

Science

FINDINGS

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issue one hundred sixty six / october 2014

"Science affects the way we think together."

Lewis Thomas

The Stream Subsurface: Nitrogen Cycling and the Cleansing Function of Hyporheic Zones

"When you put your hand in a flowing stream, you touch the last that has gone before and the first of what is still to come."

—Leonardo da Vinci

Imagine molecules of water in a stream, billions upon billions flowing downstream every second. Imagine these molecules hitting a gravel bar. Most molecules adjust course, flowing around the diversion, but some flow into the gravel bar. As they enter the subsurface, or hyporheic zone, their flow slows dramatically. On this particular day, it will take 27 hours for these molecules to move through a 16-foot long gravel bar in a small stream surrounded by agricultural land in Oregon's Willamette Valley.

Any pollutants dissolved in the stream water also are carried into the hyporheic zone. In the slow underground flow, these pollutants come into intimate contact with films of bacteria and other microorganisms that coat the surfaces of each grain of sediment. These microorganisms can feed on organic carbon dissolved in the water, initiating biochemical reactions that can influence water quality downstream.



Jay Zarnetske

Researchers prepare an experiment that traced the subsurface flow of water through a gravel bar to determine which mechanisms control a stream's denitrification process.

Nitrogen is a common water pollutant. It is also a naturally occurring element, essential to plant growth and stream productivity. Natural systems are able to produce bioavailable forms of nitrogen and to process it. Problems arise when the natural system is overloaded with nitrogen. Humans have approximately doubled the amount of nitrogen entering the world's ecosystems each year. Sources of nitrogen pollution include runoff

IN SUMMARY

Nitrogen is an element essential to plant growth and ecosystem productivity. Excess nitrogen, however, is a common water pollutant. It can lead to algal blooms that deplete the water's dissolved oxygen, creating "dead zones" devoid of fish and aquatic insects.

Previous research showed that the subsurface area of a stream, known as the hyporheic zone, regulated amounts of waterborne nitrogen, but the nature of that role was unclear. Forest Service and university scientists undertook a suite of experiments to learn what factors determine if the hyporheic zone will be source or a sink for nitrogen.

They conducted a field study using a nitrogen isotope to monitor the flow path of water through the hyporheic zone of a gravel bar in a Willamette Valley stream. This experiment confirmed that the hyporheic zone can be either a net source or a net sink of nitrate—a reactive bioavailable form of nitrogen. Further analysis revealed that the residence time of water and uptake rate of oxygen by microorganisms in the hyporheic zone determine if this subsurface area functions as a nitrate source or sink.

The scientists then developed a theoretical framework to predict this nitrate source or sink potential of any hyporheic zone. Using this kind of information, stream restoration projects could be designed to maximize the self-cleansing process of hyporheic zones and help control water pollution.

from fertilized fields and pastures. Exhaust from cars and other internal-combustion engines also release substantial nitrogen to the atmosphere, which subsequently falls to earth as acid rain. This excess nitrogen fertilizes rivers, lakes, and oceans and can trigger algal blooms. The algae then dies and its decomposition depletes the water's dissolved oxygen. This contributes to near-shore "dead zones" in lakes and oceans such as seen in the Gulf of Mexico.

A team of scientists from the Pacific Northwest Research Station (PNW), Oregon State University (OSU), and Utah State University (USU) developed a set of studies to better understand the nitrogen cycle within stream hyporheic zones. These studies focused on denitrification, a self-cleansing process through which nitrogen pollution can be removed from streams. Knowing the thresholds controlling denitrification is valuable information that could be used to help reduce nitrogen pollution.

