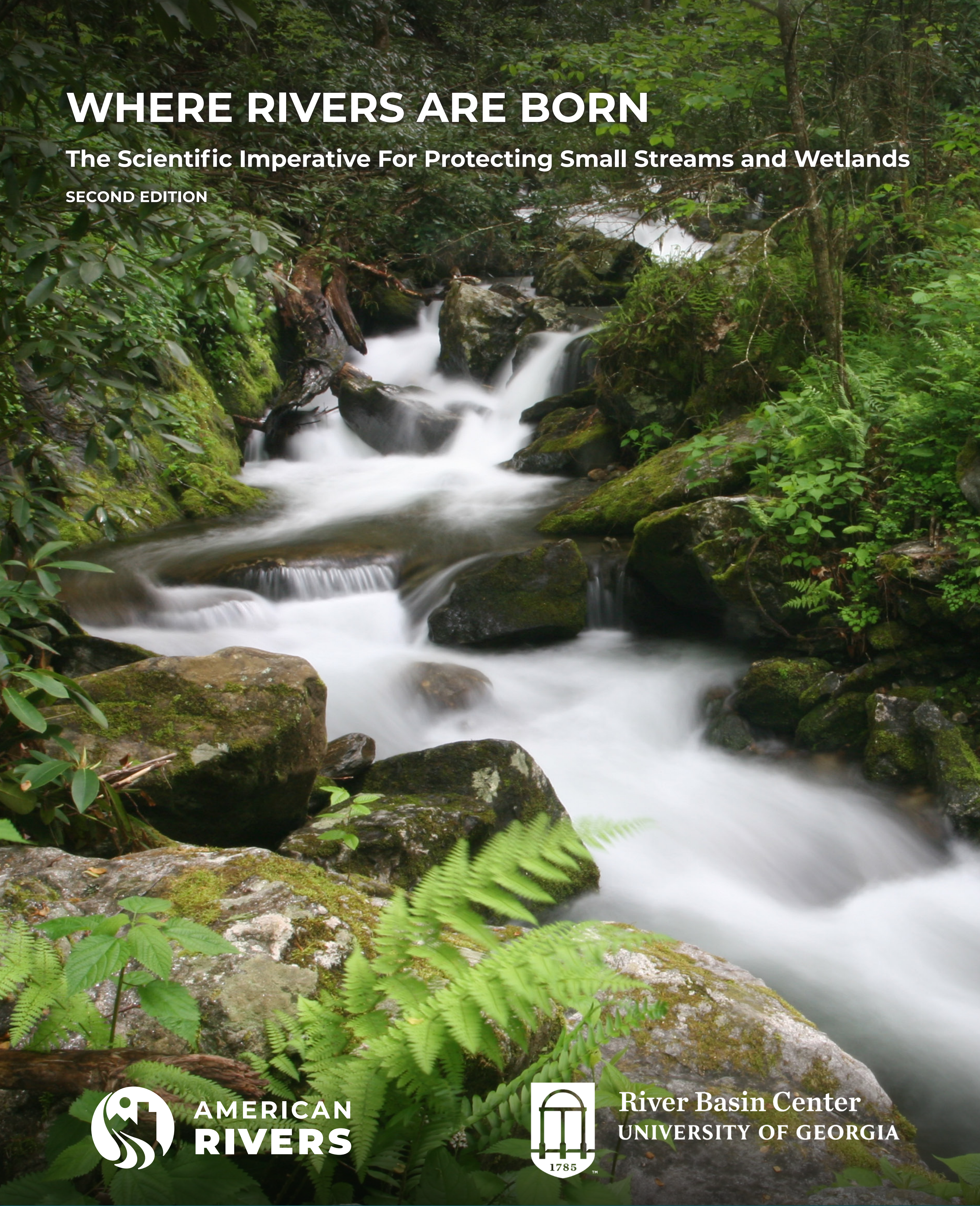
WHERE RIVERS ARE BORN

The Scientific Imperative For Protecting Small Streams and Wetlands

SECOND EDITION



AMERICAN RIVERS

River Basin Center
UNIVERSITY OF GEORGIA

Authors

Seth Wenger, PhD
Professor, Odum School of Ecology / Director of Science, River Basin Center
University of Georgia, Athens, GA

Ellen Wohl, PhD
Professor, Warner College of Natural Resources
Colorado State University, Fort Collins, CO

Susan Colvin, PhD
Assistant Professor, College of Science, Engineering and Technology
Minnesota State University, Mankato, MN

Craig Brinkerhoff, PhD
Gaylord Donnelley Postdoctoral Fellow, Yale School of the Environment / Yale Institute for Biospheric Studies
Yale University, New Haven, CT

John Richardson, PhD
Professor Emeritus
University of British Columbia, Vancouver, BC

Additional Contributors: Emily Bernhardt, PhD (Duke University) provided valuable advice on the content and organization of this document. Emma Rosi, PhD (Cary Institute, emerita) made extensive contributions to the section on natural recycling. Emily Underwood created original artwork for this edition. Freshwaters Illustrated provided photos under license.

This is a revised version of the original edition of Where Rivers Are Born, first published by American Rivers in 2003. Parts of the original are quoted within this edition. The authors of the original edition were Drs. Judy Meyer, Louis Kaplan, Denis Newbold, David Strayer, Christopher Woltemade, Joy Zedler, Richard Beilfuss, Quentin Carpenter, Ray Semlitsch, Mary Watzin, and Paul Zedler.

COVER PHOTO: UPPER SHOPE FORK, COWEETA HYDROLOGIC LABORATORY, NC.
PHILLIP BUMPBERS

Executive Summary

All of humanity and the entire global economy depend on a daily supply of clean water. Most of that water originates in small streams and wetlands—the headwaters—which are often unnamed and unmapped. Yet these anonymous headwaters are essential for maintaining downstream water quality, preventing flooding, providing wildlife habitat and improving peoples' quality of life. This document summarizes the scientific basis for the value and benefits of small streams and wetlands, which are often unnoticed, unappreciated and unprotected, and yet are a critical part of the natural infrastructure that sustains humanity. This second edition is an update to the original version, first published in 2003, and draws on hundreds of relevant scientific papers that have been published in the past two decades.

In the United States, the Clean Water Act has proven remarkably successful at protecting and improving water quality, to the substantial benefit of the American people. Part of this success is because the Act was historically interpreted as protecting most small streams and wetlands. However, shifting definitions of the "Waters of the United States"— the legal term for the Clean Water Act's jurisdiction— have resulted in different degrees of protection under different federal administrations. At the time of this writing, new rules are again under consideration that could substantially reduce protection for many headwater streams and most freshwater wetlands. The authors of this document were motivated by the belief that people should have access to good scientific information so they can express informed opinions about the policies that affect their lives. Thus, we have endeavored to distill the science of headwater streams and wetlands into straightforward and understandable language.

Small streams comprise the great majority (80% or more) of the overall length of the stream network. However, the precise extent of the small stream network is highly uncertain, because maps don't reliably record many streams, especially those that are non-perennial (that is, streams that don't flow year-round). It's important to recognize that even when there isn't visibly flowing water in a stream, there is often water moving within the streambed, and in the soils adjacent to the stream. Similarly, most of the apparently "isolated" wetlands are actually connected to streams and rivers via groundwater, and are helping to maintain clean water supplies in rivers downstream.

