Hyporheic Denitrification

Internal Nitrogen Processing in Streams and Floodplains

The 2014 Expert Panel looked at this group of research studies that evaluate nitrogen dynamics in restored streams and floodplains using N mass balances, stream N tracer injections, N isotope additions, denitrification assays, and other methods, usually under base flow conditions. Most of the research studies have occurred in restored and non-restored streams, and floodplain wetlands in the Baltimore metropolitan area (Kaushal et al., 2008; Lautz and Fanelli, 2008; Klocker et al., 2009; Mayer et al., 2010; Harrison et al., 2011).

Mayer et al. (2010) examined N dynamics at groundwater-surface water interface in Minebank Run in Baltimore County, Maryland, and found the groundwater–surface water interface to be a zone of active nitrogen transformation. Increased groundwater residence time creates denitrification hot spots in the hyporheic zone, particularly when sufficient organic carbon is available to the system. Increased groundwater and stream flow interaction can alter dissolved oxygen concentrations and transport N and organic matter to microbes in subsurface sediments, fostering denitrification hot spots and hot moments (Mayer et al., 2010; Klocker et al., 2009).

Lautz and Fanelli (2008) found that anoxic zones were located upstream of a stream restoration structure in a low velocity pool and oxic zones were located downstream of the structure in a riffle, regardless of the season. They also found the restored streambed can act as a sink for nitrate and other redox-sensitive solutes, and that water residence time in the subsurface hyporheic zone plays a strong role in determining the spatial patterns of these practices. They suggest that the installation of small dams in restoration projects may be a mechanism to create denitrification hotspots.

Kaushal et al. (2008) analyzed denitrification rates in restored and un-restored streams in Baltimore, and found higher denitrification rates in restored streams that were connected to the floodplain as compared to high bank restoration projects that were not. Kaushal also noted that longer hydrologic residence times are important to remove N. Additional research by Klocker et al. (2009) reinforces the notion that "restoration approaches that increase hydrologic connectivity with hyporheic sediments and increasing hydrologic residence time may be useful in stimulating denitrification".

Sivirichi et al. (2011) compared dissolved nitrogen and carbon dynamics in two restored stream reaches (Minebank Run and Spring Branch) and two un-restored reaches (Dead Run and Powder Mill) in Baltimore. They concluded that restored stream reaches were a net sink for TDN and a net source for DOC. By contrast, the un-restored urban reaches had a net release of TDN and net uptake for DOC.

High denitrification rates were observed in both summer and winter in urban riparian wetlands in Maryland (Harrison et al., 2011). Restored streams in NC had higher rates of nitrate uptake in the summer, but this can be explained by increased stream temperature and reduced forest canopy cover (Sudduth et al., 2011).

The maximum amount of internal stream and floodplain nitrogen reduction appears to be limited or bounded by the dominant flow regime that is delivering N to the stream reach. Internal N processing is greatest during base flow conditions, and is masked due to the short residence times of high flow events that quickly transit the stream reach. Stewart et al. (2005) measured the relative proportion of annual nutrient loads delivered during storm flow and base flow conditions for five urban watersheds in Maryland that had 25 to 50% imperviousness. Stewart found that base flow nitrate loads were 20 to 30% of total annual nitrogen load, with one outlier of 54% that appeared to be influenced by sewage sources of nitrogen.

The Panel identified a series of factors that could promote greater dry weather N reduction:

- Increase retention time in flood plain wetlands;
- Add dissolved organic carbon via riparian vegetation, debris jams, instream woody debris, and where applicable, re-expose hydric soils in the pre-settlement floodplain;
- Reconnect the stream to floodplain and wetlands during both dry weather flow and storm flows through low floodplain benches, sand seepage wetlands, legacy sediment removal, or other techniques;
- Focus on streams with high dry-weather nitrate concentrations that are often delivered by sewage exfiltration;
- Ensure the restored reach is sufficiently long in relationship to the contributing channel network to achieve maximum hydrologic residence time;
- Install instream and floodplain wetland practices with a high surface area to depth ratio and in some cases add channel length or create multi-channel systems;
- Attenuate flows and reduce pollutants through upstream or lateral stormwater retrofits.

Updated Research on Hyporheic Denitrification

Since the most recent version of the Stream Restoration Expert Panel Report (2014), there has been a rapid increase in stream restoration projects often motivated by the desire to achieve nutrient and sediment reductions for the Chesapeake Bay TMDL. In the past, many projects emphasized the prevented sediment approach to reduce bank erosion within the stream channel (Group 1, 2020). More recent efforts focus on stream restoration designs that reconnect stream channels with their floodplains and promote more interaction between stream flows and groundwater.

There are several recent studies measuring how streambed and floodplain denitrification rates are influenced by stream and floodplain restoration. The recent research generally supports the conclusions of the original expert panel, but also has refined our understanding of where and when denitrification occurs in stream and floodplain restoration projects. Table 5 summarizes some of the key recent denitrification studies that were reviewed by both groups, and supports the following general conclusions:

- *There is ample support for updating the fixed dimensions of the hyporheic box* which was the concept for active hyporheic zone in the 2014 Expert Panel Report. Clay lenses or bedrock layers often restrict hyporheic exchange and the depth of these layers can vary by physiographic region. Denitrification is also less likely to occur deeper below the floodplain surface due to distance from the root zone, which provides a critical carbon source for promoting denitrification (Mayer et al 2010, Hester et al 2016, Doll et al 2018, Duan et al 2019, Hartranft 2019).

