

Special Section: Hydrological Observatories

Core Ideas

- Development of a 300-km² mountainous headwater testbed began in 2016 in the East River.
- The testbed can be used to explore how watershed changes impact downgradient water availability and quality.
- System-of-system, scale-adaptive approaches can potentially improve watershed dynamics simulation.
- We have new approaches to monitor and simulate water partitioning and system responses.
- The East River watershed has been developed as a “community” testbed.

S.S. Hubbard, K.H. Williams, D. Agarwal, J. Banfield, H. Beller, N. Bouskill, E. Brodie, B. Dafflon, D. Dwivedi, N. Falco, B. Faybishenko, P. Nico, C. Steefel, T. Tokunaga, P.A. Tran, H. Wainwright, and C. Varadharajan, Lawrence Berkeley National Lab., Berkeley, CA 94720; J. Banfield, Earth and Planetary Science, Univ. of California, Berkeley, CA 94720; R. Carroll, Desert Research Institute, Reno, NV 89512; R. Maxwell, Colorado School of Mines, Golden, CO 80401; H. Steltzer, Ft. Lewis College, Durango, CO 81301. *Corresponding author (sshubbard@lbl.gov).

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The East River, Colorado, Watershed: A Mountainous Community Testbed for Improving Predictive Understanding of Multiscale Hydrological–Biogeochemical Dynamics

Susan S. Hubbard,* Kenneth Hurst Williams, Deb Agarwal, Jillian Banfield, Harry Beller, Nicholas Bouskill, Eoin Brodie, Rosemary Carroll, Baptiste Dafflon, Dipankar Dwivedi, Nicola Falco, Boris Faybishenko, Reed Maxwell, Peter Nico, Carl Steefel, Heidi Steltzer, Tetsu Tokunaga, Phuong A. Tran, Haruko Wainwright, and Charuleka Varadharajan

Extreme weather, fires, and land use and climate change are significantly reshaping interactions within watersheds throughout the world. Although hydrological–biogeochemical interactions within watersheds can impact many services valued by society, uncertainty associated with predicting hydrology-driven biogeochemical watershed dynamics remains high. With an aim to reduce this uncertainty, an approximately 300-km² mountainous headwater observatory has been developed at the East River, CO, watershed of the Upper Colorado River Basin. The site is being used as a testbed for the Department of Energy supported Watershed Function Project and collaborative efforts. Building on insights gained from research at the “sister” Rifle, CO, site, coordinated studies are underway at the East River site to gain a predictive understanding of how the mountainous watershed retains and releases water, nutrients, carbon, and metals. In particular, the project is exploring how early snowmelt, drought, and other disturbances influence hydrological–biogeochemical watershed dynamics at seasonal to decadal timescales. A system-of-systems perspective and a scale-adaptive simulation approach, involving the combined use of archetypal watershed subsystem “intensive sites” are being tested at the site to inform aggregated watershed predictions of downgradient exports. Complementing intensive site hydrological, geochemical, geophysical, microbiological, geological, and vegetation datasets are long-term, distributed measurement stations and specialized experimental and observational campaigns. Several recent research advances provide insights about the intensive sites as well as aggregated watershed behavior. The East River “community testbed” is currently hosting scientists from more than 30 institutions to advance mountainous watershed methods and understanding.

Abbreviations: LBNL, Lawrence Berkeley National Laboratory; RMBL, Rocky Mountain Biological Laboratory; SNOTEL, Snow Telemetry.

Increasing human populations and resource-intensive lifestyles are driving a growing demand for clean water, food, and energy. In parallel, extreme weather, land-use change, climate change, fire, and other perturbations are significantly reshaping interactions within watersheds throughout the world. While watersheds are recognized as Earth’s key functional unit for assessing and managing water resources, hydrological processes in watersheds also mediate most, if not all, biogeochemical interactions that support terrestrial life on Earth (e.g., National Research Council, 2012). While society is dependent on water resources and the biogeochemical benefits provided by watersheds, the scientific community is at an early stage of developing a predictive understanding of how watersheds function as integrated hydrological–biogeochemical systems. This limitation hinders resource managers, who strive to optimize energy, agricultural, water, and other societally important systems under changing environmental conditions (e.g., Carpenter et al., 2015).

Several formidable challenges inhibit a predictive understanding of watershed hydrological–biogeochemical function across the length and time scales relevant for resource

management. A key challenge is associated with the variety of complex interactions that occur in a watershed, including interactions among plants, microorganisms, organic matter, minerals, dissolved constituents, and migrating fluids. These interactions occur across a wide range of scales, both within and across watershed compartments, as well as along extensive lateral gradients. Abundant recent literature has documented how multiscale heterogeneity within a watershed influences its function (e.g., Harvey and Gooseff, 2015; Cole et al., 2007; Hotchkiss et al., 2015; Duncan et al., 2013). Research has also illuminated the disparity between time and space scales associated with relevant processes. For example, studies have suggested that the relevant spatial scale for the heterogeneity that governs hydrological states and fluxes is on the order of 100 m (Wood et al., 2011) and that the scale relevant for biogeochemical dynamics is on the order of 1 m or less (e.g., Taş et al., 2018; Burt and Pinay, 2005; Groffman et al., 2009; Frei et al., 2012; McClain et al., 2003). Recent research has focused on exploring hydrologic controls on biogeochemistry, including hotspots and hot moments (Groffman et al., 2009; Gu et al., 2012; Arora et al., 2016a; Dwivedi et al., 2018; McClain et al., 2003; Czuba and Fofoula-Georgiou, 2015; Vidon et al., 2010; Wainwright et al., 2016). Several important studies have emphasized the need for new research paradigms for analyzing complex and dynamic watersheds under future conditions (e.g., Harte, 2002; Maxwell et al., 2007; Milly et al., 2008, 2015; Vörösmarty et al., 2010; Ehret et al., 2014). Process-based, integrated hydrologic numerical models have been used to predict the response of watersheds to perturbations (e.g., Camporese et al., 2014; Maxwell et al., 2014; Troch et al., 2013; Riley and Shen, 2014; Sulis et al., 2010; Dwivedi et al., 2018). While these approaches show significant promise, a challenge remains to develop the capability to simulate hydrologically driven biogeochemical watershed dynamics both accurately and tractably.

The East River watershed in the Upper Colorado River Basin was specifically developed to improve predictions of hydrology-driven watershed biogeochemical behavior. A set of recent and related studies performed in a semiarid floodplain of the Upper Colorado River Basin located near Rifle, CO, informed the scientific questions, observational design, and approaches underway at the East River watershed site. The Rifle studies were performed to identify key controls on hydrology-driven biogeochemistry and to test new approaches for characterizing and simulating multiscale behavior up to the floodplain scale. A particular emphasis was placed on exploring the value of fine space or timescale information for informing reactive transport models and improving prediction of floodplain-scale exports of C to the Colorado River. Research included consideration of the floodplain microbial community diversity (Castelle et al., 2015; Brown et al., 2015; Hug et al., 2016a, 2016b; Long et al., 2016; Anantharaman et al., 2016) and metabolic potential (Jewell et al., 2016); the contribution of vadose zone microbial respiration to the floodplain C cycle (Tokunaga et al., 2016); the identification of hotspots and hot moments using geophysical approaches (Wainwright et al., 2016); and the impact of hotspots and hot moments on floodplain reactive transport

predictions of floodplain exports to the Colorado River (Arora et al., 2017; Yabusaki et al., 2017). Important for the design of the larger East River watershed study described here, the Rifle, CO, modeling efforts indicated that exclusion of fine-scale information in the floodplain model (such as reaction pathways derived from metagenomic information and heterogeneity associated with floodplain hotspots) resulted in the underprediction by 230% of CO₂ fluxes to the atmosphere as well as the underprediction by 160% of groundwater inorganic C exports to the Colorado River relative to models that included the detailed information (Arora et al., 2016b, 2017).

While the Rifle, CO, studies focused on a single subsystem of a watershed (a floodplain), extension to scales of the East River watershed requires consideration of (a) how hydrological, vegetation, and subsurface biogeochemical interactions vary across different watershed subsystems, (b) how different subsystems of a watershed respond to perturbations, and (c) how the interactions and associated exports from watershed subsystems propagate through and aggregate into integrated downgradient watershed responses, such as stream water discharge or metal and nutrient concentrations. Regarding perturbations, global climate models predict that shifts toward lower snowfall, earlier snowmelt, and faster runoff will be widespread in western North America in the late 21st century (Diffenbaugh et al., 2013; Higgins and Shi, 2001). Some models also predict reduced spring precipitation and late monsoon precipitation, which in snow-dominated systems could increase the duration between snowmelt and the occurrence of the summer monsoon (Rauscher et al., 2008; Seth et al., 2011) and lead to plant water stress. Given these expected gradual changes, as well as increasingly frequent abrupt events (such as floods, droughts, and wildfires), resource management requires improved prediction of the cumulative hydro-biogeochemical response of watersheds to pulse and press perturbations.

Improving predictive understandings of watershed dynamics and response to perturbations is particularly important for mountainous watersheds due to their societal relevance yet vulnerability to environmental change. Mountainous watersheds provide 60 to 90% of water resources worldwide and have accordingly been referred to as the “water towers” of the world (Viviroli and Weingartner, 2008). Observational evidence suggests that mountain water resources and associated societal services are being threatened by global warming trends (e.g., Beniston and Stoffel, 2014). Climate change has already begun to affect mountain systems in the past few decades by altering snowpack and snowmelt timing (e.g., Lukas et al., 2015), including in the Rocky Mountains (Pederson et al., 2013). Decreased snowpack results in lower albedo and thus increases in the surface absorption of solar radiation. Greater absorbance of short- and longwave radiation can increase the soil temperature and decrease soil moisture (Fyfe and Flato, 1999; Rangwala et al., 2013; Stewart et al., 2005; Stewart, 2009), which, along with increasing air temperature, can contribute to vegetation mortality and vegetation succession in mountainous systems (Allen et al., 2010; Williams et al., 2013).

Vegetation changes, in turn, can create feedbacks on the spatial and temporal energy and water budget components (Biederman et al., 2015; Carroll et al., 2016). This combination of climate and vegetation processes can alter the distribution water partitioning patterns in a non-uniform manner within the watershed, resulting in earlier snowmelt, variable evapotranspiration, shifting patterns of soil water utilization, decreased stream flow and groundwater recharge, increased fluid residence times (Engdahl and Maxwell, 2015), and increased metals and solute loading (Manning et al., 2013; Todd et al., 2012). These changes are expected to lead to unknown impacts on biogeochemical interactions, including plant–soil microbial interactions and microbe–mineral dynamics (Bearup et al., 2014; Mikkelsen et al., 2013) that are important for downgradient water quality.

Watershed Characteristics and the Watershed Function Project

Recognizing the societal importance yet vulnerability of mountainous watersheds to increasingly frequent perturbations, the East River of the Upper Colorado River Basin in Colorado has been designated as a headwaters mountainous watershed testbed. Led by the Lawrence Berkeley National Laboratory (LBNL), this watershed is one of several in a network supported by the USDOE Biological and Environmental Research Subsurface Biogeochemistry Program (<https://doesbr.org>). The East River watershed serves as a testbed for the USDOE Watershed Function Scientific Focus Area (hereafter called the Watershed Function Project) and collaborating institutions. Among other societal benefits, the Colorado River and its tributaries supply more than 1 in 10 Americans with water for municipal use, as well as irrigation water for more than 2.2 million ha of land. The basin also supports more than 4200 MW of electrical generating capacity, providing power to hundreds of local areas and millions of people (Bureau of Reclamation, 2012).

The East River watershed is representative of headwater catchments in the Upper Colorado Basin (Markstrom et al., 2012). It is located northeast of the town of Crested Butte (Fig. 1a; 38°55' N, 106°56' W) and encompasses the Rocky Mountain Biological Laboratory (RMBL). The East River is one of two major tributaries that form the Gunnison River, which in turn accounts for just under half of the Colorado River's discharge at the Colorado–Utah border. The approximately 300-km² East River watershed encompasses the drainages of the East River, Washington Gulch, Slate River, and Coal Creek (Fig. 1b). The watershed has an average elevation of 3266 m, with 1420 m of topographic relief and pronounced gradients in hydrology, geomorphology, vegetation, and weather. The area is defined as having a continental, subarctic climate with long, cold winters and short, cool summers. The watershed has a mean annual temperature of ~0°C, with average minimum and maximum temperatures of –9.2 and 9.8°C, respectively; winter and growing seasons (Fig. 1c and 1d) are distinct and greatly influence the hydrology and biogeochemistry. The

watershed receives an average of 1200 mm yr^{–1} of precipitation (PRISM Climate Group, 2015), the majority of which falls as snow (based on analysis of data from SNOTEL stations in the watershed). Excursions in river discharge are driven primarily by snowmelt in late spring to early summer, with mid- to late-summer monsoonal rainfall inducing rapid but punctuated increases in flow. The watershed is comprised of montane, subalpine, and alpine life zones that collectively include aspen, meadow, mixed conifer, sagebrush, grasses, sedges, and an incredible diversity of forbs (Harte and Shaw, 1995). Land use in the watershed has included tourism, skiing, cattle ranching, mining activities, as well as ranchette and urban development. The watershed geology includes a diverse collection of Paleozoic and Mesozoic sedimentary rocks, including the Mancos shale, that have been intruded by Tertiary igneous laccoliths and ore-rich stocks (Gaskill et al., 1991).

The East River watershed encompasses the RMBL (www.rmbll.org), which has a 90-yr history of biological and ecohydrological measurements including detailed precipitation records pertaining to snow accumulation, snow water equivalent, and snowmelt date beginning in 1977. The RMBL has the capability to provide laboratory and greenhouse space, dining and housing, and both logistical support and community outreach to a diverse collection of public and private stakeholders with interests in the watershed. The East River watershed also encompasses one of the world's longest, continuously running soil warming experiments (Harte and Shaw, 1995; Saleska et al., 2002; Harte et al., 2015), described below.

The Watershed Function Project (watershed.lbl.gov) is using the East River watershed as a testbed to develop predictive understanding of how perturbations to the mountainous watershed impact downgradient discharge of water and constituents. While recent research suggests that the timing of groundwater level excursions in the region may change in the future (e.g., Chen et al., 2016), there is little understanding of how future precipitation, temperatures, and snowmelt timing may influence water partitioning and downgradient biogeochemistry. The Watershed Function Project's focus is on improving predictions of multiscale mountainous watershed dynamics at episodic and seasonal to decadal timescales—timescales that can be used to inform optimal resource management. The project is motivated and designed using insights developed at the Rifle, CO, floodplain. In particular, the Rifle studies indicated that incorporation of fine-scale information into models can indeed improve predictions of larger system behavior. However, results from the Rifle floodplain also forced a recognition that acquiring such fine-scale information over a 300-km² watershed both is intractable and may not be required for accurate prediction of the aggregated watershed response to hydrological perturbations.

