Stream Restoration BMP Database: Version 1.0 Summary Report

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Abstract and Benefits

Abstract:
The International Stormwater Best Management Practice (BMP) Database (www.bmpdatabase.org) is a long-term project that has recently been expanded to include a database module for stream restoration practices. The new Stream Restoration Database (SRDB) is intended to be used as a tool to help support stream restoration water quality crediting programs, stream restoration practice selection and design efforts, and stream restoration performance evaluations. The project provides guidance on project characteristics that should be reported with stream restoration projects, provides a project information storage tool for crediting programs, and will eventually serve as a resource to support credit quantification with reasonable, geographically appropriate input values for crediting equations. Ultimately, the SRDB is envisioned as a supporting tool to improve stream restoration practice selection and designs and/or better target practices to achieve water quality and restoration goals.

The primary focus of this report is to summarize the initial findings of the first release of the SRDB (SRDB 1.0). This report also integrates findings from an extensive literature review completed as an initial task supporting the project and from the concurrently completed WE&RF-sponsored report Stream Restoration as a BMP: Crediting Guidance. The report provides an overview of several general categories of stream restoration practices, introduces the SRDB structure and reporting parameters, provides guidance on performance evaluation approaches for stream restoration studies, provides summaries of stream restoration performance studies based on the first release of the SRDB, and identifies research needs. As the SRDB grows, future summary reports are anticipated to be more quantitatively oriented. This initial summary report is predominantly qualitative due to the limited number of studies entered into the first version of the database that are suitable for synthesized summary analysis.

Benefits:

- Provides recommended standardized monitoring and reporting protocols for stream restoration studies.
- Provides a summary of the water quality benefits of various stream restoration practices based on an extensive literature review.
- Summarizes nutrient and sediment related benefits for stream stabilization, riparian buffers, in-stream enhancement, and floodplain reconnection.
- Provides guidance on performance evaluation approaches for water quality data collected as part of stream restoration projects.
- Identifies research needs and data gaps related to stream restoration practices.

Keywords: Stream restoration, bed and bank stabilization, in-stream enhancement, hyporheic exchange, floodplain reconnection, riparian buffer, water quality credit, pollutant trading, pollutant crediting, performance evaluation, nutrient control, sediment control.
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# Acronyms and Abbreviations

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<td>BA</td>
<td>Before-After</td>
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<tr>
<td>BACI</td>
<td>Before-After-Control-Impact</td>
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<tr>
<td>BMP</td>
<td>Best Management Practice</td>
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<tr>
<td>CDF</td>
<td>Cumulative Distribution Frequency</td>
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<tr>
<td>N</td>
<td>Nitrogen</td>
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<tr>
<td>P</td>
<td>Phosphorus</td>
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<tr>
<td>SRDB</td>
<td>Stream Restoration Database</td>
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<td>SRP</td>
<td>Soluble Reactive Phosphorus</td>
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<tr>
<td>TMAL</td>
<td>Total Maximum Annual Load</td>
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<td>TMDL</td>
<td>Total Maximum Daily Load</td>
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<tr>
<td>TKN</td>
<td>Total Kjeldahl Nitrogen</td>
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Executive Summary

Stream restoration provides many benefits such as improved aquatic life and associated terrestrial life conditions and ecosystem services, protection of property and infrastructure, floodwater storage, reduced sediment and nutrient loading, infrastructure protection, and other benefits. Stream restoration can help meet water quality goals such as complying with total maximum daily loads (TMDLs), source water protection, and habitat improvement for aquatic life. Stream restoration projects may provide pollutant trading/crediting and mitigation opportunities where water quality regulatory programs require pollutant reduction within a watershed.

The International Stormwater BMP Database (www.bmpdatabase.org) is a long-term project that has grown and evolved over the past 20 years to help document the observed performance of urban stormwater BMPs based upon field monitoring studies. The database has recently expanded to include database modules for agricultural practices and for stream restoration practices. The new SRDB can be used as a tool to help support stream restoration water quality trading/crediting programs and other performance evaluations by providing guidance on project characteristics that should be reported with stream restoration projects, providing a project information storage tool for crediting programs, and eventually serving as a resource to support credit quantification with reasonable, geographically appropriate input values for crediting equations. Ultimately, the SRDB is envisioned as a supporting tool to improve stream restoration designs and/or better target practices to achieve restoration goals.

The primary focus of this report is to summarize the initial findings of the first release of the SRDB. This report also integrates findings from an extensive literature review (Lammers, 2015) completed as an initial task supporting the project and from the concurrently completed WE&RF-sponsored report Stream Restoration as a BMP: Crediting Guidance (Bledsoe et al., 2016). This report provides an overview of stream restoration practices, introduces the SRDB structure and reporting parameters, provides guidance on performance evaluation approaches for stream restoration studies, provides summaries of stream restoration performance studies based on the first release of the SRDB, and identifies research needs. As the SRDB grows, future summary reports are anticipated to be more quantitatively oriented. This initial summary report is primarily qualitative due to the limited number of studies entered into the database that are suitable for synthesized quantitative summary analysis.

Based on the initial release of the SRDB, the following conclusions are drawn regarding stream restoration practices and the database itself:

1. The SRDB provides a framework for consistently monitoring and reporting information useful for evaluating the water quality related benefits of various stream restoration practices. To date, water quality parameters reported in stream restoration studies with the most monitoring data are sediment and nutrients. Stream restoration practices with the most well developed data sets, although still limited, included bed and bank stabilization, riparian buffers, in-stream enhancement, and floodplain reconnection.

2. The empirical evidence for stream restoration as a water quality BMP is improving, but additional research is needed, especially for regions and stream types that are poorly represented in the literature. Similarly, some practices have a stronger empirical basis than others, and some practices have inherently higher functional capacity for nutrient removal than others. Currently, the relative magnitude of benefits is also more certain than the absolute magnitude of the benefits.

3. The studies available indicate that stream restoration can provide water quality improvement, but more data are needed to assess which practices are most effective and under which conditions. As expected, water quality data are highly variable between the studies and from year-to-year or
season-to-season within the same study (e.g., precipitation and runoff conditions vary year-to-year). This variability presents a challenge when attempting to detect a statistically significant change in concentrations and loads for an individual study or a group of studies of the same practice. Generally, larger reductions in sediment and nutrients can be expected for restoration projects completed within streams with elevated concentrations relative to those with low concentrations.

4. The SRDB 1.0 has significant data gaps, particularly with regard to individual event data and study metadata. These gaps are due to the fact that the primary data sources were peer-reviewed journal articles, which typically only report partial data sets and summary statistics. While the database can accept summary statistics, the underlying detailed datasets are ultimately more useful for conducting independent analyses of stream restoration practices.

5. Even with more data in the SRDB, analytical challenges will remain due to differences in monitoring study designs. For example, some monitoring studies sample upstream and downstream of a restoration project, while others compare post-restoration to pre-restoration or to a control or reference stream. More complex monitoring designs include all of the above to capture both temporal and spatial variations in water quality. These differences make it difficult to automate the summary and analysis of stream restoration performance data.

6. While there is substantial guidance available for monitoring surface waters, there is limited practical guidance available for monitoring the water quality performance of stream restoration projects. Recent guidance on assessing stream restoration projects has focused on functional approaches (e.g., Harman et al., 2012; Davis et al., 2014). Such assessments are much needed and include measurement of physicochemical parameters, such as temperature, dissolved oxygen, and nutrients; however, the monitoring guidance is somewhat general. Additional guidance is needed on monitoring design, monitoring equipment, use of sensors, and selection of locations, parameters, and sample frequencies as they relate to factors such as seasonality, flow variability, stream type, surface-groundwater interactions, and riparian condition.

7. As the SRDB grows, there will be greater options for analyzing and utilizing the data sets. For example, with larger water quality datasets for each restoration practice type, the practices with the highest potential for improving water quality could be assessed statistically. Hypothesis tests on paired and unpaired datasets could be completed to make determinations of statistically significant differences in pollutant concentrations and loads. Meta analyses that consider design attributes, geomorphological parameters, and hydro-physiographic region may also be possible with a more robust data set.

8. Most of the studies entered in SRDB 1.0 did not provide the complete set of requested information in the Stream Restoration Database User’s Guide. Going forward, studies that report original sampling event data and more complete metadata should be targeted for upload. As future studies are considered for entry into the SRDB, highest priority should be placed on entering studies that have event-based data, which may require additional correspondence with the original researcher and/or utilization of more grey literature studies, which tend to provide more detail than condensed journal articles.

9. Direct measurement of the water quality benefits of stream restoration is very challenging. For this reason, monitoring approaches that incorporate surrogate (proxy) measures are also an important aspect of evaluating the benefits of stream restoration practices. Functional assessment approaches and rapid assessment indicators of stream restoration functions greatly simplify monitoring and reduce costs. However, they provide less quantitative water quality information.
CHAPTER 1.0

Introduction

The benefits of stream restoration in urban, agricultural, silvicultural, and other settings are diverse and widely recognized. Representative benefits include improved aquatic life conditions and ecosystem services, protection of property and infrastructure, floodwater conveyance and storage, reduced sediment and nutrient loading, and other benefits. Stream restoration can help meet water quality goals such as complying with TMDLs, source water protection, and habitat improvement for aquatic life. Stream restoration projects may provide pollutant trading and mitigation opportunities, particularly where water quality regulatory programs require pollutant reduction within a watershed. Stream restoration may be an overlooked nutrient reduction strategy in areas where more traditional efforts (e.g., stormwater and agricultural best management practices) have failed to yield the desired water quality improvements.

The International Stormwater BMP Database is a long-term project that has grown and evolved over the past 20 years to help document the performance of urban stormwater BMPs (www.bmpdatabase.org). The database has recently expanded to include performance modules for agricultural practices and for stream restoration practices. With this expansion, the BMP Database has become an integrated repository of available data on the efficacy of BMPs from a variety of sectors for reducing pollutant loading and improving water quality (Figure 1-1). The new Stream Restoration Database (SRDB 1.0) can be used as a tool to help support stream restoration crediting programs by providing guidance on project characteristics and water quality outcomes that should be reported with stream restoration projects, providing a project information storage tool for crediting programs, and eventually serving as a resource to support credit quantification with reasonable, geographically appropriate input values for crediting equations. Ultimately, the SRDB is envisioned as a supporting tool to improve stream restoration designs and/or better target practices to achieve restoration goals.

![Figure 1-1. International Stormwater BMP Database modules and goals.](image-url)
The primary focus of this report is to summarize the initial findings of the first release of the SRDB. This report also integrates findings from an extensive literature review (Lammers, 2015) completed as an initial task supporting the project and from the concurrently completed WE&RF-sponsored report *Stream Restoration as a BMP: Crediting Guidance* (Bledsoe et al., 2016). The report is organized as follows:

- Overview of and introduction to stream restoration practices.
- Overview of the SRDB structure and reporting parameters.
- Performance evaluation approaches for stream restoration studies.
- Summary of stream restoration literature review findings.
- Qualitative and quantitative findings for studies entered into the SRDB.
- Case studies illustrating potential future quantitative summary approaches.
- Conclusions and research needs.

As the SRDB grows, future summary reports are anticipated to be quantitatively oriented. This initial summary report is more qualitative due to the limited number of studies entered into the database that are suitable for synthesized summary analysis.

### 1.1 Stream Restoration Practices of Primary Focus for the SRDB

A variety of stream restoration practices have been studied in the literature; however, four categories currently have the most well-developed data sets and are the focus of this initial data summary. These practices include bed and bank stabilization, riparian buffer restoration, in-stream enhancement, and floodplain reconnection. Brief definitions and background on these practices follows to provide context for the data summary.

#### 1.1.1 Bed and Bank Stabilization

Bed and Bank Stabilization includes direct channel modifications such as installation of grade control structures to prevent incision (and increase bank stability via toe protection) as well as direct bank stabilization. Grade controls can include log and rock drop structures. Bank stabilization practices may be resistive (increasing bank resistance to erosion) and/or redirecive (reducing the erosive power of the stream by redirecting the flow). Resistive practices include various combinations of riprap, revetments, and bioengineering (vegetation). Redirecive practices include vanes, j-hooks, spurs/groynes, bendway weirs, and guidebanks.

Regardless of the specific design, bed and bank stabilization techniques are intended to lead to more stable channels and reduced sediment and nutrient loadings. It is important to note that bank erosion is a beneficial natural process that allows channel migration and provides sediment to streams. Complete cessation of bank erosion is neither practical nor desired (Florsheim et al., 2008); however, changes in watershed hydrology or sediment supply can significantly destabilize channels, leading to accelerated bank erosion, increased sediment and nutrient loading, floodplain disconnection, and accelerated change.

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1 These descriptions were originally developed to support the WE&RF supported companion report to the SRDB titled *Stream Restoration as a BMP: Crediting Guidance* (Bledsoe et al., 2016).
channel incision and widening (Booth, 1990), which can result in infrastructure damage. Preventing adverse impacts early in the sequence of channel evolution should be the goal of bed and bank stabilization projects.

Nutrient reduction quantification due to reduced erosion requires estimates of both bank and bed erosion rates (i.e., volume or mass of sediment eroded per length of channel per year) as well as the nutrient content of the sediment (e.g., mass of phosphorus per mass of sediment). The product of these two values yields the total nutrient loading rate. This analysis can be used to predict avoided nutrient loading via bed and bank stabilization. There is substantial uncertainty in predicting future erosion rates and determining the proportion of future erosion that may be avoided by channel stabilization. For example, the Channel Evolution Model (CEM) predicts a sequence of channel erosion from incision (bed lowering) and subsequent widening, followed by deposition and eventual stabilization (Figure 1-2). Arresting this process early in the sequence will likely provide greater avoided sediment and nutrient loading than installing erosion protection in the aggradation/deposition stage. Variations of this CEM have also been proposed, recognizing that other channel forms such as braiding can occur and that channel evolution is largely dependent on site-specific factors such as hydrology, relative resistance of bed and banks, and vegetation (Booth and Fischenich, 2015; Cluer and Thorne, 2014; Hawley et al., 2012).

Allowing for natural channel mobility and adjustment is an ideal goal of stream restoration projects. However, in urban and other settings where streams are often highly constrained by infrastructure and adjacent land uses, some form of channel armoring may be the only practicable alternative. In such cases, it is important to recognize that this alternative may be accompanied by an increased risk of downstream instability due to decreased sediment supply. In other words, erosion protection in one reach could “starve” a downstream reach of sediment and initiate instability (Kondolf, 1997). This underscores the need to consider stream restoration in an overall stream and watershed management context and evaluate potential impacts beyond the bounds of the restoration efforts. This includes incorporating knowledge about the current and future watershed hydrology and sediment supply and its impacts on stream hydraulics. Bank stabilization structures may be more prone to failure in urban and urbanizing watersheds that have a flashy hydrologic regime and ineffective stormwater controls. Bioengineered bank stabilization projects that rely exclusively on plant materials may have a higher risk of failure especially in the first few years as vegetation establishes. In such cases, hybrid approaches that combine armoring and vegetation may be the most appropriate (Bentrup and Hoag, 1998). For example, a combination of longitudinal stone toe, soil lifts, an emplaced carbon source such as sawdust, and willow plantings could result in a laterally armored channel that has appreciably more riparian function than a channel with a riprap blanket. Thus, there is a spectrum of potential benefits and watershed effects that should be considered for bed and bank stabilization beyond erosion control.
Figure 1-2. Incised channel evolution model.
As proposed by Schumm et al. (1984) (from NRCS, 2007). Note how installing channel control structures in Stage II can prevent significant sediment loading and widening predicted in Stage III but later intervention may result in less avoided sediment and nutrient loading. $Q_2$ is the instantaneous peak flow with a two-year recurrence interval; $h$ is the bank height; $h_c$ is the critical bank height for failure; $\nabla$ is the water surface elevation.
1.1.2 Riparian Buffers

Preservation or restoration of minimally disturbed vegetated areas adjacent to streams is a common strategy aimed at reducing pollutant discharges to streams by retaining and processing pollutants in both the surface and subsurface. Surface removal occurs primarily through immobilization and deposition of sediment-bound nitrogen and phosphorus (and other pollutants). Subsurface removal can occur via plant uptake and microbial metabolism. However, reduced oxygen conditions (which may be beneficial for subsurface nitrate removal) can cause phosphorus dissolution and increase groundwater phosphorus concentrations (Newbold et al., 2010). Additional benefits of riparian buffers include increased bank stability, stream shading to reduce water temperatures, and supply of in-stream wood and organic carbon to streams. Buffers may consist of predominately grasses, trees, or some mixture of both. Establishment and protection of intact riparian buffers may require some combination of direct planting and grazing management/livestock exclusion.

Sediment and nutrient removal in buffers tends to increase with increasing buffer width, decreasing slope, increased vegetation density and maturity, increased soil permeability, increased organic carbon content, and other factors. For example, Mayer et al. (2007) observed that buffers wider than 50 m removed more nitrate than 0-25 m wide buffers, although buffers as narrow as 30 m have shown very high removal efficiency (Pinay et al., 1993). There is evidence that nitrate removal in grass or forested buffers is not significantly different (Mayer et al., 2007). Likely more important is the interaction between the organic carbon-rich soil within the rooting zone and the nitrate-laden groundwater. Furthermore, denitrification (microbial conversion of nitrate [NO₃⁻] to nitrogen gas [N₂]) often occurs at discrete points in space (“hot spots”) and in time (“hot moments”) when conditions are favorable (i.e., available nitrate, carbon, and anoxia). In some agricultural areas, tile drains may route groundwater through riparian buffers with little or no nutrient removal, limiting the effectiveness of these buffers for subsurface nutrient removal.

Riparian buffers may be less effective at reducing in-stream sediment and nutrient concentrations if they are installed in a patchwork throughout a watershed, assuming all other factors are equal. (Realistically, some breaks in buffer continuity are likely to occur, even naturally in some cases.) Intact buffers (i.e., no or few breaks along a stream length) provide the greatest potential for improved water quality, even if total buffer length is equal (Figure 1-3). Gaps in non-continuous buffers (or storm drain pipes or tile drains that bypass buffers) allow unimpeded nutrient loading which reduce the benefits of established buffers (e.g., Collins et al., 2013). Additionally, the vast majority of stream length in a watershed is in small headwater streams that naturally have a greater connection to the uplands and therefore a greater potential benefit from riparian buffers. These headwater streams may also see greater in-stream water quality improvement due to their smaller size relative to the buffer widths. There are also significant interactions between riparian buffers and bank stabilization. On one hand, buffers increase bank stability through root reinforcement. Conversely, unstable banks and incising channels may result in undercutting of the riparian zone, which lowers groundwater tables and reduces nutrient removal because of a disconnection with the rooting zone.
1.1.3 In-Stream Enhancement

A common symptom of stream degradation is simplification of the channel\(^2\) and associated loss of habitat. Many stream restoration projects attempt to increase geomorphic complexity via installation of structures. Structures vary widely and can include j-hooks, cross-vanes, constructed riffles, and log-jams. Beaver reintroduction is also a potential restoration strategy and has the added advantage of being self-sustaining as beavers reconstruct and repair dams following damaging flood events. These structures can increase habitat heterogeneity and may increase nutrient retention and cycling by increasing hydraulic retention time and encouraging hyporheic exchange (Figure 1-4). Simply adding large woody debris to streams, either directly via anchored log jams or indirectly through establishment of riparian buffers, can also increase channel complexity and hyporheic flow (Roberts et al., 2007). Hyporheic flow potential at individual structures can be assessed by considering the difference in hydraulic head across the structure, along with knowledge about the hydraulic conductivity of the bed material.

