The Effects of Ecosystem Restoration on Nitrogen Processing in an Urban Mid-Atlantic Piedmont Stream

Paul Mayer, Elise Striz, Robert Shedlock, Edward Doheny, Peter Groffman

Abstract

Elevated nitrate levels in streams and groundwater pose human and ecological threats. The U.S. EPA, USGS, Institute of Ecosystem Studies, and Baltimore County Department of Environmental Protection are collaborating on a multi-year study of the impacts of stream restoration on nitrogen processing in Minebank Run, a Piedmont stream in Baltimore County, Maryland. The study is designed to investigate the nitrate removal capacity of this stream before and after restoration. Restoration techniques such as bank re-shaping, bank reinforcement, and energy dissipation structures will be constructed to reestablish geomorphic stability lost due to impacts from storm water runoff. We will quantify the effects of specific restoration techniques on microbial denitrification, a process that removes nitrate but which requires anaerobic (saturated) conditions and adequate supply of dissolved organic carbon from detritus and organic soils. Restoration may enhance denitrification by increasing groundwater saturation and/or by increasing carbon supply to denitrifers in the subsurface. Therefore, stream geomorphology, surface flow, groundwater flow, and geochemistry are being quantified throughout the stream reach and in a network of 51 wells and piezometers installed at the site corresponding to the restoration techniques of interest. Denitrification activity will be measured throughout the stream and related to limiting factors such as dissolved organic carbon and dissolved oxygen. 3-D hydrologic models of nitrate movement will be developed for the watershed. Our study results will be used to develop stream restoration approaches for reducing nitrate pollution in urban watersheds.

Keywords: urban stream, restoration, assessment, nitrate, denitrification, hydrology

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Introduction

Urban streams undergo ecological degradation from various stressors such as channel incision from flashy storm water runoff, chronic atmospheric and terrestrial nutrient inputs, and hydrologic disconnection from the floodplain. However, stream restoration is considered to be a means of alleviating such stressors. Restoration may include numerous individual structural manipulations, each with the potential to alter ecosystem processes. Yet, relatively little effort has been devoted to understanding the basic ecology of urban streams or the response of urban streams to restoration. Here we describe a multi-investigator project currently underway that proposes to identify ecosystem structural and functional response to stream restoration at Minebank Run, a stream located on the eastern Piedmont of Maryland in a highly urbanized region north of Baltimore. Minebank Run is located in a watershed that flows into Chesapeake Bay.

Our research focus is on nitrate nitrogen, a pollutant that threatens ecosystem and human health. Restoring streams in a manner that attenuates and removes nitrate may be a cost-effective means of improving water quality in urban watersheds.

Our research approach was to examine Minebank Run before and after restoration to measure and identify controls on microbial denitrification, a natural process occurring in soils and groundwater that removes significant amounts of nitrate in waters by transformation to a biologically inactive gas form. Denitrification is an anaerobic process requiring low or depleted oxygen levels (Tiedje et al. 1982). Microbial denitrifiers require a source of carbon for respiration and often are limited by carbon supply (Korom 1992). Therefore, understanding when and where in the watershed carbon and oxygen levels are optimal for denitrification is critical to identifying approaches for enhancing the conditions necessary to effect nitrogen removal from the stream.

A full understanding of the effects of restoration on nitrate processing in urban streams will require simultaneous study of both biotic and abiotic stream processes. Therefore, our approach depends upon the efforts of several research teams to evaluate the biology, geology, hydrology, and chemistry of an urban stream before and after restoration (Figure 1).

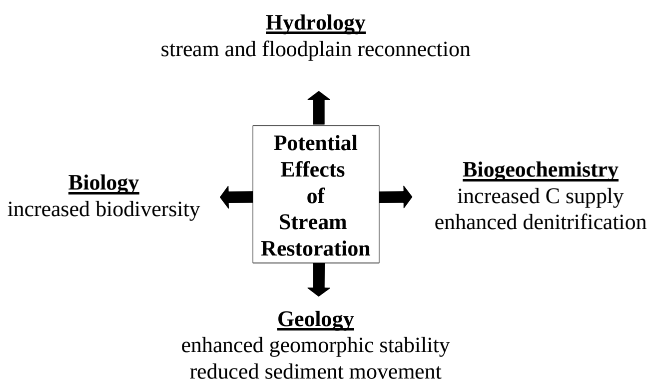

Figure 1. Potential effects of stream restoration.