The East River watershed has been developed using a “system of systems” approach. This approach involves identification of archetypal watershed subsystems that are small enough to be studied in detail (such as a montane hillslope or a subalpine meadow) and that can be used to inform larger scale predictions

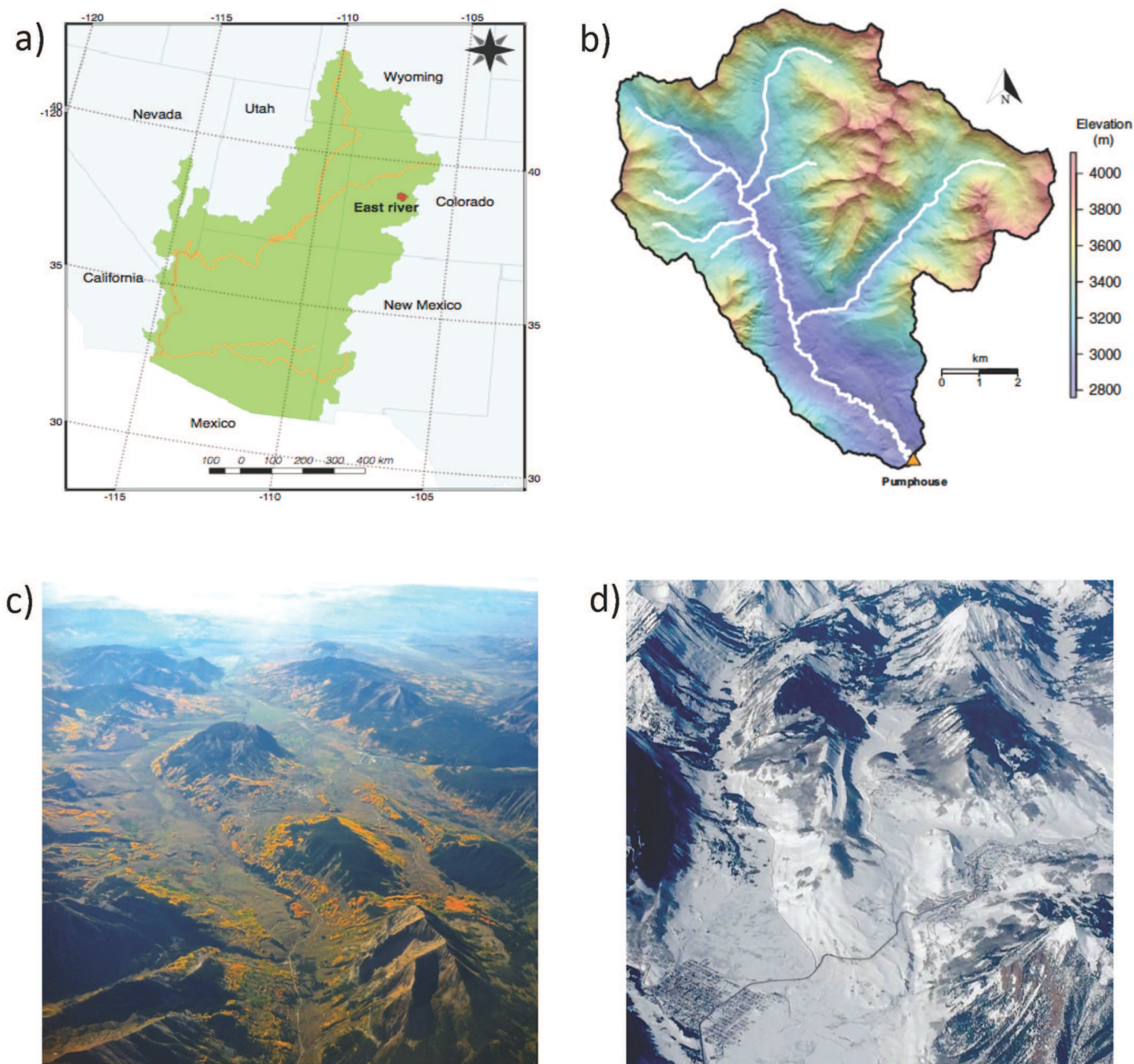


Fig. 1. (a) Location of the East River, CO, watershed within the Colorado River Basin; (b) elevation map; (c) aerial view of the East River during the growing season (courtesy of Joseph Guardiola); and (d) aerial view of the East River watershed during the winter season (courtesy of Sam Faivre).

of cumulative watershed behavior. The approach focuses on quantifying how fine-scale processes occurring across compartments (e.g., bedrock to canopy, terrestrial to aquatic) of different watershed subsystems (floodplain, meadow, hillslope) contribute to the aggregated, time-dependent export of downgradient water, N, C, and metals (Fig. 2).

Mechanistic simulation of watershed hydrology-driven biogeochemistry across scales and compartments is computationally challenging due to the importance of capturing gradients and representing flow and reactive processes in localized regions of the watershed where such processes may exert an outsized impact on the aggregated watershed concentration and discharge behavior. As such,

a “scale-adaptive” construct serves as the organizing framework for the project, which postulates that the integrated watershed response to perturbations can be adequately predicted through consideration of interactions, feedbacks, and response to hydrological perturbations occurring within a limited number of watershed subsystems, such as a subalpine meadow or a montane hillslope. The technological centerpiece of the Watershed Function Project at the East River is a Scale-Adaptive Watershed Simulation Capability (SAWASC), which is being developed and tested at the site. The scale-adaptive capability will rely on adaptive mesh refinement approaches, which are numerical techniques for dynamically adjusting the resolution of computational grids to enable more accurate local calculations where

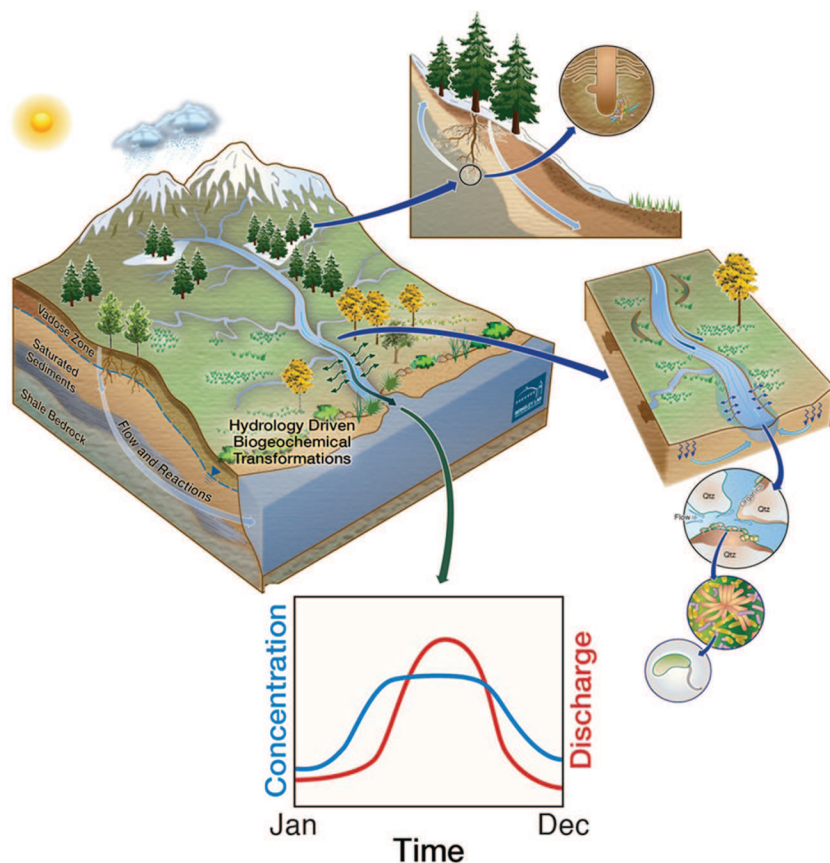


Fig. 2. The Watershed Function project is developing system-of-systems, scale-adaptive approaches in the East River watershed to quantify how spatially variable responses to perturbations propagate through the system and lead to an aggregated downgradient watershed discharge and concentration signature.

and when needed, providing a multiresolution approach to simulating complex multiscale watershed processes. The scale-adaptive simulation capability is also incorporating adaptive modeling capabilities, whereby different physics and mathematical algorithms may be used at different scales. The ability to dynamically use variable resolution and physics in mechanistic watershed reactive transport models is expected to provide a path forward for balancing between accuracy and tractability associated with mechanistic simulation of watershed hydro-biogeochemistry. The developing scale-adaptive reactive transport modeling approaches at the site are also envisioned to be a critical component for simulating system-within-systems behavior—and aggregation of that behavior—from the genome to the watershed scale.

Driven by the Watershed Function Project grand challenge compound question of “how do mountainous watersheds retain and release water, nutrients, C and metals over episodic to decadal timeframes, how do they respond to hydrological perturbations, and what are the ramifications for downgradient water availability and quality,” the Watershed Function Project has identified the following six supporting scientific questions that are being addressed at the East River watershed:

1. How do perturbations to individual watershed subsystems, including early snowmelt and drought, lead to downgradient exports of water, C, N, and P from that subsystem?
2. How do hydrological perturbations alter the connectivity between subsystems of mountainous watersheds?

3. How do subsystem responses to perturbations contribute to aggregate signatures of water, C, N, P, and trace-metal exports from the watershed?
4. When and where do fine-scale representation of processes significantly improve prediction of watershed hydrology and biogeochemistry, and how can they be tractably represented in models?
5. Do perturbations that impact water flow and nutrient transport in pristine systems enhance or suppress metals release from mining-impacted systems having otherwise similar watershed characteristics?
6. Which insights and methods are critical for improving operational forecasting predictions of water quantity and quality in response to a range of pulse and press perturbations?

Research performed under the Watershed Function Project, initiated in 2016, has focused on the first three scientific questions, with an early emphasis on exploring the effect of snowmelt perturbations on the water and N cycles in the East River watershed. Snowmelt was chosen as a priority hydrological perturbation because the project can take advantage of natural snowmelt events as well as manipulated snowmelt experiments to study the effects, and because snowmelt impacts a broad suite of hydrological–vegetation–biogeochemical processes in unknown ways. For example, interactions between hydrology, vegetation, and biogeochemistry are likely to change with decreasing snowfall, earlier snowmelt, and increasing soil and air temperature, with the magnitude and direction of the change often highly localized. For example, greater water

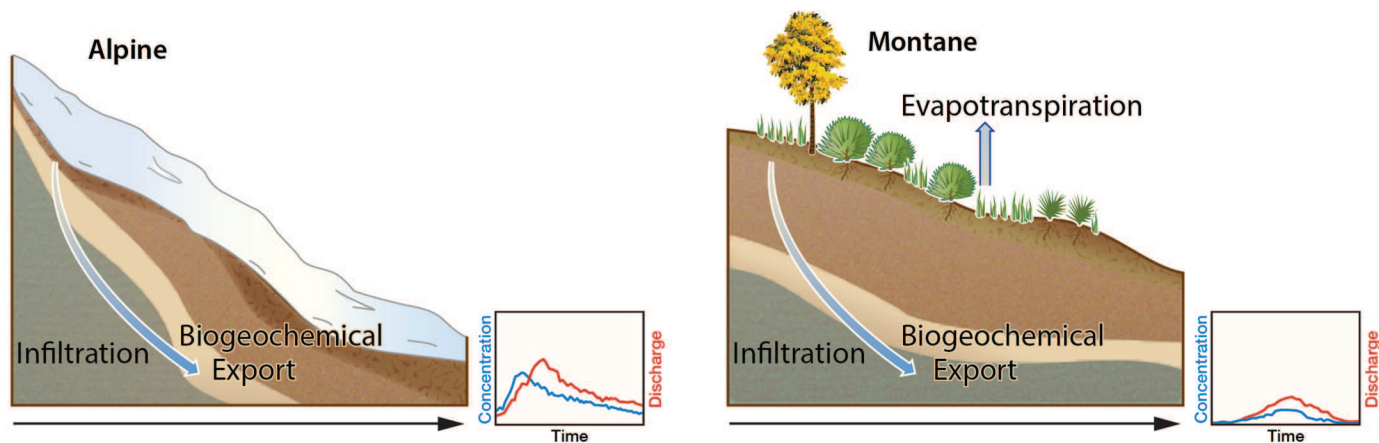


Fig. 3. Schematic illustration indicating how hydrological-vegetation-subsurface biogeochemical interactions occurring within distinct watershed subsystems can lead to dramatically different contributions to downgradient exports of water and constituents. Examples shown include (left) an alpine hillslope, where earlier snowmelt in a region where plants are not yet active may increase infiltration and subsurface inputs of carbon and nutrients, leading to downgradient exports of water and constituents, and (right) a montane hillslope, where earlier snowmelt may lead to vegetation growth and thus higher evapotranspiration and less subsurface input, resulting in much smaller exports from that subsystem. Many other scenarios are possible—these examples are intended to conceptually convey how spatially variable interactions between contributing hydrology, biogeochemistry and vegetation can lead to different concentration-discharge exports and thus contribute in different ways to an aggregated watershed signature.

infiltration due to earlier snowmelt may occur at higher elevations in the watershed, such as within subalpine biomes (Fig. 3a). If vegetation phenology in such upland hillslope subsystems does not catch up with snowmelt, plants may not be ready to use the available water, in which case the water, together with mobilized nutrients (such as N) would infiltrate into the subsurface and be transported downgradient. However, at lower elevations, such as montane hillslopes and floodplains (Fig. 3b), vegetation may be ready to take advantage of water from an earlier snowmelt, leading to vegetation growth and nutrient use. In this case, the earlier snowmelt in this lower elevation subsystem could lead to increased evapotranspiration and decreased groundwater recharge and more retention of nutrients, such as N.