Moderating water flows is among the most economically valuable services of headwater streams and wetlands: they simultaneously ameliorate floods and maintain water supplies. They do this by slowing water down, providing opportunities for it to infiltrate into shallow groundwater, where it can continue to feed downstream rivers during low flow periods. Headwater streams and wetlands also trap sediment and contaminants (many of which bind to sediment), protecting water quality downstream. In addition, headwaters– including non-perennial streams– are particularly good at providing natural cleansing of water by processing excess nutrients, which otherwise could cause algal blooms in rivers, lakes and coastal areas downstream.

Small streams and wetlands provide additional benefits, including the often-overlooked function of natural recycling of dead plant and animal material. This again helps to maintain good downstream water quality, but it also provides long-term storage of carbon, which otherwise could contribute to climate change. Headwaters also support a remarkable amount of biodiversity, serving as a nursery for economically-important species such as trout and salmon, but also harboring numerous species that are not found in any other habitats. Finally, small streams and wetlands contribute to human well-being, providing opportunities for nature connection that helps to reduce stress and enhance peoples' happiness and productivity.

When headwater streams are altered, degraded or destroyed, their benefits disappear along with them. Downstream flooding becomes worse, water supplies become less reliable, water quality declines, and human well-being can suffer. Even though the loss of a single small stream or wetland may seem inconsequential, the aggregate economic cost of losing many small streams and wetlands is undoubtedly enormous. Fortunately, we have learned a lot in recent decades about what works (and what doesn't) in the restoration of streams and wetlands. Many communities are now investing substantial sums of money in rejuvenating urban streams and wetlands, including "daylighting" streams that were previously piped and buried, to recover the benefits they once provided. But restoration is expensive; it is much more efficient not to lose those benefits in the first place. The most effective way to maintain the supply of clean water on which the world depends is to provide adequate protection to small streams and wetlands.

Introduction

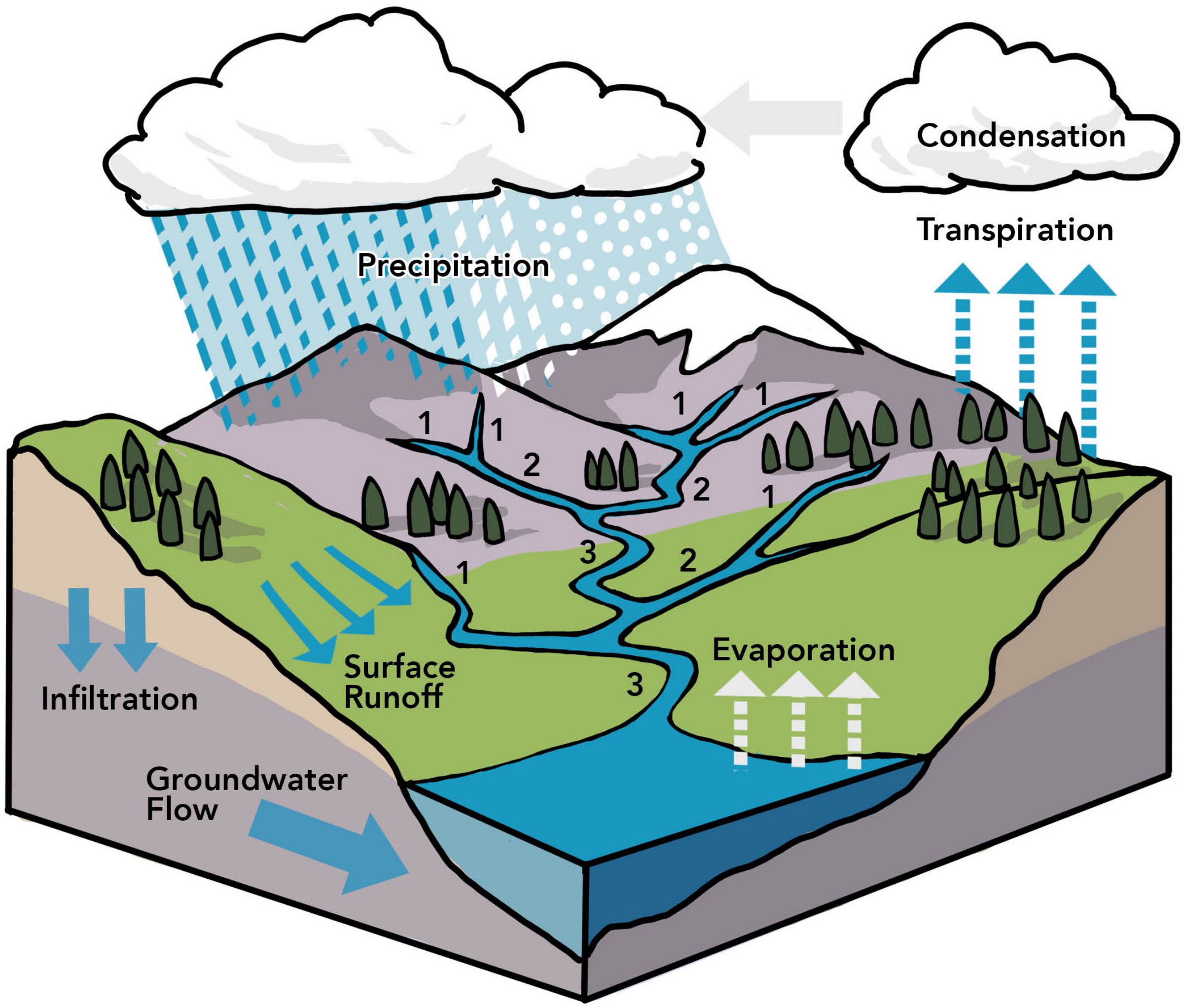
There is nothing more essential to human existence than water. Everything we eat, drink, wear, drive, and live inside requires water to produce—in fact, the entire economy of the planet depends on a daily supply of water. Even the virtual world needs water: at the time of this writing, cooling of data centers is among the fastest growing demands for municipal water in the US.

Most of the world depends heavily on nature for its water supply. The Earth's water cycle—powered by the sun and gravity—is a system of purifying, recycling and distributing water throughout the globe that operates at zero cost to humanity. Although desalinated seawater provides water in some arid areas, this is less than 1% of the human supply of fresh water; the vast majority is delivered as precipitation and distributed via streams, rivers, and aquifer recharge. Along the way most of it is naturally purified and requires only modest treatment and disinfection to be ready for human use.

Streams, rivers and wetlands are critical components of the water cycle, and provide numerous economic benefits, which are sometimes referred to as "ecosystem services." While provision of water for human use is the most important of these services, it is far from the only one. Streams and rivers in their natural state (or near-natural state) also provide flood control, sediment trapping, biodiversity, recreational opportunities, aesthetic values, and benefits to human health.

Although it's natural to think of streams and rivers as linear, in reality they are intimately connected with the terrestrial landscape on either side and with groundwater beneath them. The full "riverscape" is three-dimensional, with water, materials dissolved in the water, and organisms regularly moving between the channel and the adjacent valley, as well as between the channel and the underlying sediment. The riverscape facilitates infiltration of water that recharges underlying aquifers, helping to store water and keep the river flowing during dry periods. The riverscape provides habitat for fishes, birds, and other plants and animals that people value. The riverscape can provide space for flood waters to spread out and slow down, as well as space for excess sediment to be stored. The soils of a floodplain can store substantial amounts of organic carbon, keeping that carbon from entering downstream waters or the atmosphere. A riverscape is an ecosystem that provides valuable services to human communities, but the ability to provide these benefits declines when the riverscape is fragmented, or when parts of it are destroyed or degraded by human activities.

Our focus in this document is on the small streams and wetlands that form the headwaters of the riverscape—the places where rivers are born. Because they are small and because their connections to rivers may not always be on the surface, the headwaters are often under appreciated and unprotected. These headwaters are collectively the largest part of the riverscape but most are small and may flow or hold water only seasonally or after precipitation events. Yet these small streams and rivers provide critical services of enormous value to human society.



