Scientific Focus Area: Hydrobiogeochemical Process Dynamics in the Groundwater–Surface Water Interaction Zone

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Developing a predictive understanding of the subsurface interaction zone and its linkages with the water cycle

The subsurface interaction zone is a critical environmental interface where groundwater and surface water meet, extending within sediments beneath and along the inland margins of most streams and rivers. Due to seasonal changes in surface water volumes driven by precipitation, this zone experiences water flows that are dynamic in direction and magnitude, which produce significant surface water exchange and recirculation. Microorganisms flourish in surrounding sediments as nutrients present in both surface water and groundwater are mixed.

This interaction zone influences ecosystem health and surface water quality and displays feedbacks to climate. Contaminants and nutrients in groundwater can be transformed to less harmful forms in this zone, while biogenic processes may generate greenhouse gases. Understanding the function of this zone and developing robust models that predict its control on environmental chemical fluxes to surface water are crucial for sustainable energy, agriculture, and legacy waste management. A Scientific Focus Area (SFA) project led by Pacific Northwest National Laboratory (PNNL) is addressing these challenges. The project is supported by the Department of Energy's (DOE) Office of Biological and Environmental Research (BER) as part of BER's Subsurface Biogeochemical Research (SBR) program.

The project's field site is a free-flowing section of the Columbia River (called the Hanford Reach) in eastern Washington state. Research activities are being conducted in the subsurface interaction zone, which is a strip of land paralleling the river that includes the hyporheic zone, near-shore groundwater aquifer, and the vadose zone. The biogeochemical functioning of this zone and solute transport both within and through it are controlled by the local groundwater gradient and the annual riverine water cycle, with large increases in river stage occurring in spring from snowmelt. The overall system is highly sensitive to climate change, which influences the distribution between rainfall and snow in the Columbia River basin, the timing and amount of recharge and runoff, and the height and dynamics of the water table in the near-shore aquifer.

Key Scientific Gaps

The Hydrobiogeochemical Process Dynamics in the Groundwater–Surface Water Interaction Zone SFA addresses:

- Factors controlling the dynamics, extent, and function of the subsurface interaction zone in a changing climate.
- Role of subsurface interaction zone processes in controlling the flux of contaminants, nutrients, and biogenic gases between groundwater and surface water.
- Development of robust models that integrate microbiology, hydrology, and geochemistry for local- and regional-scale predictions.

Sample Collection. ***(Above)*** *A researcher stands ready to download continuous measurements of water level, specific conductance, temperature, and dissolved oxygen from a piezometer installed within the Columbia River hyporheic zone.* ***(Right)*** *Gas collection chambers (shown) are used to monitor biogenic gas emissions from the hyporheic zone under both submerged and drained conditions. The chamber is connected directly to an analytical device for real-time gas flux measurements.*

Bridging Spatial and Temporal Scales

SFA research includes fundamental process identification and quantification, integration of modeling and experimentation at multiple physical scales, and implementation of a novel and computationally efficient multiscale modeling framework. This framework will quantitatively link fine-scale process understanding with application-scale phenomenological models at the reach and watershed scales. Research activities include reach-scale behavior, local-scale behavior, fine-scale biogeochemical processes, multiscale science and modeling, and data assimilation.

Columbia River Field Site. *The Hanford Reach is a 70-km, undeveloped, and free-flowing stretch of the Columbia River in eastern Washington state. It is bordered by agriculture on the east and north and the Hanford site on the west and south. It has many islands, an active riparian zone, and complex channel physiography.*

Reach-scale behavior research assesses the effects of daily, seasonal, and yearly variations in the hydrologic cycle and climate on groundwater–surface water interactions, carbon and nitrogen transformations, and biogenic gas emissions from the subsurface interaction zone, including their feedbacks to climate. The influences of river channel structure, larger-scale geomorphic features, and hyporheic zone residence times on biogeochemical fluxes are explicitly considered.

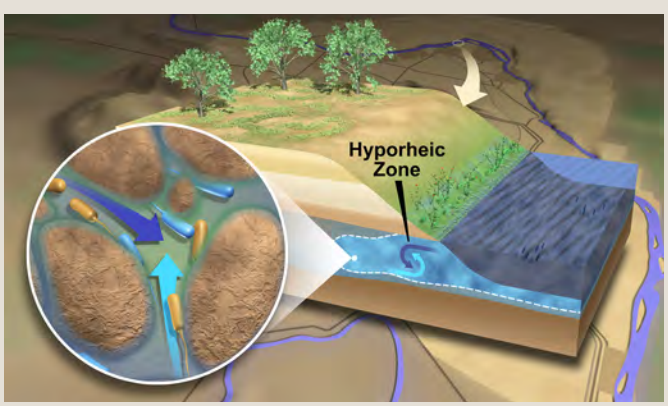
Local-scale behavior research monitors microbial community structure, biogeochemical processes, and hydrology across the groundwater–surface water mixing zone, encompassing coarse- and fine-grained sediments during short- and long-duration surface water intrusion events. Novel ecological modeling techniques are being applied to determine the relationships among hydraulic conductivity, biogeochemistry, contaminant and nutrient transfer, and ecological processes shaping microbial communities.