The upper half of Minebank Run was restored in 1998 and 1999 to improve geomorphic stability and reduce channel incision. The remaining lower reach will be restored in 2004 with using a similar engineered approach employing techniques such as a) installing step-pool structures designed to reduce erosion, b) reshaping stream banks to reconnect stream channel to flood plain, c) armoring stream banks against erosion with large boulders, d) reconstructing stream meander features and riffle zones, and e) re-establishing riparian plant communities.

Restoration may enhance denitrification by reestablishing flood plain hydrology and/or increasing carbon availability. Structures installed in the stream channel to reduce erosion also may trap organic matter long enough to create enriched anoxic zones conducive for denitrification to occur. Restoring and replanting riparian zones may provide the necessary litter inputs for supplying carbon. But, because much of the riparian zone in urban systems cannot be reclaimed or replanted (Paul and Meyer 2001, Pickett et al. 2001), carbon-containing compounds (e.g. glucose, ethanol, yard waste) may need to be added to the stream or subsurface to provide adequate carbon supply to microbes. (Obenhuber and Lowrance 1991, Qian et al. 2001). Therefore, identifying stream features, either natural or constructed, where high denitrification activity occurs may provide important nitrate reduction tools and direct future restoration efforts (Burt, et al. 1999, Groffman et al. 2002, Groffman and Crawford 2003).

Our broader objectives were to: 1) assess ecosystem benefits of restoration, 2) identify stream restoration methods that enhance nitrate control, 3) develop predictive models of stream hydrology, and 4) develop ecologically-based guidelines for stream restoration. Lab and field-based research has and will be conducted collaboratively by scientists from U.S. Environmental Protection Agency, U.S. Geological Survey, Baltimore County Department of Environmental Protection, and Institute of Ecosystem Studies. The data presented here characterizes the unrestored condition of Minebank Run. Our results are preliminary in the sense that we cannot yet compare the conditions of the restored stream with our baseline information. However, the information collected to date provides critical insight into the level of ecosystem function in this degraded urban stream.

Methods

Data presented here relate to the potential controls on dentrification, including overall dissolved organic carbon, dissolved oxygen, and concentrations of bio-reactive nitrogen (nitrate plus nitrite). We collected surface water samples from the Minebank Run and groundwater samples from piezometers nests installed in the stream channel. Piezometers were installed in three locations along the stream corresponding to planned restoration measures including bank reshaping, deposition of rip rap, and stream channel relocation. Piezometers consisting of 2.5 cm diameter stainless steel pipes with 0.25-mm wire-wrapped screen at the bottom 15-cm of the standpipe were positioned in nests of 3 at 61, 122, and 183 cm below the surface of the stream bed.

Additional triplicate nests of piezometers were installed on each stream bank perpendicularly to the channel approximately 4m from the stream piezometers at depths that matched the mean sea level of the corresponding stream bed depths. A total of 33 piezometers and 4 surface water stations were sampled. Water was sampled seasonally in December 2001, March, May, July, and October 2002. Water was collected with a peristaltic pump through a flow cell and Hydrolab instrument to measure dissolved oxygen. Samples were stored on ice and filtered in the lab with 0.45 micron filters for dissolved organic carbon (DOC). DOC was measured on a Dohrman or Tekmar instrument that measures organic carbon directly via UV-persulfate digestion method. Nitrate and nitrite concentrations were measured on unfiltered samples using Lachat Flow Injection Analyzer.

We measured microbial biomass carbon and denitrification enzyme activity (DEA) in hyporheic sediments sampled at the shallow depth of the near and in-stream piezometers described above and in saturated, deep floodplain sediments that were taken when wells were established for groundwater flowpath analysis. Microbial biomass carbon was measured using the chloroform fumigation-incubation method (Jenkinson and Powlson 1976). Soils were fumigated to kill and lyse microbial cells in the sample. The fumigated sample was inoculated with fresh soil, and microorganisms from the fresh soil grew vigorously using the killed cells as substrate. The flush of carbon dioxide (CO_2) released by the actively growing cells during a 10-day incubation at field moisture content were assumed to be directly proportional to the amount of carbon and nitrogen in the microbial biomass of the original sample. A proportionality constant (0.45) was used to calculate biomass carbon from the CO_2 flush. Carbon dioxide was measured by thermal conductivity gas chromatography.

DEA was measured using the short-term anaerobic assay developed by Smith and Tiedje (1979) as described by Groffman et al. (1999). Sieved soils were amended with nitrate, dextrose, chloramphenicol and acetylene, and were incubated under anaerobic conditions for 90 minutes. Gas samples were taken at 30 and 90 minutes, stored in evacuated glass tubes and analyzed for N_2O by electron capture gas chromatography.