The studies conducted by Steve Wondzell (PNW); Jay Zarnetske, an OSU graduate student at the time; Roy Haggerty (OSU); and Michelle Baker (USU) yielded information about the fundamental hydrologic and biogeochemical processes in play. Building on these findings, the scientists developed a model for predicting if the hyporheic zone will be

KEY FINDINGS	
• The hyporheic zone in streams can be a source or sink of bioavailable nitrogen in the form of nitrate (NO ₃).	
• The distinction between net nitrification and net denitrification depends on the residence time of water in the hyporheic zone and uptake rates of oxygen.	
• The amount of denitrification in anaerobic portions of the hyporheic zone is limited by the supply of dissolved organic carbon that can be readily used by microorganisms.	
• These findings explain widely contrasting results of other studies that variously identified the hyporheic zone as either a net source or sink of NO ₃ .	

a source or sink of nitrate (NO₃). Zarnetske, now an assistant professor at Michigan State University, took the lead and was advised by Wondzell and Haggerty.

The researchers focused their attention on the stream's hyporheic zone—where surface stream water mixes with shallow "ground waters" found in the streambed, gravel bars, and shallow aquifers underlying riparian zones. The flow of stream water through these subsurface locations creates unique environmental conditions that are distinct from true surface and ground waters.

People have been studying denitrification in the hyporheic zone for about 30 years, Wondzell explains. However, quantifying the controls on, and rate at which, hyporheic zones help "clean" nitrogen-polluted streams has proven difficult. In fact, studies over the past three decades have arrived at seemingly contradictory conclusions: some identified the hyporheic zone as a net source of bioavailable nitrogen, while other studies concluded that the hyporheic zone was a nitrogen sink.

The denitrification studies began with a search for a suitable stream where several

Purpose of PNW Science Findings

To provide scientific information to people who make and influence decisions about managing land.

PNW Science Findings is published monthly by:

Pacific Northwest Research Station
USDA Forest Service
P.O. Box 3890
Portland, Oregon 97208

Send new subscriptions and change of address information to:

pnw_pnwpubs@fs.fed.us

Rhonda Mazza, editor; rmazza@fs.fed.us

Cheryl Jennings, layout; cjennings@fs.fed.us

Science Findings is online at: <http://www.fs.fed.us/pnw/publications/scifi.shtml>

To receive this publication electronically, change your delivery preference here:

<http://www.fs.fed.us/pnw/publications/subscription.shtml>



Vincent Adams

Researchers collected water samples from 11 small monitoring wells to determine the levels of dissolved oxygen, nitrate, ammonia, and dissolved organic carbon at different points along the gravel bar.

experiments could answer different fundamental questions. “Drift Creek was selected as a candidate site because it has background nitrate levels that are a little higher than often found in the Willamette Valley. It’s more comparable to what is found east of the Rockies,” Zarnetske explains. Further, the hydrology of the site enabled the researchers to better track the water through the hyporheic zone than in previous studies.

“In steep mountain streams, for example, flow paths can be dominated by a vertical dimension, moving from high points to lower points, leaving one pool and reemerging in the next

pool downstream. It’s tricky to follow,” says Zarnetske. “In Drift Creek, there is some vertical movement, but a larger lateral component that is easier to track.”

As part of the process, the scientists installed 11 small monitoring wells along the gravel bar. They then released a small amount of a nitrogen isotope ($^{15}\text{NO}_3$) into the stream and were able to trace its progress along flow-paths through the stream and gravel bar. “By using a stable isotope, only a tiny amount of nitrate needs to be added as a tracer so there is virtually no change in the overall amount of nitrogen in the stream. Stable isotopes are

naturally occurring and are not dangerous for any life form,” Wondzell explains.