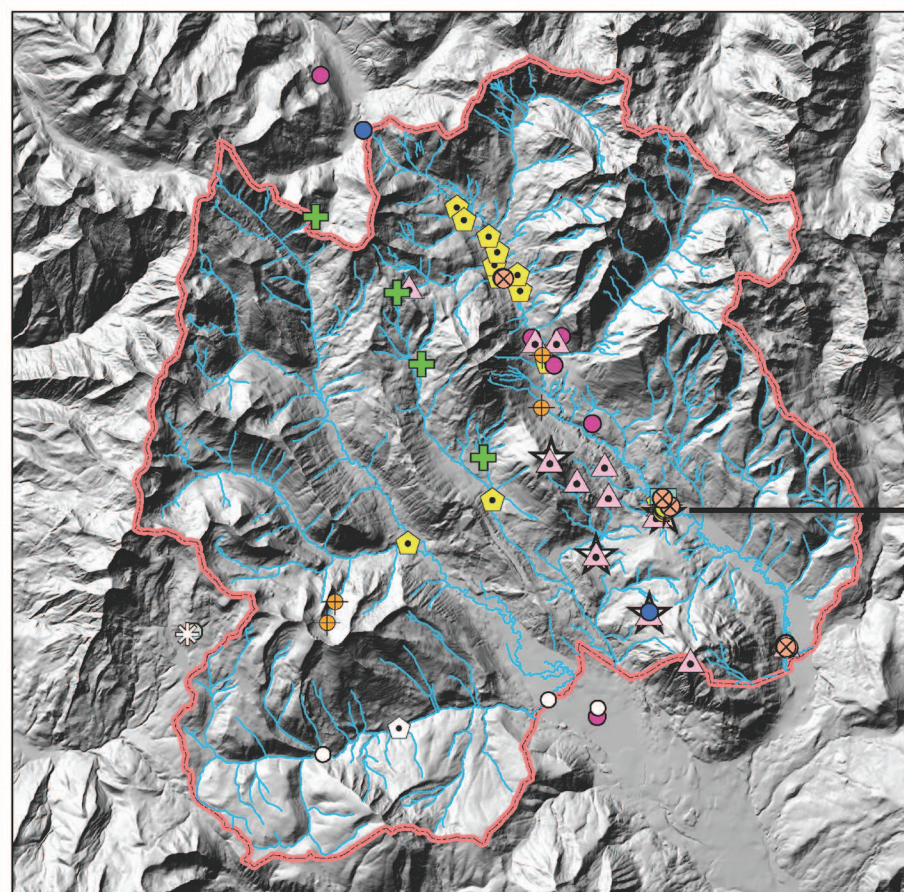
The LBNL is developing the East River watershed as a “community” testbed. Through leveraging infrastructure and ongoing activities, many investigators beyond the Watershed Function Project are able to use the site to test hypotheses and develop new methodologies and insights in a cost-effective manner. The community watershed approach also enables individual research efforts to benefit from and contribute to broader watershed challenges. Indeed, more than 450 individuals from academic, industry, federal, state, private, and non-governmental organizations are engaged in research at or have taken advantage of the East River watershed or the Rifle predecessor site, including researchers stemming from seven countries and 33 states in the United States. Currently, researchers from approximately 30 institutions besides LBNL are active at the East River site.

Observational Infrastructure and Experimental Campaigns

To address the supporting scientific questions, the East River watershed infrastructure development schema includes the following three aspects, which are further described below:

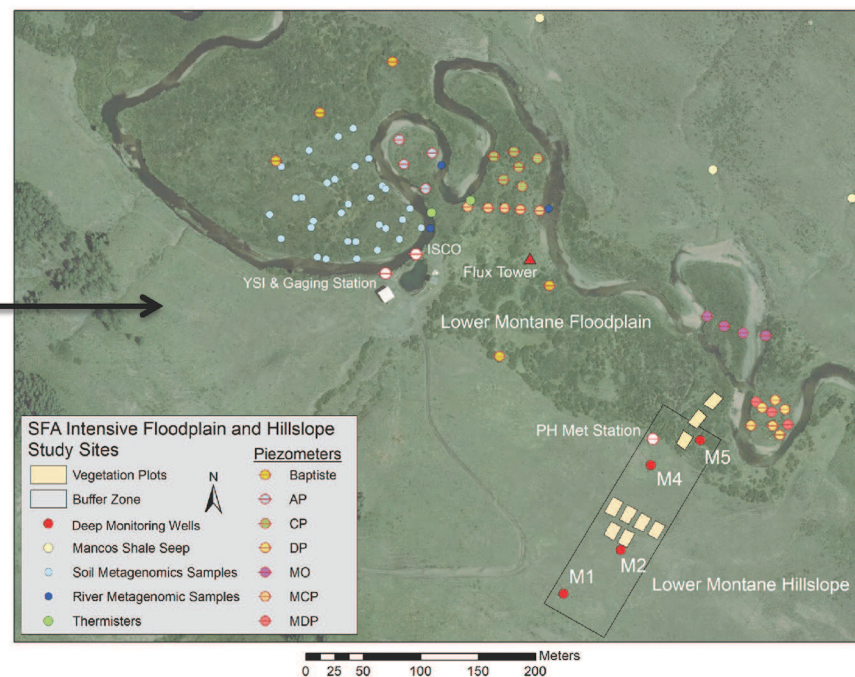
1. Distributed watershed monitoring stations provide synoptic, long-term measurements of hydrometeorology, stream discharge, groundwater elevation, snow properties, surface water and groundwater quality, and other measurements at specific locations throughout the watershed (Fig. 4a).
2. A collection of focused, intensive study sites are heavily instrumented and used to collect measurements that capture seasonal variations in hydro-biogeochemical processes as a function of position in the landscape. Of note, two lower montane intensive study sites have been the focus of significant Watershed Function Project research since the project’s inception in 2016, including a hillslope and a floodplain intensive site (Fig. 4b). The floodplain site encompasses an extensive riparian corridor, multiple meander bends, differentially aged floodplain deposits, regions of vertical and lateral hyporheic exchange, oxbows, and channel fill deposits. The adjoining hillslope study site terminates at the floodplain edge. Together, they encompass an area of 30 ha and are underlain by Mancos shale with varying degrees of fracturing and weathering. Development of additional intensive sites within the watershed is currently under discussion, including subsystems that have different characteristics relative to the current intensive sites (e.g., life zone, vegetation cover type, aspect, bedrock composition).
3. A network of satellite study sites allows investigations across gradients in elevation, fluvial geomorphology, vegetation, water quality and bedrock composition. Satellite sites include areas of both natural observation and experimental manipulation; several of the satellite sites are associated with collaborative activities. The current network of satellite sites includes locations focused on metals export, weathered and unweathered Mancos shale, deep (>100 m) groundwater wells, long-running experimental soil warming plots, and comparative floodplain sites spanning a range of geomorphic conditions from high to

a)



- | | | |
|--------------------|----------------------|---------------------|
| SFA Current Domain | Active SNOTEL | Met Stations |
| Stream | Proposed SNOTEL | EC Flux |
| SFA C-Q | Snow Pit | Ecohydrology |
| SFA ISCO | Snow Melt | Deep Well |
| USGS Q | Cloud Seed Generator | 10-m Well |
| | | Piezometer Networks |

b)



- | SFA Intensive Floodplain and Hillslope Study Sites | |
|--|----------|
| Vegetation Plots | Baptiste |
| Buffer Zone | AP |
| Deep Monitoring Wells | CP |
| Mancos Shale Seep | DP |
| Soil Metagenomics Samples | MO |
| River Metagenomic Samples | MCP |
| Thermistors | MDP |

PH Met Station
M1 M2 M4 M5
Lower Montane Hillslope

Fig. 4 (a) Map of the East River watershed depicting the network of stream gauging/stream water sampling locations, meteorological stations, and other distributed and specialized measurement sites in the watershed—continuous measurements of snow water equivalent (SWE) are made at the two SNOTEL locations and at one of the meteorological stations; (b) East River floodplain and hillslope intensive sites, located in a lower montane region of the East River watershed, with symbols indicating select instrumentation and wellbore locations.

low sinuosity. Of particular note and supplementing the lower montane hillslope study site, the Watershed Function Project has established four additional satellite sites spanning a gradient in elevation (upper montane, lower and upper subalpine, and alpine) to explore coupling between vegetation, soil, and hydrological process interactions accompanying snowmelt manipulation and experimental acceleration of the first snow-free date.

Instrumentation and experiments performed across this network of distributed, intensive, and satellite sites are described below.

Synoptic, Long-Term Watershed Point Observations

A collection of synoptic observational systems have been developed by the Watershed Function Project and are distributed throughout the watershed, including a network of 17 stream-gauging stations encompassing all major tributaries within the study area, with rating curves established for each to quantify stream discharge (Q). Each station also constitutes a stream-water analyte concentration (C) sampling location, with daily to weekly or biweekly samples collected since May 2014 for the analysis of anions, cations, trace metals, dissolved organic and inorganic C, and hydrogen and oxygen isotopes of water, enabling the generation of tributary specific C - Q profiles within the watershed. The USGS maintains four additional gauging stations of relevance at Coal Creek, Slate River, and East River below Cement Creek and at Almont. In partnership with the RMBL, LBNL has expanded and upgraded a meteorological network comprised of six stations spanning an elevation gradient from 3500 to 2400 m. To date, six deep (10–100 m) groundwater monitoring wells have been installed and used for quantification of seasonal variations in geochemical composition; four of these wells are also used to record seasonal excursions in groundwater elevation in an effort to better explore coupling between surface water and groundwater dynamics from year to year stemming from variations in snowpack thickness, snow water equivalent, and the onset and magnitude of monsoonal summer precipitation within the watershed.

Several specialized observational systems also provide critical hydrometeorological and atmospheric deposition information within the watershed. Complementing the network of elevation-specific meteorological stations, long-term data records are available from the Butte and Schofield Snow Telemetry (SNOTEL) and Crested Butte Cooperative Observer Network stations, as well as NOAA National Operational Hydrological Remote Sensing Center stations. Constraints on the annual atmospheric deposition of N species and other aerosols at the site are provided through the presence of the USEPA Gothic, CO, Clean Air Status and Trends Network station, which is collecting data under the National Atmospheric Deposition Program, and several Weather Underground stations.

The synoptic measurements facilitate an understanding of annual and seasonal trends at the East River. The total precipitation (Fig. 5a) and snow water equivalent (Fig. 5b) from the Butte

SNOTEL station indicates that the site has recently experienced quite different water years. Historical analysis of SNOTEL data (not shown) indicates that 2015–2016 represents an average year for the site, that 2016–2017 was a high water year, and that 2017–2018 is on track to being a very low water year. Figure 5c shows the spring–summer discharge values at the floodplain intensive site, which is located about 2 km from the Butte SNOTEL station. This figure indicates that excursions in river discharge are driven primarily by snowmelt in late spring and early summer, with mid-to late-summer monsoonal rainfall inducing rapid but punctuated increases in flow. Figure 5d compares the seasonal patterns of river discharge, dissolved inorganic C (DIC) and dissolved organic C (DOC, or more specifically, non-purgeable organic C) for the last several years. Figure 5d indicates consistent seasonal patterns of discharge and associated C fluxes, where the greatest DOC flux occurs during the rising limb and the greatest DIC occurs before the spring freshet.

Spatially Distributed Watershed Datasets

Several airborne and remote sensing campaigns have been performed in the East River watershed during the past few years. A lidar dataset covering a large fraction of the watershed was collected during 2016 and 2018, enabling the creation of a publically available digital elevation model of the watershed with a spatial resolution of <0.5 m (Fig. 6; Wainwright and Williams, 2017). Additional watershed-wide, remote-sensing datasets have recently been collected. Three NASA Airborne Snow Observatory (ASO) datasets have been collected, including on 4 Apr. 2016 (Fig. 7a), 30 Mar. 2018, and 24 May 2018. Estimation of dense, spatially distributed snow depth over the East River during 2016 and 2018 is being performed using lidar and ASO snow datasets. Airborne electromagnetic and radiometric datasets were collected by the USGS in fall 2017 (acquisition led by Burke Minsley, USGS) to characterize the variability in subsurface properties. Carroll et al. (2018) interpreted USGS Landfire 30-m raster maps (USGS, 2013) and classified them by dominant life forms across the site (Fig. 7b). They reported sparse vegetative land cover of alpine conditions and forests. A hyperspectral airborne campaign was performed in June of 2018 in collaboration with National Ecological Observatory Network; the acquired data will be used to further investigate the vegetation distribution across the East River watershed.

The watershed geology includes Paleozoic and Mesozoic sedimentary rocks that have been intruded by Tertiary igneous laccoliths and ore-rich stocks (Gaskill et al., 1991). Cretaceous Mancos shale forms the primary bedrock of the study site. The Mancos is a marine black shale with spatially variable composition, including regions of elevated metal, metalloid, and pyrite content (Morrison et al., 2012). Varying degrees of alteration are present, stemming from igneous dikes, sills, and laccoliths cross-cutting the catchment as well as from weathering. The USGS geologic map of the Gothic quadrangle (which covers the East River hillslope and floodplain intensive sites discussed here) is shown in Supplemental Fig. S1. Other available nearby geologic