- *Enhanced denitrification can occur in floodplain soils as well as in the channel.* Recent research also supports a shift from a hyporheic box focused primarily on the streambed to an expanded hyporheic zone that extends across the restored floodplain. Denitrification not only occurs within and below the stream channel, but also in hotspots throughout the restored floodplain.

  Denitrification can be enhanced when the hyporheic exchange zone is restored, floodplains are re-connected to hyporheic aquifers or wetlands, and plants provide an active carbon source. Denitrification rates are variable in space and time, but tend to increase at restoration sites with high hydraulic conductivity, connectivity to stream channel surface water, and mature floodplain plant communities (Kaushal et al 2008, Craig et al 2008, Mulholland et al 2008, Mayer et al 2010, Harrison et al 2011, WEP 2016, CBP 2019, Forshay et al 2019, Hartranft 2019).

- *Increasing the geomorphic complexity of the stream/floodplain system promotes greater denitrification.* Restored streams that increase the connectivity of the floodplain and restore greater geomorphic complexity are often linked to higher denitrification rates. This complexity can involve increasing channel sinuosity, restoring multi-thread channels, and installing instream wood and riffle structures to reduce flow velocities and increase in-stream transient storage (Cluer and Thorne, 2014, Tuttle et al 2014, Hester et al 2018, Lammers and Bledsoe 2017).

- *A strong technical foundation exists to derive an average unit area denitrification rate for the hyporheic zones associated with restored streams and reconnected floodplains.* More than a hundred denitrification research studies from across the Chesapeake Bay watershed and globally provide a basis for updating the estimated hyporheic denitrification rate formulated by the original expert panel (see Table 5).

Table 5: Denitrification in Hyporheic Zones				
Summary: Restoring stream channels by increasing floodplain connectivity increases denitrification rates compared to unrestored streams. Increased denitrification occurs in a series of hot-spots and hot-moments, driven by factors including floodplain connectivity with the hyporheic zone, hydraulic residence time, nitrate concentrations and the available supply of organic carbon.				
Citation	*Region*	*SR Type*	*Duration*	*Key Measurements*
Kaushal et al 2008	CB	NCD	1-2 yr	Denitrification rates in reconnected floodplains
Mulholland et al 2008	CB, OCB	NRS	1-2 yr	Uptake and denitrification as a function of stream nitrate concentrations
Klocker et al 2009	CB	NCD	1-2 yr	Nitrate uptake in restored and unrestored streams
Mayer et al 2010	CB	NCD	2-5 yr	Factors that influence denitrification rates in restored streams
Harrison et al 2011	CB	NCD	1-2 yr	Denitrification rates in urban floodplain wetlands
Weller et al 2011	CB	NRS	1-2 yr	Stream nitrate levels as a function of riparian buffers
Tuttle et al 2014	OCB	NCD	1-2 yr	Denitrification rates in streambed sediments
Hester et al 2016 & 2018	CB	FR	N/A	Model simulated nitrate removal in hyporheic zone and floodplain
Newcomer-Johnson et al 2016	CB, OCB	FR	N/A	Meta-analysis of nutrient uptake in restored streams.
Lammers and Bledsoe 2017	CB, OCB	FR	N/A	Meta-analysis of streambed and riparian denitrification rates
Mcmillan and Noe 2017	OCB	NCD	1-2 yr	Sedimentation and nutrient processing in restored floodplains
Audie 2019	CB	LSR	5+ yr	Groundwater residence time, groundwater nitrogen
Duan et al 2019	CB + Lab	RSC	< 1 yr	Effect of carbon inputs on nitrogen retention
Forshay et al 2019	CB	LSR	5+ yr	Stream and groundwater nitrate vs. denitrification

Key		
CB: Chesapeake Bay Watershed OCB: Outside the Chesapeake Bay Watershed	NCD: Natural channel design LSR: Legacy sediment removal RSC: Regenerative stormwater conveyance NRS: Non-restored stream FR: Floodplain restoration	Duration >1 yr 1-2 yr 2-5 yr 5+ yr

Pollutant Dynamics in Restored Stream Channels

Fewer studies are available to demonstrate the actual change in pollutant loads as they pass through an individual stream restoration project. These experiments are very difficult, as they require long-term monitoring of very complex and dynamic systems over a wide range of flow conditions. Nutrient sampling is needed at the top and bottom of the reach, but may also be needed in the hyporheic zone, floodplain or aquifer to fully capture the nutrient transformations occurring in space and time. Lastly, the upstream nutrient and sediment loads delivered to the stream reach can be extremely variable and are not dictated by the stream restoration approach. Further, within reach contributions of nutrients from stormwater or groundwater sources complicate pollutant load comparisons. Several notable long-term studies on pollutant dynamics in restored stream channels are summarized in Table 7 and outlined below:

- *Upstream and site conditions are an important factor in determining the in-stream nutrient levels of a restored reach.* Incoming nitrate concentrations are one of the most important factors in determining denitrification rates within a stream restoration. Further, the capacity of restored stream systems to trap and retain sediments and nutrients in the long-term may depend on the magnitude of sediment loads originating upstream and the physical setting (gradient, watershed position) of the restoration (Tuttle et al 2014, Filoso et al 2015, Filoso 2020, Mueller-Price et al 2016, Lammers and Bledsoe 2017).