The Water Cycle and Stream Order. This figure illustrates the water cycle, in which evaporation from open water and transpiration by plants produce water vapor, which condenses into precipitation (rain and snow), providing fresh water that feeds streams and rivers through runoff and groundwater flow. The numbers indicate "stream order", a way of numbering streams according to their position in the network (see text on Page 7, *Defining Headwater Streams*). Illustration by Emily Underwood.

Headwaters in a Changing World

There is overwhelming scientific consensus that elevated greenhouse gases from fossil fuel combustion (and other human activities) are contributing to changes in global climate patterns, including elevated air and water temperatures, altered precipitation, and shifts in air and water currents. These climate changes, in turn, affect nearly every physical and ecological process on the planet– from sea level rise to metabolic rates to the timing of bird migrations. This means that the ecosystem services of headwater streams and wetlands are also in flux in ways that are not yet fully understood. However, challenges to understanding how changing climate and human communities are affecting headwater streams and wetlands should not preclude us from acting on what we do know, which is that small streams and wetlands provide vital services on which human communities rely. In fact, there is every indication that these services will become even more important in a warming world.

Overview of this Document

This document is an update of a version written by Dr. Judy Meyer and colleagues in 2003 for American Rivers. Portions of the original text resonate today as well as they did when originally published, and we have retained a few of these (e.g., "Where Are Rivers Born?" on page 6), while other sections have been updated to reflect new scientific understanding and changes to policy. Like the original edition, our focus is on North America, and we specifically discuss linkages to the United States Clean Water Act, the primary statute protecting water resources in the US. However, the scientific basis for the value and services of headwater streams and wetlands applies equally across the globe.

WHERE ARE RIVERS BORN?

Although 19th century explorers often searched for the headwaters of rivers, the birthplace of most rivers cannot be pinpointed. The origins of rivers are many anonymous tiny rills that can be straddled by a 10-year-old child, and no one trickle can reasonably be said to be "the" start of that river. Rather, rivers arise from a network of streamlets and wetlands whose waters join together above and below ground as they flow downstream. As other tributaries join them, creeks grow larger, eventually earning the title "river." The character of any river is shaped by the quality and type of the numerous tributaries that flow into it. Each of the tributaries is, in turn, the creation of the upstream waters that joined to form it.

The ultimate sources of a river often appear insignificant. They could be a drizzle of snowmelt that runs down a mountainside crease, a small spring-fed pond, or a depression in the ground that fills with water after every rain and overflows into the creek below. Such water sources, which scientists refer to as headwater streams and wetlands, are often unnamed and rarely appear on maps. Yet the health of these small streams and wetlands is critical to the health of the entire river network. The rivers and lakes downstream from degraded headwater streams and wetlands may have less consistent flow, nuisance algal growth, more frequent and/or higher floods, poorer water quality, and less diverse flora and fauna.

Small streams and wetlands provide crucial linkages between aquatic and terrestrial ecosystems and also between upstream watersheds and tributaries and the downstream rivers, lakes, water-supply reservoirs, and coastal areas. This paper summarizes the scientific basis for understanding how small streams and wetlands mitigate flooding, maintain water quality and quantity, recycle nutrients, create habitat for plants and animals, and provide other benefits.

This text is adapted from the first edition with minimal edits.

The diversity of headwater streams. Photos clockwise from top: Ellen Wohl, Craig Brinkerhoff (2), Phillip Bumpers , Ellen Wohl

Headwater Stream Extent and Connectivity

Defining headwater streams

Traditionally, scientists have classified streams by "order," a number that indicates the position of the stream in the network. A "zero-order" stream is a drainageway that lacks defined banks but still provides a pathway for water to flow; like headwater wetlands, zero-order streams also provide important benefits, especially sediment trapping and nutrient transformations, described below. "First-order" streams are the smallest streams with defined channels. Sometimes there is a clear initiation point for the first-order stream, but other times it may be ambiguous. A second-order stream is formed when two first-order streams join together, while third order streams are formed by two second-order streams, and so on (see figure on page 5). Some scientists have proposed strict definitions of headwaters; for example, in 2002 Gomi and colleagues suggested that headwaters are where a first-order stream joins with another first-order stream, and their individual properties start to average out into a network. However, in this document, we consider headwater streams to be all zero-order, first-order, and second-order streams. These small streams constitute at least 80% of the stream network in the US.

Some headwater streams, such as those emerging from springs, are perennial, which means that they flow year-round. However, most headwater streams are non-perennial: they cease to flow for at least a part of the year. They can be further categorized as intermittent (which have seasonal flow from a mix of groundwater and precipitation) and ephemeral streams (which flow only during and immediately after rain events). Non-perennial streams are a major component of most stream networks; in regions such as the U.S. desert Southwest, non-perennial waterways comprise ~85% of the total stream length. Globally, it is estimated that 51-60% of the world's waterways (by length) are non-perennial. Even some large rivers may naturally cease to have surface flow during the summer or dry season. Importantly, though, lack of visible water doesn't necessarily mean that the stream or river is completely dry– see "Much of the Riverscape is Underground," on page 9. Even during dry periods, non-perennial streams can provide valuable ecosystem services, and the process of drying and rewetting can promote important biogeochemical processes, such as nutrient processing. Thus, whether a stream is perennial or non-perennial is not a good indicator of the benefits it provides.

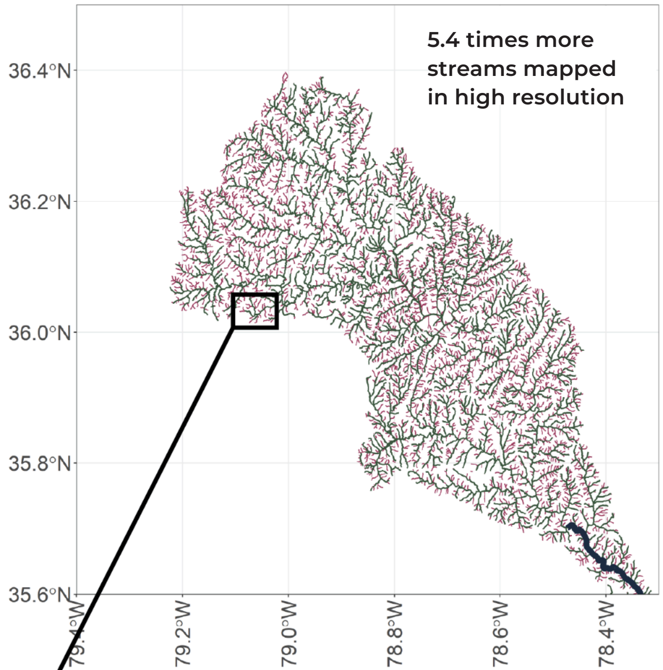
The Extent of Headwater Streams is Underestimated.

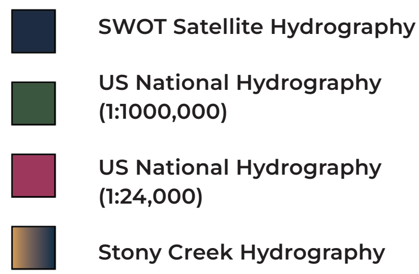
Headwater streams are not reliably mapped in most places. Standard reference maps, such as US Geological Survey topographic maps or the US National Hydrography Dataset, omit zero-order streams and many first-order streams. Studies based on in-person surveys have shown that headwater networks are vastly longer than what is commonly mapped (see figure on page 8).