The percentage of total annual flow that moves through the hyporheic zone at an individual structure is typically 1% or less (Azinheira et al., 2014; Gordon et al., 2013), but the cumulative effect of multiple structures could be significant and result in particulate retention and denitrification. Hyporheic

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\(^2\) Channel simplification refers to the loss of complex channel features, such as pools and riffles, in-stream wood, and bars that drive hyporheic exchange processes and provide important habitat for fish and macroinvertebrates. Causes of channel simplification may be direct (e.g., dredging or channelization) or indirect (e.g., altered sediment or flow regime which causes channel erosion or deposition).
exchange and nutrient retention will likely be highest during baseflow whereas structures likely provide little or no nutrient retention during storm events.

Organic carbon availability is essential for microbial processes and nutrient cycling. Restoring organic carbon fluxes may be an important component of an in-stream enhancement restoration strategy focused on nitrate reduction. This could be accomplished through the placement of log jams and riparian buffer restoration, which could restore both short-term (i.e., leaf litter) and long-term (i.e., large wood) carbon inputs to streams (Stanley et al., 2012).

![Figure 1-4. Conceptual diagram of hyporheic flow in natural channels.](image)

Figure 1-4. Conceptual diagram of hyporheic flow in natural channels. Hyporheic flow paths indicated with dashed lines. Installed structures can induce hyporheic exchange similar to what is observed in natural riffles. Adapted from Hester and Gooseff (2010).

### 1.1.4 Floodplain Reconnection

Natural floodplains can be important nutrient sinks (e.g., Forshay and Stanley, 2005), a function which is often lost as floodplain-channel connections are severed via channelization, incision, or levee construction (Loos and Shader, 2016). Hydrologic reconnection of floodplains and streams can be achieved by lowering stream banks, removing or breaching levees, raising the channel bed, wood recruitment and log-jam formation, removing infrastructure from undeveloped floodplains, and complete channel reconstruction. Whatever the method, floodplain reconnection tends to raise the riparian groundwater table and allows for more frequent overbank flows. This increases sediment and nutrient retention and processing while providing ancillary benefits such as enhanced aquatic and riparian habitat, reduced in-channel erosive power and downstream flooding, and increased aquifer recharge. Floodplain reconnection can increase nutrient retention through overbank deposition as well as increased groundwater denitrification in the riparian zone (Fink and Mitsch, 2007; Kronvang, 2007; Roley et al., 2012a, 2012b). Construction of a two-stage ditch, a specific form of floodplain reconnection typically associated with agricultural channels, can increase denitrification and phosphorus retention in nutrient-laden waterways (Davis et al., 2015; Mahl et al., 2015).

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3 Regulatory floodplain considerations are often an important consideration for design and implementation of this practice and should be evaluated accordingly, as is the case for other types of stream restoration practices.
1.2 Stream Restoration Database Overview

The overall objective of the SRDB is to enable consistent reporting and compilation of critical aspects of stream restoration projects that are monitored for water quality and other performance metrics. The SRDB follows a relational database model that organizes data into twelve tables of information, as illustrated in Figure 1-5. Study information is entered into a simple Microsoft Excel workbook and then uploaded to a master database in Microsoft Access. The database is designed so that direct monitoring data, summary statistics, and functional assessment metrics can be reported at multiple locations and points in time. Appendix A provides a list of the reporting parameters recommended in the Stream Restoration Database. Additional detail is available in the User’s Guide accessible at http://www.bmpdatabase.org/stream.html. Brief descriptions of the content of the tables shown in Figure 1-5 are also provided below.

![Figure 1-5. Generalized stream restoration database structure.](image)

1.2.1 Study

The purpose of the “Study” table is to provide basic descriptive information about the project purpose(s), geographical information associated with the project location, relevant reports or publications documenting project conditions, a summary of benefits documented by the researcher, available data types, and identification of documents provided to support the study information (e.g., reports, photos, cross-sections, channel profiles, sampling and analysis plan, calculations, model results, etc.). Information about the study design, duration and scale are also requested.

1.2.2 Watershed

The purpose of the “Watershed” table is to provide basic data about the overall watershed characteristics upstream of the restoration study that influence conditions in the stream. Examples of the types of information (metadata) requested include:

- Drainage area.
- Geologic setting.
- Upland and floodplain soils.
- Watershed slope.
- Controls on hydraulic regime.
- Extent of watershed served by BMPs.
- Imperviousness (total and hydraulically connected).
- Land use/land cover, including in the stream corridor.
1.2.3 Stream

The purpose of the “Stream” table is to document key physical characteristics of the stream and its valley. Most studies will include at least two records for stream characteristics. These are typically conditions before improvements were implemented (control) and conditions after improvements were implemented (treatment). Alternatively, spatially based “treatment” and “reference” stream conditions may be entered instead of a before-after approach. Multiple combinations of treatments, controls and reference streams are also accommodated. Some studies may also have information on stream conditions corresponding to several temporal phases: before, interim (during establishment of improvements) and established (or “after”). For some network-scale studies, it is also possible that multiple tributaries (individual stream entries) may be described in this table. Examples of characteristics requested include:

- Stream condition (e.g., impairment).
- Valley setting.
- Channel geometry/condition (e.g., channel type, bedforms, planform, average bank height, channel width, depth and slope).
- Flow regime information.
- Bed and bank materials (e.g., soil bulk density, gradation of materials, P and N content).
- Vegetation types.

1.2.4 Design

The purpose of the “Design” table is to document key attributes of the stream restoration design associated with a “Stream” record. The intent of the table is to provide basic design information to enable comparison and identification of features influencing performance. For crediting programs that require that certain design standards be met, the Design table can be used as a tool to document these characteristics and ensure that the design criteria of the local entity were met. Examples of information requested include:

General Information:
- Stream restoration practice type.
- Channel length restored.
- Design approach/methods.
- Fluxes managed.
- Year completed.
- Riparian width restored.
- Goals/performance standards.

Description of measures implemented:
- Bank stabilization measures.
- Bed stabilization measures.
- Riparian buffer reestablishment.
- Floodplain reconnection/reconfiguration.
- Habitat enhancement/features.
- Barrier removal/fish passage.
- Infrastructure protection measures.

Information is also requested regarding operation, maintenance and replacement, expected establishment periods, expected stream response time, and expected design life.
1.2.5 Monitoring Approach and Data

The “Monitoring” series of tables includes information on the monitoring setup (related to experimental design), monitoring events and monitoring data. The monitoring setup and monitoring events tables are used to relate the monitoring data to locations and events. Events may include a time series of individual monitoring events and/or statistical summaries of annual or multi-year data.

Examples of monitoring data allowed for each data category include:

- **Chemical data**: Chemical data can be provided for surface water, groundwater, soil, or other media. Results can be provided as concentrations, loads, or rates. Information is requested on sample type (e.g., composite), sample size, and laboratory methods.

- **Hydrologic data**: Hydrologic data can be provided for surface flow, groundwater, pore water, and precipitation. Examples of data types include water depth, volume, flow rate, velocity, shear stress, stream power, and others.

- **Biological data**: Biological data are focused on the fauna present in biological assessments such as biomass, index of biotic integrity (IBI), invertebrate community index (ICI), fish abundance, and others.

- **Physical (habitat) characteristics**: Physical data generally include habitat-related characteristics, including characteristics such as canopy coverage, stream substrate characterization, erosion rates, and other physical characteristics.

The primary focus of the initial SRDB is chemical data, although some limited information for other data types has also been provided for some studies.

1.2.6 Contacts

Contact information for a stream restoration project is important to record to enable follow-up correspondence, accountability for long-term maintenance and even as a resource for contractors who have experience in a particular geographic area. Contact records can be added for the owner, sponsor, researcher, maintenance contractor, designer, construction contractor, monitoring entity, or other relevant contact.

1.2.7 Costs

The “Cost” table accepts data related to both the stream restoration project and monitoring costs. The cost table is set up in a manner that allows a user to enter multiple records per study related to various costs. The type of cost being recorded is selected from a picklist, with an accompanying field for a narrative description to be provided by the data provider. The cost of stream restoration practices is a significant area of interest nationally, particularly as related to comparison of various improvements that could be implemented in a watershed to achieve water quality and aquatic life goals.
CHAPTER 2.0

Stream Restoration Performance Study Designs and Performance Evaluation Approaches

Prior to conducting performance analysis and synthesis of stream restoration studies in the SRDB, it is important to understand the types of experimental design commonly used for such studies and to understand some of the analysis constraints commonly present in currently available data sets. This chapter provides this background information on common experimental designs, a summary of analysis constraints for the SRDB 1.0, an overview of recent metadata analysis approaches developed by others (Palmer et al., 2014, Newcomer-Johnson, 2016) and an overview of the analysis approach applied to the SRDB 1.0.

2.1 Common Monitoring Approaches for Stream Restoration Studies

Monitoring programs for purposes of water quality performance evaluation typically require some type of baseline monitoring to document baseline or existing conditions, as well as some type of implementation and effectiveness monitoring. There are three general types of stream monitoring locations that may be considered in a performance study design:

- **Treatment:** The treatment is the restoration action, which focuses on the “impact” or performance of the project. Monitoring may focus on improvements to the water quality of the stream or on the specific pollutant removal mechanisms and rates for which the project is intended to establish or enhance.

- **Control:** A control site has characteristics that are very similar to the treatment site; however, no treatment is applied. The hydrologic, hydraulic, and water quality conditions that the control site is exposed to should also be similar to the treatment site. Monitoring should replicate the monitoring at the treatment site.

- **Reference:** A reference site represents the desired or targeted condition. An example would be a stream with similar characteristics to the treatment and control sites, but in a relatively natural setting.

Control, reference, and treatment sites should be similar in drainage area, stream flow, geology, land use, gradient, vegetation, and potentially other factors (Roni and Beechie, 2013).

At a minimum, all projects should have some type of before and after or upstream and downstream assessment. The most common approaches include the use of a before-after or a before-after control-impact (BACI) design (or some variation of these approaches). The four basic monitoring designs (which can be enhanced through the use of replicates) include:

- **Before-After (BA):** This approach involves monitoring the treated site before and after restoration. This is the simplest monitoring approach, but interpretation can be affected by natural trends or conditions at the time of monitoring.

- **Before-After-Control-Impact (BACI):** Building upon the before-after study design, a control site can be added to reduce the possibility of interpreting a natural trend as a treatment effect and to reduce the effect of temporal variability. In this case, the control and the treatment are both monitored before and after the restoration is implemented.
Post-Treatment Designs: In cases where “before” data are not available for comparison due to planning and funding constraints, post-treatment monitoring designs rely on a comparison of treatment and appropriate control or reference reaches. This design assumes that the control reach was similar to the treatment reach before restoration was implemented. In many cases, the control can be directly upstream of the restored reach (and thus may be referred to as upstream/downstream monitoring design). There are two general types of post-treatment monitoring designs: the intensive post treatment (IPT) and extensive post treatment (EPT) design. The IPT approach focuses on long-term monitoring for a few pairs, whereas the EPT approach focuses on monitoring more pairs of locations spatially. (See Roni and Beechie [2013] for additional discussion.)

Indirect Methods: Indirect monitoring methods are those that attempt to quantify performance of a stream restoration projects by using surrogate parameters, tracer injections and/or data collected from locations other than in-stream (e.g., groundwater, surface runoff, etc.). Tracers are often used in nutrient spiraling studies where a known quantity of nutrients are added to the stream and uptake rates are estimated based on first-order dynamics (Stream Solute Workshop, 1990).

The studies included in SRDB 1.0 include a mixture of these approaches, which pose challenges when attempting to synthesize and compare performance among studies.

2.2 Challenges in Evaluating Performance of Stream Restoration Projects

Although monitoring and evaluation provides important information on restoration project effectiveness, Yochum (2015), Roni and Beechie (2013), Palmer et al. (2005), Bernhardt et al. (2005) and others continue to show that only a small fraction of restoration projects internationally are adequately monitored. Roni and Beechie (2013) identify multiple explanations for inadequate monitoring and reporting that range from inadequate funding to technical and non-technical issues. These issues include a lack of clearly defined questions, improper study design, inadequate spatial and temporal replication, insensitive monitoring parameters, poor project implementation or management, and lack of periodic analysis and publication of results (citing Reid, 2001, Roni, 2005 and Roni et al., 2008).

The literature review and initial population of the SRDB identified similar challenges as previous researchers who have attempted to synthesize water quality performance of stream restoration projects. In particular, the lack of consistent study designs and standardized data reporting constrain the types of analyses that can be performed. Over the long-term, the SRDB is designed to help improve consistency of monitoring and reporting and thereby allow for more comprehensive analyses to be conducted in the future.

Some of the challenges related to developing monitoring programs to verify the benefits of stream restoration projects include:

- Monitoring design – what are the performance metrics and where should they be assessed?
- Long-term monitoring to verify “success” – how long should monitoring be conducted? This may be especially important as significant erosional events may be infrequent.
- Minimum monitoring requirements – how many measurements or samples should be collected and for which parameters?
- Timing of sample collection and performance assessment intervals – under what hydrologic conditions should samples be collected?
There is not a one-size-fits-all answer to these questions and the ideal monitoring design is often not met due to practical and funding constraints. Ideally, multiple years of pre-project monitoring data would be available for BA and BACI designs. The required number of samples is affected by the variability of the monitoring parameters selected. In some cases, data may already exist for non-project related reasons and can be used for pre-project characterization, provided that important factors such as collection methods are considered. From a practical perspective, most monitoring programs will also be limited in breadth of the monitoring that can conducted. Generally, it is preferable to monitor fewer parameters more robustly, than to monitor many parameters infrequently. Roni and Beechie (2013) suggest that the selection of monitoring parameters should be:

- Tied to the objectives of the project.
- Relevant to the monitoring questions or hypotheses.
- Sensitive or responsive to the restoration action.
- Efficient to measure.
- Limited in variability.

While the focus of the SRDB is primarily on water quality, it is important to recognize that stream restoration projects may be implemented for many reasons, with water quality being an ancillary or a secondary objective in many cases. Additionally, some restoration projects are completed to meet regulatory requirements, such as compensatory mitigation, which may or may not include water quality performance goals or metrics.

Monitoring methods are important for obtaining representative samples. Significant guidance already exists on stream monitoring and sampling methods (e.g., USGS, 2016; Davis et al., 2014, ADEQ, 2005; OEPA, 2013). However, limited nationally applicable guidance is available for assessing and documenting improvements to water quality as a result of stream restoration projects. This lack of guidance has led to a wide variety of monitoring and assessment protocols used by various researchers.

Comparing restoration effectiveness among studies is difficult, primarily due to the lack of consistent monitoring and reporting protocols and the unique features of individual projects. This issue is especially pertinent to the SRDB because a major goal of this effort is to allow for quantitative meta-analysis of restoration effects, specifically related to sediment and nutrient reduction and retention. Projects often have site-specific goals and objectives, necessitating unique sampling strategies and data analysis. However, a benefit of the SRDB is to provide a standardized list of comparable metrics that practitioners can monitor and share to facilitate more direct inter-site comparison. As more data are uploaded for a variety of restoration projects, the scientific evidence for stream restoration’s impact on nutrient and sediment dynamics and water quality will improve.

### 2.3 Previous Meta-Analysis Efforts for Stream Restoration Studies

Several studies have reviewed the practice of stream restoration broadly (e.g. Bernhardt et al., 2005; Wohl et al., 2005, 2015), but few have explicitly examined the efficacy of stream restoration projects in detail. Three recent reviews by Palmer et al. (2014), Newcomer-Johnson et al. (2016), and Smucker and Detenbeck (2014) have attempted to fill this gap, providing quantitative evidence for the relative efficacy of various restoration practices for achieving specific project objectives. Due to the paucity of data and the lack of consistent assessment and reporting methods among selected studies, generalized performance conclusions are limited. The first two reviews used a categorical and mostly qualitative approach to determine whether or not improvements in a specific assessment category were observed, while Smucker and Detenbeck (2014) performed a quantitative meta-analysis comparing urban, restored, and reference stream conditions. Highlights from these reviews are summarized below.
2.3.1 Palmer et al. (2014)

Palmer et al. (2014) assessed stream restoration effectiveness by examining metrics in four categories: water quality, morphology/physical characteristics, biophysical processes, and biological characteristics. They partitioned restoration projects into six classes:

- Channel hydromorphic (e.g., channel reconfiguration).
- In-stream hydromorphic (e.g., structure installation or bank armoring).
- Riparian restoration (e.g., riparian planting or protection).
- In-stream or riparian wetland creation.
- Watershed action.
- Other (e.g., acid mine drainage treatment, dam removal).

Although Palmer et al. (2014) examined a variety of metrics with which to quantify restoration success, nutrient water quality and nutrient dynamics are the two most pertinent to the SRDB. For nutrient water quality, they found that 100% of riparian restorations showed improvement (N = 32) compared to 60% of watershed action (N = 5). Improvements in nutrient dynamics were more variable. High rates of improvement were observed for riparian restoration (88%, N = 17) and in-stream hydromorphic practices (63%, N = 8) but were low for wetland creation (25%, N = 4) and channel hydromorphic practices (14%, N = 7). Improvements were based off the observations and definitions of each individual study and were not necessarily statistically significant. Additionally, sample sizes were small and more studies are needed to adequately assess relative effectiveness of various restoration strategies. Furthermore, different studies examined different aspects of water quality improvement, making direct comparison difficult. For example, one study in the watershed action category quantified the impact of septic tank removal on in-stream phosphorus concentrations while another examined differences in organic carbon fluxes and their effect on in-stream denitrification. These are disparate processes and failure to find improvement in one area does not necessarily mean no overall water quality enhancement. Still, this review suggests that riparian restoration, watershed action, and in-stream hydromorphic projects can result in nutrient-related water quality improvement while projects focusing on channel hydromorphic and wetland creation have less evidence of success.