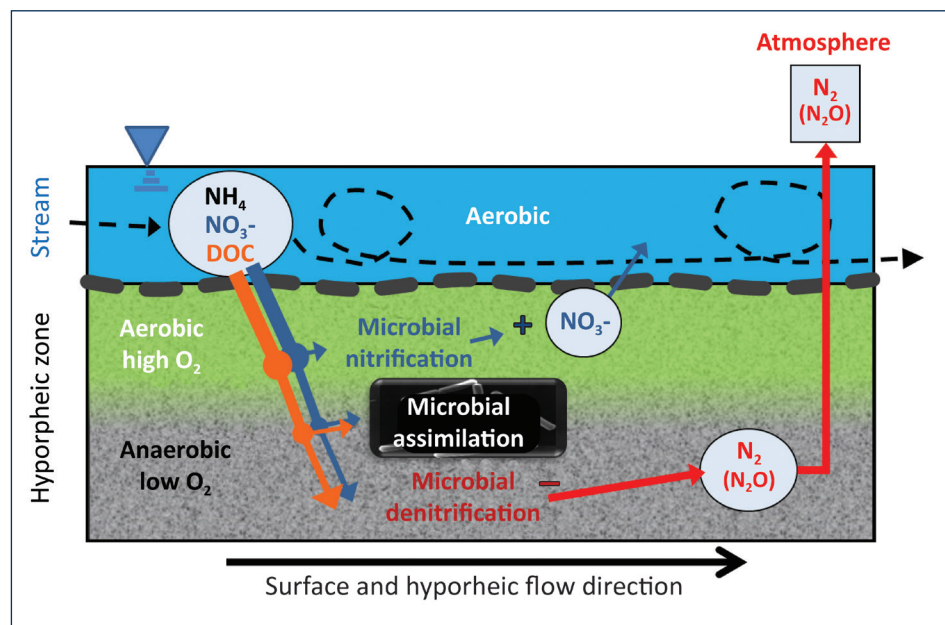
They collected water samples around the clock that were later analyzed in a laboratory to determine the levels of dissolved oxygen, nitrate, ammonia, dissolved organic carbon, and isotopes. The experiment revealed that this hyporheic zone was a hot spot for nitrogen transformation. Nitrate was both produced within and removed from the system. And, time spent in the hyporheic zone was the trigger—a key threshold exists between the production and removal functions. But to understand how and why a stream can be either a source or a sink for nitrate requires understanding what happens in the hyporheic zone.

WHAT HAPPENS IN THE HYPORHEIC ZONE?

“**B**acteria in the streambed get energy by consuming or decomposing things that are carried by the hyporheic flow of water,” Wondzell says. “Bacteria will preferentially decompose the easily digestible—the labile—forms of carbon. They can do it fairly quickly through an aerobic metabolism.”

This decomposition process produces a spare electron. Typically, oxygen is used as the electron receptor, Wondzell explains, which means the available oxygen is rapidly used up if a lot of labile dissolved organic carbon is being consumed. “Once the oxygen is used up, the subsurface water environment becomes anaerobic, causing a major shift in respiratory pathways. The bacteria need to shift to a different terminal electron receptor because there is no more oxygen,” says Wondzell.

“In freshwater environments, nitrate is often the next most favorable terminal electron receptor used by bacteria, once oxygen is depleted,” Wondzell continues. “The respiration process begins using nitrate as the terminal electron receptor.” As part of this anaerobic process, the stream nitrate is converted to dinitrogen gas, which escapes to the atmosphere. This is considered a permanent loss of nitrate from surface water, and if this is a dominant process in the hyporheic zone, the hyporheic zone is referred to as a sink because less nitrate is coming out than went in.



Surface water supplies nitrate (NO_3^-), dissolved organic nitrogen (DON), and dissolved organic carbon (DOC) to the hyporheic zone. Depending on the amount of available oxygen, microbes in the hyporheic zone will induce chemical reactions that either produce more nitrate that stays in the stream or transforms into nitrogen gases (N_2O and N_2) that return to the atmosphere.

In this first study, “We wanted to look at the factors that affect the amount of denitrification that occurs,” says Wondzell. “If the rate of biological activity for the bacteria and microbes on sediment surfaces was slow relative to the rate at which water in the stream

supplies nitrogen to the subsurface, then the limiting factor would be biological—how fast the bacteria were munching through nitrate. Alternatively, if the rate of biological activity for the bacteria doing the denitrification was very rapid, then something else would likely limit denitrification.”

HYDROLOGY OR BIOLOGY: WHAT IS THE LIMITING FACTOR?