There have been recent efforts to combine field data with satellite imagery to build better maps of stream networks, but headwater extent remains underestimated because it is impossible to survey every watershed, and models and satellite sensors are generally too coarse to map the smallest streams. High-resolution, high-accuracy maps are only available in certain watersheds that are intensely managed or used for research. In fact, even state-of-the-art satellites like NASA/CNES's Surface Water and Ocean Topography Mission, which provides unprecedented measurements of the world's surface waters, struggle to map headwater extent due to spatial resolution. And even when small streams are included on maps, they can be misclassified. These small streams are also underrepresented by monitoring networks: only 8% of USGS streamgage monitoring stations are on headwater streams.

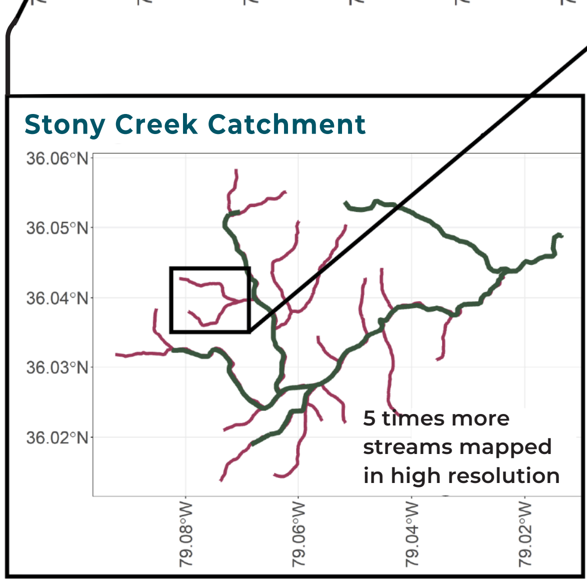
Non-perennial streams represent a particular mapping challenge, because they may not contain water at the time they are surveyed. Further complicating the matter is that some perennial streams are shifting to non-perennial, particularly in arid/semi-arid regions, due to shifts in climate and increases in human water withdrawals. We find that non-perennial streams, despite their importance, continue to be undercounted in headwater estimates.

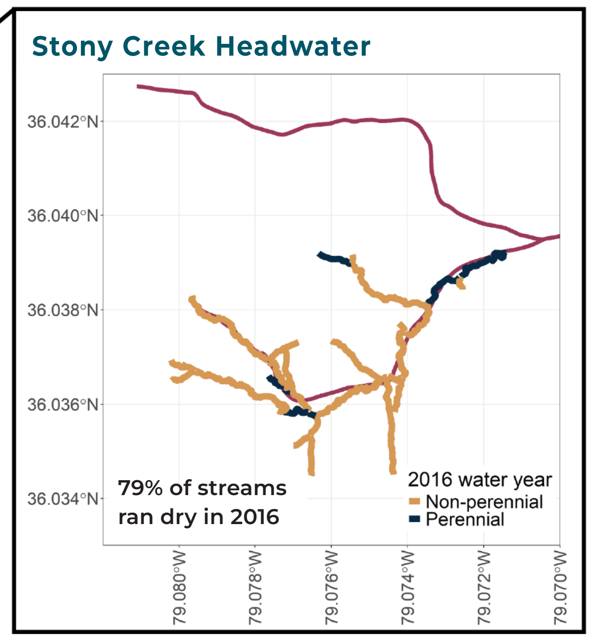
How maps underestimate headwater stream extent.





Mapping headwaters in the upper portion of the Neuse River basin in North Carolina. Observational datasets of headwater extent vary greatly depending on their spatial resolution, with even our highest resolution maps unable to reconcile all channels identified in the field (here using field surveys from the Stony Creek catchment as an example, courtesy of Barefoot and colleagues, 2019). Regardless of map resolution, non-perennial streams further complicate extent estimates: 79% of the Stony Creek reaches ran dry in 2016 and globally the majority of the world's waterways are non-perennial.





Data sources: SWOT SWORD River Database, USGS/EPA NHDPlus, USGS NHDPlus-HR, Barefoot et al. (2019)

Artificial drainages are the headwaters in many agricultural and urban areas

Historically, people have tended to eliminate headwater streams and wetlands in human-dominated landscapes to make room for other land uses. Many productive agricultural areas in the Midwest, California and Florida were wetlands before people deliberately drained them by lowering the water table by ditching or using tile drains. Wetland drainage in the United States increased dramatically during the 1850's to the early 1900's due to federal policies granting states reclamation rights to swamps and wetlands, western expansion, and large scale infrastructure such as factories producing materials for tile drainage. More than half of the wetlands in the lower 48 now have been converted to cropland or other uses, and the rate of wetland loss appears to be accelerating. Streams have not fared much better: today, the stream headwaters in many agricultural landscapes are straight drainage ditches, which provide only a portion of the functions once performed by the natural stream and wetland system.

In urban areas, many headwater streams have been buried in pipes, leaving only the larger streams and rivers. Flow in these remaining streams tends to be "flashy"-- i.e., characterized by low base flows punctuated by frequent high flows– due to the efficient delivery of stormwater runoff from impervious surfaces via drains and piped segments of the stream network. In these systems, natural headwater streams are absent; instead, the pipes, stormdrains and even the streets themselves function as artificial headwaters, again providing a much-reduced set of benefits. In recent years many cities have recognized that losing their natural stream networks came at a cost, and have embarked on stream improvement programs that involve "daylighting" previously buried streams, as well as improved stormwater management programs to better manage runoff and associated contaminants.

Small Streams Provide Critical Land-Water Connections

Because they comprise most of the river network by length, headwater streams cumulatively provide the greatest opportunity for connections to the landscape. At terrestrial-aquatic interfaces, headwater streams source, store, and transform terrestrial materials and nutrients. As a stream flows, it links headwaters to downstream rivers, ponds, wetlands, and even other terrestrial ecosystems. Floods and runoff from rainstorms also enhance land-water connections, with water flowing in and out of the channel laterally along the stream corridor and longitudinally into previously dry, non-perennial channels. These land-water connections are critical to sustaining river ecosystems.

Much of the Riverscape is Underground

When people think of a stream, they typically think of the flowing water they can see. But this is only part of the story: in most streams and rivers, much of the flow is actually within, under and adjacent to the streambed, moving through sand and gravel or even in the soil along the stream banks. This "hyporheic zone" is intimately connected with the surface, and plays a number of critical roles. It is the location of important biological activity (particularly nutrient processing); it provides habitat for many aquatic organisms; and it moderates surface water temperatures– cooling water in the channel in the summer and warming it in the winter. Many streams and rivers that are classified as non-perennial actually flow year-round– it's just that the flow is beneath the surface for part of the year.