Results

The seasonal pattern of DOC concentration in surface water did not necessarily match that in groundwater (Figure 2). March groundwater DOC levels were high on average when compared to surface water, though concentrations in the piezometers were highly variable. This result may reflect the seepage of high carbon waters from the riparian zone into the banks and/or hyporheic zone. The reverse is true in July when surface water DOC levels were much higher than in groundwater. High surface water DOC levels may reflect runoff events discharging allochthonous material from the riparian zone into the stream and/or increased production of autochthonous material in stream from epiphytic algae.

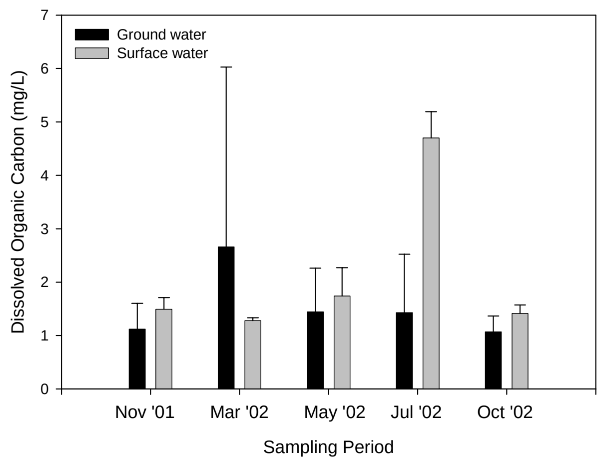

Figure 2. Mean surface water and groundwater DOC concentration over time at Minebank Run, Baltimore County, MD, USA (Error bars = 1 SD).

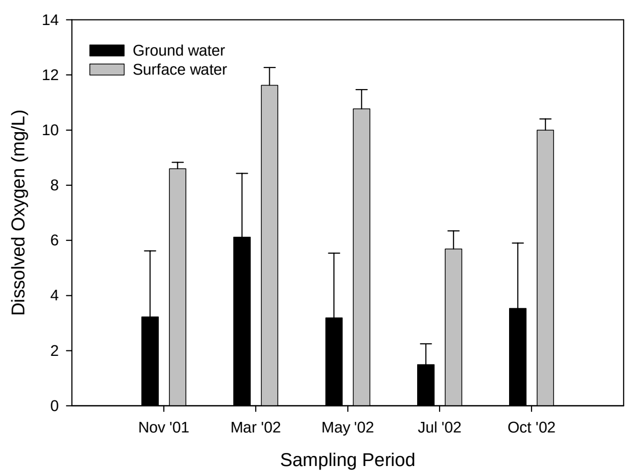

Figure 3. Mean surface water and groundwater dissolved oxygen concentration over time at Minebank Run, Baltimore County, MD, USA (Error bars = 1 SD).

Seasonal patterns of dissolved oxygen (Figure 3) and of bioreactive nitrogen (Figure 4) in groundwater and surface water appear much more synchronized. That is, groundwater oxygen levels match that of surface water because hyporheic flow appears to strongly dictate the amount of oxygen entering the groundwater. Oxygen levels declined dramatically in July when a mid-summer drought reduced base flow of the stream creating some stagnant pools. On average, nitrogen responds similarly but with greater variability in groundwater concentrations during a sampling period (Figure 4).

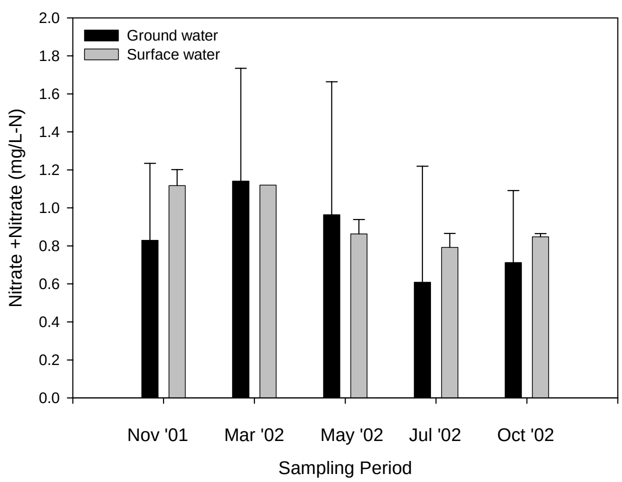

Figure 4. Mean surface water and groundwater bioreactive nitrogen concentration at Minebank Run, Baltimore County, MD, USA (Error bars = 1 SD).

