Catalina Mountains in New Mexico and Arizona.

A tree grows near Boulder Creek: a ponderosa pine extends its roots into rock below.

They're providing researchers with a new understanding of the critical zone - the region between the top of the forest canopy and the base of unweathered rock.

"The critical zone is our living environment," says Enriqueta Barrera, program director in NSF's Division of Earth Sciences, which funds the CZO network. "The CZOs offer us new knowledge about the critical zone and its response to climate and land-use change."

They're the first systems-based observatories dedicated to understanding how Earth's surface processes are coupled, she says. "They will help us predict how the critical zone affects the ecosystem services on which society depends."



Location of Boulder Creek, and tributary Fourmile Creek, with red burn scar from a wildfire.

The water cycle, the breakdown of rocks and eventual formation of soil, the evolution of rivers and valleys, patterns of plant growth and landforms all result from processes that take place in the critical zone.

"The CZOs," says Barrera, "are fostering a new view of the critical zone as one holistic system."

Fast-moving water - and fire - in the critical zone

What are the long-term effects of the Fourmile Canyon Fire and other wildfires on watersheds such as Boulder Creek?

Studies of streams after wildfires have yielded conflicting results. Some show increases in pH (water that's more basic than acidic), turbidity, nutrients, sulfate and metals. Other research reports few effects.

"Many of these studies sampled water chemistry at intervals that didn't catch rapid changes," says Anderson. "At the Boulder Creek CZO, we're conducting high-frequency stream sampling, and evaluating how upland hydrologic and biogeochemical processes affected by fire influence downstream water quality."

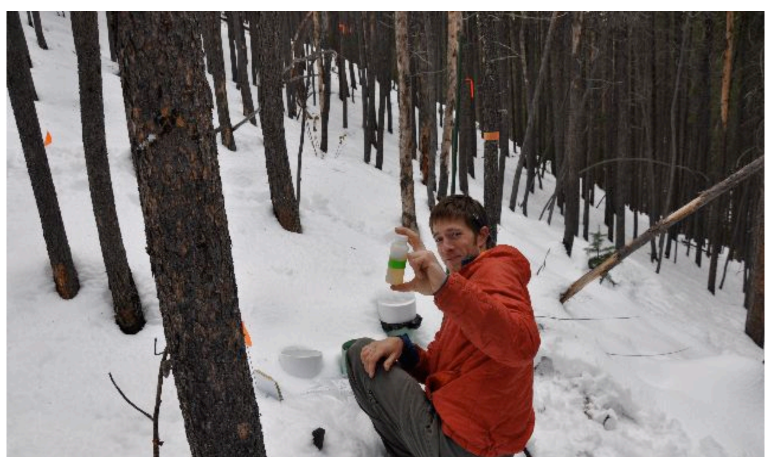
Since the Fourmile Canyon Fire, scientists at the Boulder Creek CZO and the U.S. Geological Survey have been tracking discharge rates, nutrients, metals and ecosystem characteristics such as numbers and species of invertebrates that live in streams.

Runoff from burned north- and south-facing slopes is being measured to assess how hillslopes respond differently following fire.

Instruments have been placed on the hillslopes, and in soils along Boulder Creek's banks, to record changes. Stream water and soil chemistry are being compared with those of nearby unburned areas.

Monitoring continues during snowmelt when water levels are high, and during "gully washer" summer thunderstorms.

In the summer of 2011, for example, a severe storm led to an 8,100 percent increase in stream discharge in Fourmile Creek, a tributary of Boulder Creek. "That was three times higher than had ever been measured," says Anderson.



Researcher T. Joe Mills samples winter snows in the Boulder Creek watershed.

The storm flooded homes and blocked roads with sediment. It also resulted in concentrations of in-stream total suspended solids that were 4,000-fold above baseline.

Some of that sediment remains in the creek channel, then flows downstream when more rain falls in the area.

"Such precipitation events can lead to catastrophic erosion that affects long-term sediment loads," says Anderson. "Increases in turbidity, nitrate and what's called dissolved organic carbon in turn may affect drinking water treatment processes."