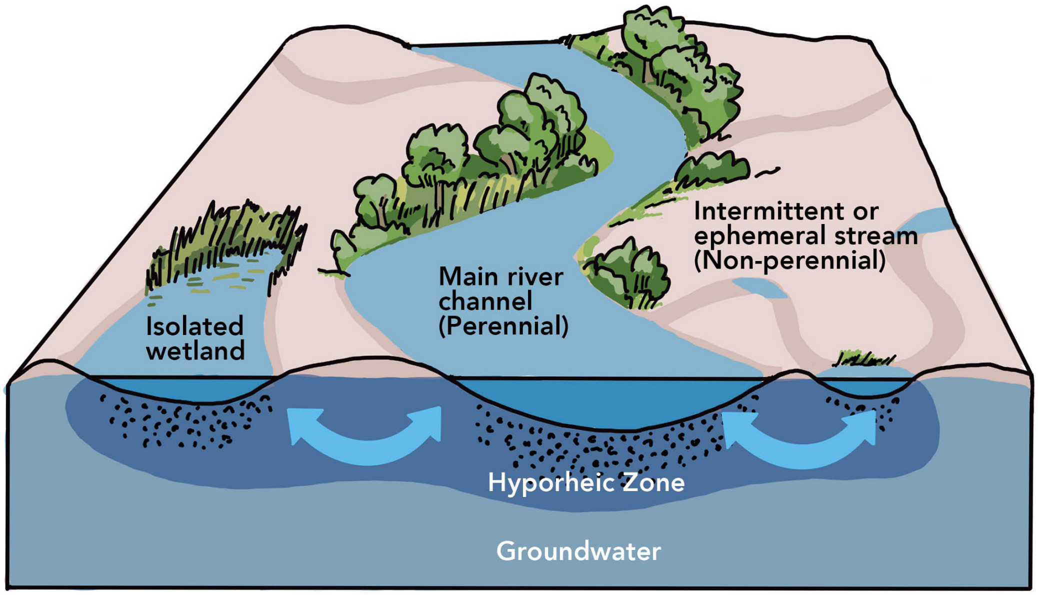
Wetlands are sometimes referred to as "isolated" or "disconnected" from other water bodies when they lack a surface-water connection [reference to the box on WOTUS]. But it is unusual for a wetland to be genuinely

THE CLEAN WATER ACT

The Clean Water Act, passed in 1972 with broad bipartisan support, is the primary federal statute protecting U.S. surface waters. The intent of the Act is to "restore and maintain the chemical, physical, and biological integrity of the Nation's waters." The Clean Water Act is widely regarded as a major success in reducing point source pollution—i.e., pollution from industrial and municipal discharges. Today, the streams and rivers of the US have much higher water quality than they would have in the absence of the Clean Water Act. Non-point source pollution is also regulated under the Act, which has encouraged the development of municipal stormwater runoff management programs and other actions to reduce the introduction of contaminants into streams, rivers and wetlands. Nevertheless, many rivers and streams do not meet their "designated uses" under the Clean Water Act, particularly in urban and agricultural areas, due to impaired water quality. Water quality impairment is particularly likely in low-income communities, rural agricultural communities, and many communities of color, creating issues of environmental justice.

In addition to water quality protections, the Clean Water Act historically provided protection against dredging and filling of wetlands and streams under the "No Net Loss" policy that required loss of wetland and stream functions to be replaced in kind. That is, if a wetland was destroyed, a new wetland needed to be constructed, or existing degraded wetlands needed to be enhanced. However, narrowing of the definition of "waters of the United States" has greatly reduced the jurisdiction of the Clean Water Act, rendering many (perhaps most) headwater streams and wetlands unprotected at the federal level (see WOTUS box on page 10).

disconnected; even when there is no visible surface connection, there is often a subsurface connection. This is readily evident in locations where groundwater pumping has lowered the water table and caused nearby wetlands to go dry. Seemingly isolated wetlands often play an economically valuable role in purifying water that ultimately ends up in aquifers and rivers that are used for water supply. Thus, the safer assumption is to consider all wetlands to be "connected" unless there is good evidence to the contrary.



Much of the Riverscape is Underground. Even during dry periods, both non-perennial streams and apparently "isolated" wetlands are often connected to perennial streams and rivers by shallow groundwater. Illustration by Emily Underwood.

THE EVOLVING DEFINITION OF WOTUS

The Clean Water Act only regulates "navigable water," which is further defined as "Waters of the United States" (WOTUS). The original definition of WOTUS was quite inclusive, covering not just navigable waterbodies but the great majority of streams and wetlands that flowed into them. However, the definition of WOTUS has shifted over the years in response to alternative interpretations under different federal administrations and in response to court rulings.

In a 2023 case, Sackett v. the Environmental Protection Agency, the United States Supreme Court ruled that WOTUS includes only 1) traditional navigable waters, the territorial seas, and interstate waters; 2) tributaries to traditional navigable waters, the territorial seas, and interstate waters that are "relatively permanent, standing or continuously flowing bodies of waters;" and 3) wetlands that have a continuous surface connection to waters in either of the preceding categories. This decision effectively eliminated Clean Water Act protections from a large proportion of wetlands (as much as 91% of nontidal wetlands, according to some interpretations), regardless of their actual hydrologic connection to navigable waters. It also eliminated protection for many non-perennial streams and rivers, although the exact number depends on the interpretation of "relatively permanent." As detailed in this document, both wetlands and non-perennial streams and rivers provide a broad suite of valuable services; therefore, their loss carries very real economic costs to society.

The exact definition of WOTUS will continue to evolve with future court interpretations of the Sackett ruling, as well as federal administrative rule making. It would likely require a congressional amendment to the Clean Water Act to permanently define WOTUS in a way that is inclusive of headwater streams and wetlands. In our view, a more inclusive definition would be consistent with the goal of the Act to "restore and maintain the chemical, physical, and biological integrity of the Nation's waters," and with the best available current scientific understanding. In the meantime, many streams and wetlands remain unprotected in the US, except where states and local governments have extended protections beyond federally recognized WOTUS, which they are legally allowed to do. Indeed, both at the state and local levels there exist a variety of tools to provide either regulatory protection or financial incentives to encourage voluntary protection of streams and wetlands. While relatively few state and local jurisdictions currently provide robust protections that are independent of the federal definition of WOTUS, that could change with growing recognition of the limited protections now afforded at the federal level.