The hydrology of a mountain stream, tumbling over rocks as it rushes downstream, is much different than that of a stream meandering through a field. Steep streams have strong physical forces pushing water through coarse sediment. “If water is moving quickly through a hyporheic zone, it’s well oxygenated,” Wondzell explains. “The

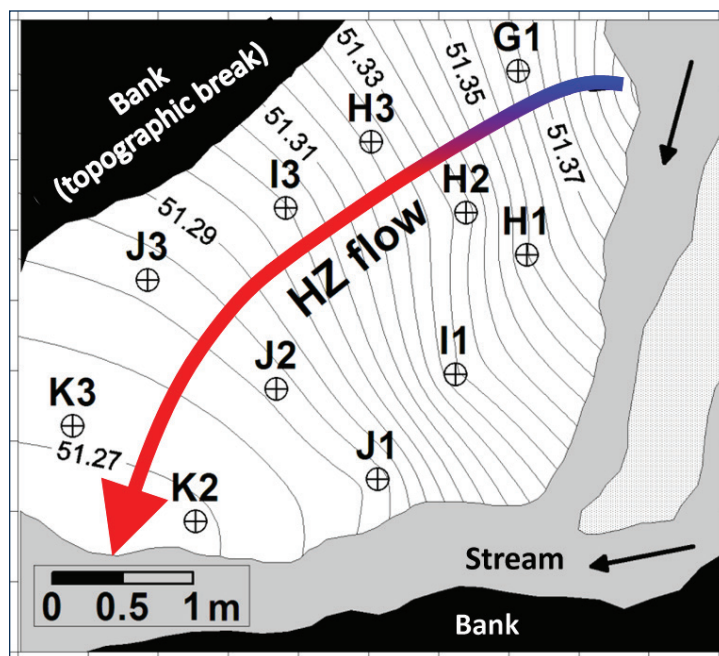
streambed sediment is often so coarse that water does not become anoxic.” The available oxygen is not used up by microbial respiration, which means that “nitrate can actually be produced by other biogeochemical reactions, which then release it back to the stream. In this case, the hyporheic zone becomes a source of nitrate. This is impor-

tant in the Oregon Cascades, where productivity of mountain streams is limited by the amount of available nitrogen,” he says.

In streams with more gradual elevation decline, like those in a large valley, finer textured sediment particles get deposited into the fabric of sediment that makes up a gravel bar. The physical forces pushing the water through

sediment are weaker, and the space between gravel particles can become plugged with sand and clay. Overall, water moves much more slowly through the hyporheic zones of these streams. “If the flow path is slow, then water becomes anoxic and the gravel bar becomes a nitrogen sink,” Wondzell says. The longer it takes for the water to pass through, the more time it gives the bacteria in the biofilms that coat the substrate sediments to remove the pollutants.

Further study into the biological process at work revealed that the amount of easily digested dissolved organic carbon limited the denitrification process. When the scientists added labile dissolved organic carbon to the stream study site, significantly more nitrate was removed by the gravel bar hyporheic zone. This told the scientists that denitrification is tightly coupled to carbon dynamics and that the carbon and nitrogen cycles for river systems need to be modeled as coupled processes.