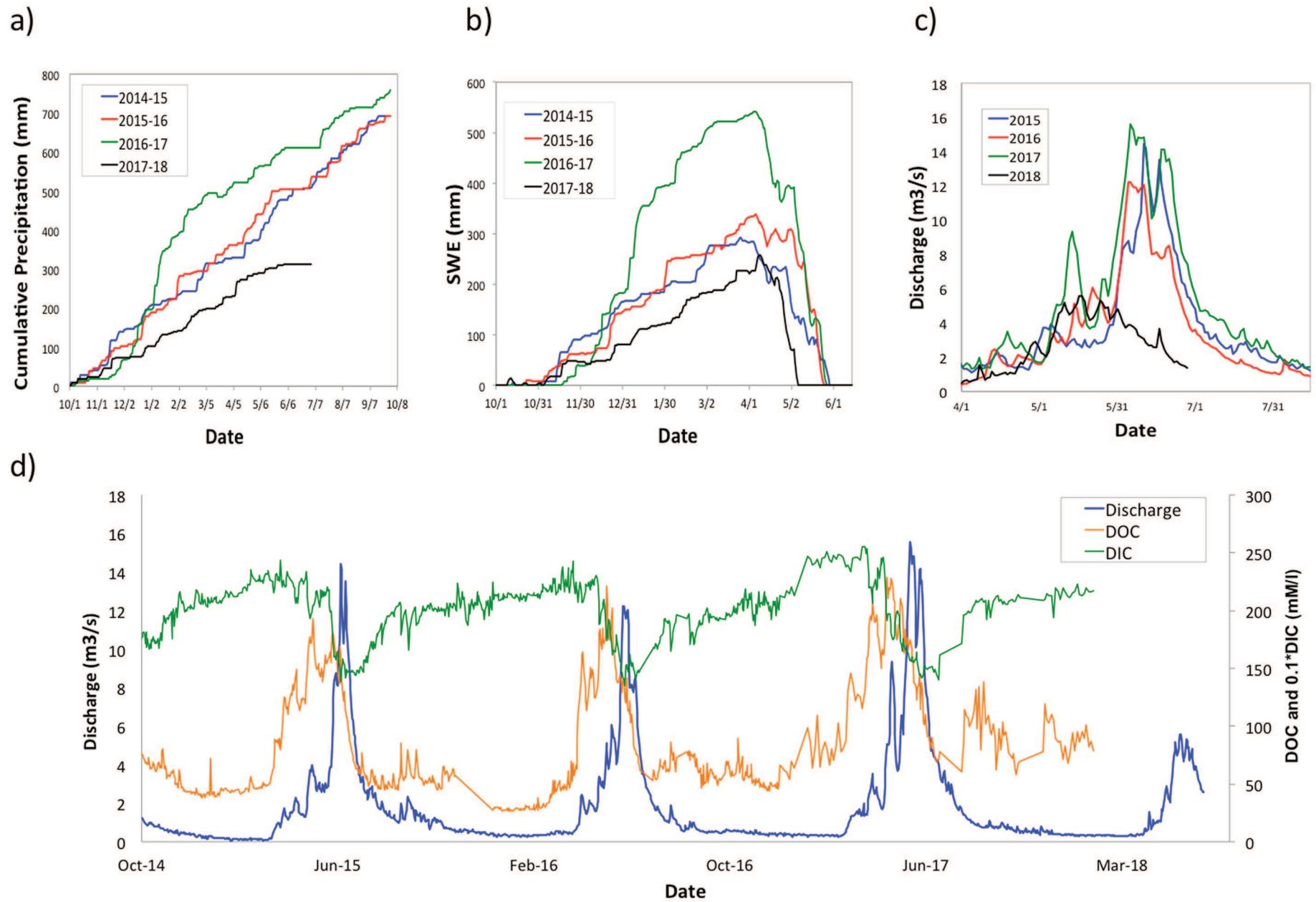


Fig. 5. Annual and seasonal variations in select parameters in recent years at the site, including (a) cumulative total precipitation; (b) snow water equivalent (SWE); (c) spring–summer discharge; and (d) seasonal trends of discharge, dissolved organic carbon (DOC), and dissolved inorganic carbon (DIC) during the same four water years. Data in (a) and (b) are from the Butte SNOTEL station, and data in (c) and (d) are from the Watershed Project Pumphouse station in the Lower Montane Floodplain intensive site.

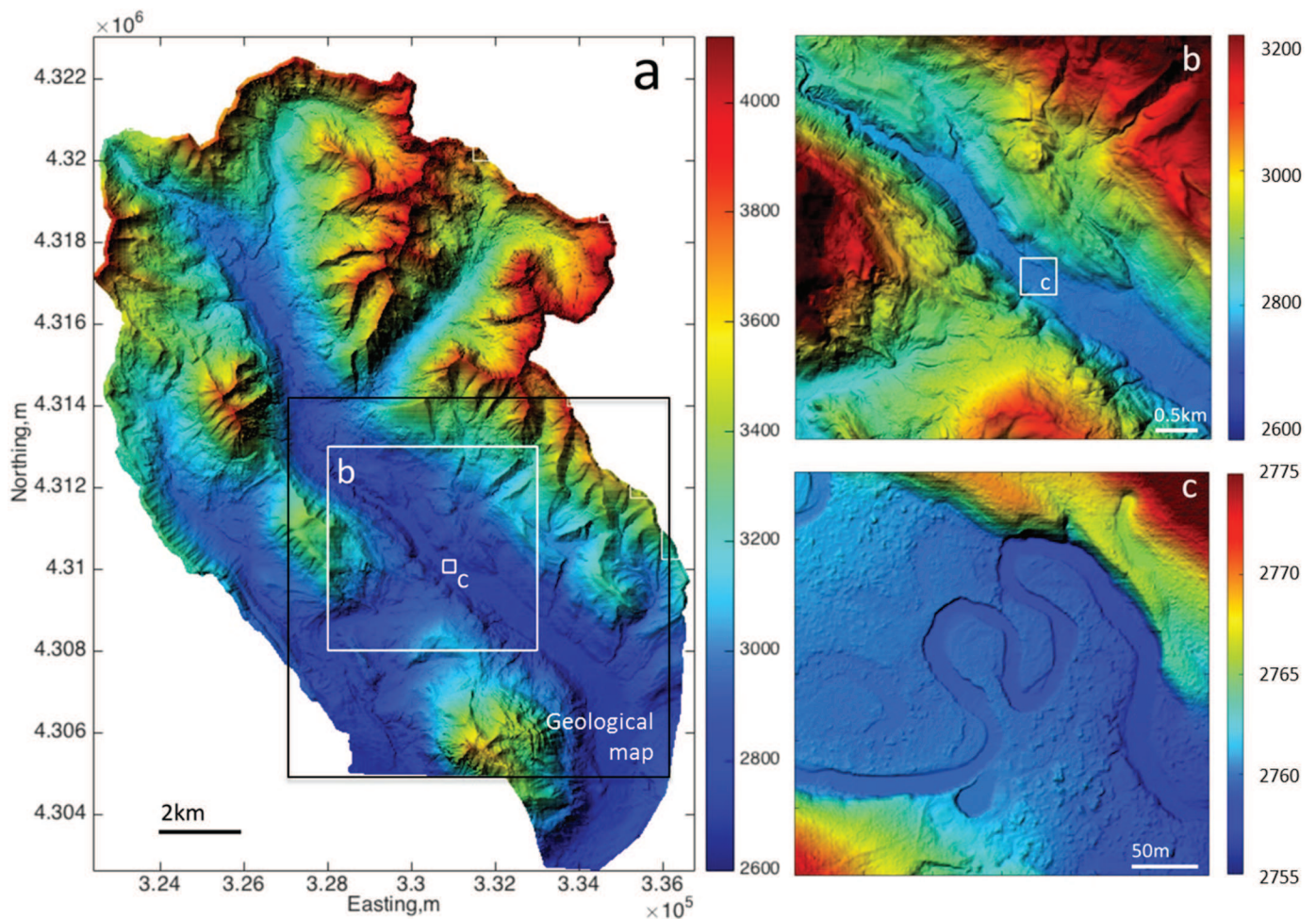


Fig. 6. Lidar reconstructed 0.50-m digital elevation model (DEM) of the East River Scientific Focus Area watershed site showing various scales of resolution corresponding to the hierarchical investigation and modeling domains important for the Watershed Function project. Scales range from those of (a) the watershed to (b) low-gradient, meandering reaches of the East River to (c) individual meander bends and former channel deposits (from Wainwright and Williams, 2017). The black box outlined in (a) indicates the region covered by the geologic map provided in the supplemental material.

maps include the USGS quadrangle of the Maroon Bells (Bryant, 1969), Snowmass Mountain (Mutschler, 1970) and Oh-be-Joyful (Gaskill et al., 1967). Due to historic mining activities and naturally mineralized rock, Slate River and Coal Creek catchments are more heavily impacted by heavy metals, such as As, Cu, Cd and Zn, than the comparatively pristine East River and Washington Gulch catchments.

Dedicated Campaigns and Experiments at Intensive Sites

The aforementioned floodplain and hillslope intensive study sites are the focus of a range of dedicated measurement campaigns and experiments (Fig. 7b). An extensive instrumentation network exists at the floodplain intensive site, including two stream-gauging stations; stream-water quality parameter sondes; sediment collection pads; automated, year-round stream sampling for water chemistry; dozens of monitoring wells, piezometers and transducers; and a continuous water isotope monitoring station. A winter-accessible building enables year-round data collection and water sampling

along with wireless telemetry for real-time data access. Select surface and subsurface measurements along the hillslope intensive site transect include vertically resolved aqueous and gas-phase compositions, pressures, and temperatures that are sampled down to 10 m below the soil surface at four wellbore stations along a 200-m transect (Fig. 8), autonomous electrical resistance tomography transects and associated distributed soil moisture and temperature probes, an integrated meteorological station, and an eddy covariance flux tower. Pole-mounted cameras pointed at the hillslope and floodplain sites provide daily images of snow, water inundation, and vegetation dynamics. Six hillslope and three floodplain ecophysiology study plots are equipped with soil moisture and temperature probes. Data streams are telemetered from both intensive sites, providing real-time and continuous information.

Detailed microbial community genome (metagenomic) investigations are underway using samples collected along a hillslope-to-floodplain transect, in combination with focused investigations at both the hillslope and floodplain intensive sites. These studies are being performed to determine the geochemical,

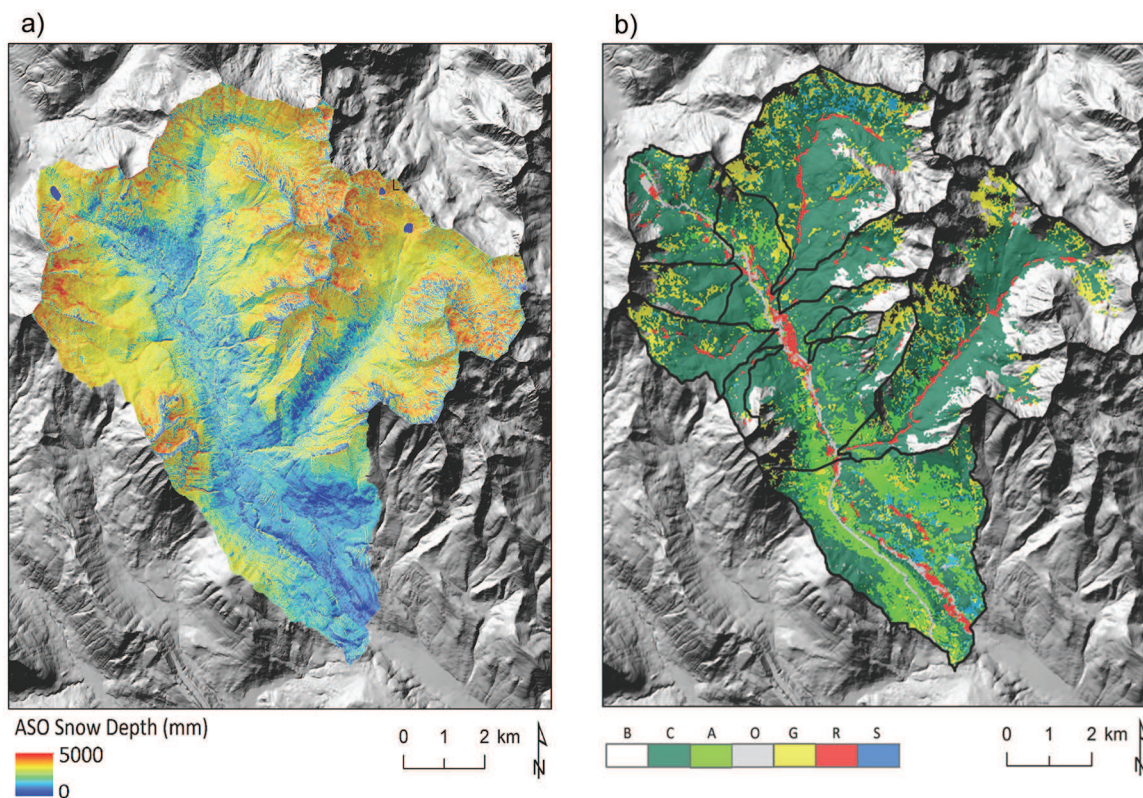


Fig. 7. (a) Airborne Snow Observatory (ASO) snow depths for 4 Apr. 2016 at 3-m resolution; and (b) spatial distribution of vegetation type in the East River: B = barren/alpine, C = conifer, A = aspen, O = other, G = grass, R = riparian, and S = shrub (figures modified from supplementary information provided by Carroll et al., 2018).

depth, space, and seasonal controls on the distributions and functional capacities of microorganisms that mediate the key biogeochemical processes of interest. Samples along the transect have been collected at multiple times and depths for detailed microbiological and geochemical analyses. The metagenomic hillslope-to-floodplain transect study design enables consideration of the impact of landscape position on microbiome structure and associated biogeochemical processes. Focused metagenomic

investigations are underway along the floodplain riparian corridor to explore microbially mediated processes and variations within and across meanders. Extensive analysis is underway using soil samples from the meander-associated floodplain intensive site, where 94 soil samples were collected over the 10- to 25-cm depth interval from an upstream, midstream, and downstream meander reach. The DNA sequence information from individual samples was processed and assembled using standard methods. One hundred

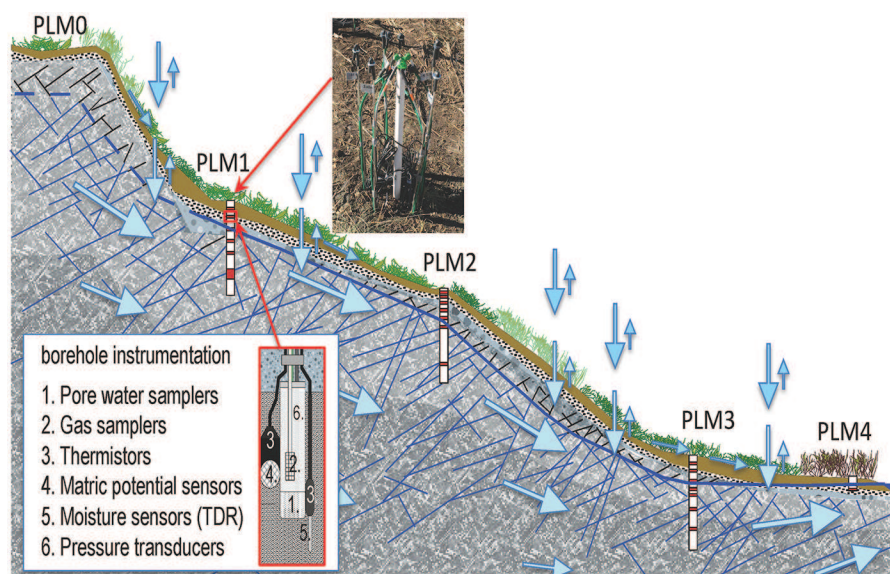


Fig. 8. Schematic cross-section along the hill-slope intensive site, indicating conceptual model of shallow sediments overlying fractured Mancos shale and the location and type of wellbore instrumentation installed along the hillslope transect. The blue arrows indicate the conceptual model of hydrological fluxes.

eighty-four near-complete draft genomes, representing 94 different organisms have been recovered through ggKbase binning (Matheus Carnevali et al., 2018). Metagenomic investigations at the hillslope intensive site focus on exploring the impact of variation in vegetation type on hillslope soil biogeochemistry.