Small Streams and Wetlands Provide Critical Benefits

Flood Control and Water Supply

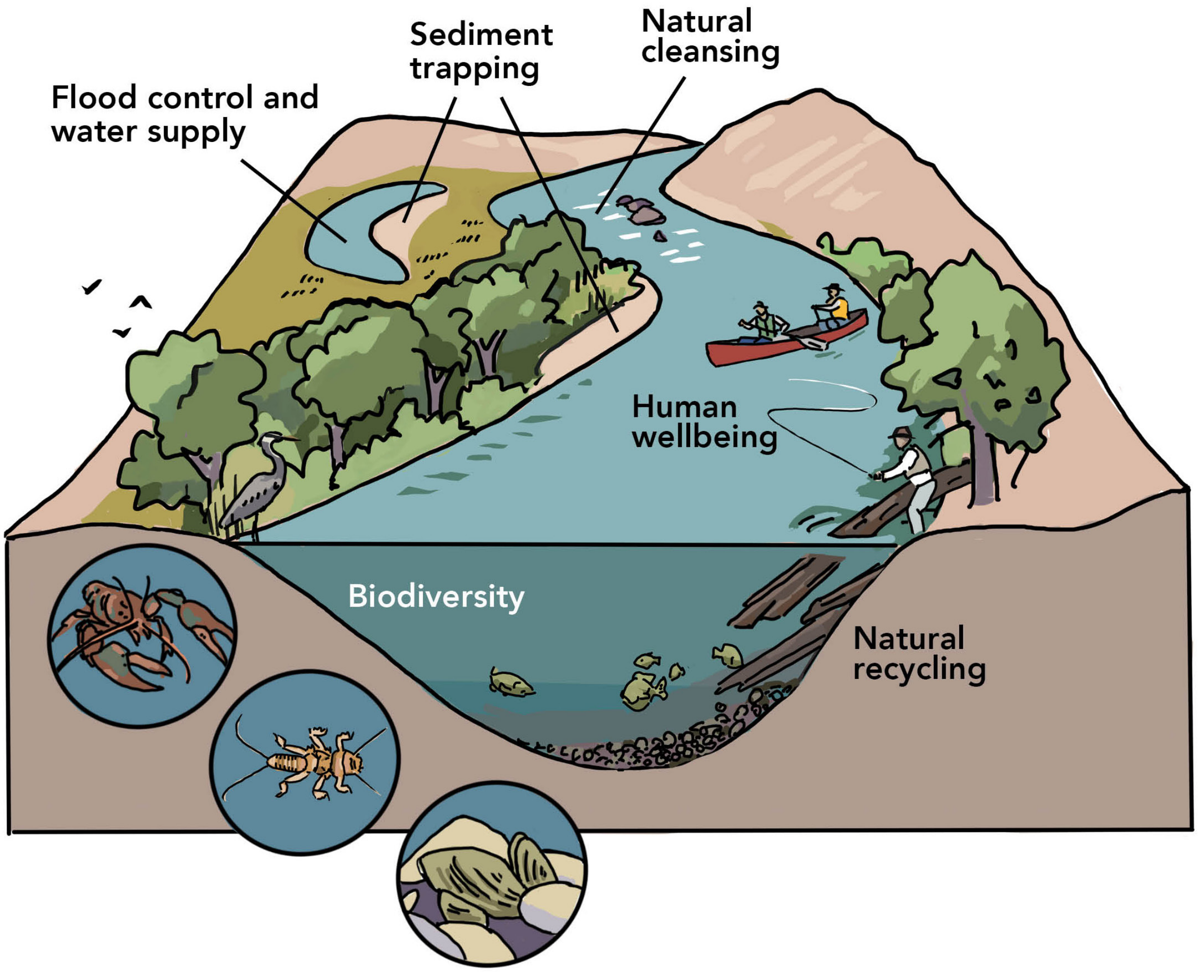
Rainfall and snowmelt coming from uplands enter small streams that join to form larger streams and then rivers. This downstream progression results in greater volumes of water moving within a river channel as the area contributing upland runoff and tributary flows increases. Small streams can either temporarily store some of this water during periods of flooding, or pass the flood waters quickly downstream. Beaver dams, logjams, and wetlands on the floodplain or along the stream channel can slow the passage of flood waters. Connectivity between a channel and the adjacent floodplains or between the channel and sediment beneath the channel surface can also reduce the highest flow during a flood, temporarily storing some of the flood water and releasing it gradually. On the other hand, small streams that have been channelized or buried underground in pipes, small streams that have been disconnected from their floodplains by levees or development of the floodplains, and wetlands that have been filled or paved, all pass water downstream very efficiently. This leads to higher flood peaks. The majority of the total stream miles in any river network are in small streams, so the cumulative effects of temporarily storing versus efficiently passing flood waters downstream can be enormous.

In regions such as the U.S. Midwest, wetlands such as prairie potholes store snowmelt and rain water, reducing floods and recharging aquifers. Prairie potholes are depressional wetlands, a remnant from glaciation. Slow decomposition in wetlands has resulted in a rich organic soil, favorable for agriculture, which has led to the draining and plowing of at least half of the original wetlands in the Midwest (in some states, more than 80% have been lost). The loss of water storage has prompted some states, such as Minnesota, to develop programs to restore historic wetlands specifically to reduce downstream flooding and maintain regular water supplies.

Storage of flood waters within a river system is mostly temporary, but that doesn't make it unimportant. The downstream movement of water can be slowed for minutes by a logjam, for hours by a beaver dam or wetland, and for days to weeks on floodplains and belowground. Eventually this stored water returns to the channel, however, and this gradual return feeds the flow of streams and rivers during dry periods. While any individual small stream corridor may not store much water, dozens to hundreds of little streams each contributing their stored water can make the difference between a river that goes dry and one that flows year-round. Whether they realize it or not, many municipalities benefit from the natural water storage of intact stream networks to maintain a steady supply of drinking water. When headwater streams and wetlands are degraded, the water supply can become less reliable, requiring communities to invest in artificial reservoirs to replace this lost service.

Sediment Trapping

As with water, small streams can store sediment or efficiently transmit the sediment downstream, where it can cause problems from excess turbidity that clogs water-supply intakes to accumulation in the channel that exacerbates flooding. In their natural state, headwater streams and wetlands tend to be good at storing sediment, but human alterations often reduce the sediment storage capacity. This is important because fine sediments, like silt and clay, tend to bind contaminants, such as phosphorus, metals and others, so sediment storage in headwaters provides the benefit of reducing downstream contamination. For example, phosphorus is an important nutrient for living organisms, but human activities have increased phosphorus levels in the environment and excess phosphorus now contributes to eutrophication, as described in "Natural Cleansing," below. Sediment storage in small streams is enhanced by many of the features that enhance temporary storage of water. Wetlands and obstructions to flow, such as logs and beaver dams in the channel, reduce the velocity of the flow and cause sediment to settle in the channel and on the floodplain. A channel connected to its floodplains has more space to store sediment in overbank areas. Sediment stored on the floodplain can also be covered by vegetation, which further stabilizes the sediment. Storage of sediment along small streams both reduces sediment-related hazards downstream, and creates benefits in the small streams by providing habitat for plants and eventually for animals.



The many benefits of headwater streams and wetlands. Natural cleansing refers to the ability of headwaters to trap and transform pollutants such as excess nutrients. Natural recycling refers to the transformation of dead plant and animal material into new organisms. Both functions help to protect downstream water quality. Illustration by Emily Underwood.

Natural Cleansing

All manner of materials make their way to rivers and streams: excess fertilizer from agricultural fields, heavy metals from car brake pads, plastic bags washed into storm drains, even shopping carts of unknown origin. Many of these things are harmful to aquatic ecosystems, damaging to human water supplies, and dangerous to recreational users. Even dust and rainfall can bring harm: for example, mercury (a powerful neurotoxin) is released into the atmosphere from coal-fired power plants and later deposited downwind, often finding its way downhill to accumulate in streams and wetlands. But the good news is that, while some contaminants (like plastics and PFASs, known as "forever chemicals") can be long-term problems, small streams and wetlands are remarkably good at storing and processing many contaminants, helping to protect downstream water quality.

Nutrients. Nitrogen, phosphorus, and other nutrients are essential for plants (and for other living organisms), which is why they are often added as fertilizer in both agricultural and residential landscapes. However, excess nutrients in runoff can cause "eutrophication" (over-fertilization) of streams, rivers, lakes, and coastal areas, leading to reduced water quality and blooms of algae. Excess algae can make streams unsuitable for species adapted to clear water, such as trout, and some algae can produce unpleasant odors and even toxins. Each year, harmful algal blooms cause billions of dollars in economic losses in the U.S., mainly due to effects on tourism.

Headwater streams are particularly efficient at retaining and processing nutrients, preventing them from causing problems downstream. That's partly because small, shallow streams have more physical contact between water and the stream bed than larger rivers and lakes, providing more opportunities for nutrients to be bound to sediment or to be transformed by microorganisms into less harmful forms. One study found that nutrients can travel less than 65 feet in a headwater stream before being removed from the water. Non-perennial streams play particularly important roles in nutrient processing, because they tend to have the greatest amount of contact between water and the channel. However, nutrient processing also varies seasonally, peaking during the drying period, with some nutrients later released during the re-wetting period.

Headwater wetlands are also important locations for nutrient removal. Studies have found that a wetland can remove 25-55% of the phosphorus and 29-44% of the nitrogen in the water that passes through it. Not all wetlands are net sinks for nutrients, and some wetlands may transition between accumulating and releasing nutrients, but studies have shown that the great majority of wetlands are net sinks through time (i.e., they capture and store or transform nutrients).

