A stream's role in watershed nutrient export

Robert O. Hall, Jr.*

Department of Zoology and Physiology, University of Wyoming, Laramie, WY 82071

The small watershed concept developed by Bormann and Likens (1) is a powerful means to understand how watershed ecosystems function (2–4). The approach requires estimating both element inputs to a watershed (e.g., atmospheric deposition, weathering) and outputs, usually via the stream that drains the watershed. Outputs are calculated as the product of stream water element concentration and stream discharge at a gauging weir at the base of the watershed. Differences between inputs and outputs are caused by physical, chemical, or biological processes within the watershed. By experimentally manipulating a watershed, e.g., harvesting the trees, it is possible to estimate the biotic contribution to net element retention (5). One of the central findings from this type of research is that element export can dramatically increase after forest removal; e.g., nitrate–nitrogen concentrations can increase dramatically. If the small watershed approach is used to interpret only terrestrial processes, then a central assumption is that the stream is solely a transport mechanism out of the watershed, and any modifications to element export by the stream itself are minimal relative to changes caused by the terrestrial component of the ecosystem. As originally conceived, the small watershed approach included the stream as part of an integrated watershed ecosystem (1), but elevated element export after experimental forest removal showed that the terrestrial component of the ecosystem exerted much, if not most, of the control over element export and retention. Thus, ecologists applied this approach broadly to address terrestrial ecosystem function, for example, hypotheses of forest ecosystem nutrient retention during succession (2, 4), the role of riparian zones on controlling nutrient export from agricultural watersheds (3), and potential impacts from atmospheric deposition (6).

Stream ecologists, using budget approaches inspired by Bormann and Likens (7, 8) and more process-oriented studies of nutrient fluxes from water columns to sediments (9–11), have since shown that streams themselves can be important sites of processing and retaining nutrients. Despite the knowledge that streams can be biogeochemical hot spots, stream element processing has not been experimentally linked to watershed elemental export. In this issue of PNAS, Bernhardt *et al.* (12) have demonstrated, for the first time, how processes within streams affect interpretation of watershed exports of nitrate nitrogen. They show that, after a large disturbance to the forest, nitrate concentrations in stream water were attenuated downstream of the disturbance. This research links the understanding that streams are biogeochemically reactive systems with fast rates of nitrogen conversion (10) with the overall pattern of nutrient export from a forested watershed ecosystem.

Fig. 1. Damaged tree limbs cover a stream in a HBEF watershed after the ice storm. Photograph courtesy of Robert Steltzer.

In the winter of 1998, an ice storm removed a portion of forest vegetation in watersheds within the Hubbard Brook Experimental Forest (HBEF) (Fig. 1). After this storm, Bernhardt *et al.* (12) sampled the streams draining these watersheds both at the gauging weir at the base of the watershed and longitudinally along the stream reach up the watershed. As was previously observed from experimental vegetation removal at HBEF, nitrate concentrations in the stream water increased after the ice storm from reduced uptake by terrestrial vegetation combined with increased nitrification in soils, i.e., the conversion of ammonium to nitrate by chemoautotrophic bacteria (5). However, unlike previous experiments at HBEF, the ice storm disturbed a discrete elevation band of vegetation within the watersheds; thus, it was possible to estimate the degree to which the high-nitrate signal attenuated from the damaged zone downstream to the gauging weir at the base of the watershed. They found that the stream nitrate concentration decreased quickly along a stream reach transect from the damaged zone to the weir, and that this decrease was caused by instream nitrate uptake by microbes and not just from dilution via the inputs of low-nitrate groundwater. Over an annual scale, exports of nitrate at the weir would have been 80–140% higher given no stream removal of nitrate. Indeed, after the ice storm, the stream took up more nitrate than the annual export from the base of the watershed.

Bernhardt *et al.* (12) show that that the disturbance itself increased the streams' capacity to retain more nitrate. The fraction of nitrate removal in the stream section below the damaged zone was much higher after the ice storm than before, suggesting increasing rates of N processing. Mechanisms behind this increase may include an opening of the forest canopy that stimulated primary production by algae, which has been strongly correlated with nitrate uptake in other streams (11). Increased wood in the channel may retain organic detritus and associated microbial de-

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See companion article on page 10304.

*E-mail: bhall@uwyo.edu.

composers, which will also have higher rates of nutrient uptake (13). Thus, the stream may provide a negative feedback, whereby the high exports from the disturbance are mitigated by increased rates of instream uptake.

Currently there is much interest in understanding controls on N loss from watersheds, because excess N from atmospheric deposition and fertilizer runoff is acting as a pollutant by stimulating algal and microbial production in marine and freshwater ecosystems (14). Despite high inputs, much N added to watersheds remains there, and controls on watershed N export are not well understood. For example, nitrate exports have declined at HBEF during the past decade despite increases in nitrogen deposition. Mechanisms for this decline in exports are unclear, although there is evidence that interannual climate variability and past disturbance interact with inputs and biotic uptake to control long-term patterns in N export (15). Concurrently, there is the observation that at larger river-basin scales, only 20% of N inputs are exported by rivers to the ocean (16). It is clear that terrestrial biota can powerfully control N export (4, 5), and that riparian interfaces between terrestrial ecosystems and rivers can have particularly high rates of N storage and loss (17, 18), but it is less clear as to the role streams play in controlling watershed export. Although streams occupy a small area of the watershed, they have high rates of N transformation. Two questions are (*i*) to what degree do processes in stream channels control watershed nitrate export and (*ii*) what is the fate of this transformed nitrate? Based on findings from Bernhardt *et al.* (12), at the small-watershed scale, stream processes can indeed be quite important in removing nitrate. Given that instream uptake exceeded watershed export, it is possible that some of the temporal pattern of N loss from HBEF watersheds may be in part caused by variation in stream channel processes; mechanisms for these changes may relate to forest disturbance (12).

> **A forest and a stream are functionally linked in their response to disturbance.**

Although there is increasing evidence that dissolved nitrogen can be attenuated by stream channels (12, 19) and rapidly taken up and transformed (10, 11), it is less clear as to how much of nitrate that is added to rivers is permanently removed by denitrification relative to being transformed from nitrate to particulate organic forms that may be either exported quickly or stored in sediments or floodplains. Previous budget studies have shown that removal of dissolved nitrogen by rivers can be substantial (19, 20), and small-scale process studies show that nitrate is rapidly transformed, but the fate of this removed nitrate is unknown. Indeed, the reach–scale process experiments (e.g., ref. 10) and budget studies are rarely linked so as to estimate how reach–scale processes affect nutrient export. In the case of HBEF, short-term experimental nitrate additions show quick uptake by the stream; uptake rates of nitrate downstream of the damaged zone in watershed 1 were higher than 15 of 17 estimates from these short-term experiments (21), showing that net rates of uptake after the ice storm were actually higher than those measured by using short-term addition studies.

Bernhardt *et al.* (12) show that a forest and a stream are functionally linked in their response to disturbance; in this case, they interact such that the stream retained nitrate as the forest lost nitrate. Their research provides a means to understand the complex response of watershed nutrient export to disturbances. Stream nitrogen concentration data that are used to test hypotheses of forest nutrient retention (2, 22), may be more clear when considering the stream's potential role on nutrient processing and export.

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