The microbiome approach underway in the East River watershed leverages prior methodological advances that were established during the Rifle aquifer research effort. A specific aim of the current work is to scale up community genome (metagenomic) methods to enable analysis of many more samples than were tractable previously, thus providing large-scale biogeochemical constraints for modeling and, perhaps more importantly, identifying landscape regions that are hotspots for processes of interest (e.g., denitrification, N_2 fixation). Our methods involve the cultivation-independent determination of which organisms are present and provide direct insights into the specific compound transformations that they mediate. The fundamental data are hundreds (or thousands) of genome sequences, from which it is possible to predict metabolic capacities (e.g., the ability to degrade specific categories of carbohydrates, to reduce sulfate, to fix CO_2 and by what pathway). This is critical, given that microorganisms probably determine the rates and products of reactions involving NH_3 , NO_3 and other nitrous oxide compounds, S compound oxidation and reduction, and innumerable transformations involving C compounds (both organic molecule oxidation and CO_2 fixation).

To explore interactions among soil biogeochemical processes, hydrology, and vegetation phenology in response to snowmelt timing, snowmelt manipulation campaigns are ongoing at both intensive and satellite sites in the watershed. Snowmelt timing affects the date when patches of meadow and forest are first snow free, which in turn influences vegetation growth. The timing of snowmelt varies with elevation gradient in the watershed. The snowmelt experimental sites span elevations from 2765 to 3475 m, or from montane to alpine life zones; they are aligned with the vegetation gradient study site established in 2003 (Enquist et al., 2015; Sloat et al., 2015). For each of four experimental sites along the gradient, three control and three experimental plots have been established. In each experimental plot, an attempt to accelerate snowmelt is made by placing black fabric on the snow surface to increase energy absorption by the snow. A fifth alpine site, located at 3566 m, includes three additional control plots. Use of the black tarps has induced acceleration of the snowmelt timing by 2 to 3 wk compared with adjacent control plots. Advancing the timing of snowmelt experimentally in this manner allows exploration of how an induced acceleration affects hillslope hydrologic, plant, and microbial coupling.

The ongoing snowmelt manipulation experiments complement two other significant observation–experimental studies that have been performed in the East River watershed. Harte et al. (2015) performed a >25-yr aboveground warming experiment in the East River watershed focused on quantifying warming impacts on snowmelt, vegetation succession, and C and nutrient cycling. This study documented that warming was associated with earlier

snowmelt, lower soil C, and an increase in woody biomass compared with control plots. Sloat et al. (2015) combined an 11-yr C flux observational study along an elevation gradient in the watershed with a water manipulation experiment performed during a drought year. Their study documented the influence of forest–summer drought (the period between snowmelt and the onset of monsoon precipitation) on C exchange, revealing that the timing of the growing season precipitation is more important for net ecosystem productivity than the total amount in this system.

Early Scientific Insights

Here we provide a snapshot of select scientific insights and methodologies associated with the East River watershed. Given that this site was initiated only in 2016, significant research is in progress, and several of the vignettes described below are associated with studies that have not yet been published or have been published since 2016. The general current focus is on developing methods to quantify spatiotemporal variability associated with the water and N cycle, subsystem responses to perturbations, and how responses from individual subsystems propagate throughout the system to generate an integrated watershed response. These highlights were chosen to illustrate the range of investigations and datasets associated with the East River watershed community testbed, including activities at the intensive site as well as watershed-wide efforts. (See the Watershed Function Project website for a complete list of related publications and abstracts: watershed.lbl.gov.)

Select Recent Advances: Intensive Site Investigations

The East River intensive sites were developed to enable quantification of the distribution of properties and interactions among processes across key compartments at different locations in the watershed. Early research at the East River intensive sites has focused on addressing the Watershed Function Project's first supporting scientific question of how distinct watershed subsystems respond to hydrological perturbations and on quantifying the intensive site exports. Selected examples of early research at the hillslope and floodplain intensive sites are provided here, including the development of new characterization and computational approaches to quantifying seasonal water partitioning and the variability of and interactions among hydrological and biogeochemical processes.

Motivated by the importance but difficulty of monitoring interactions among vegetation, land surface, and subsurface watershed compartments, Dafflon et al. (2017b) developed a method to coincidentally and autonomously monitor above- and belowground watershed processes and their interactions and has tested the approach at the East River hillslope intensive site. The strategy exploits above- and belowground measurements that are coincidentally acquired using electrical resistivity tomography (ERT) to monitor soil processes, airborne imagery, or pole-mounted optical cameras to monitor land surface processes and vegetation dynamics, and point probes to measure soil temperature and moisture.

Electrical resistivity tomography, soil probes, and pole-based camera datasets are currently being collected autonomously and daily along the 160-m hillslope traverse, schematically indicated in Fig. 9. The time-lapse electrical resistance tomography data are collected using 1.25-m electrode spacing and were inverted using the Boundless Electrical Conductivity Tomography (BERT) approach (Günther and Rücker, 2017; Fig. 9a). Constrained by point measurements, the electrical resistivity data serve as a proxy for soil water content. The green chromatic coordinates extracted from aircraft- or pole-based sensors serve as a proxy for vegetation vigor during the summer season. Figure 9b shows a comparison of data along the hillslope during the 2017 growing season, including electrical resistivity in the top 50 cm extracted from the ERT transect, scaled dielectric constant from point measurements indicating shallow soil moisture, and greenness index extracted from an aircraft-based RGB mosaic (Dafflon et al., 2017a). In general, the results illustrate a significant positive correlation between inferred soil moisture and vegetation vigor during the growing season, as well as lateral variations in vegetation and soil moisture as a function of position along the hillslope. The approach is being used to explore how these relationships change and to identify significant perturbations, such as snowmelt. In general, the new monitoring approach is providing an unprecedented window into critical zone

interactions (in space and time), revealing significant below- and aboveground co-dynamics.

The extreme heterogeneity in elevation and hydrogeological properties of the East River mountainous watershed exerts an influence on vegetation type and processes, which in turn is expected to exert a significant control on water partitioning within the watershed and exports from subsystems of the watershed. To improve our understanding of vegetation distribution and its response to hydrological perturbations, new methods are needed to characterize and monitor plant communities tractably, in high resolution and across large spatial extents. To address this gap, Falco et al. (2018) developed an approach to characterize heterogeneous plant functional types using remote-sensing data and a new data fusion and machine-learning approach. Their remote-sensing data fusion framework utilized a spectral-spatial classification strategy that was based on support vector machine and morphological contextual analysis. The framework integrates plant spectral and structural information, derived from high-resolution multispectral satellite images and airborne lidar data. In particular, the plant height (computed through subtraction of a digital terrain model and a digital surface model) was exploited to better discriminate species with similar spectral signatures. The new approach was tested in a region that encompassed the East

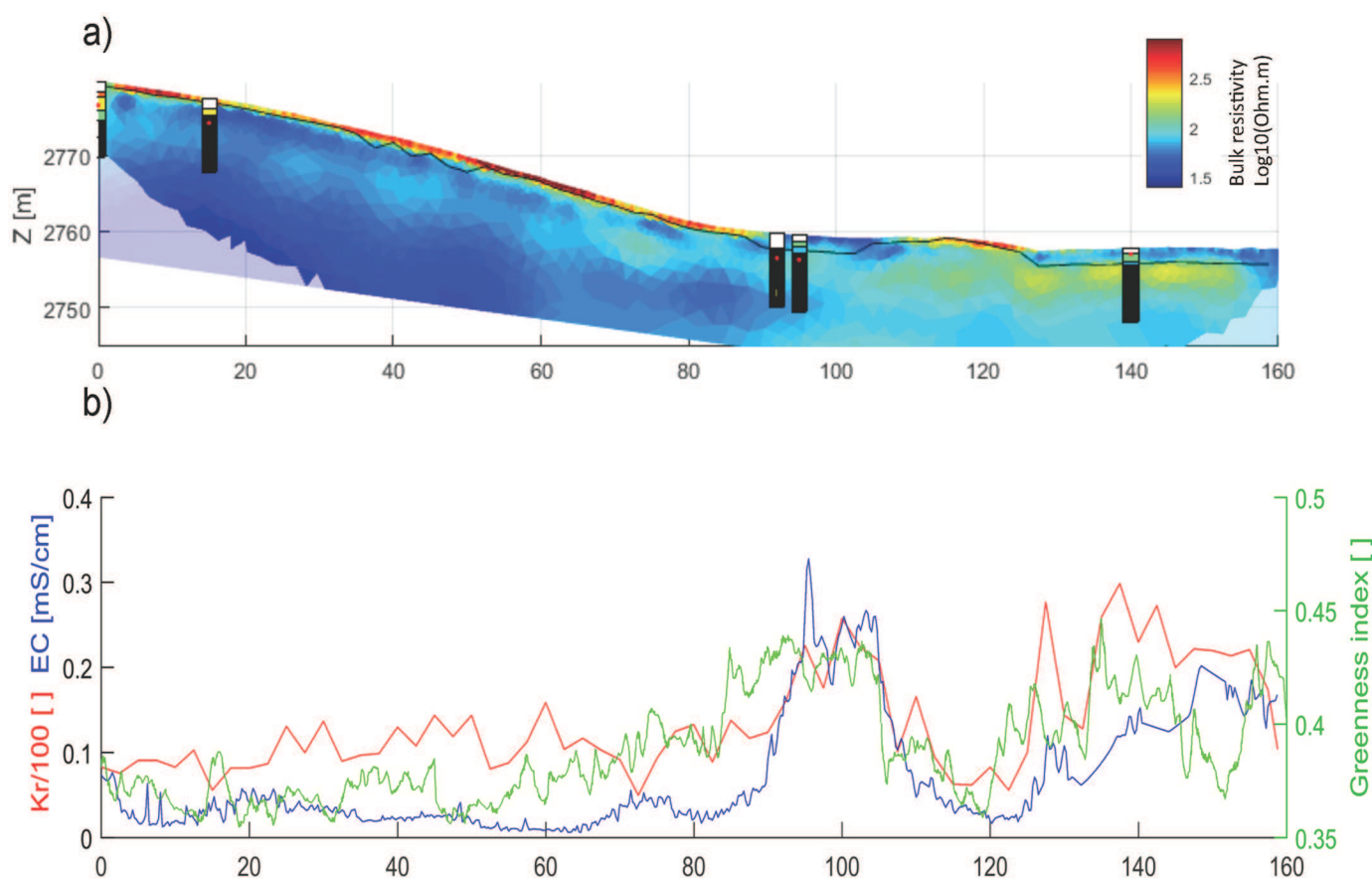


Fig. 9. (a) Electrical resistivity along a hillslope transect at the hillslope intensive site; (b) relationship between electrical conductivity (EC) extracted from the top 50 cm of the dataset, using a scaled dielectric constant ($K_r/100$) as a proxy for soil moisture and Greenness as a proxy for vegetation vigor along the transect, revealing the significant correlation between above- and belowground properties along the hillslope on a single day during the 2017 growing season (from Dafflon et al., 2017a).

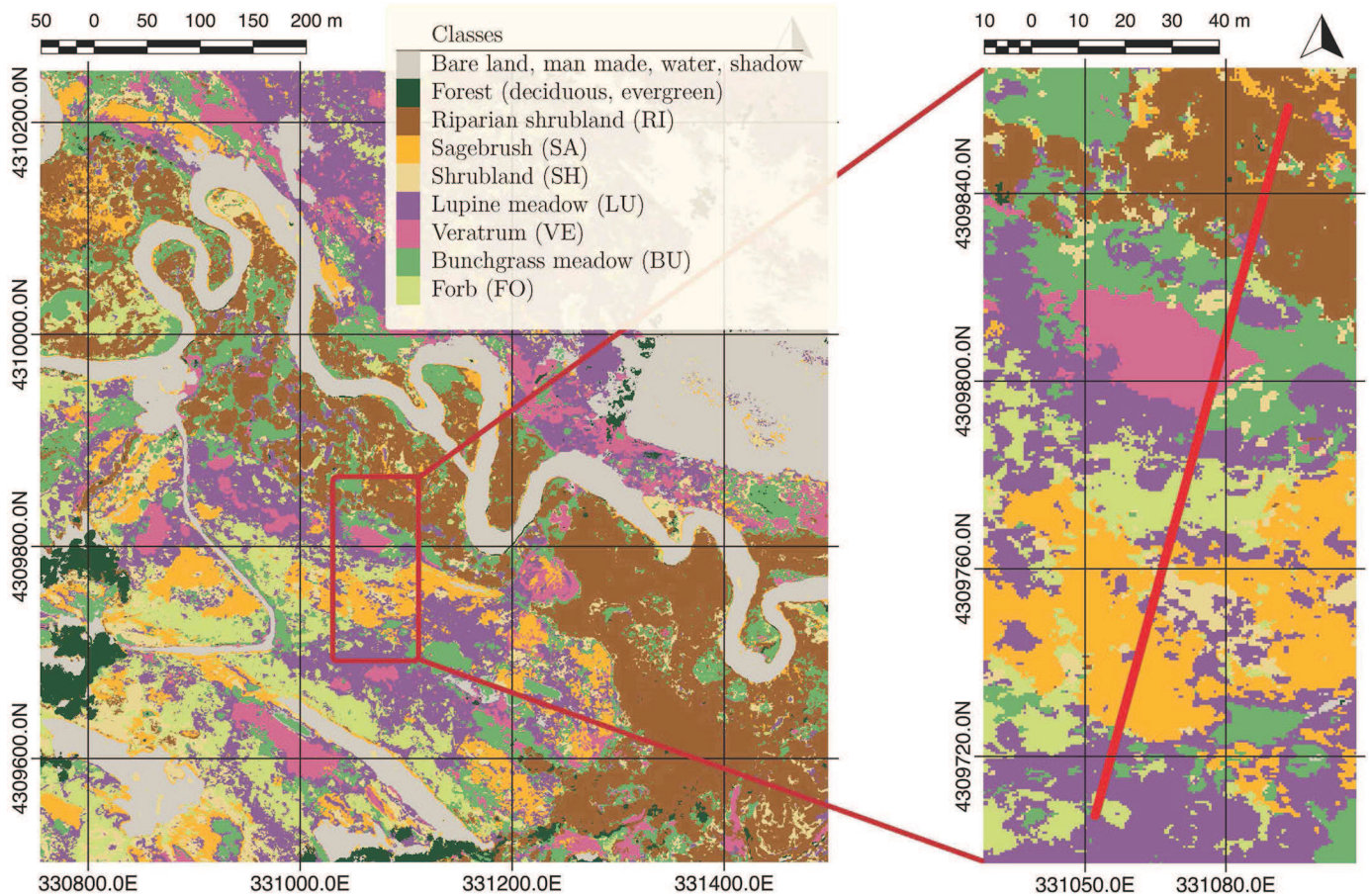


Fig. 10. Estimates of plant functional type distribution across a region that encompasses the hillslope and floodplain intensive sites (left), including the location of the electrical resistance tomography transect shown in Fig. 9a (right) (from Falco et al., 2018).