When headwater streams or wetlands are degraded, filled or piped, nutrients travel further downstream, reaching large rivers, lakes and coastal areas in higher concentrations. Even the removal of streamside forests can reduce the effectiveness of nutrient removal, because it can cause streams to change form, becoming narrower and deeper over time, and therefore providing less contact between water and stream bed. In short, degradation or destruction of the headwaters not only causes loss of the benefits provided by those streams and wetlands themselves, it leads to reduced benefits downstream due to increased frequency of algal blooms, decreased water quality, and the associated loss of recreational and aesthetic benefits.

Other Contaminants. The role of headwater streams and wetlands in storing and processing contaminants other than nutrients has received less research attention. However, many contaminants bind readily to sediments, so the sediment storage benefits of headwaters (described above) also tend to provide the additional benefit of reducing downstream contaminant concentrations. The degree of storage and processing can vary greatly in both space and time, however, depending on conditions such as the amount of dissolved oxygen and pH.

Natural Recycling

The first two paragraphs below are from the first edition.

Recycling organic carbon contained in the bodies of dead plants and animals is a crucial ecosystem service. Ecological processes that transform inorganic carbon into organic carbon and recycle organic carbon are the basis for every food web on the planet. In freshwater ecosystems, much of the recycling happens in small streams and wetlands, where microorganisms transform everything from leaf litter and downed logs to dead salamanders into food for other organisms in the aquatic food web, including mayflies, frogs, and salmon.

Like nitrogen and phosphorus, carbon is essential to life but can be harmful to freshwater ecosystems if it is present in excess or in the wrong chemical form. If all organic material received by headwater streams and wetlands went directly downstream, the glut of decomposing material could deplete oxygen in downstream rivers, thereby damaging and even killing fish and other aquatic life. The ability of headwater streams to transform organic matter into more usable forms helps maintain healthy downstream ecosystems.

The movement and transformations of carbon have become major topics of research in recent decades because carbon is a core component of carbon dioxide and methane, which are among the greenhouse gases causing climate warming. The riverscape, including headwater streams, constitutes a key part of regional and global carbon cycles. Rivers receive carbon from weathering of rock, introduction of soil, deposition of leaves and other plant material, and from photosynthesis by algae and other organisms. Rivers can then transport this carbon downstream to the oceans, release the carbon as a gas to the atmosphere, recycle the carbon into living tissues of riverine microbes, plants, and animals, or bury and store the carbon in floodplain sediment. The balance among these different fates of carbon in a river depends on river characteristics such as water and air temperatures and sediment deposition and storage on the floodplain. Wetlands and wet floodplains that retain sediment are especially large sinks for carbon; these floodplain sediments tend to have much higher concentrations of organic carbon than sediments in adjacent uplands. Although small streams have narrow floodplains relative to large lowland rivers such as the Amazon, the cumulative storage along many small stream floodplains can result in substantial quantities of carbon removed from the atmosphere.

NORTHERN LEOPARD FROGS IN WYOMING, FRESHWATERS ILLUSTRATED

Biodiversity

Small Streams. As a habitat, small streams provide conditions unique from those of larger waterbodies downstream. For one, shallow streams have few large-bodied predators, providing a relatively safe place for many small species, as well as the immature stages of larger species such as salmon. In shallow streams the role of predator is taken by smaller organisms, such as small or juvenile fish, some amphibians, insect larvae (e.g., dragonflies), and crustaceans. Second, many headwaters have a high amount of connectivity between groundwater and surface water, which moderates temperatures (cooler in summer, warmer in winter), especially when the stream is shaded by trees. Third, flows tend to be smaller, lacking the force to rearrange rocks and logs, so habitat can be more stable for species not tolerant of flood damage. Finally, the base of the food web is largely leaf litter and other organic matter, supporting a rich community of detritivorous species (i.e., organisms that consume dead material, especially fallen leaves).

Even though they are small, headwater streams can support high levels of biodiversity. One of the most intensively studied headwaters is the Breitenbach in Germany. Decades of study of that single small stream have documented over 1800 species, including over 1000 species of aquatic insects. In headwaters of the USA, particularly in long-term ecological sites, comparably high biodiversity has been found. In studies in the Coweeta Hydrological Laboratory in North Carolina almost 300 species of stream invertebrates have been documented, whereas in H.J. Andrews Forest in Oregon almost 460 species of stream invertebrates have been noted. Even the algal community in a headwater stream can include more than 100 distinct species.

CADDISFLY, ISTOCK IMAGES

Even within a single basin, headwater streams can be characterized by unique habitats and communities. Coastal watersheds in Alabama have both darker and clearer streams, with the former containing large amounts of wood and high dissolved organic carbon, and the latter having less organic matter and often higher velocities. The different water chemistry and physical conditions produce quite different fish assemblages. Even when adjacent streams experience similar conditions, they can differ substantially in their animal communities. Aquatic insect species that lack adult winged stages are seldom able to migrate down through larger streams and then up into adjacent headwaters. However, even adult aquatic insects seem to preferentially fly upstream, maintaining themselves within single headwater streams. All these traits lead to individual headwaters supporting high and unique diversity from other streams in their watersheds.

There are many groups of freshwater organisms in headwater streams that remain poorly characterized, particularly microbes (fungi, bacteria, archaea), protists and microinvertebrates (nematodes, rotifers, and others), all of which tend to be underrepresented in studies of biodiversity. It is likely that when we have better surveys, we will have a better appreciation of the enormous biodiversity that occupies our headwaters. An enhanced understanding of the ecology of these lesser known taxa may allow for more prescribed application of stream restoration practices that better aid the basal components of stream food webs.

Headwater Wetlands. *Note: this section was adapted from the first edition with minimal editing.* Some species of plants and animals prefer or require ephemeral wetlands. Certain zooplankton, amphibians, and aquatic plants need the wet phase of an ephemeral wetland to complete all or part of their life cycles. Other species that rely on ephemeral wetlands wait out the aquatic phase, flourishing only when pools shrink or disappear. For example, although adult spotted salamanders are generally terrestrial, during the springtime they trek to vernal pools to breed and reproduce. So-called amphibious plants, including button celery, meadowfoam, wooly marbles and many others do the opposite; although they live in water, they cannot reproduce until water levels drop.

One type of ephemeral wetland found in both California and the Northeast is known as a vernal pool because it generally fills with water in the spring. In California, blooming flowers ring the edges and fill depressions of such pools. Of the 450 species, subspecies, or varieties of plants found in California's vernal pools, 44 are vernal pool specialists. Several such plants are already on the Endangered Species list. If California's vernal pool habitats were completely destroyed, at least 44 species would disappear.

VERNAL POOL IN PENNSYLVANIA.
FRESHWATERS ILLUSTRATED

Other ephemeral wetlands also make significant contributions to biodiversity. A study of wetlands in the Southeast including cypress-gum swamps, cypress savannas, and grass-sedge marshes, found that plants from one wetland are often very different from those in others nearby. Such differences in nearby habitats increase overall biodiversity in a region. In some cases, differences in periods of wetting and drying appear to be important for the persistence of many species. Different wetting and drying patterns explain some differences between Gromme Marsh and Stedman Marsh, two prairie pothole wetlands in Wisconsin. Although the two marshes are only about 450 yards apart, they have different species of dragonflies; also, Stedman Marsh has damselflies and caddisflies that Gromme Marsh lacks.

Amphibians are key parts of the food web in small wetlands. Some wetlands are hot spots for amphibian biodiversity; twenty-seven amphibian species, one of the highest numbers of amphibian species known from such a small area, inhabited a 1.2-acre ephemeral wetland in South Carolina. Other small wetlands in the region have been found to have similar numbers of amphibian species, demonstrating how small wetlands are especially important for maintaining the regional biodiversity of amphibians.