Patterns of DOC by depth and location (Figure 5) indicate that mean DOC concentration is higher in the stream and hyporheic zone than in the banks, suggesting that autochthonous inputs of carbon (e.g. algae and aquatic vegetation) are significant. Furthermore, mean DOC increased (but with high variability) at the 183-cm depth suggesting a deposition of carbon perhaps because sediment layers were less porous at this depth.

Dissolved oxygen concentrations declined with depth in both the stream channel and the banks (Figure 6). Oxygen in the banks remained relatively high even at the 183 cm depth and corresponded closely to oxygen concentration in the stream hyporheic zone. Depending on the height of the bank, piezometer depth in the banks was over 3 meters below the surface of the soil. Therefore, the close correspondence in oxygen between stream channel and banks suggests that oxygen flows from the hyporheic zone into the banks.

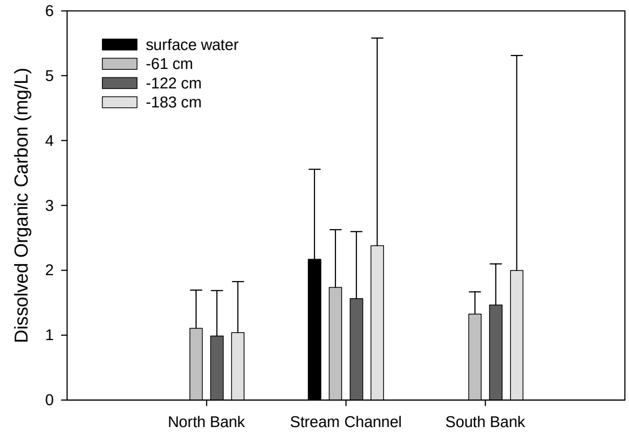

Figure 5. Mean DOC concentration in stream channel and groundwater at Minebank Run, Baltimore County, MD, USA (Error bars = 1 SD).

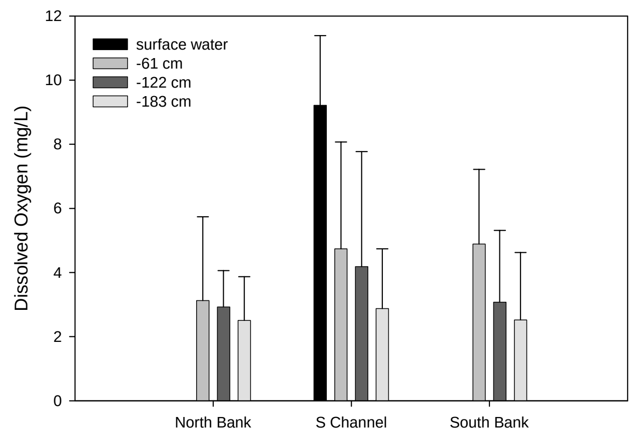

Figure 6. Mean dissolved oxygen concentration in stream channel and groundwater at Minebank Run, Baltimore County, MD, USA (Error bars = 1 SD).

In general, mean bioreactive nitrogen concentrations decreased with depth but, most notably, were higher on the north bank of Minebank Run (Figure 7), reflecting, perhaps, the influence of runoff (e.g. fertilizer) from a suburban residential development on the north side of the stream. The area along the south bank of Minebank is several hundred meters from the nearest concentrated urban development.

Microbial biomass carbon and DEA (Figures 8 and 9) were both higher in hyporheic sediments (in and near stream piezometers) than in deep floodplain sediments. These results support the idea that the hyporheic zone is responding to and processing carbon and nitrate from upstream and/or riparian sources. These results also suggest that the restoration technique(s) that increase carbon flow to these sediments could increase denitrification capacity of the stream ecosystem.

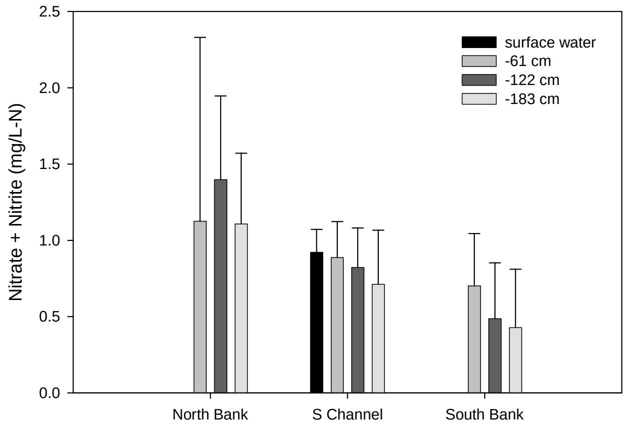

Figure 7. Mean bioreactive nitrogen concentration in stream channel and groundwater at Minebank Run, Baltimore County, MD, USA (Error bars = 1 SD).