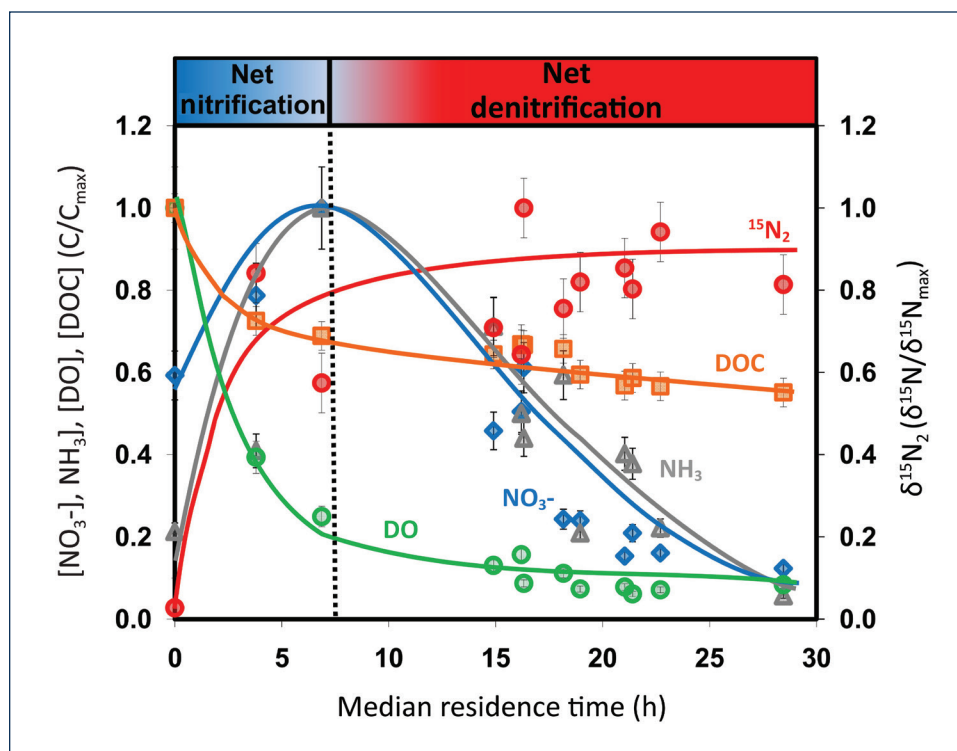
Map of the Drift Creek study site showing tracer observation sites. The arrow represents a single simulated flow path through the gravel bar. Where the arrow is blue, aerobic conditions in the hyporheic zone led to net nitrification. Where the arrow is red, anaerobic conditions led to net denitrification.

LOOKING FOR PATTERNS ACROSS TIME

With the basic science now in hand, the next step was to construct a practical theoretical framework to predict the nitrate source or sink potential of any hyporheic zone. Land managers could then include the hyporheic zone in stream management designs. Stream channel restoration projects could be designed, for example, to maximize the denitrification potential of gravel bars. The framework would also allow for scaling across a landscape gradient, and would be something that would work when applied to all waterways, regardless of size.

Zarnetske approached this framework challenge with a novel perspective. “The subsurface environment is highly variable in its ability to convey water and solutes, so I thought, let’s look for patterns across time, not across space. Ultimately, the residence time of water in the subsurface should account for this spatial variability.” Previous research was spatially focused, which explains the divergent findings about whether hyporheic zones are sources or sinks for nitrate. “By using a residence time perspective to examine where and how the threshold varies, we can model it in a very different way than when thinking about what happens 1 meter versus 2 meters into a gravel bar.”

The field experiments had provided essential data and fundamental information that the scientists then brought back to their labs and used to build a framework for conducting simulations. “Using theory implemented in a numerical model, we synthetically created many different hyporheic zones to explore conditions that didn’t exist at the experimental



This conceptual model shows a continuum between net hyporheic nitrification and denitrification as a function of residence time. When water moves slowly through the hyporheic zone, microorganisms use up the dissolved oxygen (DO) in the water and begin using nitrate (NO_3^-), which is converted to dinitrogen gas ($^{15}\text{N}_2$) and released to the atmosphere in what is considered a permanent loss.

site, and explored the controls of the hyporheic zone functioning as a source or sink of nitrogen,” Zarnetske explains. “In effect, it was like going out and sampling tens of thousands of streams and studying the data, but we were able to do it all on the computer.”

The scientists conceptualized the framework in terms of supply and demand for oxygen,

where the physics of hydrology controls supply and the biology of microbial respiration controls the demand. These two factors were mathematically combined into a dimensionless ratio between residence time and oxygen uptake rate.

“This dimensionless approach is what makes this framework potentially very powerful and



Jay Zarnetske

The self-cleansing abilities of the hyporheic zone can complement the pollution control service offered by riparian buffers.

transferable,” says Zarnetske. “We can start to model whole watersheds and hyporheic zones across systems and compare them to another place or another time. We can go to any stream and make these measurements of residence time and oxygen concentration, and make a process-based determination if they will function as a net source or net sink of nitrate—simply by measuring these two parameters.”