River floodplain and hillslope intensive sites. Figure 10 reveals the distribution of nine plant functional types that are considered to be critical for watershed functioning in these intensive sites. The high-resolution (0.5 by 0.5 m) results obtained using the new method were compared with conventional approaches for characterizing plant type using multispectral data, which do not use structural information as part of the estimation methodology. The results revealed that the new framework improved the estimation of plant functional types over conventional methods. It also revealed that the method significantly improved the estimation of meadow plant communities, which due to their mixed special characteristics or similar structure are often challenging to estimate using conventional approaches. Ongoing research is focused on integrating data collected using unmanned aerial vehicles with the above- and belowground autonomous monitoring approach described above to coincidentally monitor critical zone dynamics in high spatiotemporal resolution and across larger regions.

To address the supporting science questions posed by the Watershed Function Project, it is imperative to understand how water partitions in different watershed subsystems, how partitioning changes with time and in response to hydrological perturbations, and how the spatially variable water partitioning behaviors aggregate to yield a cumulative watershed discharge with

time. While there have been several recent advances in methods to characterize soil and vegetation properties important to the water cycle, components such as evapotranspiration and groundwater recharge are notoriously difficult to measure. The hillslope and floodplain intensive sites provide an excellent platform to integrate a variety of datasets, such as those described above, with mechanistic, high-resolution models facilitating exploration of water partitioning in different watershed locations. While integration of available data with numerical models generally helps to improve simulation accuracy, development of approaches that enable assimilation of increasingly available streaming field datasets holds significant potential for increased resolution and decreased uncertainty associated with simulation predictions. Building on concepts developed by Tran et al. (2018), an integrated model calibration–data assimilation framework and tested at the hillslope-intensive site. The assimilation framework includes an inverse parameter estimation scheme, a data assimilation algorithm, and the Community Land Model (CLM), which simulates the hydrological-thermal dynamics from the top of canopy to the bedrock. In the CLM, evaporation is defined as the loss of water to the atmosphere; in winter, sublimation at this location accounts for 100% of the simulated evaporation. The data–model assimilation strategy is schematically illustrated in Fig. 11a. In general, the

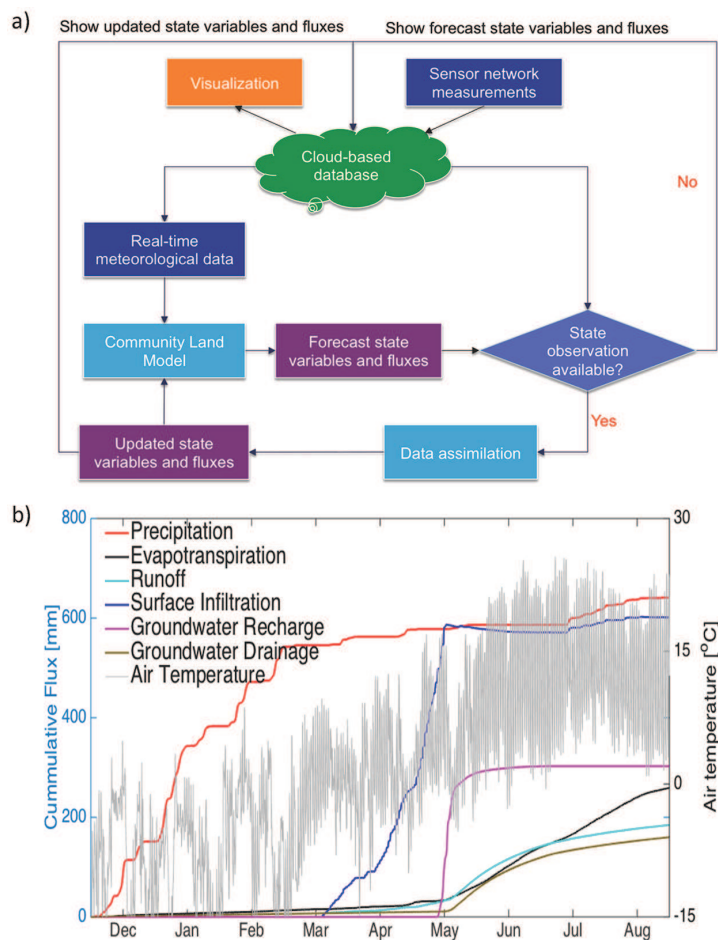


Fig. 11. (a) Model-data assimilation flowchart: the cloud-based database (green box) was used for containing and visualizing both inputs and outputs of data assimilation, the dark blue boxes represent real-time observations obtained from the sensor network including meteorological data (for hydrological simulation) and soil moisture and soil temperature measurements (for data assimilation) in this study, the light blue boxes denote the surface–sub-surface model and data assimilation algorithm, and the purple boxes indicate the model outputs of state variables and fluxes (state variables consist of profiles of soil moisture and soil temperature, while fluxes include evaporation, transpiration, infiltration at the soil surface, runoff, groundwater recharge, and groundwater drainage; (b) estimation of water balance components with time at the hillslope intensive site obtained from the model-data assimilation strategy, including precipitation, evapotranspiration, runoff, surface infiltration, groundwater recharge and draining, as well as measured air temperature at the hillslope intensive site (following Tran et al., 2018; from Hubbard et al., 2017).

framework first uses observations to estimate parameters for CLM and then uses the model to predict hydrological-thermal state variables and their associated fluxes. When and where observations are available, they can be assimilated into the model to improve predictions. The data–model assimilation scheme was applied at the hillslope intensive site using autonomously collected measurements during a simulation period from 1 Dec. 2016 to 15 Aug. 2017. The inputs for simulation included locally available air temperature, precipitation, wind speed, humidity, atmospheric pressure, and shortwave and longwave radiation. Soil moisture (at depths of 0.09 and 0.6 m) and soil temperature measurements (at depths of 0.18

and 0.6 m) along the hillslope were used for model calibration and assimilation. Comparison of model estimates and data (not shown) indicate that the new inversion scheme performs well. Figure 11b shows the estimated water partitioning with time obtained from the model calibration–data assimilation framework at the hillslope intensive site. The figure indicates that infiltration mainly occurs from mid-March to early May, associated with snowmelt. Infiltration appears to be negligible during the summer period (May–August). In contrast, evapotranspiration is very large in summer due to high air temperature, and very small in winter due to low air temperature and snow cover. Surface runoff, groundwater recharge, and groundwater drainage contribute most significantly from the beginning to the middle of May. During the simulation period, 95% of the precipitation delivered to the hillslope left the site: 41% was lost by evapotranspiration, 29% by surface runoff, and 25% by groundwater drainage. The newly developed framework is useful for understanding water partitioning at the hillslope intensive site and for reducing model parameter uncertainty (Hubbard et al., 2017). In general, the study also illustrated how models can take advantage of increasingly available streaming field data for improving model prediction in real time.

Several studies have recently investigated hydrological and geochemical processes at the floodplain intensive site. Malenda (2018) combined core data, hydraulic conductivity estimates from slug tests, ground-penetrating radar signatures, historical maps of former channels, lidar-based elevation and normalized difference vegetation index data to infer three-dimensional fluvial stratigraphy in two meanders of the floodplain intensive site that had different geometries. While floodplain parameters are often represented as homogeneous in watershed models, this study documented structural features in the meanders that could influence flow and reactions. Using unmanned aerial vehicles and fiber optic digital temperature sensors, Pai et al. (2017) studied surface water–groundwater interactions within the floodplain and estimated hydraulic gradients through East River meander bends. This work documented the “shortcutting” of flow through terrestrial meander pathways and also indicated that the shortcutting may drive variations in vegetation density.

The intensive sites have also been the host for the integration of measurements and models focused on understanding how hydrological transients influence subsurface biogeochemical fluxes. To investigate how biogeochemical processes in the hyporheic zone influence biogeochemical cycles as well as stream biogeochemistry, Dwivedi et al. (2017a, 2017b) developed a biotic and abiotic reaction network using available measurements, integrated the network into the reactive transport simulators, and used model simulations to explore three-dimensional reactive flow and transport simulations. Simulation of surface water flow using Amanzi-ATS (Arctic Terrestrial Simulator) demonstrated that the model was able to reproduce correctly the naturally forming East River network (Fig. 12b). Simulation of hydrology-driven

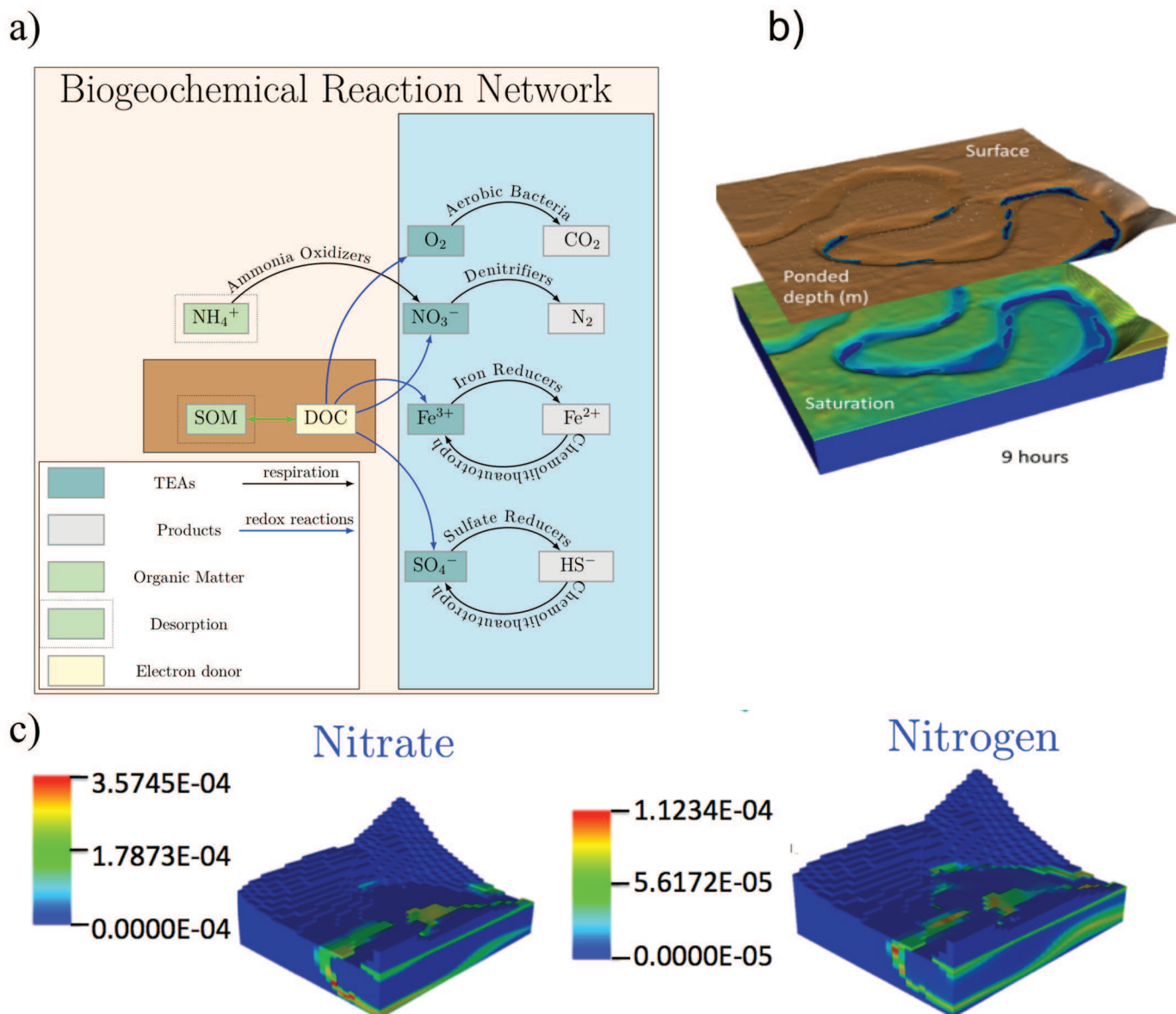


Fig. 12. (a) Reactive transport network developed for the East River meanders and used within PFLOTRAN; (b,c) examples of three-dimensional simulations of hydrological and biogeochemical responses to changes in river stage at the floodplain intensive site. Nitrate transforms into various reduced nitrogen species in the organic-C-rich sediments; nitrate and nitrogen concentrations given in units of moles per liter (modified from Dwivedi et al., 2017a).

biogeochemistry was performed using PFLOTRAN, with a focus on numerical exploration of the biogeochemical responses to river stage within an intra-meander region at the floodplain intensive site. The key geochemical processes included in this study were microbially mediated redox reactions (Fig. 12a) and aqueous speciation and mineral precipitation–dissolution reactions. The three-dimensional model domain of two stream meanders was 330 m (x) by 400 m (y) by 48 m (z) (Fig. 13c). The model domain was uniformly discretized with 10-m horizontal (x and y) and 0.25-m vertical (z) resolution, and the groundwater and boundary water chemistry information needed for the model was obtained from field measurements. In particular, simulations explored hyporheic exchanges at the river–terrestrial interface and across the

heterogeneous terrestrial meander (“shortcuts”), including the effect of stream-water level transients on the export of C, N, and Fe. The simulations also explored the biogeochemical transformation of N and C species as a function of the residence time. Comparison of simulation results and measurements (not shown) suggested that the model was able to capture the observed trends of measured NO_3^- and dissolved O_2 values across the meander reasonably well. The simulations suggested that hyporheic flow paths created lateral redox zonation within intra-meander regions, which considerably impacted N export into the stream system. Simulation results further demonstrated that low water levels led to higher concentrations of dissolved Fe in the groundwater, which was exported to the stream on the downstream side under

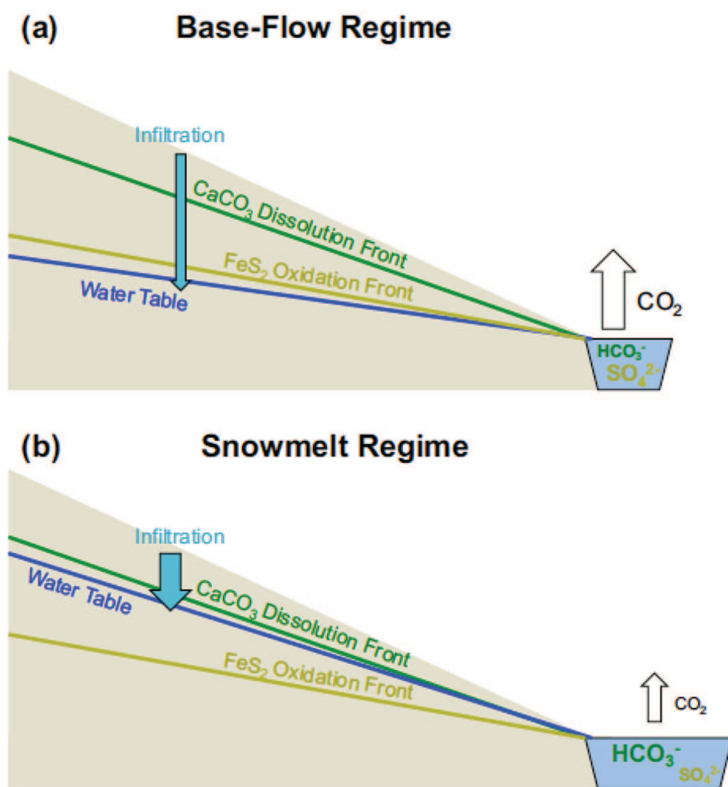


Fig. 13. Conceptual model from Winnick et al. (2017), showing infiltration depths relative to subsurface reaction fronts under (a) base flow conditions and (b) snowmelt conditions, along with relative concentrations of bicarbonate and sulfate in surface water and relative CO₂ efflux rates.

higher water conditions. The study documented the value of reactive transport models for understanding biogeochemical fluxes associated with stream-water stages at the floodplain intensive site and for identifying important factors that contribute to redox gradients and exports.