These studies are but a few of "many taking place at the Boulder Creek CZO on everything from how the 'architecture' of the critical zone affects its hydrology, to the role trees play in the critical zone's evolution," says Anderson.

Scientist Ken Nelson studies the soils beneath trees at the Boulder Creek CZO.

The Front Range: a regional water tower

With its high peaks, the Colorado Front Range "harvests" precipitation from the atmosphere. Most of that precipitation falls as snow. The snowpack becomes a reservoir, and the mountains act as a water tower.

"The distribution of water resources in western North America is actually controlled by the geologic history of the region," says Anderson. "It sets the location, height and width of the moisture-trapping and moisture-holding mountain ranges."

Forests near Boulder Creek - and everywhere in the West - are found in mountain ranges. Moisture is high enough there for trees to flourish, and precipitation evaporates more slowly.

But where forests grow, fires often aren't far behind. "With more droughts in recent years," says Anderson, "we're more at risk of fires."

The role of erosion

The Front Range - more than 10,000 feet high at its crest - is eroding, says Anderson, but very slowly.

For the most part, "it's cool and moist there," she says, "and 'soil-mantled'--the soil wasn't scraped away by the glaciers that covered the region in the distant past."

Most of this slowly eroding terrain has been sliced by rivers, which have hollowed out deep canyons such as Boulder Canyon.

"The canyons are giant drains carved into the terrain," says Anderson. "They lower the water table of surrounding slopes. Their erosion history sets up broad regions of well-drained forested landscape."

That well-drained landscape is the corridor where big fires, such as the one in Fourmile Canyon, have happened.

"The topography of the Front Range is interconnected with water and fire in the landscape," says Anderson.

Past is prologue?

At Boulder Creek, scientists are looking down into the subsurface, Anderson says, "to understand how the landscape evolved into its present state, and how that controls everything from where forests are found, to how fast weathering of subsurface rock takes place, to a watershed's ability to collect and store water." And, perhaps, to put a fire out.

Meanwhile, the creek flows onward, cutting into the mountain landscape as it goes - and carrying parts of the Rockies with it.

"Amber and white and black in the arrested spaces," wrote H.H. Jackson in 1878 in *Bits of Travel at Home*, "[Boulder Creek] whirls under bridges and round the corners, doubles on itself, leaps over and high above a hundred rocks in a rod, breaks into sheafs and showers of spray, foams and shines and twinkles and glistens; and if there be any other thing which water at its swiftest and sunniest can do, that it does also, even to jumping rope with rainbows."

A perfect description, says Anderson, of the role of fast-flowing streams in the critical zone.

See web-version for video:
"Where Rock Meets Life"
http://www.nsf.gov/discoveries/disc_summ.jsp?cntn_id=126540&org=NSF

El Yunque, Majestic Rocky Icon of Puerto Rico: Impervious to the Ravages of Time?

Anvil-shaped promontory formed inside an ancient supervolcano

27 February 2013

The peak El Yunque presides over the island of Puerto Rico.

El Yunque. It could be the name of an ancient chieftain.

On the island of Puerto Rico, in a sense it is.

El Yunque, which means "the anvil" in Spanish, is a majestic, flat-topped promontory. It stands high above rivers and streams below, and has been an icon since pre-Columbian times.

The barren rock, some 3,412 feet tall, lords it over miles of rainforest that surround it on all sides.

El Yunque is usually enshrouded by mist from clouds. Swept constantly by trade winds, it's often buffeted by hurricanes.

The rock is showered with rain an average of three times a day - in total, more than 14 feet of rain every year.

With Puerto Rico's tropical climate, El Yunque should be covered with vegetation and should be eroding rapidly, says scientists. But it isn't.

Waterfalls cascade down El Yunque's steep sides.

A long-lived chieftain endures: but how?

To solve the mystery of El Yunque, researchers from the National Science Foundation's (NSF) Luquillo Critical Zone Observatory (CZO) set out to quantify the current rate of the rock's erosion.

The Luquillo CZO is one of six NSF CZOs in watersheds across the nation.