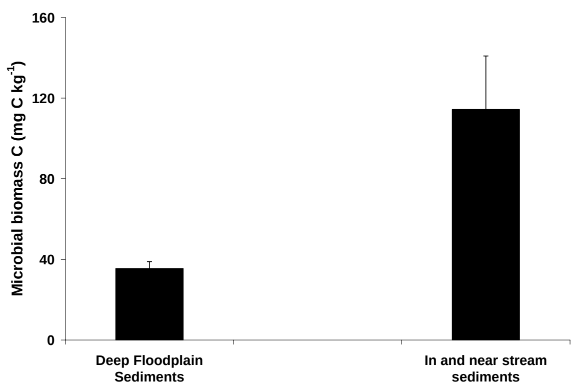

Figure 8. Microbial biomass carbon (C) in hyporheic (in or near stream) and deep floodplain sediments from Minebank Run, sampled in November 2001.

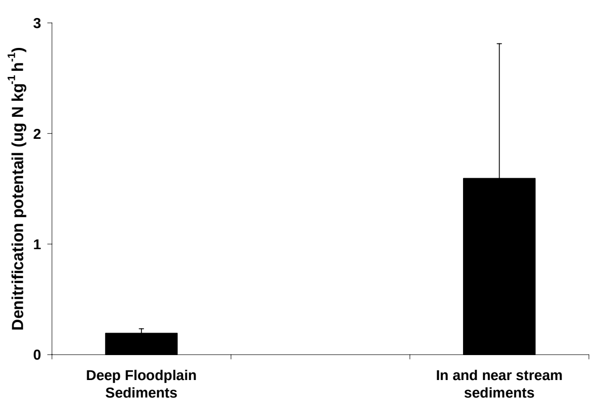

Figure 9. Denitrification enzyme activity in hyporheic (in or near stream) and deep floodplain sediments from Minebank Run, sampled in November 2001.

Conclusions

DOC levels at Minebank Run were relatively low throughout the study but seasonal patterns are evident in the surface water. Stream sediments appear to be supplied with carbon from upstream sources. Thus, restoring riparian vegetation where possible may serve to increase carbon input to the stream. However, artificial additions of carbon (yard waste, ethanol, etc.) also may be an important management approach to increasing denitrification at Minebank Run and other urban streams.

Dissolved oxygen levels were lowest in July at Minebank Run probably due to a combination of drought conditions, low base flow, and high water temperatures. Corresponding nitrate and nitrite levels also were low in July suggesting that nitrogen removal from urban streams may vary seasonally or, at least, in relation to conditions conducive to producing low dissolved oxygen levels. However, nitrogen uptake by vegetation also may be important. Therefore, it may be easier to effect a reduction in stream nitrogen during spring or summer seasons whereas nitrate may be transported with little biological transformation during colder months and/or high base flow. Regardless of season or temperature, precipitation events can potentially flush nitrogen and organic matter rapidly out of the system and into receiving water bodies (e.g. Chesapeake Bay), bypassing any processing by denitrifying microbes. Channel restoration techniques effective at reducing the flashy flows at Minebank also may reduce the potential for nitrogen flush and/or increase the retention of carbon in the channel. Other techniques involving channel and bank reshaping may reconnect stream and floodplain hydrology in a way that increases the duration or region of saturation in carbon-rich soils of the riparian zone. Such changes may sustain a high potential for denitrification.

Management of nitrogen in urban streams via restoration will require a combination of technologies and approaches specific to the chemistry, geology, hydrology, and biology of the site. With the project still in the pre-restoration stage, we cannot assess the effects of stream restoration on denitrification or on overall water quality. However, we expect to demonstrate that nitrogen processing in urban streams is strongly controlled by geomorphology, hydrology, and carbon supply. If true, such results would point to a number of ecologically based guidelines for stream restoration that would optimize the nitrogen attenuation capacity of urban streams in a manner that would benefit overall water quality and ultimately, ecosystem health.

Acknowledgments

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