Winnick et al. (2017) investigated hydrologic controls on weathering fluxes at the floodplain intensive site using concentration–discharge (C – Q) relationships for major cations, anions, and organic C. They showed that C – Q relationships for several stream solutes highlighted the couplings between hydrologic flow regime and biogeochemical reaction fronts (Fig. 13). In particular, cation and anion concentrations demonstrated that carbonate weathering, which dominated the solute fluxes, was promoted by both H₂SO₄ derived from pyrite oxidation in the shale bedrock and H₂CO₃ derived from subsurface respiration. Sulfuric acid weathering dominated during base flow conditions (when waters infiltrated below the inferred pyrite oxidation front), whereas H₂CO₃ weathering played a dominant role during snowmelt as a result of shallow flow paths. Differential C – Q relationships among solutes suggest that infiltrating waters approach calcite saturation before reaching the pyrite oxidation front, after which H₂SO₄ reduces carbonate alkalinity. This reduction in alkalinity resulted in CO₂ outgassing when waters equilibrated to surface conditions, and reduced the riverine export of C and alkalinity by roughly 33% annually. The

study demonstrated that differential C – Q relationships among major solutes can provide unique insights into the complex subsurface flow and biogeochemical dynamics that operate at catchment scales. Winnick et al. (2017) postulated that future changes in snowmelt dynamics controlling the balance of H₂CO₃ and H₂SO₄ weathering may substantially alter C cycling in the East River and other mountainous watersheds.

Select Recent Advances: Analysis of Watershed Observations and Larger Scale Simulations

Here we describe select data analysis and modeling efforts that are underway across larger regions of the East River watershed site. Paired with the dense data–model information provided at the smaller intensive sites, these more spatially extensive studies are geared toward addressing the Watershed Function Project’s third scientific question of “how do subsystem responses to perturbations contribute to aggregate signatures of water, C, N, P and trace metal exports from the watershed?” Below, we describe recent advances using data-driven approaches to explore relationships between diverse and distributed watershed measurements and to estimate first-order controls on seasonal streamflow generation. We also describe the use of models that traverse many watershed subsystems to explore controls of vegetation and warming on water partitioning.

Motivated by the importance of snowmelt volume and timing on the functioning of mountainous watersheds, Wainwright et al. (2017) developed a data-driven approach to explore historical seasonal relationships between precipitation and air temperature on snow and streamflow dynamics and tested it at the East River. Using historical operational datasets collected at different locations in the watershed, including snow telemetry and stream gauge station networks, they used correlation analysis and principal component analysis to investigate inter-annual variability during the last 30 yr. They found that although peak snow water equivalent exerted a significant control on snowmelt timing and annual total discharge, spring temperature also had a significant effect. In particular, they found that increasing spring temperatures were linked to earlier peak flow, reduced and distributed peak flow, and reduced total annual discharge. They also found that spring temperature explained 7 to 20% of the variability in the first bare-ground date and 9 to 20% of the variability in total discharge. Additionally, the results indicated that summer monsoon precipitation did not contribute significantly to annual discharge due to increased evapotranspiration during that period, which highlights the importance of snow to water resources in this watershed. This data-driven study illustrated a straightforward approach to using diverse historical datasets for beginning to explore key relationships important for refining hypotheses and guiding field measurements.

Carroll et al. (2017, 2018) also used a data-driven approach with East River datasets, in this case to identify first-order controls on seasonal streamflow generation. They used a multivariate,

end-member mixing analysis approach with a suite of high-frequency chemical and isotopic observations collected throughout the watershed. Mixing models were developed across 11 nested basins (0.38–84.7 km²) in the East River watershed, which spanned a gradient of climatological, physical, and geological characteristics. Hydrographic separation analysis indicated that seasonal contributions of groundwater to streams were significant. Specifically, the mean annual groundwater flux to streams ranged from 12 to 33%, while maximum groundwater contributions of 17 to 50% occurred during baseflow. They found that groundwater recharge increased in basins of high relief and in upper subalpine life zones, where maximum snow accumulation was coincident with reduced conifer cover and lower canopy densities (Fig. 14). Although mechanistic modeling is underway at the East River watershed to explore causal linkages and predict how the East River watershed will behave under different possible future conditions, the statistical findings associated with these studies are being used to guide hypotheses and new field observations.

Pribulick et al. (2016) used numerical approaches to explore how vegetation change and warming air temperatures influence water partitioning at different elevations in the East River watershed. In mountainous systems, vegetation change can occur

abruptly (in response to drought, fire, or insect-induced tree mortality) as well as through gradual succession. While the hydrologic response associated with vegetation change and temperature increase has been explored independently, few studies have compared the impacts of both in a systematic manner. Understanding the hydrological response to both types of perturbations is particularly important in snow-dominated headwater systems that provide streamflow for continental river systems, such as the East River watershed. Pribulick et al. (2016) used an integrated hydrologic model ParFlow-CLM to simulate surface–subsurface interactions along three transects in the East River watershed, each with 10-m resolution. The transects were located at three different elevations in the East River watershed (a higher elevation, a middle elevation, and a lower elevation transect) each differing in terms of average vegetation, air temperature, and precipitation. The three regions currently contribute to watershed flow in different ways. The highest elevation alpine headwaters transect contributes flow via a steep gradient near the uppermost region of the watershed, the mid-elevation subalpine Gothic Mountain transect contributes waters to the medium-grade East River, and the lower elevation montane Mount Crested Butte region contributes flow to the low-grade meandering floodplain. Transects located

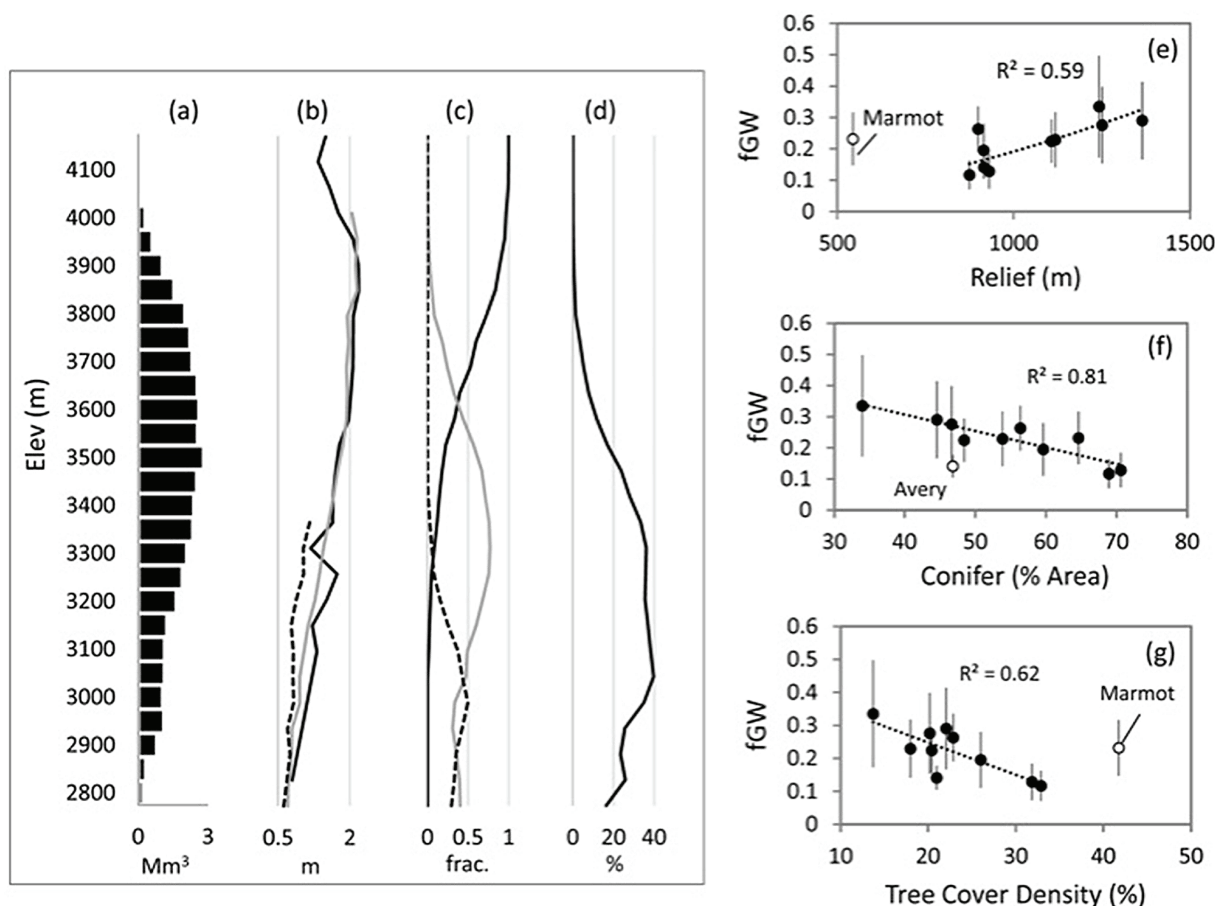


Fig. 14. East River elevational trends in (a) snow water equivalent, Mm³, (b) snow depth by vegetation type, (c) vegetation type as a fraction of basin area, and (d) tree canopy density, where the vegetation type is indicated as barren (solid black), conifer (solid gray), and aspen (dashed black); regressions of the sub-basin fraction of streamflow that is groundwater, fGW (annual mean $\pm$ range) with respect to (e) relief, (f) conifer by area, and (g) tree cover density, with data points excluded from a regression shown as a white symbol (modified from Carroll et al., 2018).

within the three regions used spatially variable vegetation type, geology, and soil property distributions obtained from available watershed data for model parameterization, as well as meteorological forcing data. The results (Fig. 15) suggested that while warming temperatures have the largest impact on snow, vegetation changes can have a significant influence on evapotranspiration. The results indicated that the hydrological impacts due to warming generally outweighed those resulting from vegetation change, but heterogeneity associated with each of the transects led to varying degrees of response. The combination of both vegetation change and warming led to predictions of greater changes to streamflow amount and timing than either warming or vegetation change alone, indicating a nonlinear response from these systems to multiple perturbations. The complexity of the hydrological responses to warming and vegetation changes underscores the value of integrating observational data into surface–subsurface models and challenging models with observations.

Data Management System and Policy

The project’s data management efforts include (i) managing and archiving the diverse data collected by the project and releasing those data publicly with appropriate citation information, (ii) providing information to the public about field activities and data collection through an interactive portal, (iii) performing quality assurance and quality control of priority datasets, and (iv) creating a data integration engine and interactive search portal that enables discovery, fusion, and visualization of the diverse data for further synthesis and analysis.

The data management and assimilation system associated with the East River watershed includes several tools to discover, access, upload, process, and visualize data. Data from the instrumentation network described above and other data from laboratory characterization of field samples are curated and archived in a database. A range of data have been entered into the database, including more than five million data points from measurements collected across 50 locations, more than 3000 aqueous geochemical samples from 28 locations (with more than 70,000 analyte–location pairs), and specialized datasets (such as geophysical, remote sensing, and model output). Automated data quality assurance and quality control (QA/QC) is performed on several datasets using statistical methods to identify and flag anomalies in meteorological, water level, and geochemical data. In some cases, statistical approaches are used to automatically remove the anomalies. The data-cleaning approaches facilitate the use of the data for many applications, including the estimation of both evapotranspiration and river discharge with time, and the development of model drivers from the network of meteorological stations. In addition, team members and collaborators have access to a web portal where they can upload and download data files as packages with the metadata needed to enable discovery and obtain a digital object identifier (doi) for citation. This tool facilitates early archiving and internal distribution of working data prior to its curation in the database for complete preservation and also allows grouping campaign- or publication-specific data together for easier distribution.