2.3.2 Newcomer-Johnson et al. (2016)

Newcomer-Johnson et al. (2016) focused specifically on the nutrient-related benefits of restoration projects that increased hydrologic connection in the stream-riparian system. This hydrologic reconnection was grouped into four categories:

- Floodplain reconnection.
- Streambed reconnection.
- Increased stream surface area.
- Increased wetland surface area.

Across the 114 studies examined, 62% showed positive results, 26% showed neutral results, and 12% showed negative results related to nutrient retention and reduction. Many of the negative results were one of three types: lower denitrification rates in restored streams due to limited carbon availability, nutrient export (of at least some constituents) from restored floodplains and wetlands, and increased nutrient release after adding wood to a nutrient-poor stream. Assessment methods varied among studies but generally fell within three broad categories: water chemistry monitoring, mass balance approaches, and quantification of denitrification rates. Assessments included before-after sampling of a restoration
project and comparison between restored and reference sites. Some studies included more detailed monitoring of in-stream and pore-water chemistry at individual restoration structures. Generally, the Newcomer-Johnson et al. (2016) review found that most monitored restoration projects that focused on restoring hydrologic connectivity resulted in nutrient-related water quality improvements.

### 2.3.3 Smucker and Detenbeck (2014)

Smucker and Detenbeck (2014) performed a quantitative meta-analysis to compare ecosystem condition in urban degraded, urban restored, and reference streams. They focused primarily on out-of-channel restoration practices, including riparian buffers, stormwater ponds, and created wetlands. Their analysis approach calculated unit-less response ratios based on 38 studies. Their analysis showed that while restored sites had a median water quality response ratio of 128% compared to urban sites, this difference was not statistically significant. Similarly, the nutrient response ratio of 113% showed improvement, but this was again not statistically different from no observed change. In other ecological categories (e.g., biodiversity, macroinvertebrates, periphyton), restored streams did show statistically significant improvements over urban unrestored streams. For example, mean measures of ecosystem attributes in restored streams were 156% of unrestored urban streams and these differences were statistically significant. Measures of biodiversity in restored streams were 132% of those in unrestored streams. The authors identified a variety of challenges associated with conducting this type of analysis. One of the key practice implications identified by Smucker and Detenbeck included the need for better tracking of restoration practices, continued monitoring and improved access to data.

### 2.4 Recommended Quantitative Performance Evaluation

As described in Section 2.1, most stream restoration studies include two to four monitoring locations to characterize potential project benefits. Benefits are typically quantified by comparing monitoring data collected at these locations, which may represent before and after, upstream and downstream, control (or reference) and treatment, or a combination thereof. Methods to compare water quality data range from simple comparisons of mean concentrations and loads to more complex hypothesis testing to determine statistically significant differences. While the latter is generally recommended and preferred, it requires a large number of data points to adequately characterize the statistical distribution of data at each location or condition being compared. This section provides recommended data analyses for assessing performance of stream restoration projects, either individually or as a group, assuming adequate data are available to characterize data distributions. Example application of these data analysis methods are provided for the restoration case studies described in Section 3.6.

#### 2.4.1 Basic Summary Statistics

Basic summary statistics include measures of location or central tendency (e.g., mean, median), measures of spread or variability (e.g., standard deviation, interquartile range), and measures of skewness or symmetry (e.g., coefficient of skewness). Environmental data tend to be positively skewed, so the use of the median or geometric mean to describe the central tendency is generally preferred. While these basic summary statistics are informative, simple comparisons of the central tendencies of two or more data sets cannot be used to assess statistical differences. Instead, graphical data analyses and comparative hypothesis tests should be completed to evaluate whether two data sets are statistically significantly different.

#### 2.4.2 Graphical Data Analysis

Graphical data analysis is an essential component of any data summarization effort. In addition to the commonly used time-series plots, there are two types of plots generally recommended for comparing
water quality data for two or more datasets: boxplots and quantile plots. Boxplots (or box and whisker plots) provide a schematic representation of the central tendency and spread of the data. Side-by-side boxplots can provide an indication of whether two datasets are statistically different.

Quantile plots can be used to visually display the empirical distribution of a dataset. They are constructed by ranking the sample data and then calculating the plotting position (or non-exceedance frequencies) for each data point. The ranked data are placed on the x-axis and the corresponding plotting positions (i.e., percentage of total data points below the value on the x-axis) are placed on the y-axis. This produces an empirical approximation of the cumulative distribution function (CDF) where the probability of a random sample value being less than or equal to an observation can be directly determined. When two or more data sets are plotted on the same graph, direct comparisons of any quantile can be made.

### 2.4.3 Comparative Hypothesis Testing

The use of comparative hypothesis tests is recommended for assessing whether a stream restoration project or group of similar projects provide statistically significant improvement to water quality. These methods can be used to compare totally independent (non-paired) sets of data, such as sampling event data collected before and after restoration, or dependent (paired or matched) data sets, such as the upstream and downstream samples collected during the same post-restoration time periods.

For independent data sets, the recommended approach is to use Mann-Whitney rank-sum test (Mann and Whitney, 1947), which is a non-parametric (i.e., distribution free) hypothesis test to evaluate whether two data sets are statistically different. This test is available in most commercial software packages and is preferred over the commonly used t-Test because the t-Test can only be used on normally distributed data and does not work well for small sample sizes (Helsel and Hirsch, 2002). For multiple dataset comparisons (for example if there are multiple sample locations), the Mann-Whitney test may be applied iteratively. This iterative application is referred to as Dunn’s procedure (Dunn, 1964).

For paired data sets, the Wilcoxon signed-rank test (Wilcoxon, 1945) is recommended. This test evaluates the sign of the differences of all paired data points to determine whether one dataset is consistently larger than another dataset.

### 2.5 Summary of Approach Applied for SRDB

While the data analysis methods described above are generally recommended for comparing datasets and assessing performance of stream restoration practices, the SRDB 1.0 does not contain enough studies with sampling event data to apply these techniques to the database as a whole. Therefore, the performance analysis approach selected for this initial summary includes a combination of qualitative and quantitative approaches. These approaches build on experiences of others in the stream restoration arena (Palmer et al., 2016, Newcomer-Johnson, 2014) and on approaches used for the International Stormwater BMP Database (Geosyntec and Wright Water Engineers, 2008, 2014) and the more recent Agricultural BMP Database (Wright Water Engineers and Geosyntec, 2014), accessible at www.bmpdatabase.org. Ideally, future releases of the SRDB will enable application of more quantitative analysis; however, care has been taken for this initial summary report to not overstate findings quantitatively. For example, in many studies, it is clear that water quality benefits have occurred as a result of stream restoration projects; however, the absolute magnitude and statistical significance of those benefits is much more difficult to characterize at this time.
SRDB Literature Review, Data Summary, and Findings

The initial population of the SRDB was completed in a two-phase process. The first phase focused a broad literature review of stream restoration studies, as discussed in Section 3.1. The second phase included entry of a subset of studies from the literature review into the SRDB. Sections 3.2 through 3.5 provide an overview of the studies entered into the SRDB, a summary of analysis constraints, qualitative analyses of the studies entered, and limited quantitative analyses of available pollutant concentration and load data. Section 3.6 provides a case study with substantive event-based data that is used to demonstrate the types of analyses that could be produced in future SRDB analyses if additional event-based data sets are obtained and entered into the SRDB.

3.1 SRDB Literature Review Synthesis

As the first task in this project, a broad literature search was completed to identify stream restoration studies and syntheses that focused on sediment and nutrient water quality improvement. The literature review serves these purposes: 1) provides a current compilation of stream restoration literature, 2) provides a qualitative summary of the stream restoration benefits provided by researchers, 3) provides a pool for studies useful for initial entry into the SRDB, and 4) enables synthesis of research needs for stream restoration studies.

A total of 128 literature resources were compiled, reviewed, and summarized, as provided in Appendix B. The review included 114 peer-reviewed journal articles, three theses, and 11 gray literature reports. A tabular summary of the 128 studies is also provided in the SRDB 1.0, which enables users to utilize the full literature review as part of the database itself. Study metadata and monitoring data were extracted in more detail for a subset of 24 studies from the literature review and entered into the SRDB format, as described in Section 3.2. Additional studies from the literature review are suitable for entry in future releases of the SRDB.

3.1.1 Summary of Findings from SRDB Literature Review

Based on the SRDB literature review (Lammers, 2015, provided in Appendix B), qualitative observations relevant to monitoring and assessment of stream restoration for water quality improvement are summarized below.

- **Bank Stabilization**: In unstable channels with high soil nutrient concentrations, accelerated bank erosion may be a significant source of sediment, phosphorus, and potentially nitrogen, to receiving waters. Bank stabilization may therefore be a relatively simple way to reduce nutrient loading and is already a common practice to increase channel stability and protect infrastructure. Although estimating historic or present erosion rates is possible, quantification of future channel evolution and load reduction is more challenging.

- **Riparian Buffers**: Buffers remove groundwater nitrate, protect streambanks, supply in-stream wood and organic carbon to increase in-stream processing and are generally less intrusive and more cost-effective than channel reconstruction projects. Buffers can also reduce upland sediment, phosphorus and other particulate pollutant loading in surface runoff to the stream if upstream runoff is routed through them rather than bypassed. Additionally, when groundwater conditions are amenable, organic carbon soil amendments can encourage denitrification and addition of metal oxides can enhance phosphorus retention.
Floodplain Reconnection: Floodplain reconnection aims to attenuate peak flows and increase hydraulic residence time to promote sediment and nutrient retention during high flows. Pollutant removal may be limited due to infrequent inundation of the reconnected floodplains, but additional research on overall load reduction benefits is needed at larger spatial and temporal scales to better understand the effectiveness of these types of projects at improving in-stream quality.

In-Stream Enhancement: Structures that are already incorporated into stream restoration designs can be constructed to encourage hyporheic exchange and nutrient processing through enhanced geomorphic complexity and bedforms. In contrast to floodplain reconnection, in-stream enhancement is expected to primarily improve the quality of low flows (base flows) when a greater proportion of the flow can interact with groundwater.

Upland Controls: While not a stream restoration strategy, managing point and non-point discharges of water and sediment and reducing nutrient loading through source controls remains an essential strategy for improving water quality and overall watershed health. Although complete stormwater retrofits are likely not feasible in many developed watersheds, steps to reduce streamflow amplification and flashiness can reduce the risk of channel erosion and potentially improve in-channel nutrient processing. Additionally, controlling non-point nutrient sources can reduce nutrient loading to streams and may improve the efficiency of in-channel nutrient processing. A combination of watershed restoration strategies that reduce nutrient inputs to streams, reestablish riparian functions, provide balanced water and sediment regimes, and increase in-stream nutrient processing and retention will likely be most effective for improving water quality.

3.1.2 Research Needs Identified in SRDB Literature Review

Even with the increase in published stream restoration monitoring studies, a lack of consistent methodology and reported metrics remains, making direct comparisons and synthesis of restoration technique performance challenging. While the increase in monitoring is a promising trend, there also needs to be an improvement in the quality and consistency of monitoring programs. Restoration monitoring should focus on metrics that are specific to project objectives (Palmer et al., 2005). Furthermore, monitoring should be pre-planned and hypothesis driven (e.g., bank stabilization will reduce phosphorus loads by 10%) rather than conducted as an afterthought. There may be significant lag time between completion of restoration projects and observed improvements (Meals et al., 2010), requiring long-term monitoring that may be perceived as impractical and cost-prohibitive. Monitoring of control, reference, and restored sites can provide critical information on how restored channels may have evolved over time in the absence of restoration interventions. In addition, uncertainty remains on details of in-stream nutrient dynamics and processing. Given these limitations, the following areas are recommended for improving stream restoration performance evaluations:

- Improved design of sampling methodologies and more rigorous data collection are needed to more accurately and effectively assess performance of stream restoration projects. Monitoring plans should be designed with sufficient statistical power to assess changes in water quality. Sampling frequency can radically alter the length of monitoring required to detect changes and trends (Meals et al., 2010). Paired watershed and BACI experimental designs may be more robust than simple before/after restoration monitoring by accounting for climatic and hydrologic variability and are structured to assess whether significant differences exist between reference, control, and restoration sites. However, in practice, BACI designs may be limited by use of a single control site (Underwood, 1994) and paired watershed designs often have insufficient sample sizes and monitoring periods (Loftis et al., 2001).
Controlled experiments arguably have the greatest potential to assess relative impact of different restoration strategies. Ideally, these would be conducted on one or more streams in a single watershed with similar impairment to adequately quantify the individual and cumulative impacts of restoration methods.

A better understanding of the chemical fate and transport of phosphorus in streams is required. LINX / LINX-II (Mulholland et al., 2009; Webster et al., 2003) and other experiments have provided important insight into in-stream processing and cycling of ammonium and nitrate and a similar effort should be made for phosphorus. It has likely been relatively neglected up to this point because there is no mechanism for permanent phosphorus removal from stream systems (e.g., unlike denitrification), but burial in bed or floodplain deposits may serve as effective removal mechanisms at engineering time scales and these processes deserve further examination.

Additional monitoring and reporting of the potential successes of stream restoration projects for nutrient management are needed from diverse geographic locations. While the studies summarized in the literature review (Lammers, 2015) and incorporated within the SRDB cover most of the U.S. as well as international locations, there are some more highly represented regions (e.g., the Chesapeake Bay watershed). This is largely a function of where nutrient management issues are of most concern, but it is important to note that observations from one region may not be representative of stream-nutrient dynamics in other environments. To account for these potential differences, it is essential to expand the understanding of stream restoration and nutrient dynamics in other locations.

Existing studies suggest that certain restoration strategies may enhance nutrient retention and removal in stream and riparian systems. However, this is still an emerging science with insufficient evidence to precisely quantify the effects of different restoration strategies across regions and various hydrologic, geologic, and land use contexts. Given the increasing attention stream restoration has been receiving, an increasing emphasis on improved effectiveness monitoring, and the growing number of published studies on the impact of stream restoration on nutrient dynamics, the future looks promising for improved understanding of the efficacy of stream restoration as a nutrient and sediment management tool.

### 3.2 Studies Entered in the SRDB 1.0

Although the number of stream restoration studies with sufficient data to confidently assess the performance of stream restoration projects is increasing, there is still relatively limited information for quantitatively evaluating the water quality performance of different restoration techniques. For the initial release of the SRDB, the data summary focuses on the studies that implemented direct monitoring approaches including BA, BACI, and post-treatment monitoring designs. Due to limited monitoring event data for the various restoration practice types, the possible analyses are constrained. The selected approach includes a combination of qualitative analysis of researcher-documented performance and quantitative summary of study data statistics. Case study examples are also provided to illustrate the types of analyses that could be completed with a more robust data set consisting of discrete monitoring events. Once the SRDB is sufficiently populated, more complete and potentially useful quantitative analyses of the performance of various stream restoration practices could be documented.

As part of the literature review described in Section 3.1, the 128 literature resources were characterized according to characteristics such as geographic location, stream and watershed attributes, type of restoration practice, design elements, monitoring and assessment methods, pollutants evaluated, and data availability. This initial characterization was used to prioritize a subset of studies for entry into the SRDB, as summarized in Table 3-1. Appendix C provides a narrative summary report for each of these studies generated from queries of the Access database tables.
<table>
<thead>
<tr>
<th>Reference</th>
<th>Report Title or Source Documents</th>
<th>Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baker and Vervier 2004</td>
<td>Hydrological Variability, Organic Matter Supply and Denitrification in the Garonne River Ecosystem</td>
<td>France</td>
</tr>
<tr>
<td>Carline and Walsh 2007</td>
<td>Responses to Riparian Restoration in the Spring Creek Watershed, Central Pennsylvania</td>
<td>Pennsylvania</td>
</tr>
<tr>
<td>Charbonneau and Resh 1992</td>
<td>Strawberry Creek on the University of California Berkeley Campus: A Case History of Urban Stream Restoration</td>
<td>California</td>
</tr>
<tr>
<td>Collins et al. 2013</td>
<td>The Effectiveness of Riparian ‘Restoration’ on Water Quality—A Case Study of Lowland Streams in Canterbury, New Zealand</td>
<td>New Zealand</td>
</tr>
<tr>
<td>Cottonwood Creek Stabilization</td>
<td>Stream Reclamation, Water Quality Benefit Evaluation - Interim Status Report (2011). Also Various Cherry Creek Basin Water Quality Authority Annual Reports, Presentations, Fact Sheets and Long-term Database</td>
<td>Colorado</td>
</tr>
<tr>
<td>Coyote Gulch</td>
<td>Technical Report Coyote Gulch Data Summary/Record and Associated Trade Credit (multiple Bear Creek Watershed Association reports 2012-2014)</td>
<td>Colorado</td>
</tr>
<tr>
<td>Doyle et al. 2003</td>
<td>Hydrogeomorphic Controls on Phosphorus Retention in Streams</td>
<td>Wisconsin</td>
</tr>
<tr>
<td>Filoso and Palmer 2011</td>
<td>Assessing Stream Restoration Effectiveness at Reducing Nitrogen Export to Downstream Waters</td>
<td>Maryland</td>
</tr>
<tr>
<td>Fink and Mitsch 2007</td>
<td>Hydrology and Nutrient Biogeochemistry in a Created River Diversion Oxbow Wetland</td>
<td>Ohio</td>
</tr>
<tr>
<td>Harrison et al. 2012</td>
<td>Microbial Biomass and Activity in Geomorphic Features in Forested and Urban Restored and Degraded Streams</td>
<td>Maryland</td>
</tr>
<tr>
<td>Hines and Hershey 2011</td>
<td>Do Channel Restoration Structures Promote Ammonium Uptake And Improve Macroinvertebrate-Based Water Quality Classification In Urban Streams?</td>
<td>North Carolina</td>
</tr>
<tr>
<td>Hoellein et al. 2012</td>
<td>Effects of Benthic Habitat Restoration on Nutrient Uptake and Ecosystem Metabolism in Three Headwater Streams</td>
<td>Michigan</td>
</tr>
<tr>
<td>Hubbard et al. 2003</td>
<td>Assessment of Environmental and Economic Benefits Associated with Streambank Stabilization and Phosphorus Retention</td>
<td>Mississippi</td>
</tr>
<tr>
<td>Kasahara and Hill 2006</td>
<td>Hyporheic Flows Induced by Constructed Riffles and Steps in Lowland Streams in Southern Ontario, Canada</td>
<td>Ontario, Canada</td>
</tr>
<tr>
<td>Kaushal et al. 2008</td>
<td>Effects of Stream Restoration on Denitrification in an Urbanizing Watershed</td>
<td>Maryland</td>
</tr>
<tr>
<td>McMillan et al. 2014</td>
<td>Influence of Restoration Age and Riparian Vegetation on Reach-Scale Nutrient Retention in Restored Urban Streams</td>
<td>North Carolina</td>
</tr>
<tr>
<td>Meals 2001</td>
<td>Water Quality Response to Riparian Restoration in an Agricultural Watershed in Vermont, USA</td>
<td>Vermont</td>
</tr>
<tr>
<td>Miller et al. 2014</td>
<td>Estimating Sediment and Phosphorus Loads from Streambanks With and Without Riparian Protection</td>
<td>Oklahoma</td>
</tr>
<tr>
<td>Orzetti et al. 2010</td>
<td>Stream Condition in Piedmont Streams with Restored Riparian Buffers in the Chesapeake Bay Watershed</td>
<td>Virginia</td>
</tr>
<tr>
<td>Richardson et al. 2011</td>
<td>Integrated Stream and Wetland Restoration: A Watershed Approach to Improved Water Quality on the Landscape</td>
<td>North Carolina</td>
</tr>
<tr>
<td>Robertson and Merkley 2009</td>
<td>In-Stream Bioreactor for Agricultural Nitrate Treatment</td>
<td>California</td>
</tr>
<tr>
<td>Tuttle et al. 2014</td>
<td>Channel Complexity and Nitrate Concentrations Drive Denitrification Rates in Urban Restored and Unrestored Streams</td>
<td>North Carolina</td>
</tr>
<tr>
<td>Wallace et al. 1995</td>
<td>Influence of Log Additions on Physical and Biotic Characteristics of a Mountain Stream</td>
<td>North Carolina</td>
</tr>
<tr>
<td>Watershed Conservation Resource Center</td>
<td>Examples of Implemented Stream Restoration Projects and Estimated Total Phosphorus Reductions</td>
<td>Arkansas</td>
</tr>
</tbody>
</table>
3.3 SRDB 1.0 Analysis Constraints