Zarnetske continues, “There’s an explosion of new sensor technology coming on the market that will make oxygen measurements much easier and more robust. Further, hydrologists are continually improving our ability to quantify hyporheic residence times. If we



LAND MANAGEMENT IMPLICATIONS



- The “self-cleansing” processes in the stream channel or adjacent hyporheic zone can help control nitrogen pollution in streams and rivers. This can complement the pollution control service that riparian buffers provide and minimize the amount of land needed to support this ecosystem service.
- The modeling predictions generated from these studies are quantitatively based and linked to whole-network estimates of hyporheic exchange. This means that predictions could be scaled up to whole watersheds.
- The detailed knowledge about the hydrology and biogeochemistry of hyporheic zones revealed in these studies provides a solid scientific foundation to help integrate the hyporheic zone into stream management decisions.

can quantify these two parameters, we should be able to make some reasonable predictions about overall ecosystem services of the hyporheic zone.”

Riparian buffers are often used to intercept pollutants before the runoff enters the stream, but buffers require a substantial investment of land. It’s also impossible for riparian buffers to intercept all the diffuse sources of nitrogen pollution that enter waterways.

Wondzell and Zarnetske found that their study stream’s hyporheic zone was responsible for the removal of at least 17 percent of the nitrate entering the stream. By understanding how the hyporheic processes work, stream restoration projects could be designed to support and enhance this ecosystem service.

Nearly 60 million people in the United States drink water that flows off national forests and grasslands. As demand for clean water

increases with the world’s growing population, it will be even more important to understand the details of this ecosystem service. The self-cleansing processes occurring in hyporheic zones could be used to help control pollution of inland waters.

“Water, like religion and ideology, has the power to move millions of people. Since the very birth of human civilization, people have moved to settle close to it. People move when there is too little of it. People move when there is too much of it. People journey down it. People write, sing, and dance about it. People fight over it. And all people, everywhere and every day, need it.”

—Mikhail Gorbachev

FOR FURTHER READING

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WRITER’S PROFILE

Rhonda Mazza is a science writer with the Pacific Northwest Research Station. She can be reached at rmazza@fs.fed.us.



U.S. Department of Agriculture
Pacific Northwest Research Station
1220 SW Third Avenue
P.O. Box 3890
Portland, OR 97208-3890

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Steve Wondzell is a research ecologist with the Pacific Northwest Research Station who is studying riparian ecohydrology—the study of interactions between hydrological, geomorphological, and ecological processes that create, maintain, or

modify aquatic and riparian habitats, and the ways in which these processes either interact with, or are affected by, land-use practices. His research is helping to reveal, for example, what factors control stream temperature—findings that will help inform management strategies to address a changing climate. Wondzell holds a Ph.D. in forest ecology from Oregon State University.

Wondzell can be reached at:

USDA Forest Service
Pacific Northwest Research Station
3200 SW Jefferson Way
Corvallis, OR 97331

Phone: (541) 758-8753
E-mail: swondzell@fs.fed.us



Jay Zarnetske is an assistant professor at Michigan State University. His goal is to reveal the role of hydrology on complex ecosystem patterns and processes, such as those seen in watershed nitrogen and carbon cycles.

His work focuses on environments in which surface and ground waters interact, such as hyporheic zones, riparian zones, and wetlands. Zarnetske's work also includes large-scale analyses of watershed carbon export and the responses of arctic streams to global change. He has a Ph.D. in water resource science from Oregon State University.

Zarnetske can be reached at:

Department of Geological Sciences
Michigan State University
288 Farm Lane (NS 206)
East Lansing, MI 48824

Phone: (517) 353-3249
E-mail: jpz@cns.msu.edu

COLLABORATORS

Roy Haggerty, Vrushali A. Bokil, Ricardo González-Pinzón, Oregon State University

Michelle Baker, Utah State University