Fine-scale biogeochemical process research develops fundamental understanding of coupled hydrologic and biogeochemical processes that control the reactive transport of nutrients (carbon and nitrogen), contaminants (technetium and chromium), and the production of gaseous species (carbon dioxide, nitrous oxide, and methane) in subsurface interaction zone sediments. An enzyme-based biogeochemical modeling strategy (right) is being developed to support improved predictions of nutrient and contaminant processing in the interaction zone.

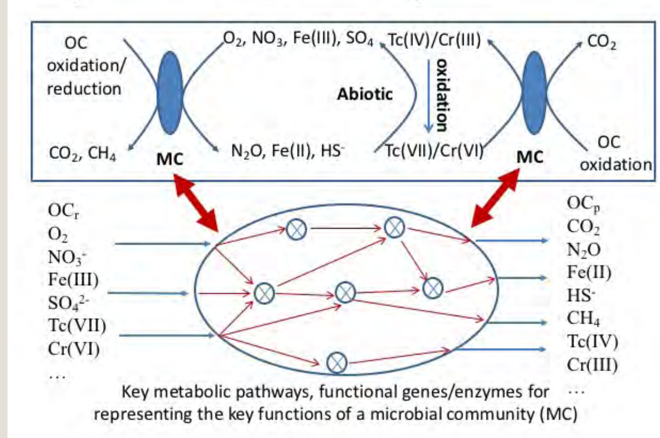
Multiscale science and modeling activities are developing and testing a novel modeling approach against observational data. This approach integrates bottom-up rigorous model development and optimal hybrid multiscale model deployment into a framework for application-scale modeling that balances predictive accuracy and computational burden. The approach uses macroscale diagnosis criteria to adaptively apply efficient upscaled models when appropriate, as well as hybrid multiscale models when needed.

Data assimilation activities are maintaining a central data repository for quality assurance and control; integrated analysis and multi-process interpretation; and dissemination of project observation, experimental, and modeling datasets to the scientific community. These efforts will drive uncertainty quantification and improve model predictability through iteration between model conceptualization and new experimental and field data.

Integrating field and laboratory studies at the fine, local, and reach scales into a multiscale modeling framework will enable a predictive scientific underpinning for larger-scale Earth system models linked through common modeling methods used at the interface between reach and regional scales.



Hyporheic Zone. *Surface water and groundwater mix in a river's hyporheic zone. The circular inset illustrates some features of this zone, including tiny grains of sediment, the mixing of water from both sources, and microbes that actively ply these waters and sediments.*



Biogeochemical Reaction Network. *This dynamic biogeochemical reaction network model—incorporating genome-informed, microbial community–based metabolic pathways—is being parameterized to simulate key enzyme synthesis and functions, biomass growth, organic matter metabolism, and the valence transformations of nitrate and contaminants (technetium and chromium).*

Toward Predictive Understanding

Ultimately, the SFA aims to develop a predictive understanding of the groundwater–surface water interaction zone and its linkages with the water cycle in terms of both seasonal and annual fluctuations. Hydrologic impacts on fundamental biogeochemical and ecological processes will be incorporated into a multiscale modeling framework that forecasts system responses and feedbacks to environmental changes. The project will evaluate, quantify, and model the influences of this interaction zone on discharges of groundwater contaminants to surface waters and the fluxes of biogenic gases involved in climate change from the land surface–surface water interface.

SFA research results will also provide essential knowledge and predictive models for large and small rivers worldwide that connect with glacio-fluvial aquifers, and for high latitude/elevation catchments with coarse-grained sediments.

For more information about the Groundwater–Surface Water Interaction Zone SFA, go to **sbrsfa.pnnl.gov**.

Contacts and Websites

Principal Investigators
John Zachara, john.zachara@pnnl.gov, 509.371.6355
Jim Fredrickson, jim.fredrickson@pnnl.gov, 509.371.6943
Tim Scheibe, tim.scheibe@pnnl.gov, 509.371.7633

BER Program Managers
David Lesmes, david.lesmes@science.doe.gov, 301.903.2977
Paul Bayer, paul.bayer@science.doe.gov, 301.903.5324

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