In addition to the Luquillo site, CZOs are located in the Southern Sierra Nevada; Christina River Basin on the border of Delaware and Pennsylvania; Susquehanna Shale Hills in Pennsylvania; Boulder Creek in the Colorado Rockies; and the Jemez River and Santa Catalina Mountains in New Mexico and Arizona.

They're providing scientists with a new understanding of the critical zone - the region between the top of the forest canopy and the base of unweathered rock.

"The critical zone is our living environment," says Enriqueta Barrera, program director in NSF's Division of Earth Sciences, which funds the CZO network. "The CZOs offer us new knowledge about this important zone and its response to climate and land-use change."

The CZOs are the first systems-based observatories dedicated to understanding how Earth's surface processes are coupled, she says. "They will help us predict how the critical zone affects the ecosystem services on which society depends."

The water cycle, the breakdown of rocks and eventual formation of soil, the evolution of rivers and valleys, patterns of plant growth and landforms all result from processes that take place in the critical zone.

Lord of the forest ring

El Yunque stands above them all.

To find an answer to El Yunque's slow erosion rate, scientists Jane Willenbring, Gilles Brocard and the late Frederick Scatena of Penn State University used a new approach to calculate how it has changed over time.

Morning mist hides the rocky face of El Yunque.

The method involves counting isotopes, or variants, of certain chemical elements that accumulate in rocks when they're hit by cosmic rays.

Using these particular isotopes, called cosmogenic nuclides, the researchers confirmed that forest soils that aren't disturbed by human activity erode at rates of 250 to 500 feet per million years.

Undisturbed forested areas in Puerto Rico, for example, have eroded some 1.6 to 3.2 inches since Europeans first landed there in 1498.

The late scientist Fred Scatena (left) and colleagues near a weather station on East Peak.

These rates are slow compared with those of most tropical areas, says Willenbring.

The scientists also found that the presence of forests can greatly reduce erosion, even in a steep tropical environment with frequent hurricanes.

An ecological view over the Luquillo Mountains

"At the beginning of the project," says Willenbring, "everyone thought that the Luquillo Mountains were about 30 million years old. But our research demonstrates that the Luquillo critical zone is about 10 times younger than that.

"It's eroding and chemically weathering at a wide range of rates. But its thick weave of matted roots and vegetation holds in the soil and stabilizes the hillslopes such that they erode more slowly than one would expect."

On the other hand, she says, Puerto Rico waterfalls such as the well-known La Coca Falls are eroding very quickly. Water rushes in torrents through steep canyons and gullies, carrying gravel and boulders with it.

"The wave of erosion - whether fast or slow - affects all parts of the critical zone," says Willenbring, "and sets the tempo for how quickly minerals and nutrients are ferried to the surface, which in turn feed the forest above.

"We were surprised by how connected the landscape is. It seems as though even the trees understand geomorphology.

"How passive are soil microbes and trees? Do they position themselves where it's best to live, or do they actively change the environment they're already in.

Glimpse of El Yunque's past...and future?

To answer these questions as they apply to El Yunque, cosmogenic nuclides allowed the researchers to make the first measurements of the erosion rate of the peak.

El Yunque's barren surface is eroding at a rate of just 13 feet per million years.

The Rock has only lost 0.08 inches of its height since Europeans first arrived on the island.

That relatively slow rate of erosion explains why El Yunque juts above the surrounding landscape, and lacks the soil needed to support the growth of plants on its surface.

"The texture and composition of the rocks that form El Yunque are more erosion-resistant than those of the surrounding landscape," says Willenbring.

But how did The Rock get there in the first place?

El Yunque is a remnant of an ancient supervolcano, Hato Puerco. This volcano was one of the region's largest and most active volcanic centers during the Cretaceous period 145-66 million years ago.

El Yunque and East Peak from below. The U.S. Navy once had a facility on East Peak.

Geoscientists are studying erosion on El Yunque, a hard-headed "cap" on the island.

"El Yunque's hardness and chemical properties came from being 'cooked' in the chamber of that ancient volcano," says Willenbring. Other rocks weren't subjected to this same heating, and are less resistant to chemical breakdown and erosion.