The data management and assimilation system has developed Javascript-based portals that allow users to search, download,

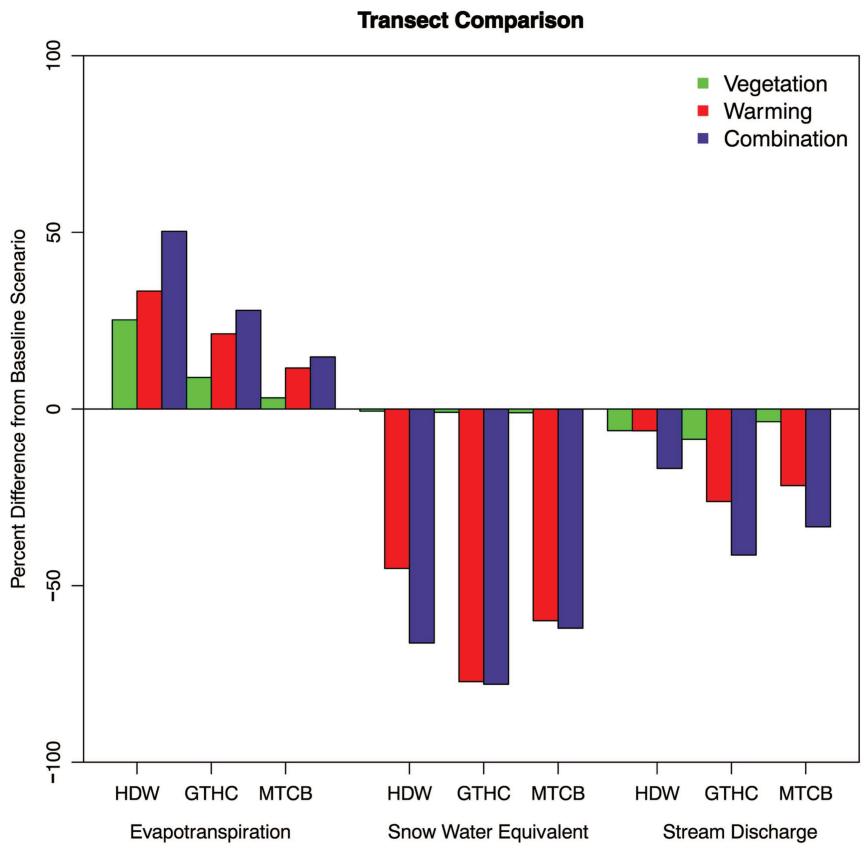


Fig. 15. Annual changes in evapotranspiration, snow water equivalent, and stream discharge simulated using ParFlow-CLM across high elevation (HDW), mid elevation (GTHC), and lower elevation (MTCB) transects in the East River watershed and as a function of imposed changes in vegetation, climate warming, or both (from Pribulick et al., 2016).

visualize, and explore data. The integrated results are presented to users via a web portal that enables intuitive search, interactive visualization, and download of integrated datasets (Fig. 16a). The interactive visualizations of time-series data (Fig. 16b) are created using the dygraphs charting library (<http://dygraphs.com/>). Additionally, a public interactive portal of field activities across the East River watershed site (<https://wfsfa-data.lbl.gov/watershed/>) has been developed to inform the broader community about data collection associated with the Watershed Function Project as well as collaborating projects (Fig. 16c). Sites can be filtered by their key measurements and other metadata, leading to a detailed site landing page.

Central to the Watershed Function Project's data management and assimilation system is a data integration brokering service developed at LBNL called BASIN-3D, or Broker for Assimilation, Synthesis and Integration of eNvironmental Distributed, Diverse Datasets (Fig. 17) implemented as a Django/Python application (<https://www.djangoproject.com/>). BASIN-3D is designed to provide unified access to diverse data types (such as hydrology, climate, biogeochemistry, or model output) located on distributed data sources (such as the project's Rifle and East River field databases and other external data sources). It connects to the data sources in real time using web services, retrieves a selective view of the data pertinent to the user queries, and transforms the data streams into abstracted representations to provide an integrated view. Thus BASIN-3D enables clients to always have access to the latest data from each of the sources but to interact with the data as if they were integrated in local storage. BASIN-3D allows representation of spatial data at various scales, from point measurements to site and regional scale observations, and is currently implemented to support time-series data formats (which is the predominant form of data at the East River). BASIN-3D is able to serve up the integrated data to a variety of clients including web portals, simulation codes, or analysis engines.

The Watershed Function Project's data management policy is designed to make the project's research data available internally to team members and externally to the public as rapidly as possible. The policy separates data into those generated using Watershed Function Project resources and data made available from external collaborators. The full policy is downloadable from the website (watershed.lbl.gov).

Summary and Future Perspectives

Climate change, extreme weather, land-use change, and other perturbations are significantly reshaping interactions within watersheds throughout the world. While mountainous watersheds are recognized as the “water towers” for the world, hydrological processes in these watersheds also serve as the origins of biogeochemical cycles. Developing a predictive understanding of watershed-scale hydrological and biogeochemical functioning is challenging because complex interactions occurring within a heterogeneous landscape can lead to a cascade of effects on

downstream water availability and quality. Although these interactions can have significant implications for energy production, agriculture, water quality, and other benefits valued by society, considerable uncertainty exists associated with predicting watershed hydro-biogeochemical dynamics.

The East River watershed has been developed as a community headwaters testbed to explore how mountainous watersheds retain and release water, nutrients, C, and metals and how they respond to early snowmelt, drought, and other disturbances. Underpinning the research is a motivation to document if and to what extent small-scale processes influence large-scale watershed behavior, or if “more is different.” Building on insights developed through studies at the Rifle study site, the Watershed Function Project is using the East River watershed to test a system-of-systems approach, which postulates that the integrated watershed response to disturbance can be adequately interrogated through consideration of interactions and feedbacks occurring within a limited number of archetypal subsystems, each having distinct vegetation–subsurface biogeochemical-hydrological characteristics. A technological centerpiece of the project is the development of scale-adaptive models capable of simulating the aggregated watershed response to perturbations in a manner that honors the complexity yet is computationally tractable.

Since 2016, many different East River watershed datasets have been acquired and used within newly developed approaches to explore bedrock-to-canopy and terrestrial-to-aquatic interactions and exchanges across this site. Key characteristics of the investigations include the integration across disciplines to address hydrological partitioning and its influence on biogeochemistry, an emphasis on quantifying above- and belowground interactions and feedbacks, and coordinated iteration between development of new characterization and modeling approaches. The early Watershed Function Project focus is on the response to early snowmelt along a lower-montane hillslope-to-floodplain transect, as well as exploring how exports from the intensive site aggregate toward the development of a cumulative watershed response. The vignettes provided above illustrate how hillslope and floodplain subsystems of the watershed respond to snowmelt. Examples include the development of new above- and belowground characterization and monitoring approaches for understanding vegetation distribution and bedrock-through-canopy hillslope interactions, new coupled modeling approaches that take advantage of increasingly available streaming data to estimate hillslope water partitioning with time, new characterization and modeling approaches for understanding hydrological flow and biogeochemical dynamics in riverine meander systems, including shortcutting through terrestrial meanders, and the role of hydrological flow on biogeochemical weathering. These results contribute to addressing the Watershed Function Project's first scientific question regarding subsystem responses to hydrological perturbations. At the watershed scale, we described recent advances in characterizing and predicting watershed behavior. Examples include investigations of how historical snowmelt and monsoon characteristics influence annual discharge across the

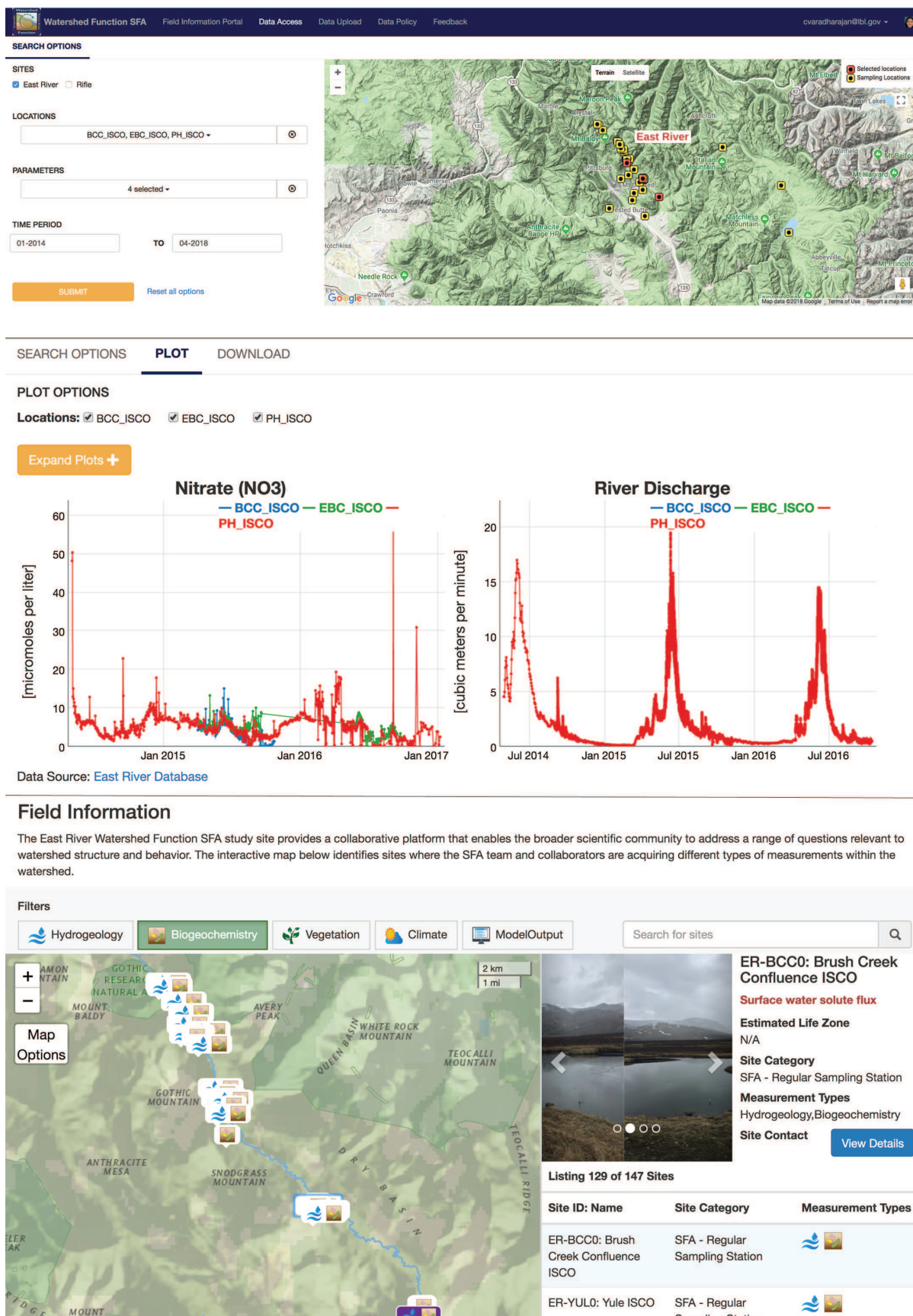


Fig. 16. Example of East River watershed data management displays including the team data dashboard enabling search and discovery of data that have been parsed and curated in a database (top), interactive data visualizations of time-series data served through BASIN-3D (middle), and the watershed information portal providing details about field data collection to the public (bottom).

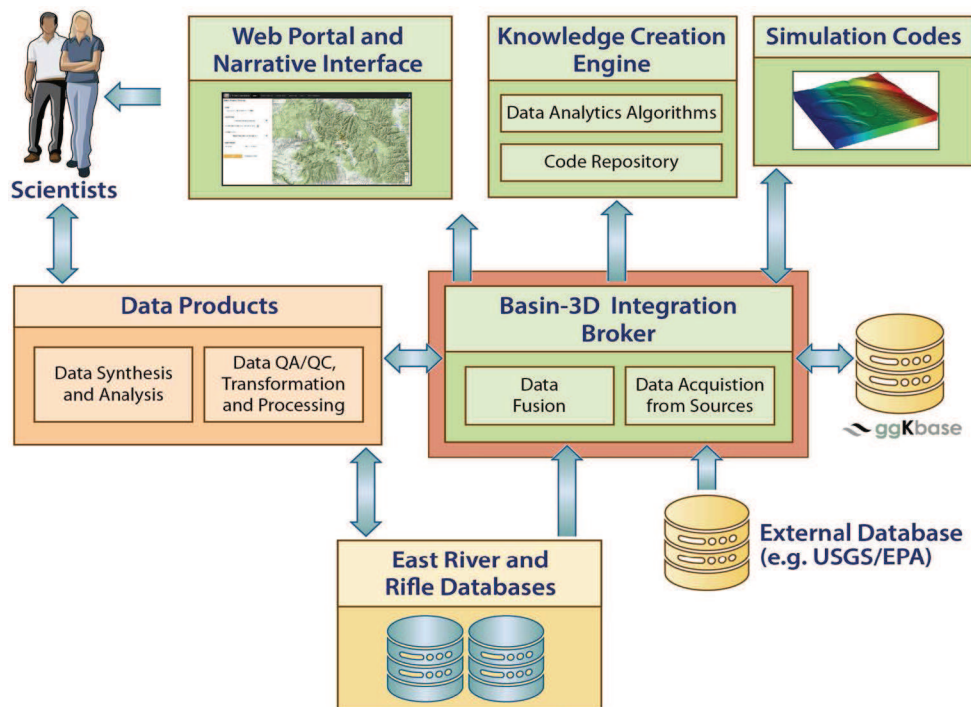


Fig. 17. A conceptual figure of the BASIN-3D data integration service for the Watershed Function data management and assimilation system, which is designed to retrieve data from distributed sources such as the Watershed Function Project and external databases and provide an integrated view of the data to a variety of clients.

entire watershed, first-order controls on streamflow generation as a function of position within the watershed, and simulations of how changes in vegetation and temperature are likely to influence water partitioning as a function of position within the watershed. These contributions are important for addressing the Watershed Function Project's third question, focused on gaining a predictive understanding of the aggregated system behavior.

Several recent and rapid technological advances have provided a springboard for exploring complex interactions at the East River watershed, and probably many other watersheds worldwide. For example, the "Internet of Things" facilitates acquisition and linkage between unmanned aerial vehicle based platforms, time-lapse geophysical soil sensor systems, flux towers, and other datasets, now allowing us to "watch" bedrock-through-canopy behavior in the watershed in an unprecedented manner. Community sequencing and bioinformatics are being used to illuminate how the subsurface microbiomes behave when sharing and competing for resources. High-performance computing capabilities, headed toward exascale, are allowing simulation of complex integrated surface–subsurface interactions including hydrology-driven biogeochemistry across resolutions and scales relevant to watersheds and beyond. Data management and assimilation tools are providing a framework for archiving, sharing, and integrating extremely diverse information in a way that holds promise for accelerating new discoveries and insights. Finally, the growing suite of hydrological observatories offers rich possibilities for collaboration, both within and across sites. Several aspects of the East River watershed effort are aimed at developing infrastructure that is broadly

useful, including development of a highly instrumented "community" mountainous watershed testbed, a management system for sharing diverse datasets, and open-source computational tools. We welcome new collaborators to the East River watershed as well as cross-site synthesis activities. More information about the East River watershed in Colorado is provided at watershed.lbl.gov.

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