Significant analysis constraints existed for this initial data summary. While the studies selected from the literature review were deemed appropriate for entry into the SRDB 1.0, none of them included all of the information requested in the SRDB reporting protocols (see User’s Guide and Data Entry Spreadsheets). Additionally, most of the studies were based on peer reviewed literature that contained summary statistics without underlying event-based data provided in the papers, which limits the types of quantitative analysis that can be conducted by a third party. Also, many of the study reports contained graphs of collected data, but did not include tabulated data; therefore, additional follow-up with the original researcher would be necessary to enable independent analysis. Finally, many of the quantitative design parameters and site meta-data requested for entry into the SRDB were not reported in the literature or were not in a form that was directly transferable into the data entry spreadsheets. Therefore, although the initial version of the SRDB is a significant step in standardizing and consolidating stream restoration studies that focus on water quality improvement, additional efforts are needed to make the database a more useful analytical tool through continued population of the database with additional performance studies that both follow the reporting protocols and that provide more detailed data sets. An appropriate follow-up task to this initial database development effort would be to contact original researchers and request underlying datasets for the entered studies to further populate the SRDB data tables.

3.4 Qualitative Analysis – Study Objectives and Findings Summary

Various types of qualitative information were entered into the SRDB for each study. This information is used to classify and characterize studies, which can be further used to facilitate data queries and analysis. The sections below summarize the range of restoration study objectives and the reported performance results for studies included in the SRDB 1.0. More detailed summary reports for each study are provided in Appendix C.

3.4.1 Summary of Restoration Study Objectives

Stream restoration may be completed for a variety of reasons and many projects have multiple objectives. Table 3-2 provides a count of the objectives identified for the studies entered into the SRDB 1.0. Given that the focus of the initial data entry was on performance studies that included sediment and nutrient effects reporting, it is not surprising that water quality management is the primary objective identified (19 out of 24 studies). Other top ranking objectives included bank stabilization (14), riparian vegetation re-establishment (12), channel incision stabilization (11), and floodplain reconnections (8). While fish passage and habitat improvement are common goals of stream restoration projects, projects that did not include the collection of water quality data were not targeted for initial upload to the SRDB.
Table 3-2. Count of Studies by Restoration Objectives

<table>
<thead>
<tr>
<th>Restoration Objectives</th>
<th>Number of Studies</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water Quality Management</td>
<td>19</td>
</tr>
<tr>
<td>Bank Stabilization</td>
<td>14</td>
</tr>
<tr>
<td>Riparian Vegetation Re-establishment</td>
<td>12</td>
</tr>
<tr>
<td>Channel Incision Stabilization</td>
<td>11</td>
</tr>
<tr>
<td>Floodplain Reconnection</td>
<td>8</td>
</tr>
<tr>
<td>Channel Reconfiguration</td>
<td>5</td>
</tr>
<tr>
<td>Aesthetics, Recreation, and/or Education</td>
<td>4</td>
</tr>
<tr>
<td>In-stream Habitat Improvement</td>
<td>4</td>
</tr>
<tr>
<td>Stormwater Management</td>
<td>4</td>
</tr>
<tr>
<td>Infrastructure Protection</td>
<td>3</td>
</tr>
<tr>
<td>Reestablish Sediment Balance</td>
<td>2</td>
</tr>
<tr>
<td>Improve Flood Conveyance</td>
<td>1</td>
</tr>
<tr>
<td>Flow Modification</td>
<td>1</td>
</tr>
<tr>
<td>In-stream Species Management</td>
<td>1</td>
</tr>
<tr>
<td>Public Safety</td>
<td>1</td>
</tr>
<tr>
<td>Dam Removal/Retrofit</td>
<td>0</td>
</tr>
<tr>
<td>Fish Passage</td>
<td>0</td>
</tr>
<tr>
<td>Permit Requirement</td>
<td>0</td>
</tr>
</tbody>
</table>
Table 3-3 provides abbreviated purpose statements for each of the 24 studies included in the SRDB. The diversity of monitoring goals and approaches illustrates the difficulty in comparing data among studies. For example, some studies examined nutrient uptake while others measured changes in nutrient concentrations or loads. Both approaches may be valid to assess restoration success but they do not lend themselves to direct comparison among sites.

### Table 3-3. Study Purpose Statements

<table>
<thead>
<tr>
<th>Study ID and Reference</th>
<th>Study Purpose Statement</th>
</tr>
</thead>
<tbody>
<tr>
<td>2016005, Baker and Vervier, 2004</td>
<td>Measure denitrification during high and low flow along a gradient of surface water–groundwater mixing in the nitrate contaminated alluvial aquifer of a river to understand its potential importance to the N budget, and its range of temporal variability. Selected three wells in three neighboring land cover types for the study: Gravel Bar, Native Riparian, and Poplar Plantation.</td>
</tr>
<tr>
<td>2016014, Carline and Walsh, 2007</td>
<td>Quantify the effects of stream bank fencing with narrow grass buffer strips on channel morphology, stream substrate composition, and macroinvertebrate communities at the reach scale and sediment loads at the catchment scale in two second-order streams with unrestricted grazing by cattle and horses.</td>
</tr>
<tr>
<td>2016015, Charbonneau and Resh, 1992</td>
<td>Improve water quality and reduce erosion to enhance habitat for newly introduced native fish species (<em>Gasterosteus aculeatus</em>).</td>
</tr>
<tr>
<td>2016018, Collins et al., 2013</td>
<td>A paired-catchment design on four river reaches was used to compare restored riparian buffers with control sites upstream. Chemical water quality sampling was used in conjunction with a macroinvertebrate community assessment. Equivocal benefits of riparian restoration were observed, with improvements in some variables but not in others. The close relationship of the riparian zone with in-stream systems makes it a focus for restoration strategies to mitigate the effects of land use change.</td>
</tr>
<tr>
<td>2016123, Cottonwood Creek Stabilization</td>
<td>Control channel erosion and reduce phosphorus loading to Cherry Creek Reservoir. Stabilize 2.83 miles of stream bed and banks, increase baseflow and riparian fringe from about five to 25 acres, increase two-year floodplain from seven to 83 acres.</td>
</tr>
<tr>
<td>2016125, Coyote Gulch</td>
<td>Implement actions under the Bear Creek Reservoir TMDL by reducing phosphorous loadings from bank erosion and stormwater runoff into Bear Creek Reservoir, improve wetlands habitat, provide informational and educational opportunities, and measure the post-construction phosphorous reduction efficiency of the channel improvements.</td>
</tr>
<tr>
<td>2016023, Doyle et al., 2003</td>
<td>Analyze the effects of geomorphic controls and dynamic reestablishment on nutrient retention metrics following dam removal in Wisconsin. Attempts to isolate the relative influences of biochemical process, background nutrient concentration and hydrogeomorphology on MRP retention in streams.</td>
</tr>
<tr>
<td>2016027, Filoso and Palmer, 2011</td>
<td>Assess stream restoration performance for reducing nutrient transport to downstream reaches for streams in the coastal plain of western Maryland. Controls in the context of this study represented degraded stream reaches in the watershed.</td>
</tr>
<tr>
<td>2016028, Fink and Mitsch, 2007</td>
<td>Observe the function of a created river diversion wetland in the upper Ohio River basin. Focus was water quality functions and the development of herbaceous plant communities in a riparian wetland.</td>
</tr>
<tr>
<td>2016039, Harrison et al., 2012</td>
<td>Purposes: 1) quantify and compare sediment denitrification potential (DEA) among and within stream features (pools, riffles, organic debris dams), across stream condition (forested, restored, degraded), and across seasons; 2) quantify and compare methane production among stream features (pools and riffles) and stream sites; and 3) determine the controls on denitrification in stream sediments and how they vary seasonally.</td>
</tr>
<tr>
<td>2016045, Hines and Hershey, 2011</td>
<td>Assess the uptake of ammonium and effect on benthic macroinvertebrates related to restoration efforts and instream structures for urban stream sites in the North Carolina Piedmont region. WQ metrics based on injections and subsequent sampling.</td>
</tr>
<tr>
<td>2016046, Hoellein et al., 2012</td>
<td>Quantify the influence of the change in benthic habitat on several metrics of ecosystem function. Evaluate the effects of creation of upstream sediment traps paired with downstream bank stabilization and habitat amendments as a type of habitat restoration on ecosystem function. Study was replicated in three adjacent headwater streams.</td>
</tr>
<tr>
<td>Study ID and Reference</td>
<td>Study Purpose Statement</td>
</tr>
<tr>
<td>-----------------------</td>
<td>------------------------</td>
</tr>
<tr>
<td>2016047 Hubbard et al., 2003</td>
<td>Assess the potential water quality improvements and economic impacts associated with streambank stabilization and phosphorus retention.</td>
</tr>
<tr>
<td>2016050 Kasahara and Hill, 2006</td>
<td>Study the effects on hyporheic zone chemistry and nutrient removal for naturally occurring and constructed riffle in lowland streams in southern Ontario. Related study (Kasahara and Hill, 2006) studies the hyporheic exchange and residence time at same sites.</td>
</tr>
<tr>
<td>2016052 Kaushal et al., 2008</td>
<td>Quantify the effects of geomorphic stream restoration on rates of in-situ N removal via denitrification using 15 N-based &quot;push-pull&quot; methods along the riparian-zone-stream interface of a coastal stream. A secondary objective was to investigate the potential importance of the riparian-zone-stream interface as a site for mass removal of nitrate-N by coupling measured in situ denitrification rates with estimates of groundwater flow.</td>
</tr>
<tr>
<td>2016121 McMillan et al., 2014</td>
<td>Assess the influence of restoration approach (e.g., construction of cross-vanes, riffle/pools) and restoration age, specifically riparian vegetation in various stages of maturity on nutrient retention across seasons. To better understand the influence of restoration age and restoration approach, the authors investigated the relationships among age, canopy cover, sediment C, and channel complexity with multiple sites representing ranges of restoration age. Assessed potential to reduce instream NO3-N and PO4-P concentrations by measuring reach-scale retention using the nutrient spiraling approach.</td>
</tr>
<tr>
<td>2016068 Meals, 2001</td>
<td>Quantify effectiveness of livestock exclusion, streambank protection, and riparian restoration practices as tools to reduce sediment, nutrient, and bacteria runoff from agricultural land.</td>
</tr>
<tr>
<td>2016070 Miller et al., 2014</td>
<td>Four major objectives: 1) quantify the amount of streambank erosion and failure throughout the watershed, 2) quantify the magnitude and the intra-site and inter-site spatial variability in streambank soil chemistry, water soluble phosphorus (WSP), and total phosphorus (TP), 3) quantify the load of WSP and TP from streambanks in the watershed, and 4) estimate the benefit of riparian management practices.</td>
</tr>
<tr>
<td>2016078 Orzetti et al., 2010</td>
<td>Evaluate benefits of restored forest riparian buffers along streams in the Chesapeake Bay watershed by examining habitat, selected water quality variables, and benthic macroinvertebrate community metrics in 30 streams with buffers ranging from zero to greater than 50 years of age. Data was pooled from all sites and divided into &quot;young&quot; (&lt;10 years) and &quot;old&quot; (10 years and up) sites for the purpose of analysis and comparison.</td>
</tr>
<tr>
<td>2016086 Richardson et al., 2011</td>
<td>Quantify water quality improvements from a three-phased restoration project within the Duke University stream and wetland assessment management park (SWAMP).</td>
</tr>
<tr>
<td>2016088 Robertson and Merkley, 2009</td>
<td>In-stream bioreactor is used to stimulate nitrate removal in an agricultural drainage ditch. Assessments were made to determine if such an in-stream reactor could maintain desired flow-through characteristics and remain adequately reactive under all seasonal conditions. A simple method (flow regulation using an adjustable-height outlet pipe) was also demonstrated for maximizing nitrate mass removal in the reactor.</td>
</tr>
<tr>
<td>2016120 Tuttle et al., 2014</td>
<td>Purposes: 1) quantify differences in denitrification rates in the vicinity of grade control structures and 2) identify environmental controls on rates of denitrification.</td>
</tr>
<tr>
<td>2016110 Wallace et al., 1995</td>
<td>Evaluate the effect of the addition of coarse woody debris on ecological, physical and nutrient uptake parameters for paired sites at the USFS Coweeta Hydrologic laboratory.</td>
</tr>
<tr>
<td>2016122 Watershed Conservation Resource Center</td>
<td>Implement stream restoration project to protect land, improve aquatic life and terrestrial habitat, and reduce sediment and nutrient loads to the West Fork White River.</td>
</tr>
</tbody>
</table>
3.4.2 Restoration Benefits Documented by Researchers