Puerto Rico's icon is a hard-headed cap atop the island, one that escaped the geologic fate of all other rocks there.

In a humid tropical climate, long live El Yunque.

This article is dedicated to the memory of Fred Scatena, former principal investigator of the Luquillo CZO.

The Search for White Gold—Snowmelt

Thin snowpack puts ecosystems and water resources in critical condition

16 April 2013

Tracking high-elevation snowfall at NSF's Niwot Ridge LTER site in Colorado.

An American exodus, it's been called, the largest "migration" of people in modern U.S. history.

It happened during the 1930s Dust Bowl, when severe drought conditions coupled with erosion brought about an environmental catastrophe. Choking dust storms caused major economic, ecological and agricultural damage in Texas, Oklahoma and parts of New Mexico, Kansas and Colorado.

Ill winds blew across fields, plucking deep-rooted grasses and carrying them hundreds of miles. Farmlands disappeared and homes were destroyed. These "black blizzards" swirled all the way to East Coast cities such as New York and Washington.

On April 14, 1935 - "Black Sunday" - 20 of the worst of the storms turned day into night. More than 500,000 people were left homeless. Most headed due west in search of work. Some, victims of dust pneumonia or malnutrition, never made it.

For today's residents of states like Colorado, that scene is long ago and far away. Or is it? On Earth Week, with much of the Mountain West in an extreme drought, people in the Four Corners are wondering.

The search for white gold

The answer lies in white gold: snowmelt.

"Snow and its meltwaters are indeed white gold, and they're getting harder and harder to find," says Mark Williams, an ecologist at the University of Colorado-Boulder and principal investigator of the National Science Foundation's (NSF) Niwot Ridge Long-Term Ecological Research (LTER) site in Colorado.

In western North America, snow typically begins to fall in November. It piles up, reaching its peak in April. In the Rocky Mountains region, 85 percent of the water resources come from snow as it eventually melts.

At Niwot Ridge, ecologists are prospecting for white gold, no easy task at 9,800 feet up.

Facing blizzard conditions, researchers prepare to measure high-peak snow properties.

Niwot Ridge is one of 26 NSF LTER sites in mountain, prairie, coastal and other ecosystems around the world. The sites are primarily supported by NSF's Directorate for Biological Sciences, with major additional funding from its Directorate for Geosciences.

Niwot Ridge is part of the Boulder Creek, Colorado, watershed, where scientists at NSF's Boulder Creek Critical Zone Observatory (CZO) are also looking for white gold.

Their search takes them into Earth's critical zone - the region between the top of the forest canopy and the base of unweathered rock. Boulder Creek is one of six such NSF CZOs in watersheds across the country.

"The depth of winter's snowpack and timing of spring snowmelt determine how much water we will have the following summer," says Williams, who is also affiliated with the Boulder Creek CZO, "and the extent of a drought that's the most severe since the Dust Bowl."

Spring has sprung: mountain wildflowers are bellwethers of climate change.

It's 2013, not 1935. But farmers are again asking whether there will be enough water for their fields.

Water well running dry

At Niwot Ridge and Boulder Creek, scientists face howling winter winds to measure snow depth.

Without deep snows, the researchers are discovering, our water well is running dry.

"Water is critical for recharging soil moisture, keeping plants alive and replenishing stream networks," says Williams. "Those streams and rivers are what feed our reservoirs."

Water in all its forms - vapor, liquid and solid - distinguishes our planet, says John Wingfield, NSF Assistant Director for Biological Sciences.

"Much remains to be learned about the complex biological processes, and interactions of the biosphere and geosphere, in snow and ice cover," Wingfield says. "Large-scale shifts of snow and ice fields will have major downstream effects. The implications for ecosystems even far removed from high altitude and latitude snow and ice are unknown."

To find answers, Williams, Suzanne Anderson, principal investigator of the Boulder Creek CZO, and colleagues recently conducted a study of water flow on hillslopes of the Colorado Front Range. They published the results in the journal *Hydrological Processes*.

Other authors of the paper are Eve-Lyn Hinckley and Robert Anderson of the University of Colorado-Boulder, Brian Ebel of the U.S. Geological Survey and Rebecca Barnes of Bard College. Hinckley is the lead author.

