Moving Headwater Streams to the Head of the Class

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Everywhere on Earth, streams and rivers occur in hierarchical networks resembling the branching pattern of a tree, with smaller branches joining to form larger branches as water travels from uplands to lakes, estuaries, and seas. The finest branches of these networks, beginning where water flowing overland first coalesces to form a discernible channel, are called headwater streams. Conservative estimates indicate that headwater streams account for more than 70 percent of stream-channel length in the United States (Leopold et al. 1964), yet because of their small size, these streams are often missing from maps that guide the management of natural resources.

Relative to larger streams and rivers that are fed by upstream networks and affected by cumulative upstream stressors, the small drainage areas of headwater streams give these systems high levels of hydrologic independence and ecological autonomy. This independence justifies the use of headwater watersheds as building blocks in the construction of protected-area networks (Saunders et al. 2002) and their prioritization in management and regulatory efforts to protect many of the ecosystem services we value, such as clean water, recreational opportunities, nutrient removal, and biodiversity.

There is growing evidence that the water quality, biodiversity, and ecological health of freshwater systems depend on functions provided by headwater streams, which are similar in their importance to the fine branches of the human respiratory system in the lung. Among the functions of these streams are the maintenance of natural discharge regimes, the regulation of sediment export, the retention of nutrients, the processing of terrestrial organic matter, and the establishment of the chemical signature for water quality in the landscape. High levels of habitat diversity among and within these small streams create niches for diverse organisms, including headwater-specialist species of aquatic invertebrates, amphibians, and fish. Headwaters also act as refugia for riverine species during specific life-history stages and critical periods of the year, such as warm summer months.

Like the alveoli (the final branches of the respiratory tree that serve as the primary gas exchange units of the lungs), headwater streams are characterized by strong and vital interactions with the systems that surround them. Terrestrial inputs—dissolved nutrients, toxins, and particulate matter, for example—play a central role in determining the physical and chemical conditions of headwater streams (Likens and Bormann 1974) and in regulating the composition and productivity of biotic communities in these streams (Wallace et al. 1997). Because of this close terrestrial–aquatic linkage, the ecosystem services provided by headwaters and the species they support tend to be very sensitive to natural and anthropogenic disturbance of surrounding lands. Along with other distinctive qualities, this close connection creates a unique set of challenges and opportunities related to the protection of headwaters, and to research in these systems.

Conservation challenges and opportunities

It could be argued that lowland sites, where the human footprint is both intense and expanding quickly, are in greater need of formal protection than upland, headwater areas. There is no doubt that it is important to safeguard lowland sites, but it is difficult to see how any conservation action with a goal of protecting the long-term ecological integrity and ecosystem services of natural systems, whether aquatic or terrestrial, can succeed without a foundation of intact and functional headwaters. This point highlights the error of government proposals to withdraw the protection afforded under the Clean Water Act (33 U.S.C., chapter 26) to headwater streams and other "isolated" waters.

The high sensitivity of ecological processes and natural communities in headwater streams to atmospheric and terrestrial disturbances leads to low thresholds of impact. Consequently, disturbances that are spread across multiple headwater watersheds—as might result from road networks, air pollution, and diffuse patchworks of logging sites or residential development—are likely to be more detrimental than disturbances that are confined to few or to individual watersheds. When possible, minimizing the spatial extent of human disturbance in headwater areas may guard against the widespread degradation of physical and chemical conditions in these upland stream networks and the subsequent transmittal of impacts there to downstream systems.

Capitalizing on the accessibility and natural history of headwater streams to generate public support for their protection is another conservation strategy with high potential for long-term benefits. These small streams run through many backyards, schoolyards, and public parks. They can be home to net-spinning aquatic insects and 20-centimeter-long salamanders, and can serve as natural mesocosms for observing how sediment bars and dams of woody debris are formed and function. The many education and volunteer-monitoring initiatives aimed at protecting vernal pools show that this combination of accessibility and compelling natural history, when in the hands of committed and energetic people, can be an invaluable conservation tool.

Research priorities

The article by Bernhardt and colleagues (2005) in this issue of *BioScience* spotlights a question with important implications for the conservation of headwater streams: To what extent do these streams act to modify nutrients exported from the surrounding watershed, as opposed to simply being passive conduits of these nutrients? Although more work on this topic is needed, there is growing evidence that in-stream processes do play a significant role in modifying the nitrogen input–output balance of headwater watersheds. These findings suggest that interpretations of nutrient levels in headwater streams must account for both terrestrial and in-stream processes, which may act independently or interactively to affect watershed export values. They also highlight the potential for recovery times of both terrestrial and in-stream processes to limit the resilience of headwater ecosystems to anthropogenic disturbance.

There is general understanding of the role of headwaters in setting the chemical signature of fresh water at the landscape scale. As the human footprint continues to expand and competition among conservation priorities strengthens, spatially explicit, quantitative understanding of how cumulative headwater impacts affect downstream resources is likely to become critical. Especially important in this context may be mechanistic studies of how headwater watersheds that have been degraded interact with undegraded ones to affect downstream resources, and research identifying specific thresholds in the intensity and spatial extent of headwater impacts beyond which degradation of downstream resources is likely to occur.

We believe that a third research priority should be on investigations of the spatial population dynamics of species within the stream networks and associated matrices of small watersheds that make up headwater systems. The design of ecological reserves for biodiversity protection is largely dependent on understanding the population structure and dispersal patterns of resident species. Knowledge of the spatial structure of populations informs estimates of the minimum area required to prevent local extinction. Maintaining interpopulation dispersal enhances ecological resilience by increasing the likelihood of recolonization if local extinctions occur. Using a combination of direct and indirect methods (e.g., mark–recapture and population genetic analyses), this work will provide critical information on the minimum area and configuration of protected headwater areas required for species persistence.

Protect the source

Headwaters are a source of life. They are critical habitat for rare and endangered freshwater species, and guardians of many downstream resources and ecosystem services on which humans rely (Meyer et al. 2003). In the past year, deforestation in headwater drainages exacerbated flooding and landslides in Haiti, the Philippines, and Indonesia, destroying lives and property in lowland communities. Fortunately, opportunities for research, education, management, and legislation that can lead to effective, long-term protection of headwater ecosystems worldwide are as clear as the risks of failing to protect these critical ecosystems.

References cited

Bernhardt ES, et al. 2005. Can't see the forest for the stream? In-stream processing and terrestrial nitrogen exports. BioScience 55: 219–230.

Leopold LB, Wolman MG, Miller JP. 1964. Fluvial Processes in Geomorphology. San Francisco: W. H. Freeman.

Likens GE, Bormann FH. 1974. Linkages between terrestrial and aquatic ecosystems. BioScience 24: 447–456.

Meyer JL, et al. 2003. Where Rivers Are Born: The Scientific Imperative for Defending Small Streams and Wetlands. Washington (DC): American Rivers, Sierra Club.

Saunders DL, Meeuwig JJ, Vincent ACJ. 2002. Freshwater protected areas: Strategies for conservation. Conservation Biology 16: 30–41.

Wallace JB, Eggert SL, Meyer JL, Webster JR. 1997. Multiple trophic levels of a stream linked to terrestrial litter inputs. Science 277: 102–104.

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