There are multiple potential benefits of stream restoration. Table 3-4 provides a brief summary of study outcomes, as documented by the original researcher. While most researchers indicate a net benefit to water quality, habitat, and biology, as well as other functional attributes, some researchers noted limited or even negative consequences to the restoration efforts. For example, Doyle et al. (2003) showed dam removal resulted in increased phosphorus concentrations and Fink and Mitsch (2007) found a constructed floodplain expansion was a net source of phosphorus and organic nitrogen during certain times of year. Collins et al. (2013) found that riparian buffers increased dissolved oxygen and reduced turbidity, but had no observable effects on nutrient concentrations. Harrison et al. (2012) and Tuttle et al. (2014) found no difference in denitrification rates between restored and unrestored reaches that included in-stream enhancement features. These studies highlight the variability and uncertainty of stream restoration projects, but also can provide insight into the design features and environmental conditions that lead to a particular outcome. For example, the limited nutrient reduction performance in the Collins et al. study may have been due to narrow buffer widths and discontinuous riparian zones. With more studies in the database, additional analyses may be conducted to better understand the critical factors in stream restoration success. For this reason, it is important to include studies that report both successes and failures and provide adequate metadata to evaluate similarities and differences.
<table>
<thead>
<tr>
<th>Study ID and Reference</th>
<th>Benefits Documented by Researcher</th>
</tr>
</thead>
<tbody>
<tr>
<td>2016005 Baker and Vervier, 2004</td>
<td>Riparian denitrification was higher under intact native riparian forest during spring snowmelt than during baseflow in either a gravel bar or poplar plantation. Denitrification rates were most correlated with low weight dissolved organic acids and percent surface water in subsurface wells.</td>
</tr>
<tr>
<td>2016014 Carline and Walsh, 2007</td>
<td>Riparian buffers (3-4 m) and bank armoring essentially eliminated bank erosion and reduced suspended sediment concentrations 47-87%.</td>
</tr>
<tr>
<td>2016015 Charbonneau and Resh, 1992</td>
<td>Restoration of Strawberry Cr. consisted of small (&lt;45 cm) wood and rock grade control structures and bioengineered bank stabilization. In addition, specific pollutant discharges were addressed by repairing and rerouting parts of the sewage system and an aggressive public education campaign to reduce illegal dumping in storm drains. Upland erosion control measures also reduced gulley erosion and sediment inputs during large storms. Nutrient concentrations were lower post-restoration and significant biological recovery was observed. The stream may be limited in its restoration due to the inability to modify the altered urban hydrology, resulting in continued large and flashy runoff events.</td>
</tr>
<tr>
<td>2016018 Collins et al., 2013</td>
<td>Riparian buffers increased DO and reduced turbidity but had no impact on nutrient concentrations. This can be partially explained by the narrow buffers and the many gaps in the riparian zone.</td>
</tr>
<tr>
<td>2016123 Cottonwood Creek Stabilization</td>
<td>Stabilized channel, reconnected floodplain and improved riparian habitat with reduced phosphorus loading to reservoir. As of 2016, the Cottonwood Creek Stream Reclamation project and the two PRF wetland ponds have been very effective in reducing flow-weighted total TP concentration and total suspended solids (TSS) load to the downstream PRF. Since the completion of the project, the combination of these three PRFs (treatment train approach) has effectively reduced the flow-weighted TP concentration entering the Reservoir, via Cottonwood Creek, from a pre-project WY average of 143 µg/L to a post-project WY average of 78 µg/L, nearly a 46% reduction. The two wetland PRFs have shown mixed results in reducing TN, and the entire treatment train reach has shown an average increase in TN from upstream to downstream by approximately 20% since 2008.</td>
</tr>
<tr>
<td>2016125 Coyote Gulch Channel stabilization efforts successfully reducing nutrient and sediment loading to reservoir. Total phosphorus loading during baseflow conditions before stabilization averaged 20 lbs/year, whereas post-construction loading has ranged from 4.4 to 8 lbs/year. The project withstood the historic September 2013 flood.</td>
<td></td>
</tr>
<tr>
<td>2016023 Doyle et al., 2003</td>
<td>Dam removal may reduce phosphorus retention capacity, leading to an ~40% increase in downstream P concentrations. Changes to channel hydrogeomorphology (i.e. velocity and depth) likely have much less of an effect on uptake and retention than uptake processes. Therefore, restoration should focus on restoring conditions to increase uptake processes rather than simply reducing velocity and depth.</td>
</tr>
<tr>
<td>2016027 Filoso and Palmer, 2011</td>
<td>Generally, restored lowland streams exhibited net N retention during both baseflow and stormflow. This was likely because these streams had low gradients and access to floodplains and wetland complexes. Upland management of N is identified as likely to be more effective for nutrient removal than stream restoration.</td>
</tr>
<tr>
<td>2016028 Fink and Mitsch, 2007</td>
<td>A constructed floodplain wetland is a significant nutrient sink on an annual basis. However, it may be a net source of P and organic N, especially during large summer thunderstorms which are preceded by relatively dry periods.</td>
</tr>
<tr>
<td>2016039 Harrison et al., 2012</td>
<td>Denitrification potential was higher in organic debris dams than in pools, riffles, and sloughs and was higher in forested than urban degraded and urban restored streams. Reach scale nitrification and denitrification rates were similar (157-344 and 97-230 mg N m⁻² d⁻¹) in both restored and degraded sites indicating that cycling between N types is common and these sites can be N sinks.</td>
</tr>
<tr>
<td>2016045 Hines and Hershey, 2011</td>
<td>Restored sites had higher percentage of coarse substrate, lower riparian cover, and higher in-stream temperatures compared to unrestored sites. These factors led to an increase in algal biomass at these sites. Ammonium uptake lengths were significantly shorter in restored reaches. Ammonium concentrations did not differ between sites.</td>
</tr>
<tr>
<td>2016046 Hoellein et al., 2012</td>
<td>Restored sites had slightly higher nutrient uptake rates that were positively correlated with the percent of coarse substrate (gravel, cobble, boulder). This suggests that this coarse substrate provides a stable structure for biofilm development, increasing nutrient demand.</td>
</tr>
<tr>
<td>Study ID and Reference</td>
<td>Benefits Documented by Researcher</td>
</tr>
<tr>
<td>------------------------</td>
<td>----------------------------------</td>
</tr>
<tr>
<td>2016047 Hubbard et al., 2003</td>
<td>Quantification of reductions in sediment and phosphorus loading from a ~2,900 m bank stabilization project (bendway weirs and willow plantings) on Harland Creek using historical photographs to estimate pre-stabilization erosion rates. The estimated value of phosphorus removal/retention was $612/m-yr compared to the $85.11/m cost of the bank stabilization project.</td>
</tr>
<tr>
<td>2016050 Kasahara and Hill, 2006</td>
<td>Hyporheic zone nitrate removal was observed in both constructed and natural riffles. Removal may actually be higher in constructed riffles (as total mass, although removal efficiency is lower) due to steeper slopes and coarser sediment size which creates a larger hyporheic zone (including a larger aerobic zone which is detrimental to denitrification). Clogging due to high watershed sediment inputs may impact hyporheic zone exchange long-term.</td>
</tr>
<tr>
<td>2016052 Kaushal et al., 2008</td>
<td>Restored streams had lower in-stream nitrate concentrations than degraded sites. In general, the restored site with floodplain connection had the highest denitrification rate. Denitrification was positively correlated with groundwater residence time.</td>
</tr>
<tr>
<td>2016121 McMillan et al., 2014</td>
<td>The age of the restoration project controlled nutrient uptake rates. New restoration projects had more labile carbon, lower canopy cover, and higher temperature which was correlated to higher phosphorus uptake. On the other hand, older projects had greater canopy cover, lower temperature, and higher nitrate retention. Channel complexity was also correlated with nutrient uptake.</td>
</tr>
<tr>
<td>2016068 Meals, 2001</td>
<td>Livestock fencing, streambank stabilization, and riparian protection led to reduced P concentrations (-25%) and export (-42%) in a watershed in Vermont.</td>
</tr>
<tr>
<td>2016070 Miller et al., 2014</td>
<td>Miller et al. quantified bank erosion sediment and phosphorus loading on Barren Fork Creek, OK using aerial photo analysis. Erosion rates were significantly lower on sections with a forested riparian buffer compared to unforested sites. Water soluble phosphorus loading from banks accounted for ~10% of total watershed P loading while total P loading exceeded the watershed total, indicating in-stream and floodplain storage of sediment-bound P was occurring.</td>
</tr>
<tr>
<td>2016078 Orzetti et al., 2010</td>
<td>In-stream nitrate concentrations were significantly negatively correlated with buffer age, suggesting that the effectiveness of buffer nutrient removal increases with age. No trends in phosphorus concentrations were observed.</td>
</tr>
<tr>
<td>2016086 Richardson et al., 2011</td>
<td>Prior to restoration, the stream was incised and nutrient concentrations increased through the study reach. After restoration, mean nutrient concentrations decreased through the reach and were significantly lower than pre-restoration. During a storm event, nitrate loads were reduced by 64% and TP loads by 28%. Sediment retention in the wetlands and stormwater pond totaled 500 metric tonnes per year.</td>
</tr>
<tr>
<td>2016088 Robertson and Merkley, 2009</td>
<td>An in-stream bioreactor (woodchip-filled trench in the streambed) was constructed in an agricultural stream with an upstream riffle to encourage hyporheic flow. Mean in-stream nitrate concentrations were attenuated from 4.8 mg/L to 1 mg/L. Mass removal rates were up to 40 times higher than nearby constructed wetlands. The major maintenance constraint is siltation of the infiltration gallery which decreases infiltration rates. Another concern is low oxygen water in the filter effluent which could reduce in-stream oxygen below tolerable levels.</td>
</tr>
<tr>
<td>2016120 Tuttle et al., 2014</td>
<td>Denitrification rates were highly variable and were not statistically significantly different between restored and unrestored reaches. Rates were correlated with nitrate concentration and channel complexity.</td>
</tr>
<tr>
<td>2016110 Wallace et al., 1995</td>
<td>Log installation reduced velocities and greatly increased organic matter storage. Uptake lengths increased for ammonia, decreased for nitrate, and were unchanged for phosphorus.</td>
</tr>
<tr>
<td>2016122 Watershed Conservation Resource Center</td>
<td>The implementation of the West Fork White River stream restoration at Brentwood has proven to be successful in protecting land, improving aquatic and terrestrial habitat, and reducing sediment and nutrients loads to the West Fork White River.</td>
</tr>
</tbody>
</table>
3.5 SRDB 1.0 Quantitative Analysis

As described in Section 3.1, the data available in the SRDB 1.0 is limited. In addition to the small number of studies available for the various types of stream restoration, most of the studies entered only provide summary statistics for a small number of water quality parameters. This reduces the type and level of quantitative analyses possible for this initial data set. The sections below provide comparisons of instream concentrations and loads among and between studies where data are available.

3.5.1 Mean Instream Concentration Comparisons

After initial screening of the various water quality parameters entered into the database, water quality parameters with enough data for initial pollutant concentration summaries included total phosphorus, soluble reactive phosphorus (SRP), total nitrogen, nitrate-nitrite, TSS, and turbidity. Other water quality parameters are also reported in the database, but most are reported for only a few studies; therefore, they are not included in this summary. The majority of the studies entered into the SRDB only provided summary statistics such as annual or study period means and ranges; therefore, the concentration-based summaries selected for this report are based on comparison of mean values reported by various studies. In the future, it may be possible to contact the original researchers to obtain the underlying event-based data supporting these summaries, but this was not feasible within the constraints of this effort. (Two exceptions include the Coyote Gulch and Cottonwood Creek studies in Colorado.)

Figures 3-1 through 3-6 provide simple bar charts of mean annual pollutant concentrations for various studies with control and treatment results paired for each study. Some studies compared control and treatment conditions for multiple streams; in these cases, a black dividing line is provided between the studies. Each study is identified based on its unique study ID, which can be cross-referenced to Table 3-4 (as well as to the SRDB itself). To facilitate presentation of various study designs on the same graph, the following definitions have been applied:

- **Control**: Control may be represented by pre-restoration condition, inflow, or upstream condition.
- **Treatment**: Treatment may be represented by post-restoration condition, outflow or downstream condition.

Additionally, an abbreviation of the stream restoration practice category is included in the site location identifier, as indicated in the footnotes for the graphs (e.g., Fl_rec = floodplain reconnection, Stab = stream stabilization, Multi = multiple restoration practices, Rip = riparian restoration). The years represented by the data set are also indicated in the site name plotted on the graphs. It is important to note that some studies report multiple annual mean results, whereas others only have one or two years of data reported. A limitation of these graphical displays is that the variation in the data is not presented and information is not provided regarding the number and types of sampling events (e.g., baseflow versus stormflow). Hypothesis testing to evaluate statistically significant differences was not conducted. Therefore, the purpose of these graphs is to enable generalized, semi-quantitative observations of the benefits of various practices for various pollutants. Relevant observations include:

- **Overall, concentration reductions are shown for many restoration techniques and pollutants. This affirms the value of continued population of the SRDB to further refine understanding of the magnitude and conditions under which these benefits occur.**
- **The importance of a long-term data set is evident based on observation of year-to-year variation for several studies reporting annual mean data. This is true for both the control and the treatment sites. For example, if only one year of pre-restoration data is available and that year happens to have high**
pollutant concentrations, then the benefits of the stream restoration practice may be overstated (and vice versa).

- For total phosphorus, mean concentrations are presented for five streams for various years (note 2016015_S and 2016015_N are two different streams from the same study). Practices represented in this data set include floodplain reconnection, stream stabilization and a stream with multiple restoration practices implemented. In four of the five streams, annual mean concentrations were lower after stream restoration practices were implemented. The magnitude and relative reduction in total phosphorus varies from site to site and from year to year for studies with multiple years of data.

- For SRP, data are available for various time periods for four streams, with floodplain reconnection implemented for one stream and instream processing enhancements at three other streams within the same study. The floodplain reconnection study shows clear reductions in SRP, whereas the instream processing study sites do not indicate reductions. The available information does not support a determination as to whether the lack of SRP reduction is due to already low observed SRP values in the instream processing studies or whether the practice does not provide benefits.

- For nitrate, thirteen sites have mean annual nitrate concentration available. Based on visual observation of the graphs, four sites suggest nitrate reductions, six sites indicate minimal changes, two sites suggest increases in nitrate, and one has mixed findings, depending on the year. As was the case for soluble reactive phosphorus, the sites with mixed or low results had low nitrate in the control condition. Sites with the most noticeable reductions include floodplain reconnection, instream processing, and some of the stream stabilization locations.

- For total nitrogen, monitoring results for eleven sites are shown on Figure 3-4. Results for ten of the streams suggest reductions in total nitrogen. For study 2016123 (Cottonwood Creek), an increase in total nitrogen is shown during the first phase of stream restoration project, but reductions are evident in the second phase of stream restoration. For study 2016027, closer review of the eight stream site study pairs show that total nitrogen reductions are also present at the two control (CTRL) sites, which suggests that some of the observed changes in total nitrogen are due to natural temporal variations and may not be the result of restoration. Practices shown on this graph include floodplain reconnection, multi-practice restoration and stream stabilization.

- For TSS, only three studies are included in Figure 3-5. All of these studies show reductions in TSS for each year displayed on the graph. The three types of practices shown on the graph are floodplain reconnection, instream processing, and multiple-practice restoration techniques.

- For turbidity, seven stream locations are shown, with lower turbidity observed at five of these locations. Four of the sites are riparian restoration sites, two are stream stabilization sites and one is a control site association with the riparian sites. The sites monitoring turbidity differ from those monitoring total suspended solids. (Turbidity is often used as a surrogate field parameter for TSS.)

- As noted above, when the control or pre-project concentrations were already low, changes or differences in water quality were small or not observed. This has also been observed in the International BMP Database urban stormwater BMP studies. This suggests that there may be “irreducible” concentrations for pollutants that stream restoration techniques cannot further address.
Figure 3-1. Comparison of mean total phosphorus concentrations for SRDB studies.

Notes: Each bar shows the mean concentration for the treatment and related control site. The type of restoration is indicated by the suffix: “Fl_Recon” indicates floodplain reconnection, “Stab” indicates bank stabilization, “Multi” indicates multiple types of restoration. Vertical black lines indicate the division of individual studies.

Figure 3-2. Comparison of mean soluble reactive phosphorus (SRP) concentrations for SRDB studies.

Notes: Each bar shows the mean concentration for the treatment and related control site. The type of restoration is indicated by the suffix: “Fl_Recon” indicates floodplain reconnection, “Stab” indicates bank stabilization, “Multi” indicates multiple types of restoration. Vertical black lines indicate the division of individual studies.
Figure 3-3. Comparison of mean nitrate concentrations for SRDB studies.

Notes: Each bar shows the mean concentration for the treatment and related control site. The type of restoration is indicated by the suffix: “Fl_Recon” indicates floodplain reconnection, “Stab” indicates bank stabilization, “Multi” indicates multiple types of restoration. Vertical black lines indicate the division of individual studies.

Figure 3-4. Comparison of mean total nitrogen concentrations for SRDB studies.
Figure 3-5. Comparison of mean Total suspended solids concentrations for SRDB studies.

Figure 3-6. Comparison of mean turbidity concentrations for SRDB studies.

Notes: Each bar shows the mean concentration for the treatment and related control site. The type of restoration is indicated by the suffix: "Fl_Recon" indicates floodplain reconnection, "Stab" indicates bank stabilization, "Multi" indicates multiple types of restoration. Vertical black lines indicate the division of individual studies.
3.5.2 Mean Annual Load Comparisons

After initial screening of the various water quality parameters entered into the database, water quality parameters with enough data for initial pollutant load summaries were only available from three reports, which are shown in Figures 3-7 through 3-10. Depending on the study, pollutants include total phosphorus, total nitrogen, total Kjeldahl nitrogen (TKN), nitrate, and TSS. For purposes of this initial summary report, simple bar charts are provided to illustrate the observed load reductions reported by the researchers; however, in future summaries, additional characterization of hydrologic conditions is recognized as an important aspect of load comparisons (e.g., higher flows generate higher loads, even when concentration remains constant). General observations for the bar charts created to represent these studies include:

- Study #2016122 presents the results before and after stream restoration on the West Fork White River Brentwood, Arkansas conducted by the Watershed Conservation Research Center. Dramatic load reductions for total nitrogen, total phosphorus and TSS were demonstrated by this stream stabilization project.

- Study #2016068 presents the results for a riparian restoration study in Vermont using a relatively complex study design with control and treatment watershed monitoring during pre- and post-restoration conditions. The data in Figure 3-8 generally show load reductions for TKN and TSS. Reductions for total phosphorus are also suggested; however, variation in the phosphorus concentrations at the control site cause the phosphorus data to be more difficult to interpret. Restoration consisted of livestock exclusion from the stream and riparian area, bioengineered streambank stabilization, and construction of armored livestock stream crossings. The paired watershed design indicated statistically significant reductions in total phosphorus export (-42%) and concentrations (-25%) along with indicator bacteria counts (-46 to -52%) (Meals et al., 2001). Although the data show a decrease in TKN loads post-restoration (Figure 3-8), Meals et al. (2001) were not able to develop statistically significant regression equations using the paired watershed analysis approach.

- Study #20116125 includes results for nitrate and total phosphorus for a stream stabilization study for Coyote Gulch in Colorado using an upstream-downstream and before-and-after monitoring approach for multiple years of monitoring. Figure 3-9 indicates reductions in average monthly nitrate loads relative to the pre-restoration condition for six of seven post-restoration monitoring periods. (Note: Average monthly loads are used in phosphorus credit calculations by the Bear Creek Watershed Association, so the average monthly load for each year is shown in these graphs rather than annual total loads.) These reductions are also evident when evaluated on an upstream-downstream basis in most years. Figure 3-10 indicates dramatic reductions in total phosphorus loading relatively to pre-restoration conditions. Additionally, phosphorus load reductions are present for each of the seven monitoring periods following restoration when upstream-downstream comparisons are made.
Figure 3-7. Total annual pollutant loads at Arkansas stream stabilization site.

Figure 3-8. Median pollutant loads at agricultural restoration site in Vermont.
Figure 3-9. Mean monthly nitrate load at Coyote Gulch stream stabilization site.

Figure 3-10. Mean monthly phosphorus at Coyote Gulch stream stabilization site.
3.6 Case Study: Cottonwood Creek, CO

Several restoration studies from the grey literature entered into the SRDB 1.0 had enough event-based data to conduct more advanced statistical analysis. One of these studies, Cottonwood Creek, was selected to illustrate additional analysis techniques that could be applied to SRDB studies in the future.

Cottonwood Creek is a small tributary that was experiencing accelerated erosion and that flows into a reservoir (Cherry Creek Reservoir) with a nutrient control regulation in place. In 2001, a total maximum annual load (TMAL) for phosphorus was developed for Cherry Creek Reservoir with the goal of reducing nutrient loading to the lake and improving overall water quality. Efforts to reduce phosphorus loading have focused on both point and non-point sources, including watershed tributaries such as Cottonwood Creek.

The Cottonwood Creek watershed (5,500 acres) has been urbanizing since the 1980s, leading to significant channel erosion and subsequent associated sediment and phosphorus loading. Lower portions of the creek had also been relocated to the valley margin, potentially to increase available pasture area when the area was primarily used for agriculture. These issues led to an impaired stream channel with little ecological value. In an effort to reduce channel erosion and the magnitude of phosphorus loading, a series of water quality-focused restoration projects were completed. Initially, two treatment wetlands were constructed, one at the inlet to the reservoir and the other where the creek exits an upstream residential area (completed in 1996 and 2003, respectively). Influent-effluent monitoring suggest these wetland facilities have been effective at reducing total phosphorus concentrations.

Following wetland construction, the channel between these features was slated for restoration. Restoration was completed in two phases (2004 and 2008) and consisted of construction of a completely new channel with greater floodplain connectivity and reduced erosion potential (Figure 3-11). The restored reach was increased in length from 11,600 feet to 14,260 feet, decreasing channel slope and increasing sinuosity. In addition, the active two-year floodplain area was increased from 5.3 acres to over 80 acres, allowing for greater energy dissipation during floods and increased nutrient retention capability. Furthermore, riparian wetland area was increased from 0.5 acres to 20 acres, providing an additional area for phosphorus removal. Pre-restoration calculations predicted this project would reduce phosphorus loading by 730 lb P/yr through a combination of reduced bank erosion and increased nutrient retention in restored floodplain and riparian areas.