"The interaction of climate and ecosystems is an example of the critical questions that lie at the interface between scientific disciplines," says Roger Wakimoto, NSF Assistant Director for Geosciences. "The results from this study will greatly improve our understanding of the hydrologic cycle."

How will alpine species such as pikas fare in a warmer world? Biologists are finding out.

The research, conducted in the headwaters of the Rockies, shows that higher temperatures are shifting the timing of maximum snow accumulation ever-earlier and decreasing the ratio of snow-to-rain.

"It's raining a heck of a lot more than it used to," says Williams. "In times past, it did nothing but snow."

A flash-in-the-pan, rain is gone more quickly than snow. Within hours of falling, it evaporates or seeps into the ground, and doesn't have snow's longer residence time on mountainsides.

Scientist Mark Williams samples snow with help from Katya Hafich and Kendall Gotthelf.

"The slow melt of mountain snow is what keeps streams and rivers running like spigots turned on," says Williams. "Eventually, they lead right to the taps in our kitchens, bathrooms and yards."

Where, exactly, does white gold come from?

As scientists at Niwot Ridge and Boulder Creek have discovered, the mother lode is hidden in snow "water towers."

"Water towers" for the Mountain West - and beyond

Mountain ecosystems serve as "water towers" that store winter snow until it's released during spring runoff.

The water towers, however, have sprung leaks.

Subalpine forests are becoming warmer and drier during all seasons. At higher elevations, alpine tundra has longer growing seasons, warmer summers and cool and wet versus cold and snowy winters.

How long a snowpack lasts is affected by what scientists call aspect: whether a hillslope faces north or south.

In the Rockies, lodgepole pines, which prefer colder, wetter climes, dot north-facing slopes; Ponderosa pines cover south-facing, drier slopes.

"You can pretty well guess how much snow a slope will have by which way it faces," says Williams, "and by which tree species grows there."

Top: View on June 22, 2011, from Green Lakes Valley, Colorado, at NSF's Boulder Creek CZO: the valley is covered with snow.

Bottom: A year later at Green Lakes Valley on June 22, 2012: very little snow. The new normal?

A tale of two trees

Lodgepole pine-covered, north-facing slopes are usually laden with snow straight through the winter. South-facing slopes, with their Ponderosa pines, have only intermittent snow.

"North- and south-facing slopes at the Boulder Creek CZO are an excellent natural laboratory for studying the effects of climate change on water availability and soil geochemistry," says Enriqueta Barrera, NSF program director for the CZO network, supported by the agency's Directorate for Geosciences.

Williams agrees. "North-facing slopes store more water in the 'near-surface' than south-facing slopes," he says. "On south-facing slopes, water sinks quickly into the deep bedrock."

Earlier snowmelt may be changing those patterns, "which could have consequences for the health and composition of the forest," Williams says, and for water resources.

"Research at sites such as the Niwot Ridge LTER shows how catastrophic large-scale shifts in snowmelt will be," says Saran Twombly, NSF program director for the LTER network.

Lack of snow, for example, led to forest fires like Colorado's High Park Fire of June, 2012, and Waldo Canyon Fire less than a month later. The Waldo Canyon Fire was the most expensive wildfire in Colorado history. It was also the most destructive.

"White blizzard" falling

It's April 8, 2013: date of the average peak snowpack in the Colorado mountains. Despite this winter's snow drought, the day, perhaps, of a good omen.

"Heavy snow will blanket much of the west," intoned weather forecasters. Blizzard watches went up. Snowplows, fallow too long, once again geared down.

When all was said and done, more than a foot of snow fell across high peaks and low prairies.

It sparkled across the land, until spring sunlight turned it into a precious commodity: white gold.

See web-version for full photo gallery and videos:
"Scientists work in blizzard conditions at NSF's Niwot Ridge LTER Site in Colorado" and "Snow, and plenty of it, in Colorado's High Peaks--but for how long?"
http://nsf.gov/discoveries/disc_summ.jsp?org=NSF&cntn_id=127580

Trail of Fire Leads to Less Snow, Threatened Water Resources

Scientists study New Mexico's Rabbit Mountain, where forests burned in the 2011 Las Conchas fire

25 April 2013

New Mexico's 2011 Las Conchas fire as it races down the flanks of the Jemez Mountains.