- *Restored streams are dynamic systems and adjustments are expected over time.* The age of restoration can be an important factor in nutrient removal performance. This is particularly true for sites where new riparian vegetation was planted in disturbed areas following construction. As vegetation becomes stable and more robust, carbon availability improves, increasing microbial activity (McMillian and Noe 2017, Forshay 2019; Hartranft, 2019)

Table 7. Nutrient Dynamics in Restored Stream Channels

Summary: Nutrient treatment and retention in restored stream systems are dynamic and variable based on site-specific conditions. Upstream nutrient and sediment loads as well as nutrient loads supplied through groundwater sources play a significant role in in-stream loads at restoration sites and measured reductions can potentially change over time as channels adjust and newly vegetated riparian corridors mature.

Citation	*Region*	*SR Type*	*Duration*	*Key Measurements*
Tuttle et al 2014	OCB	NCD	1-2 yr	Denitrification rates in streambed sediments
Filoso et al, 2015	CB	RSC	2-5 yr	Input-output budgets of suspended sediment in a restored reach
Mueller-Price 2016	OCB	NCD/NRS	1-2 yr	Transient storage and nitrate uptake
Forshay et al 2019	CB	LSR	5+ yr	Surface water and groundwater nitrate and denitrification rates
Langland et al 2020	CB	LSR	5+ yr	N, P and TSS removal

Key

CB: Chesapeake Bay OCB: Outside the Chesapeake Bay Watershed	NCD: Natural Channel Design LSR: legacy sediment removal RSC: Regenerative Stormwater Conveyance NRS: Non-Restored Stream	Duration >1 yr 1-2 yr 2-5 yr 5+ yr

Design guidelines to promote in-stream nitrogen removal

The following design guidelines are based on a review of the literature on N removal rates driven by hyporheic exchange in restored streams. The guidelines were developed to maximize potential for nutrient removal, including varying hydraulic gradients, harvesting of hyporheic material, sizing of structures, and developing biogeochemical hot spots.

Pattern: Establishing a meander pattern in a straightened stream is not always a possibility in urban restoration projects plagued by constraints such as utilities, roads, and infrastructure. However, hyporheic exchange through meander bends can account for 46-53% of total hyporheic exchanges in a stream system (Cardenas and Wilson 2004). In another study, Kasahara and Wondzel (2003) showed that removal of sinuosity from a channel would decrease exchanges by 12%.

Profile: Geomorphic feature complexity along a stream reach will vary the vertical hydraulic gradient, thereby increasing zones of downwelling and upwelling in the channel. It is recommended to go beyond a simple riffle-pool sequence to include riffle-pool-step sequences or riffle-step-pool sequences. The steps will increase zones of downwelling that could overcome the natural hydrology of a gaining stream. The utilization of vanes and J-hooks can also create zones of downwelling and upwelling within the channel.

Hot Spots: Design and research regarding biogeochemical hot-spots is at the forefront. Stream features and structures that can be constructed specifically with nutrient dynamics in mind are encouraged. This could be a small-scale debris dams, brush material in riffles, brush sills, etc.

Materials: Whenever possible, riffle material should be (1) harvested from the original stream channel or (2) harvested from native rock material on-site. The newly constructed stream will benefit from the natural heterogeneity of harvested material and the material will likely already contain the denitrifying bacteria. Harvesting native rock on site is preferable to hauling rock from a quarry. The rock is native to the stream system, and when harvested it is a heterogeneous mixture containing the largest material you specify down to fines. This heterogeneity will provide varied flow paths and potential anoxic microsites within the riffle. A heterogeneous riffle material will also encourage hyporheic exchanges, known as pumping, along the length of the riffle as pressure builds up on the upstream end of larger rocks and boulders.

The harvesting of existing hyporheic material in conditions such as a high-clay content piedmont site where the new channel is being constructed in a floodplain containing compacted clays should be considered. Over-excavating the new channel and placing in hyporheic material from the old channel could provide a more porous material for the stream bed.

Wood, as a carbon source to the system should be encouraged, especially in low gradient streams where rock isn’t necessarily needed or present in natural channels. In essence, don't use rock when wood will do. Incorporation of wood into riffles, such as packing branches into riffle material, and the creation of brush toe or brush mattresses along banks are good options.

Construction: Compaction may be one of the largest issues in the first year for hyporheic exchange in newly constructed channels. Most construction plans specify what the compaction levels of floodplain and upland areas should be post construction and pre-planting, however they never include compaction of the channel bottom or banks during construction. This is a good opportunity to stress that in design plans.