Figure 3-11. Cottonwood Creek before (left) and after (right) Restoration.
Photos courtesy of Cherry Creek Basin Water Quality Authority.
Water quality monitoring since 1995 has shown reductions in phosphorus and nitrogen concentrations in Cottonwood Creek where it enters Cherry Creek Reservoir. Trends appear more significant for phosphorus than nitrogen, which may be expected since phosphorus reduction was the primary goal of the restoration project. However, the phased nature of the restoration makes it difficult to compare a pre- and post-restoration condition. Still, the data suggests that stream restoration has improved water quality in Cottonwood Creek, thereby likely resulting in less nutrient loading to Cherry Creek Reservoir.

Because long-term event-based concentration data were provided by the Cherry Creek Basin Authority, this project can be used to illustrate types of statistical analysis that can be conducted for stream restoration studies. Illustrations of these statistics include:

- Table 3-5, which provides basic summary statistics for the stream pre-restoration, after the Phase 1 restoration and after the Phase 2 restoration for total phosphorus, total nitrogen and TSS. The mean and median concentrations pre-restoration are higher than the Phase 2 mean and median concentrations for each analyte.

- Table 3-6 which provides results of Mann-Whitney hypothesis testing with multiple pairwise comparisons using Dunn’s Procedure to determine whether statistically significant differences exist pre- and post-restoration, based on the post-Phase 2 condition. The test results show statistically significant differences between the pre-restoration condition and the post-restoration condition for all three analytes.

- Figure 3-12a, b, and c provide boxplots for total phosphorus, total nitrogen and TSS pre-restoration, after the Phase 1 restoration and after the Phase 2 restoration. These boxplots graphically illustrate and confirm the findings of the hypothesis testing and show the range of concentrations at each location, with pollutant reductions evident following the restoration.

- Figure 3-13a, b, and c provide probability plots for total phosphorus, total nitrogen and TSS pre-restoration, after the Phase 2 restoration. The probability lines are offset, illustrating a shift in the concentrations of pollutants occurring pre- and post-restoration.

- Figure 3-14a and b provide a time series line chart of instream total phosphorus and total nitrogen concentration for baseflow and storm events over time. For phosphorus, these charts indicate that the phosphorus reductions observed over time are most evident in storm-influenced flow conditions. For nitrate, the converse is true, with nitrate reductions over time being most evident during baseflow conditions.
Table 3-5. Selected Summary Statistics for Total Phosphorus, Total Nitrogen, and TSS for Cottonwood Creek

<table>
<thead>
<tr>
<th>Location/Restoration Phase</th>
<th>Nbr.</th>
<th>Minimum</th>
<th>Maximum</th>
<th>1st Quartile</th>
<th>Median</th>
<th>3rd Quartile</th>
<th>Mean</th>
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</tr>
<tr>
<td>TP (ug/L)</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
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<td>10</td>
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</tr>
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<td>CT-1_pre</td>
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<td>948</td>
<td>6189</td>
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<td>31.4</td>
<td>48.4</td>
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</tr>
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</table>

Table 3-6. Cottonwood Creek Mann-Whitney Hypothesis Test Results for Pre-Restoration vs. Post-Restoration

Values in bold [p<0.05] indicate statistically significant differences

<table>
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<tr>
<th>Analyte</th>
<th>p-value (Two-tailed)</th>
<th>Statistically Significant Difference?</th>
</tr>
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<tr>
<td>TN</td>
<td>&lt; 0.0001</td>
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</tr>
<tr>
<td>TSS</td>
<td>0.003</td>
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</table>
Figure 3-12a, b, c. Boxplots comparing total phosphorus, total nitrogen, and TSS concentrations pre- and post-restoration below the restored reach of Cottonwood Creek.
Figure 3-13a, b, c. Probability plots comparing total phosphorus, total nitrogen, and TSS concentrations pre- and post-restoration below the restored reach of Cottonwood Creek.
Figure 3-14a and b. Trends in median annual total phosphorus and total nitrogen concentrations for baseflow and stormflow at the outlet of Cottonwood Creek into Cherry Creek Reservoir. Vertical lines indicate the completion of the two phases of restoration (2004 and 2008). Data from GEI Consultants, Inc. (2016).
CHAPTER 4.0

Conclusions and Research Needs

4.1 Conclusions

Based on the initial release of the SRDB, the following conclusions can be drawn regarding stream restoration practices and the database itself.

1. The SRDB provides a framework for consistently reporting information useful for evaluating the water quality benefits of various stream restoration practices. To date, water quality parameters with the most monitoring data available are sediment and nutrients. Practices with the most well-developed data sets, although still limited, included bed and bank stabilization, riparian buffers, instream enhancement, and floodplain reconnection.

2. The empirical basis for stream restoration as a water quality BMP is improving, but additional field monitoring studies that meet the SRDB reporting protocols are needed, especially for regions and stream types that are poorly represented in the literature. Similarly, some practices have stronger empirical basis than others, and some practices have inherently higher functional capacity for nutrient reductions than others. Currently, the relative magnitude of benefits is also more certain than the absolute magnitude of the benefits.

3. The studies available indicate that stream restoration can provide water quality improvement, but significantly more data are needed to assess which practices are most effective and under which conditions. Water quality data are highly variable between the studies and from year-to-year or season-to-season within the same study. This variability presents a challenge when attempting to detect a statistically significant change in concentrations and loads for an individual study or a group of studies of the same practice. Generally, larger reductions in sediment and nutrients can be expected for restoration projects completed within streams with elevated concentrations.

4. The SRDB 1.0 has significant data gaps, particularly with regard to individual event data and study metadata. These gaps are due to the fact that the primary data sources were peer-reviewed journal articles, which typically only report partial data sets and summary statistics. While the database can accept summary statistics, the underlying datasets are ultimately more useful for conducting independent analyses of stream restoration practices.

5. Even with more data in the SRDB, analytical challenges will remain due to differences in monitoring study designs. For example, some monitoring studies sample upstream and downstream of a restoration project, while others compare post-restoration to pre-restoration or to a control or reference stream. More complex monitoring designs include all of the above to capture both temporal and spatial variations in water quality. These differences make it difficult to automate the summary and analysis of stream restoration performance data.

6. While there is substantial guidance available for monitoring surface waters, there is limited practical guidance available for monitoring the water quality performance of stream restoration projects. Recent guidance on assessing stream restoration projects has focused on functional approaches (e.g., Harman et al., 2012; Davis et al., 2014). Such assessments are much needed and include measurement of physicochemical parameters, such as temperature, dissolved oxygen, and nutrients; however, the monitoring guidance is somewhat general. Additional guidance is needed on monitoring design, monitoring equipment, use of sensors, and selection of locations, parameters,
and sample frequencies as they relate to factors such as seasonality, flow variability, stream type, surface-groundwater interactions, and riparian condition.

7. As the SRDB grows, there will be greater options for analyzing and utilizing the data. For example, with larger water quality datasets for each restoration practice type, the practices with the highest potential for improving water quality could be assessed statistically. Hypothesis tests on paired and unpaired datasets could be completed to make determinations of statistically significant differences in pollutant concentrations and loads. Meta analyses that consider design attributes, geomorphological parameters, and hydro-physiographic region may also be possible with a more robust data set.

8. Most of the studies entered in SRDB 1.0 did not meet the complete set of requested information in the Stream Restoration Database User’s Guide. Going forward, studies that report original sampling event data and more complete metadata should be targeted. As future studies are considered for entry into the SRDB, highest priority should be placed on entering studies that have long-term, event-based data, which may require additional correspondence with the original researcher and/or utilization of more grey literature studies, which tend to provide more detail than condensed journal articles. Other sources, including permit-required, alternative compliance mitigation reports, may also be important sources of data on restoration performance.

9. Direct measurement of the water quality benefits of stream restoration is very challenging. For this reason, monitoring approaches that incorporate surrogate (proxy) measures are also an important aspect of evaluating the benefits of stream restoration practices. Functional assessment approaches and rapid assessment indicators of stream restoration functions greatly simplify monitoring and reduce costs. However, they do not provide data to substantiate quantitative water quality performance.

4.2 Research Needs

Although the empirical evidence of stream restoration’s potential to increase nutrient processing, assimilation, retention, and, potentially, permanent removal (e.g., denitrification) has increased recently, significant uncertainties remain that would benefit from additional research. Areas of future research for each restoration technique are described below, as stated in the companion report to this project Stream Restoration as a BMP: Crediting Guidance (Bledsoe et al., 2016).

1. **Bed and Bank Stabilization**: The largest sources of uncertainty are variable bank phosphorus content and channel response potential. In addition, bank nitrogen concentrations are rarely quantified so it is difficult to assess bank erosion’s potential as a nitrogen source. Future research should examine both phosphorus and nitrogen concentrations in a variety of locations and soil types to provide more generalized information. Additionally, more effort is needed to develop simple yet robust methods and models for estimating channel response potential that have fewer data requirements than existing models.

2. **Riparian Buffers**: The empirical basis for the benefits of riparian buffers is strongest for nitrate removal and removal of sediment and particulate phosphorus in surface runoff. However, research is needed to improve nutrient removal quantification methods for both surface and subsurface flow. In addition, linkages between buffers and in-stream water quality deserve additional attention.

3. **In-Stream Enhancement**: Empirical evidence for enhanced hyporheic nutrient processing is mostly at the scale of a single in-stream structure at a single baseflow discharge. Better understanding of the reach-scale influence of increased geomorphic complexity and flow variability is needed. In
addition, the variability of organic carbon fluxes to a stream and its effects on nutrient dynamics deserves further attention.

4. **Floodplain Reconnection**: Conceptually, the nutrient-related benefits of floodplain reconnection are clear. However, there have been only limited studies demonstrating significant nutrient retention in restored floodplains. Future research should focus on quantifying restoration effectiveness in a variety of geomorphic regions that differ in terms of frequency and seasonality of overbank flows, among other factors.

5. **Other Restoration Practices**: There is a lack of information on how other restoration practices (e.g., dam removal or channel reconfiguration) affect nutrient and sediment processing and removal. Additionally, more research into the cumulative and interactive effects of all restoration practices, in conjunction with more watershed-based approaches like stormwater controls and land use management, is essential for understanding these complex systems. Specifically, the impacts of upland stormwater controls on the performance and permanence of in-stream restoration projects deserves further attention. Finally, long-term monitoring is necessary to determine restoration performance over time, especially under changing land use.

6. In addition to practice-specific research needs, general research needs include:
   a. A general need for improving the empirical basis for crediting approaches across regions and stream types poorly represented in the literature (e.g., U.S. southwest and northeast; ephemeral, intermittent, and braided channels) through: 1) consistent data collection methods, 2) stratification by region and stream hydrogeomorphic type, and 3) better accounting for natural variability associated with seasonality, flow regimes, and extreme events. (These research needs are particularly relevant for floodplain reconnection and hyporheic exchange.) Collected empirical data should also be used to help improve modeling of the impact of stream restoration on nutrient dynamics, as this may be a necessary approach for projects with limited monitoring.
   b. There is a need for regional functional assessment procedures for streams to show implementation of a functional design, functions persisting over time, and to provide a benchmark for assigning quantitative nutrient reduction benefits. In addition, development of rapid assessment indicators deserves further attention.
   c. There is a need to combine both physically based models and statistical approaches into probabilistic and Bayesian network models that facilitate explicit quantification of uncertainty (Stein and Bledsoe, 2013), similar to previous applications for biological integrity of streams (Kashuba et al., 2012).
   d. Future research focused on techniques for accelerating the establishment of denitrification functions is also needed. For example, additions of carbon sources such as sawdust to streambanks, riparian zones, or in-stream features may have the potential to help “jump start” biogeochemical cycling and reduce time lags in functional performance. However, the feasibility and effectiveness of such techniques have not been well documented to date.
   e. Streams have some upper limit on nutrient removal and retention, limiting their ability to serve as nutrient sinks. While nutrient saturation in stream systems has received some attention (e.g., Earl et al., 2006), it is important to quantify this saturation point for various stream types and regions as this would serve as an upper limit on nutrient reduction benefits for stream restoration projects.
The Stream Restoration BMP Database Module is available for download by the public in Microsoft Access 2013 (which is backward compatible with Access 2010). Data entry and upload are accomplished through entry of data into an Excel 2013 Workbook, which can be uploaded to the master database in Access. Web-based tools may be developed in the future using an SQL version of the database.

This appendix outlines the major tables and data elements in the Microsoft Excel spreadsheets that comprise the database. For purposes of this Appendix, the data elements are provided in a vertical list, but data entry will occur in a horizontal manner (i.e., data elements will be column headers consistent with a standard database format).

### Simplified Database Structure and Overview of Spreadsheets for Data Entry

![Diagram of database structure](image)

**Data Priorities:**
The data entry spreadsheets request a significant amount of information. Most studies will not have all of the requested data. Data entry should be completed for all "Required" fields, at a minimum. "Important" data are needed to maximize the usefulness of the study and should be entered when such data are available. "Supplemental" data are of interest to many researchers; however, missing supplemental data would not limit the general use of study findings.

- **R** = Required
- **I** = Important
- **S** = Supplemental

**Data Types:**
When data elements are created in Access, a Data Type must be specified. All data entered into the spreadsheets must comply with validation rules associated with the data type (i.e., text cannot be entered into a number field). The most common data types include:

- Text or Short Text (< 255 words)
- Long Text (previously called "memo" in Access)
- Date/Time
- Number (additional validation may include integer, decimal, percentage, etc.)
- Autonumber (e.g., simply a record number assigned when the record is uploaded)
- Currency
- Yes/No

"Picklist" is shown when the user must select an entry type from a mandatory picklist.
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<th>Priority Level</th>
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</table>

(1) Note: Yes/No questions must be answered ("Required"), even if information is not provided.

**Supplemental Description of Terms:**

Network - multiple segments of stream with intervening tributaries.
Segment - multiple reaches of stream between two tributaries.
Reach - stream length of 10-20 annual flood top widths with relatively homogeneous stream type.
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<th>Data Element</th>
<th>Data Type</th>
<th>Entry Options/Notes</th>
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<td>Drainage Area ( hectares )</td>
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<td>Hydraulically Connected Watershed Imperviousness (%)</td>
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**Identify Stream Condition Being Characterized:**

- **Stream Condition Type**: Picklist  
  See Note 1 for picklist.  
  R

- **Describe Channel Evolution Stage**: Text  
  See Note 2. Use key words to describe stage of channel evolution, which is important for anticipating benefits gained from stream restoration.  
  I

**Valley Setting**

- **Valley Slope (%)**: Short Text  
  This will allow calculation of sinuosity  
  I

- **Lateral constraint (Describe)**: Short Text  
  Describe degree of hillslope coupling, planform confinement  
  I

- **Valley type (Describe)**: Short Text  
  Describe valley type - e.g., open floodplain, canyon, gorge, glacial, fan, delta  
  I

**Channel Geometry/Condition:**

- **Channel Type (Describe)**: Short Text  
  See Note 3 e.g., alluvial vs. non-alluvial, single thread vs. multi-thread, and preferred classification (e.g., Church, Montgomery and Buffington, Roaen, etc.), channel evolution stage (Schumm et al., Booth and Fischenich, etc.).  
  I

- **Bedforms (Describe)**: Short Text  
  e.g., cascade, step-pool, plane bed, pool-riffle, dune-ripple, other  
  I

- **Planform (Describe)**: Short Text  
  e.g., straight, meandering, braided, anastomosing, other  
  I

- **Return Period that Reaches Floodplain (yr)**: Number  
  Provide measurement guidance in User’s Guide.  
  I

- **Average Bank Height (m)**: Number  
  Provide measurement guidance in User’s Guide.  
  I

- **Average Bank Angle (%)**: Number  
  Provide measurement guidance in User’s Guide.  
  I

- **Effective Channel Slope (%)**: Number  
  Provide measurement guidance in User’s Guide.  
  I

- **Average Channel Width (m)**: Number  
  Provide measurement guidance in User’s Guide.  
  I

- **Average Channel Depth (m)**: Number  
  Provide measurement guidance in User’s Guide.  
  I

- **Channel Geometry/Condition Comments**: Short Text  
  Allows narrative description of channel geometry/condition.  
  S

**Flow Regime:**

- **Type**: Picklist  
  Perennial, Intermittent, Ephemeral  
  R

- **Primary Hydrologic Source**: Picklist  
  Rain, Rain+Snowmelt, Snowmelt, Groundwater, Reservoir Release, Effluent, Multiple  
  I

**Flow Regime Estimates:**

- **Dominant Discharge Type**: Picklist  
  bankfull, effective, half-load discharge, other  
  I

- **Dominant Discharge (m3/sec)**: Number  
  I

**Flow Estimates:**

- **1.3-yr Flow (m3/sec)**: Number  
  I

- **1.5-yr Flow (m3/sec)**: Number  
  I

- **2-yr Flow (m3/sec)**: Number  
  I

- **5-yr Flow (m3/sec)**: Number  
  I

- **10-yr Flow (m3/sec)**: Number  
  I

- **50-yr Flow (m3/sec)**: Number  
  I

- **25-yr Flow (m3/sec)**: Number  
  I

- **100-yr Flow (m3/sec)**: Number  
  I

- **Design Storm Duration (hrs) (if flow estimates are from Event-Based Modeled)**: Number  
  I

**Bank Materials—Toe:**

- **Bank Materials (Describe)**: Short Text  
  Briefly describe bank layering/stratigraphy, distinguishing between toe and rest of bank  
  R

- **Soil Bulk Density (g/cm3)**: Number  
  S

- **Consolidation**: Picklist  
  Moderately- or well-consolidated, poorly or unconsolidated fine, poorly or unconsolidated coarse  
  R

**Gravitation of Bank Materials:**

- **% clay**: Number  
  S

- **% silt**: Number  
  S

- **% sand**: Number  
  S

- **% gravel**: Number  
  S

- **% other mineral**: Number  
  S

- **% organic matter**: Number  
  S

- **Bank P Content (mg/kg)**: Number  
  S

- **Bank N Content (mg/kg)**: Number  
  S

**Describe Methods for Bank Content Analysis**: Short Text  
Laboratory methods used for measuring P&N bank content.  
S

**Bank Materials—Dominant Materials above Toe and below the 2 yr Discharge Stage:**

- **Bank Materials (Describe)**: Short Text  
  Briefly describe bank layering/stratigraphy, distinguishing between toe and rest of bank  
  R

- **Soil Bulk Density (g/cm3)**: Number  
  S

- **Consolidation**: Picklist  
  Moderately- or well-consolidated, poorly or unconsolidated fine, poorly or unconsolidated coarse  
  R
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<thead>
<tr>
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<th>Data Type</th>
<th>Entry Options/Notes</th>
<th>Priority Level</th>
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<td>Gradation of Bank Materials:</td>
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<tr>
<td>% clay</td>
<td>Number</td>
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<tr>
<td>% silt</td>
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<td></td>
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<td>% sand</td>
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<td>% gravel</td>
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<td>$</td>
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<tr>
<td>% other mineral</td>
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<td></td>
<td>$</td>
</tr>
<tr>
<td>% organic matter</td>
<td>Number</td>
<td></td>
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<tr>
<td>Bank P Content (mg/kg)</td>
<td>Number</td>
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<tr>
<td>Bank N Content (mg/kg)</td>
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<td>Describe Methods for Bank Content Analysis</td>
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<td>Bed Materials:</td>
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<td>Gradation of Surficial Bed Materials:</td>
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<td>D10 (mm)</td>
<td>Number</td>
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<tr>
<td>D16 (mm)</td>
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<tr>
<td>D50 (mm)</td>
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<td>D84 (mm)</td>
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<tr>
<td>D90 (mm)</td>
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<tr>
<td>Fines included or truncated in D estimates?</td>
<td>Yes/No</td>
<td></td>
<td>$</td>
</tr>
<tr>
<td>% Bed surface area that is exposed hardpan or bedrock</td>
<td>Number</td>
<td></td>
<td>$</td>
</tr>
<tr>
<td>% Bed surface area covered in fines &lt; 2 mm</td>
<td>Number</td>
<td></td>
<td>$</td>
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<tr>
<td>Ratio of D50 Surface Pavement to D50 of Subpavement in Coarse Grained Beds</td>
<td>Number</td>
<td>To characterize bed armorning.</td>
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<td>Vegetation Types:</td>
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<tr>
<td>Floodplain Vegetation Condition</td>
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<td>General Vegetation Type</td>
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<td>forest, herbaceous (native), herbaceous (urban manicured), herbaceous (cultivated), other</td>
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<tr>
<td>% Canopy Closure</td>
<td>Number</td>
<td></td>
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</tr>
<tr>
<td>% Native Vegetation Intact</td>
<td>Number</td>
<td></td>
<td>$</td>
</tr>
<tr>
<td>% Invasive Species</td>
<td>Number</td>
<td></td>
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<td>Describe Vegetation Types</td>
<td>Short Text</td>
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<td>Describe Methods for Vegetation Assessment</td>
<td>Short Text</td>
<td>List methods used to characterize</td>
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<td>Comments</td>
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Notes:

(1) Stream Condition Type Picklist:
- Pre-Development (Reference)
- Pre-Development (Agriculture)
- Pre-Restoration (Urban)
- Pre-Restoration (Agriculture)
- Pre-Restoration (Other)
- Post-Restoration (1 yr)
- Post-Restoration (2 yr)
- Post-Restoration (3 yr)
- Post-Restoration (4 yr)
- Post-Restoration (5 yr)
- Post-Restoration (10 yr)
- Post-Restoration (15 yr)
- Post-Restoration (20 yr)
- Post-Restoration (other)

(2) Stream Response Potential: Use key words such as those included in diagram below, or regionally specific comparable diagrams.