If a tree falls in a forest and no one is around to hear it, does it make a sound?

The answer is yes, if it happened in New Mexico's Jemez River Basin on June 26, 2011, at 1 p.m. local time.

The tipping of one tree as it creaked and fell hinted at a crackle soon to come, a fast-burning wildfire. Ultimately, the fire blazed through a large part of a 1.5-million-acre national forest.

On the day the fire started, strong, unpredictable winds blew through the trees, rustling leaves and creaking dead wood. Perhaps in a gust, a lone tree fell. On the way down, it took out a power line and sparked a fire that, by high noon the next day, had burned 43,000 acres, an acre every two seconds.

At sundown that next day, the Las Conchas fire, as it came to be called, still ran wild. The toll had climbed to more than 61,000 acres of forest. Egged on by north winds, it jumped the trails of the Pajarito Mountain ski area. Then it turned and raged south, threatening the town of Cochiti, N.M.

Within four days, it had singed more than 103,000 acres, making it the largest fire in New Mexico history at the time.

The forest and the watershed - the critical zone - left behind

What happened to the forests, rivers and streams the Las Conchas fire left behind?

To find out, scientists at the National Science Foundation (NSF) Jemez River Basin and Santa Catalina Mountains Critical Zone Observatory (CZO), one of six such NSF CZOs in watersheds across the country, lit out for the hills.

The Jemez River Basin and Santa Catalina Mountains CZO is formed by twin sites: One in the Jemez River Basin in the Valles Caldera National Preserve north of Albuquerque, N.M., in the greater Rio Grande Basin; the

Ghosts of the forest stand guard over NSF's Jemez River Basin Critical Zone Observatory and the Valles Caldera National Preserve.

critical zone structure and the cycling of water and carbon alter short-term hydrology and long-term landscape evolution?

The water cycle, the breakdown of rocks and the eventual formation of soil, the evolution of rivers and valleys, and the patterns of plant growth and landforms, all result from processes that take place in the critical zone.

"The critical zone is our living environment," says Enriqueta Barrera, a program director in NSF's Division of Earth Sciences, which funds the CZO network. "The CZOs offer us new knowledge about this important zone and its response to climate and land-use change."

other in the Santa Catalina Mountains northeast of Tucson, Ariz., in the Colorado River Basin.

In addition to the Jemez River Basin and Santa Catalina Mountains site in New Mexico and Arizona, NSF CZOs are located in the Southern Sierra Nevada, Christina River Basin on the border of Delaware and Pennsylvania, Susquehanna Shale Hills in Pennsylvania, Boulder Creek in the Colorado Rockies, and Luquillo National Forest in Puerto Rico.

CZO research provides a new understanding of the critical zone - the thin veneer of Earth that extends from the top of the forest canopy to the base of weathered bedrock.

At the Jemez River and Santa Catalina Mountains CZO, scientists are asking questions such as: How does climate variation affect arid and semiarid ecosystems? And how do feedbacks between

The CZOs are the first systems-based observatories dedicated to understanding how Earth's surface processes are coupled, she says. "They will help us predict how the critical zone affects the ecosystem services on which society depends."

Fire burns long after it's out

Water is at the top of that list of ecosystem services.

The freshwater supplies of the American West rely, for the most part, on snow.

As snow melts into water, it begins a journey that starts in the mountains and ends in faucets. When people turn on the shower or the sprinkler, they're watering themselves, and their lawns and food crops with melted snow.

The Colorado River, the Rio Grande and other rivers in the mountain west are the main sources of water for some of the driest parts of the country, say Jemez River Basin and Santa Catalina Mountains CZO scientists Jon Chorover and Paul Brooks of the University of Arizona and Adrian Harpold of the University of Colorado.

"Their flows are predominantly fed by snowmelt from high-elevation forests and meadows," says

Brooks.