Human Wellbeing

The benefits of headwater streams and wetlands described above generally accrue broadly to society, but individuals also can derive direct benefits from headwater streams and wetlands. A large body of research shows clear evidence that spending time in nature provides mental and physical health benefits to people– lowering stress, reducing depression, increasing cognitive function, decreasing blood pressure, and improving immune function. In many urban areas, some of the best opportunities for nature connection are provided by linear parks adjacent to streams and rivers, and at nature centers built around wetlands.

The economic benefits that people derive from streams, wetlands, and other elements of the natural world, though substantial, may be less important to them than connections based on personal identity. The nature of the identity varies: some people consider themselves birders, while others are anglers, and others plan trips around spring wildflowers or fall foliage. For members of indigenous groups, the connection to specific natural locations can be a critical component of cultural identity, and the relationship with nature is often explicitly reciprocal: nature provides benefits, and in turn we have a duty to care for it. All major world religions also encompass concepts of connection to nature or stewardship of nature. The term "relational values" is sometimes used to refer to the various ways that people value nature based on cultural, religious, personal or even aesthetic connections. These relational values can be difficult to quantify, but may ultimately be as important to people as the economic services provided by the natural world.

TWO-LINED SALAMANDER, FRESHWATERS ILLUSTRATED

Interventions

In recent decades there has been growing societal investment in stream and wetland restoration and rehabilitation, in part because of a growing appreciation for the benefits that these resources provide. There has also been extensive scientific study of different kinds of management approaches, and we have learned a lot about what works– and what doesn't. It's now clear that localized interventions that don't take into consideration the larger watershed context are unlikely to provide meaningful benefits to ecosystems. If there are things happening on the landscape that negatively affect the aquatic system, those must be addressed before investments in aquatic restoration can realize their full potential. For example, in most urban areas in the US, the biggest stressor is stormwater runoff from impervious surfaces. Improving stormwater management is the single best thing most cities can do to improve their streams.

A type of management action that almost always provides benefits is increasing aquatic connectivity. Increasing longitudinal connectivity by removing in-stream barriers (such as perched culverts at road crossings) allows for natural migration of fish and other aquatic organisms. In rural areas, parks, and other places where there is room, increasing a stream's lateral connectivity– giving it a place to flood during high flows– enhances its ability to provide many valuable services, including natural recycling, water quality protection, sediment trapping, and of course flood control for downstream (and often upstream) reaches. Giving a stream space also allows for the natural process of channel migration. It is perfectly normal for a healthy stream to show some signs of erosion in some places, and deposition in other places, as its channel naturally migrates.

Conversely, one kind of intervention that often fails to provide meaningful ecological benefits is reach-scale restoration that seeks to create a stable channel of a particular form based on an analogy or an ideal. This kind of restoration, sometimes under names such as "Natural Channel Design," has become a major industry because it offers a straightforward recipe for addressing local problems (or what are perceived to be problems). Of course, in places where streams are constrained by infrastructure (such as most urban areas) localized interventions to increase stability may be necessary, although they will always be more effective when accompanied by watershed-scale actions such as improved stormwater management. Otherwise, studies have shown that such reach-scale interventions generally fail to provide improvement to habitat or other ecosystem services, and therefore may not be worth their high price tag. The exception to this is stream daylighting, the restoration of a piped channel to an open reach of stream. Although expensive, the opportunity to "resurrect" a buried stream channel nearly always provides substantial benefits.

Some agricultural interventions can provide substantial benefits even within altered systems by mimicking natural processes. "Two stage ditches," for example, are essentially channels inset into a ditch that have small benches or floodplains on either side. The design offers erosion protection, increased sediment storage, greater nutrient processing, and increased wildlife habitat. Another practice that mimics natural systems is the stream buffer strip, an area alongside streams or ditches that is planted with perennial vegetation (ideally native vegetation). These buffers, depending on species composition, can reduce nutrients and herbicides entering the watercourse, act as carbon sinks, and enhance wildlife habitat and aesthetics.

AGRICULTURAL STREAM IN PENNSYLVANIA THAT LACKS RIPARIAN BUFFERS, FRESHWATERS ILLUSTRATED

BEAVER DAM ON HAGUE CREEK IN ROCKY MOUNTAIN NATIONAL PARK, COLORADO. THE VALLEY UPSTREAM IS AN EXAMPLE OF A BEAVER MEADOW, WITH MULTIPLE DAMS AND PONDS AND SECONDARY CHANNELS THAT BRANCH AND REJOIN. PHOTOS BY ELLEN WOHL

BEAVERS AND BEAVER DAM ANALOGUES

Beavers famously build dams that pond water along even very small streams. The dams also enhance the movement of water from the channel onto the floodplain, sustaining floodplain wetlands and infiltration that recharges shallow groundwater. Beaver dams store sediment, provide habitat for a wide array of other organisms, and promote surface-subsurface exchange flows that can enhance uptake of excess nitrogen. Beavers are known as "ecosystem engineers" because their dam-building activity has such a profound effect on the environment. In the last two decades, beaver reintroduction has become an increasingly common restoration tool, as landowners and resource managers recognize the benefits of beaver ponds as a highly cost-effective method of enhancing the services provided by headwater streams. Where beavers cannot survive because of limited habitat or food, human-built "beaver dam analogues" can be used to provide some of the same functions.

BEAVER DAM ANALOGUE IN SOUTH PARK, COLORADO BUILT BY ECOMETRICS. THE DAM IS DESIGNED TO RESEMBLE ONE BUILT BY BEAVERS AND IS INTENDED TO PERFORM SIMILAR FUNCTIONS.

Conclusions

It has been 22 years since the first edition of Where Rivers Are Born. In the intervening decades there have been thousands of scientific papers published on headwater streams and wetlands, deepening our understanding of their extent, ecology, and benefits. We have a better accounting of how headwaters– many of which are not mapped– control floods, maintain water supplies, trap sediment, provide natural cleansing, recycle materials, support biodiversity, and benefit human wellbeing. Although human activities have altered and even destroyed many headwater streams and wetlands, we also have learned a lot about interventions that are effective in reducing impacts and restoring valuable functions, even in highly modified landscapes.

There is a persistent tendency– perhaps natural– to underappreciate the benefits from non-perennial streams, as well as wetlands that are apparently isolated (because they lack surface water connections). Scientific studies show, however, that intermittent and ephemeral streams are critical for natural cleansing, sediment trapping, and flood amelioration, while nearly all "isolated" wetlands provide similar functions and are actually connected to nearby river systems via groundwater, subsurface flows, and episodic surface flows. In fact, the flowing water in a river is only a small portion of the overall riverscape, and a healthy river depends on connections to groundwater, to its adjacent floodplain, and to its headwaters.

In the US, the Clean Water Act has been remarkably successful at maintaining good water quality and aquatic habitat, in part because– for most of its history– it protected not just rivers but most streams and wetlands as well. However, if waters of the United States are redefined to exclude wetlands and non-perennial streams, the effectiveness of the Clean Water Act is likely to be dramatically reduced. So twenty-two years later, we reiterate the final conclusion of the first edition: The goal of protecting water quality, plant and animal habitat, navigable waterways, and other downstream resources is not achievable without careful protection of headwater stream systems.

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1. SCHUYLKILL HIGHLANDS, PA, FRESHWATERS ILLUSTRATED

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UNIVERSITY OF GEORGIA

203 D. W. Brooks Drive,
Athens, GA 30602
RIVERCENTER.UGA.EDU