![Diagram of Stream Response Potential](image)

(3) Describe dominant stream characteristics - Alluvial vs. non-alluvial, single thread vs. multi-thread, preferred classification (e.g., Church, Montgomery and Buffington, Roegan, etc.), and channel evolution stage (Schumm et al., Booth and Fischensk, etc.). Additional guidance to be provided in User's Guide for this data element.
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<tr>
<th>Data Element</th>
<th>Data Type</th>
<th>Entry Options/Notes</th>
<th>Priority Level</th>
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<tr>
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<tr>
<td>Stream_ID</td>
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<td>Selected from dropdown by user.</td>
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</tr>
<tr>
<td>Design_ID</td>
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<td>Autopopulated in spreadsheet (13-digit number = watershed ID plus two digits)</td>
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<tr>
<td>Stream Restoration Practice Type</td>
<td>Picklist</td>
<td>See Note 1.</td>
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</tr>
<tr>
<td>Channel Length Restored (m)</td>
<td>Number</td>
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</tr>
<tr>
<td>Riparian Width Restored (m)</td>
<td>Number</td>
<td>I</td>
<td>I</td>
</tr>
<tr>
<td>Reference/Guidance for Design</td>
<td>Short Text</td>
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</tr>
<tr>
<td>Design Approach</td>
<td>Picklist</td>
<td>Picklist to be developed. e.g., reference, shear stress, sediment continuity</td>
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<tr>
<td>Fluxes Managed</td>
<td>Short Text</td>
<td>Describe fluxes managed: e.g., water, sediment, wood, other organic matter, nutrients, heat</td>
<td>R</td>
</tr>
<tr>
<td>Describe Goals of Restoration Design</td>
<td>Long Text</td>
<td>Enables additional discussion regarding targeted outcomes, building upon fluxes managed.</td>
<td>I</td>
</tr>
<tr>
<td>Describe Measures Implemented to Achieve Benefits:</td>
<td></td>
<td>Describe practices implemented. e.g., barbs, vanes, bendway weirs, spur dikes, soil bioengineering, toe wood, log jams, rock walls, riprap</td>
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</tr>
<tr>
<td>Bank Stabilization Measures</td>
<td>Long Text</td>
<td>Describe practices implemented. e.g., grade control, vanes, weirs, drops</td>
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</tr>
<tr>
<td>Bed Stabilization Measures</td>
<td>Long Text</td>
<td>Describe practices implemented.</td>
<td>R</td>
</tr>
<tr>
<td>Riparian Condition/Buffer Reestablishment</td>
<td>Long Text</td>
<td>Describe practices implemented. Enter none or unknown if information not available.</td>
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<tr>
<td>Floodplain Connectivity/Reconfiguration</td>
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<td>Describe practices implemented. Enter none or unknown if information not available.</td>
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<tr>
<td>Habitat Enhancement/Instream Features</td>
<td>Long Text</td>
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<tr>
<td>Channel Reconfiguration/Planform Changes</td>
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<td>Describe practices implemented. Enter none or unknown if information not available.</td>
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<tr>
<td>Barrier Removal/Fish Passage</td>
<td>Long Text</td>
<td>Describe practices implemented.</td>
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</tr>
<tr>
<td>Other Approaches</td>
<td>Long Text</td>
<td>Describe practices implemented (e.g., fencing, beaver management). Enter none or unknown if information not available.</td>
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</tr>
<tr>
<td>Design Return Period(s) (yr)</td>
<td>Short Text</td>
<td>Describe design return period(s).</td>
<td>S</td>
</tr>
<tr>
<td>Operation, Maintenance and Replacement Description/Frequencies</td>
<td>Long Text</td>
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</tr>
<tr>
<td>Expected Stabilization/Establishment Period (months)</td>
<td>Number</td>
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<tr>
<td>Expected Response Time (range of yrs)</td>
<td>Text</td>
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<tr>
<td>Expected Design Life (range of years)</td>
<td>Text</td>
<td>Longevity of practices will vary depending on the design and other factors. Include basis of calculation or estimate.</td>
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</tr>
<tr>
<td>Comments</td>
<td>Long Text</td>
<td></td>
<td>S</td>
</tr>
</tbody>
</table>

**Practice Design Notes:**

Note 1: Picklist for Stream Restoration Practice Type (general)
Redirective Practice
Resistive Practice
Grade Control
Flow Control
Riparian Condition/Buffer Reestablishment
Floodplain Connectivity/Reconfiguration
Habitat Enhancement/Instream Features
Channel Reconfiguration/Planform Changes
Barrier Removal/Fish Passage
Passive Approaches (e.g., fencing, beaver reintroduction)
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<thead>
<tr>
<th>Data Element</th>
<th>Data Type</th>
<th>Entry Options/Notes</th>
<th>Priority Level</th>
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<tr>
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<tr>
<td>MS_ID</td>
<td>Number</td>
<td>Autopopulated in spreadsheet</td>
<td>R</td>
</tr>
<tr>
<td>Monitoring Station Name</td>
<td>Short Text</td>
<td>Multiple monitoring station records (rows) can be added in this table. User-defined monitoring station name (or monitoring unit name), e.g., Up-1, Down-1, Reach-1, Reach-2. If same location is monitored over a phased implementation period for major improvements, create a new monitoring station ID for new major phases so that data are not comingled.</td>
<td>R</td>
</tr>
<tr>
<td>Monitoring Station Type</td>
<td>Picklist</td>
<td>Picklist to be developed. e.g., pre-restoration, post-restoration, upstream, downstream, reference/control, other.</td>
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</tr>
<tr>
<td>Decimal Latitude</td>
<td>Number</td>
<td></td>
<td>I</td>
</tr>
<tr>
<td>Decimal Longitude</td>
<td>Number</td>
<td></td>
<td>I</td>
</tr>
<tr>
<td>Additional Spatial Information</td>
<td>Short Text</td>
<td>Monitoring station distance from project (approximate).</td>
<td>I</td>
</tr>
<tr>
<td>Major Influences during Monitoring Period</td>
<td>Short Text</td>
<td>e.g., large storms, drought, forest fire, etc.</td>
<td>I</td>
</tr>
<tr>
<td>Describe Protocol(s) Followed</td>
<td>Short Text</td>
<td>e.g., USGS Techniques of Water-Resources Investigations, Rapid Bioassessment Protocol (Barbour et al. 1999), others. Note: specific laboratory methods are requested for each chemical result in Monitoring Chem.</td>
<td>I</td>
</tr>
<tr>
<td>Describe Equipment/Instrumentation</td>
<td>Short Text</td>
<td>e.g., ISCO automated sampler, bedload sampler</td>
<td>I</td>
</tr>
<tr>
<td>Describe Calculation Methods</td>
<td>Short Text</td>
<td>Most applicable for &quot;physical&quot; monitoring data.</td>
<td>I</td>
</tr>
<tr>
<td>Comments</td>
<td>Short Text</td>
<td>s</td>
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</tr>
<tr>
<td>Data Types Collected at Monitoring Station:</td>
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<tr>
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<tr>
<td>Hydrologic/Hydraulic</td>
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<td>Biologic</td>
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<tr>
<td>Physical</td>
<td>Yes/No</td>
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Note: User-assigned narrative names for test site, watershed, stream and design may be "carried" in this table in addition to numeric IDs to improve user friendliness for inexperienced database users.
### Monitoring Events

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<td>Monitoring Event Period</td>
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<td>General Monitoring Date(s)</td>
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<td>General date description or period monitored in text format.</td>
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<td>Start Date</td>
<td>Date/Time</td>
<td>Applies to a series of individual sample dates.</td>
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<tr>
<td>End Date</td>
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<tr>
<td>Start Time</td>
<td>Date/Time</td>
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<tr>
<td>End Time</td>
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<td>Chemical Data (Y/N)</td>
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<td>Water quality data.</td>
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<tr>
<td>Hydrologic Data (Y/N)</td>
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<td>Hydrologic data include precipitation, flow, groundwater, etc. Ideally flow data will be provided with water quality samples.</td>
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<tr>
<td>Biological Data (Y/N)</td>
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<td>Biological data (e.g., fish, macroinvertebrates).</td>
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<td>Physical Data (Y/N)</td>
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<td>Other</td>
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<td>Flow Condition</td>
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<td>Picklist to be developed (e.g., total, average, etc.)</td>
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<td>Result</td>
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<td>Results may be concentrations and/or mass (loads), or other.</td>
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<td>Units</td>
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<td>Picklist to be developed. e.g., kg/yr, mg/L</td>
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<td>Characteristic Monitored</td>
<td>Picklist</td>
<td>Picklist to be developed. e.g., Depth, Volume, Flow Rate, Velocity, Percent Saturation, Shear Stress, Stream Power, Other</td>
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<td>Short Text</td>
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## Monitoring_Bio

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   - Monitoring

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Stream Restoration Database

Version 1.0
APPENDIX B

STREAM RESTORATION AS A NUTRIENT BMP – A REVIEW

Prepared by

Roderick Lammers, Colorado State University

October 30, 2015
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1.0 Introduction

Eutrophication of aquatic systems – excessive nutrient concentrations and subsequent accelerated primary production – is a pressing water quality problem in the U.S. and around the world (Smith et al., 1999). Certain nutrients, commonly nitrogen and phosphorus, required for plant and animal growth are often limiting in these ecosystems (Elser et al., 2007), meaning that small increases in the availability of one or both of these compounds can lead to large increases in biomass. Although necessary for proper ecological function, excessive nitrogen and/or phosphorus can lead to large algal blooms that are an increasingly common sight in coastal environments and the Great Lakes. This increase in primary productivity can lead to oxygen depletion potentially lethal to aquatic life (as algal blooms decompose) and the production of harmful toxins by certain algae species. Eutrophication significantly degrades water quality, harming aquatic life and beneficial human use of water resources. According to the EPA, nutrient pollution is the third largest source of water quality impairment in rivers and streams and the second largest for lakes, ponds, and reservoirs (EPA, 2015). Significant effort has focused on improving water quality by reducing nutrient loading to streams from upland sources. However, in-stream nutrient removal and retention may be significant (e.g. Peterson et al., 2001), leading to the suggestion that enhancing this natural removal and sequestration mechanism may be a viable strategy to improve water quality. Stream restoration is a booming business in the U.S. (>$1 billion per year industry; Bernhardt et al., 2005), and the majority of these projects state water quality improvement as one of their objectives (Bernhardt et al., 2005). However, there is a limited set of studies that examine the efficacy of stream restoration in general and even fewer that focus specifically on nutrient removal, processing and retention. The purpose of this literature review is to synthesize existing knowledge on stream restoration as a strategy for reducing nutrient loads and concentrations in aquatic systems. By aquatic system we mean the stream, floodplain and riparian area, and hyporheic zone (defined later).

2.0 Background

Water bodies are generally considered nitrogen or phosphorus limited, meaning that limited availability of one of these nutrients constrains increased primary production. However, there is no generally applicable trend on whether a type of water body is nitrogen or phosphorus limited (Elser et al., 2007); nutrient limitation instead depends on site-specific conditions. Therefore, understanding dynamics of both nutrients is important when assessing water quality impacts of stream restoration. This section provides background information on nitrogen and phosphorus including sources, bioavailability, processing, and transport in stream ecosystems.

2.1 Nitrogen

Nitrogen, like phosphorus, can be a limiting nutrient in aquatic ecosystems and is therefore a major concern for nutrient managers. Sources of nitrogen include urban wastewater effluent, septic systems, agricultural, industrial and urban stormwater runoff, natural sources (e.g. organic material decomposition) and atmospheric deposition. Most notably, combustion of fossil fuels and production and application of fertilizer have greatly increased the amount and mobility of nitrogen worldwide (Vitousek et al., 1997). Nitrogen occurs in organic form and in various inorganic forms including
ammonium \((\text{NH}_4^+)\) and nitrate \((\text{NO}_3^-)\). In natural systems, nitrogen cycles between these dominant forms through plant uptake, organic material decomposition, mineralization, and microbially-mediated nitrification (formation of nitrate from ammonia) and denitrification (conversion of nitrate into nitrogen gas). Nitrate is the most soluble form of nitrogen and is therefore commonly found in groundwater and streamwater. Ammonium is also often present in streams, although it tends to have a higher adsorption potential and often experiences rapid uptake or is quickly nitrified into nitrate (Peterson et al., 2001). Although these inorganic forms of nitrogen are often the focus of nutrient studies (likely because they are the most soluble and bioavailable), organic nitrogen may be dominant in many streams (Scott et al., 2007).

One of the primary processes of nitrogen removal from a system is denitrification. Denitrification is the anaerobic reduction of nitrate by heterotrophic bacteria under anoxic conditions, leading to the production of \(\text{N}_2\) or \(\text{N}_2\text{O}\) gas (Hill, 1996), which can then be released to the atmosphere. Denitrification thus completely removes nitrate from a system, whereas biotic assimilation merely changes the availability of the nitrogen and it may be released to the system at a later time. Rates of denitrification are expected to be highest under saturated conditions (providing both a source of nitrate and anoxic conditions) and when organic carbon availability is high (to serve as an energy source). However, denitrification is rarely a constant process. High rates of denitrification may occur in discrete locations (“hot spots”) and at discrete points in time (“hot moments”) when conditions are right (McClain et al., 2003). Nitrate may also be reduced to ammonium (dissimilatory nitrate reduction to ammonium, DNRA; Tiedje, 1988), a process which may be more common than previously recognized in streams (Burgin and Hamilton, 2007). DNRA is a fermentative process that occurs under similar conditions as denitrification (anoxia, availability of nitrate and organic carbon), but DNRA may be favored in high carbon, nitrate-limited environments while denitrification occurs under carbon-limited conditions (Burgin and Hamilton, 2007). Nitrification is the biotic oxidation of ammonium to nitrate (via the intermediary nitrite, \(\text{NO}_2^-\)). This process requires oxygen, therefore it typically does not occur in the same locations as denitrification (Ward, 2003). However, small-scale variation in oxygen availability are possible, allowing nitrification and denitrification to occur nearly simultaneously (e.g. Zarnetske et al., 2011). Nitrogen cycling and transformation is a complex issue with numerous biotic and abiotic controls. Most studies focus on net nitrogen uptake or removal from the water column (but not necessarily from the stream system), although some more sophisticated isotope tracer experiments have succeeded in quantifying total nitrate loss via denitrification (e.g. Mulholland et al., 2008).

2.2 Phosphorus

Phosphorus is naturally found in soils worldwide, although the abundance and chemical composition is associated with a number of factors including soil texture, \(\text{pH}\), metals concentrations, and the geology of the soil parent material (Brady and Weil, 2002). Total phosphorus content of streambanks and riparian soils is also correlated with these factors (Palmer-Felgate et al., 2009), although the silt-clay content may be the largest driver in some catchments (Agudelo et al., 2011; Bledsoe et al., 2000; Cooper and Gilliam, 1987; Young et al., 2013, 2012), but not others (Hongthanat, 2010; Howe et al., 2011; Kerr et al., 2011; Schilling et al., 2009; Veihe et al., 2011). Streambank phosphorus concentrations may also be higher in intensively farmed catchments (Palmer-Felgate et al., 2009) or in deforested areas (Haggard et al.,
Anthropogenic impacts have altered the global phosphorus cycle, primarily through the mining of phosphorus-bearing rock to meet the increasing demand for agricultural fertilizer. Cropland fertilizer application has in some cases led to the ongoing accumulation of phosphorus in soils, where it can become a potential source of water pollution (Carpenter et al., 1998; Smith et al., 1999).

Sources of phosphorus are generally similar to nitrogen, although atmospheric deposition is not as significant. Numerous efforts have been made to identify and quantify the various sources of phosphorus pollution in watersheds (e.g. DeWolfe et al., 2004; Kronvang et al., 1997; Sharpley and Syers, 1979). Recent evidence has made it increasingly clear that bank and bed erosion may be a significant source of particulate phosphorus loading to streams, accounting for between 10% (Sekely et al., 2002) and 40% (Howe et al., 2011) of the total phosphorus load in an individual watershed. However, sediment and phosphorus loading is only part of the picture. In-channel and overbank storage of eroded material can be an important control on downstream transport and the ecological effect of the introduced nutrients (Kronvang et al., 2013, 2007). Additionally, geomorphic complexity influences nutrient transport and cycling, primarily by impacting residence time and transient storage which has important implications for biochemical transformation and uptake (Ensign and Doyle, 2006).