Snow-covered forests are "a critical source of water in the Western U.S.," agrees Chorover. "Forests' ability to 'hold snow' can be affected by fires, tree diseases, insect-caused die-offs and other factors."

The Las Conchas fire provided a unique opportunity to "evaluate how forest fires interact with a changing climate," says Harpold, first author of a recent paper on the fire's effects on winter snow and spring snowmelt published in the journal *Ecohydrology*. Brooks and other scientists are co-authors.

Top: On Rabbit Mountain, N.M., scientists survey slopes with unburned healthy forests.

Bottom: A comparison survey of Rabbit Mountain's badly burned forests.

"Forest fires have been increasing in size and severity for the last several decades," Harpold says. "Drier and warmer-than-average conditions in New Mexico in 2011 contributed to fires like Las Conchas.

"When the fire removed the forest canopy, more water vapor was lost from the snow amount of water stored in the snowpack and surface to the dry atmosphere, reducing the released the following spring."

In essence, the scientists found, areas not burned in the fire retained more snow - and snowmelt water.

Into the Valles Caldera

Scientist Adrian Harpold digs out an instrument used to measure snowmelt chemistry.

The Valles Caldera National Preserve, it's called, a parkland that surrounds the Valles Caldera, a 13.7-mile-wide volcanic caldera in the Jemez Mountains of northern New Mexico. The preserve overlaps the Jemez River Basin CZO.

Valles Caldera National Preserve was the site of the scientists' study; their research was conducted on Rabbit Mountain near the park's southern boundary.

In November, 2011, the researchers placed instruments in several catchments, or river basins, on Rabbit Mountain. The resulting information is being used to better understand the effects of fire on the water, carbon and energy cycles of the entire Jemez River Basin.

"The Jemez River Basin CZO is perfectly situated to learning how fire affects water resources," says Brooks.

In the winter and spring of 2012, Brooks and Harpold, along with other researchers and students, collected and analyzed thousands of data points on snow depth and density in burned and unburned forests on Rabbit Mountain.

"We obtained one of the most complete datasets to date on snow hydrology and fire," says Brooks.

Spruce-fir forests dominate Rabbit Mountain's heights; ponderosa pines and oak scrublands cover the lower mountain.

Whether in spruce-fir or pine-oak, the Las Conchas fire left much of Rabbit Mountain

Paul Brooks collects samples for snow density, chemistry and physical structure.

with severe burns. Dead, limbless trees, ghosts of the forest, line the horizon.

In unburned forests, about one-third of the fresh snow that fell in the winter of 2012 was caught in trees before it reached the ground. There, shade and wind protection allowed it to accumulate over the winter.

Where trees were lost to the fire, more fresh snowfall made it to the ground. In the end, however, that was a double-edged sword: Lack of shelter from the forest canopy resulted in more of the snowpack disappearing over the winter.

"Such changes in snowpack depth have important ramifications," says Chorover, "for ecological health and for downstream water resources."

After the Las Conchas fire, if a tree falls in the forest and no one is around to hear it, does it make a sound?

If you're listening for burbling spring brooks or streaming kitchen faucets, you may hear nothing but drip, drip, drip.

Or silence.

Appendix: Image Credits

Can Marcellus Shale Gas Development and Healthy Waterways Sustainably Coexist?

1. Chuck Anderson, Penn State
2. Penn State
3. USGS
4. State of Pennsylvania
5. Chuck Anderson, Penn State
6. NPS

A Tree Stands in the Sierra Nevada

1. NSF Southern Sierra CZO/Jenny Park

2-5.: NSF Southern Sierra CZO

Science on the Graveyard Shift

1. Kyungsoo Yoo
2. Wikimedia Commons
3. Kyungsoo Yoo
4. Beth Wenell
5. Wikimedia Commons
6. Anthony Aufdenkampe
7. Kyungsoo Yoo

High-Peak Creeks, Forest Fires and Landscape Erosion: Could They Be Linked?

1. Suzanne Anderson, University of Colorado at Boulder
2. Robert Anderson, University of Colorado at Boulder
3. Suzanne Anderson, University of Colorado at Boulder
4. NASA
5. Suzanne Anderson, University of Colorado at Boulder
6. Suzanne Anderson, University of Colorado at Boulder

El Yunque, Majestic Rocky Icon of Puerto Rico: Impervious to the Ravages of Time?

1. Gilles Brocard
2. Wikimedia Commons
3. Wikimedia Commons

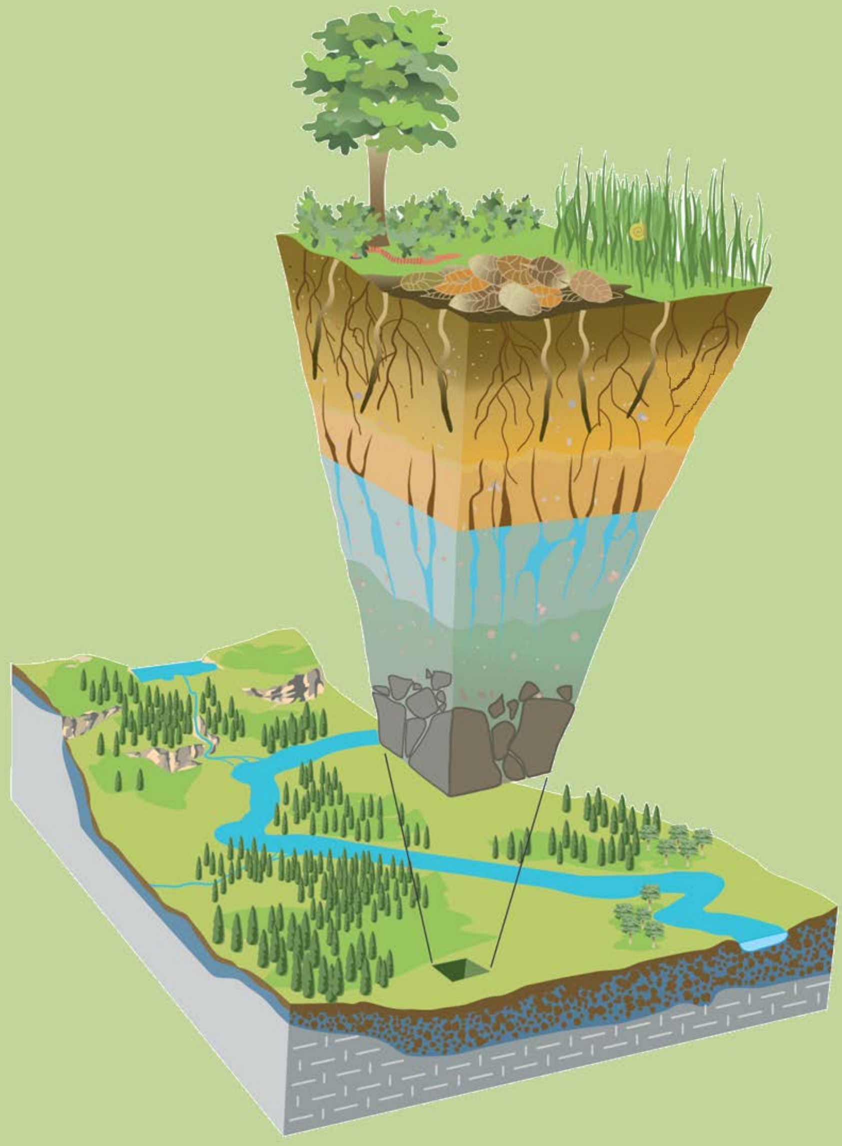
4-6.: Gilles Brocard

The Search for White Gold—Snowmelt

1. NSF Niwot Ridge LTER site
2. Ryan Vachon
3. University of Colorado
4. Ryan Vachon
5. William Bowman
6. NSF Boulder Creek CZO
7. NSF Boulder Creek CZO

Trail of Fire Leads to Less Snow, Threatened Water Resources

1. Wikimedia Commons
2. Valles Caldera National Preserve
3. Paul Brooks
4. Paul Brooks
5. Allison Peterson
6. Brian Chaszar



NSF 13-112