The chemical partitioning of phosphorus is also important to understanding its transport. Phosphorus species are relatively insoluble and are typically found adsorbed to soil particles. They have a high affinity for the larger specific surface area of clay and silt particles and are also found bound in various metal oxyhydroxides including Fe-OH, Al-OH, and Ca-OH (Brady and Weil, 2002). Phosphorus may be found in inorganic (typically phosphate, $\text{PO}_4^{3-}$) or organic form. The partitioning of phosphorus among its various states determines its bioavailability for uptake by organisms, which is directly tied to its importance as a limiting nutrient. The relative abundance of bioavailable phosphorus in sediment has been shown to vary markedly within single study sites (1-55%; Veihe et al., 2011) and between study areas (averaging 0.5-22% of total phosphorus; Nellesen et al., 2011; Howe et al., 2011; Hubbard et al., 2003; McDowell and Sharpley, 2001; McDowell and Wilcock, 2007; Thompson and McFarland, 2007).

Particulate phosphorus eroded from streambanks may not be immediately bioavailable but this can change during downstream transport. For example, if iron-bound phosphorus is placed in a reducing environment (such as a lake bottom with low oxygen levels), the iron may be reduced from Fe(III) to Fe(II), causing it to solubilize and releasing its stored phosphorus (Weitzman, 2008). Because of this, there may be a delay from when phosphorus is eroded from streambanks and when the effects of this loading are manifested (Meals et al., 2010). Additionally, sediment may serve as either a sink or a source of phosphorus depending on the difference between the sediment sportive capacity and the in-stream dissolved phosphorus concentrations (e.g. Hoffman et al., 2009; McDaniel et al., 2009). The bioavailability of phosphorus has important implications for its effects on water quality. However, because of the difficulty in both measuring bioavailable phosphorus and predicting how the forms of phosphorus will change over time, most water quality monitoring programs are focused only on total phosphorus. Unlike denitrification of nitrate, there is no biotic or abiotic process that effectively removes phosphorus from an ecosystem. Therefore, phosphorus “removal” is likely only temporary.
biotic uptake, although burial and storage in floodplain or lacustrine sediment may be a more long-term removal mechanism.

2.3 Nutrient Processing in Streams

In-stream nutrient processing is a complex and important process that has received increasing attention in recent years (see the review of Ensign and Doyle, 2006). The Lotic Intersite Nitrogen Experiments (LINX and LINX-II), for example, have greatly improved understanding of ammonium and nitrate dynamics in both developed and undeveloped watersheds across the U.S. (Mulholland et al., 2008; Webster et al., 2003). However, only limited research has focused specifically on the impact of stream restoration on in-stream nutrient processing. Urban and other degraded streams tend to incise and erode due to high water velocities and shear stresses (Booth, 1990) and have lower geomorphic complexity (i.e. bedforms, sinuosity, in-stream wood) than reference streams (Jacobson et al., 2001). Therefore, restoration typically focuses on reducing velocities and increasing channel complexity by increasing channel sinuosity, installing in-stream structures, and/or reconnecting floodplains. These altered water velocities and associated hydraulic retention times can have significant impacts on in-stream nutrient processing (Bukaveckas, 2007; Ensign and Doyle, 2005; Kasahara and Hill, 2006a; Klocker et al., 2009; Kuenzler et al., 1977; Roberts et al., 2007), regardless of whether this is a specified objective of the restoration project. Increased channel complexity and in-stream structure installation can also encourage hyporheic exchange (e.g. Crispell and Endreny, 2009; Gordon et al., 2013). The hyporheic zone is an aquifer beneath and adjacent to the stream where surface water and groundwater mixing occurs. This mixing creates physical and chemical gradients which makes the hyporheic zone an important area for biogeochemical cycling (Brunke and Gonser, 1997; Hester and Gooseff, 2010). Around constructed or natural geomorphic features, there are often distinct zones of upwelling (flow from the hyporheos to the stream) and downwelling (flow from the stream to the hyporheos) (Crispell and Endreny, 2009; Kasahara and Hill, 2006b). These exchanges can be important for nutrient retention and processing (e.g. Kasahara and Hill, 2006a).

Although the body of knowledge is increasing, the high variability in nutrient uptake across sites makes generalizations difficult (Ensign and Doyle, 2006). Floods can also significantly alter nutrient uptake dynamics in a single reach, although response is variable depending on the initial geomorphic condition (Mueller Price et al., 2015b). In addition, most studies on in-stream nutrient processing are at a single, baseflow discharge (e.g. Mulholland et al., 2008) which makes extrapolation of results to other flows challenging. In some cases, nutrient retention may be most effective at these low discharges because the higher surface area to volume ratio and lower velocities relative to high discharges encourage biogeochemical processing (Doyle, 2005), meaning they may not be representative of other flow conditions; assuming constant uptake rates across a range of natural flow variability may therefore lead to an overestimate of in-stream nutrient processing potential. However, nutrient removal may also be significant during high flows. Flooding is an important component of natural hydrologic regimes and floodplain access can encourage deposition of adsorbed nutrients and increase biological processing.

2.4 Stream Restoration
Stream or river restoration is a broad topic with varying definitions. In the stream restoration community, the definition set forth by the National Research Council (NRC) is often used: “[the] return of an ecosystem to a close approximation of its condition prior to disturbance” (National Research Council, 1992). The Society for Ecological Restoration (SER) more broadly defines ecological restoration as “the process of assisting the recovery of an ecosystem that has been degraded, damaged, or destroyed” (Society for Ecological Restoration, 2004). Wohl et al. (2005) define river restoration as “assisting the establishment of improved hydrologic, geomorphic, and ecological processes in a degraded watershed system.” Although applied to wetlands, the Society of Wetland Scientists (SWS) propose restoration as “actions taken ... that result in the reestablishment of ecological processes, functions, and biotic/abiotic linkages and lead to a persistent, resilient system integrated within its landscape” (Brown, 2000). Although each definition has its merits, the latter three are preferable over the NRC definition for several reasons. First, defining and quantifying the condition of an ecosystem prior to disturbance is problematic if not impossible. Second, the SER and SWS definitions recognize that ecosystems have natural recovery potential and that restoration ideally works with this recovery trajectory; therefore, restoration success may be defined as being on track towards some desired state as opposed to reaching some predetermined state. Identifying a desired state may be challenging because it necessarily takes into account ecosystem processes and functions rather than simply mimicking form (Ronii and Beechie, 2013). Both the Wohl et al. and SWS definitions underscore that processes (hydrologic, geomorphic, and ecological) must be evaluated to achieve meaningful results. For example, an understanding of altered water and sediment delivery resulting from land use changes is essential for designing sustainable stream restoration projects (Shields et al., 2003). In contrast, popular “analog” approaches to stream restoration may not adequately evaluate such processes when mimicking a reference site which may limit project effectiveness. Finally, the SWS definition recognizes that a restored system should have the capacity to self-repair after disturbance and be “integrated within its landscape.” Understanding the landscape context of a particular system is essential to determine constraints and what is possible at a particular site given the numerous external factors that may influence project performance. Thus, it is important to understand the watershed context of stream restoration projects when assessing effectiveness.

Many studies incorporated into this literature review assess performance of projects that followed the Natural Channel Design (NCD) methodology (Rosgen, 2006, 1996). NCD attempts to restore a degraded reach to match the geomorphic form of some nearby reference reach that is considered representative of natural and stable conditions. Restoration typically involves a combination of channel reconstruction, installation of grade control structures, and bank stabilization. This approach has been criticized for failing to account for differences in watershed condition and processes (e.g. hydrology and sediment flux) between degraded and reference sites and the focus on stability as a restoration goal rather than ecological improvement (Lave, 2009; Simon et al., 2007). Due to its widespread use, the efficacy of NCD stream restoration requires further quantification, and recent studies have started offering evidence of both success and failure (e.g. Miller and Kochel, 2009; Smidt et al., 2014), depending on the defined objective(s). However, NCD should not be considered an exclusive form of stream restoration. A wide variety of strategies are often considered stream restoration and numerous authors have attempted to
categorize them (Bernhardt et al., 2005; Roni and Beechie, 2013). For the purpose of this review, we have defined the following categories of stream restoration strategies:

- **Bed and Bank Stabilization**: This includes direct channel modifications such as installation of grade control structures to prevent incision (and increase bank stability via toe protection) as well as direct bank stabilization. Bank stabilization practices may be resistive (increasing bank resistance to erosion) or redirecive (reducing the erosive power of the stream by redirecting the flow). Resistive practices include various combinations of rip-rap, revetments, and bioengineering (vegetation). Redirecive practices include spurs/groynes, bendway weirs, and guidebanks. Grade controls can include log and rock drop structures. Regardless of the specific design, erosion protection techniques attempt to reduce erosion of the bed and/or banks, leading to more stable habitat and reduced sediment and nutrient loading.

- **Riparian Buffers**: Preservation or restoration of minimally disturbed vegetated areas adjacent to streams is a common restoration strategy aimed at preventing pollutant discharge to streams by retaining and processing nutrients in both the surface and subsurface. Additional benefits of riparian buffers include increased bank stability, stream shading to reduce water temperatures, and supply of in-stream wood and organic carbon to streams.

- **Floodplain Reconnection**: Hydrologic reconnection of floodplains and streams can be achieved through lowering stream banks, removing or breaching levees, or raising the channel bed. Whatever the method, floodplain reconnection tends to raise the riparian groundwater table and allows for more frequent overbank flows. This increases nutrient retention and processing while providing ancillary benefits such as enhanced aquatic and riparian habitat, reduced in-channel stream power (i.e. flow energy per time) and downstream flooding, and increased aquifer recharge.

- **Channel Reconfiguration**: One of the more intensive and expensive stream restoration strategies, channel reconfiguration may entail reconnection of a historically abandoned channel, partial channel realignment, or complete construction of a new channel. The goal is typically to decrease velocities by reducing slope and increasing sinuosity and is typically accompanied by other stream restoration strategies such as erosion protection and installation of in-stream structures. Reducing in-stream velocities may increase hydraulic residence time and nutrient uptake. Channel reconfiguration can also help balance sediment transport to avoid channel downcutting or loss of flood capacity.

- **In-Stream Enhancement**: A common symptom of stream degradation is simplification of the channel and associated loss of habitat. Primarily with a focus on improving fish and benthic invertebrate habitat, many stream restoration projects attempt to increase geomorphic complexity via installation of structures (e.g. riffles, cross-vanes, j-hooks, log jams). These structures can increase habitat heterogeneity and may also increase nutrient retention and cycling by increasing hydraulic retention time and encouraging hyporheic exchange. Organic carbon availability is also an important control on in-stream metabolism and nutrient cycling and restoring organic carbon fluxes may be an important restoration strategy.

- **Watershed Processes**: Streams are integrators of their environment and stream restoration is unlikely to be successful without an assessment of changes in the watershed that are
contributing to channel degradation (Roni and Beechie, 2013). Alterations to hydrology and sediment and nutrient fluxes are often primary causes of water quality degradation. Addressing these causes, rather than the symptoms in the channel, can be a successful restoration strategy to achieve measurable improvements in stream ecosystem function. Combinations of all the above measures, including addressing watershed processes, is likely to be the most successful restoration approach.

As noted previously, stream restoration is a big business in the U.S., with >$1 billion spent annually (Bernhardt et al., 2005). While the most commonly stated objective of these projects is water quality management, fewer than 10% of projects have any kind of post-restoration monitoring (Bernhardt et al., 2005), and even fewer projects have published data on changes in water quality, making it difficult to assess the effectiveness of these projects in reaching stated goals. Recent reviews have quantitatively assessed stream restoration success broadly (Palmer et al., 2014) and with a focus on specific processes (i.e. denitrification in restored hyporheic zones; Merill and Tonjes, 2014). However, to date there has been no comprehensive assessment of relative efficacy of specific restoration strategies to improve nutrient retention and processing. We have scoured the peer-reviewed literature as well as gray literature sources to collect and synthesize the current state of the science on stream restoration as a strategy for nutrient removal and retention. Appendix B provides a summary of these studies. To supplement data from specific restoration projects, we also make inferences about the potential impacts of restoration based on knowledge of stream function in both pristine and degraded systems.

3.0 Stream Restoration Strategies

The following section describes the six stream restoration strategies defined above and provides examples from the literature of their impacts on nutrient processing and retention. Although addressed separately, these restoration strategies are not mutually exclusive and successful stream restoration projects will likely utilize a mixed approach. Determining which strategies to use where requires extensive planning that considers specific watershed conditions including causes of impairment, measurable restoration objectives, and physical, social, and ecological constraints. Approaching the restoration process from this top-down perspective is essential for ensuring project success.

3.1 Bed and Bank Stabilization

Bank erosion is a natural and important process in naturally functioning rivers, contributing to habitat diversity, supplying sediment for bed and floodplain maintenance, and allowing for planform adjustment (Florsheim et al., 2008). However, channel alteration (e.g. channelization), sediment supply alteration (e.g. deforestation), and/or hydrological alteration (e.g. urbanization) can lead to an unstable channel with accelerated bank erosion as the stream self-adjusts to its altered geometry and/or altered water and sediment supply. This adjustment often proceeds through a sequence of channel incision (bed lowering) followed by bank erosion and channel widening before a new, quasi-stable geometry is reached (Schumm et al., 1984; Simon, 1989). However, streams may not linearly follow this incised Channel Evolution Model (CEM), with renewed incision and bank failure possible along the way. Recent research has even demonstrated the potential for transformation from a single-thread to a braided
planform under the right conditions (Hawley et al., 2012). Accelerated bank erosion in these systems may threaten infrastructure, impair in-stream habitat, and be a significant source of sediment and phosphorus to watersheds. Therefore, many stream restoration projects incorporate some degree of grade control and bank stabilization to halt this excessive bank and bed erosion.

A variety of studies have quantified phosphorus loading from bank erosion. Loading rates are highly variable both within and between watersheds, ranging from <1 to 1,000s of kg/km-yr (Table 1). We have identified only one study that has also considered nitrogen loading from bank erosion (Walter et al., 2007), likely because phosphorus is more commonly found adsorbed to soil particles than nitrogen, and most nitrogen studies focus on dissolved, inorganic forms. Walter et al. (2007) found relatively high streambank nitrogen concentrations, indicating that bank erosion could also be a significant source of nitrogen. However, this study was conducted on legacy sediment deposits formed behind small mill-dams built during the 17th to 19th centuries. These legacy deposits are widespread throughout the eastern U.S. and may be significant sources of sediment and nutrients in these watersheds (Walter et al., 2007; Walter and Merritts, 2008). However, much of the deposited sediment is from eroded agricultural topsoil and it is unclear if reported nitrogen concentrations are representative of naturally formed streambanks. Further research is required to assess the potential for streambank erosion to be a significant source of nitrogen in watersheds; however, since this information is not currently available, this section will instead focus largely on phosphorus and bank erosion.

Few studies have examined the direct impact of bank stabilization and/or stream restoration on reducing phosphorus loads from bank erosion, although there are some exceptions (Hubbard et al., 2003; Langendoen et al., 2012; Meals, 2001); however, published studies on phosphorus loading rates from bank erosion (Table 1) may be used as a proxy for loading reduction potential. For example, Hubbard et al. (2003) assumed bank erosion ceased on an approximately 2.9 km reach in Mississippi following installation of bendway weirs and willow plantings, allowing quantification of project benefits based on historic bank erosion rates. Using simple calculations based on avoided phosphorus removal costs, the restoration project was found to provide $612 per meter of restored channel in annual benefits from phosphorus retention, compared to the $85.11 per meter cost of the project. However, assuming that any restoration completely eliminates bank erosion is not realistic. Bank erosion modeling on a large watershed in northern Vermont indicated that various stabilization strategies (riparian planting, bank grading, or a combination of both) resulted in measurable reductions in phosphorus loading rates (14-84% reduction), but could not completely eliminate bank erosion (Langendoen et al., 2012). In fact, channel erosion may be significant following channel reconstruction and structure installation (Miller and Kochel, 2009), suggesting that in some cases, stream restoration may not impact bank erosion and associated phosphorus loading, or at least that system stabilization may not be immediate.

Bank stabilization is often used in conjunction with other restoration strategies. A combination of bank stabilization, livestock exclusion from riparian zones, and riparian planting reduced phosphorus concentrations (-25%) and total export (-42%) (Meals, 2001). Bank stabilization and riparian buffer restoration reduced suspended sediment concentrations by 47-87% (Carline and Walsh, 2007) and likely reduced associated particulate phosphorus loading as well. However, post-restoration monitoring of a
stream where bank stabilization and grade control structures were installed showed no change in nutrient concentrations (Selvakumar et al., 2010). Post-project monitoring is likely required to adequately assess the reduction in bank erosion and phosphorus loading associated with any stabilization/restoration project. Recognizing this, it has been suggested that stream restoration projects in the Chesapeake Bay watershed only initially receive credit for potential nutrient reduction for five years following project completion, after which monitoring is required to ensure the project is functioning properly before credits are renewed (Berg et al., 2013). Quantifying historic bank erosion rates is only a first step to assessing the potential for stabilization/restoration to reduce phosphorus loading since these rates may not be representative of future channel evolution. In addition, deposition of eroded sediment on banks and floodplains may be a significant sink in some watersheds (Hupp et al., 2013; Kronvang et al., 2013), meaning loading estimates from bank erosion alone may overestimate total export. The CEM predicts eroding channels will at some point adjust to a new, stable state (Schumm et al., 1984; Simon, 1989), assuming no further disturbances to the sediment and hydrologic regime. Therefore, current or historic erosion rates cannot be simply extrapolated for actively evolving channels as these systems should eventually stabilize on their own, although the time scale may range from years to decades or more. When assigning a nutrient load reduction credit to a streambank stabilization project the question arises: how much erosion and loading was actually mitigated? Answering this question is difficult and laden with uncertainty. While the CEM has been well defined and observed in many different systems (e.g. Hawley et al., 2012), it lacks a widely accepted methodology for quantification. Although channel evolution may be predicted with reasonable confidence if sufficient regional data are available, it is not advisable to transfer these results to other hydrologic and geomorphic settings without regional calibration.

Quantifying bank erosion potential is only part of the puzzle for estimating phosphorus loading from channel erosion. Bank phosphorus concentrations are associated with a number of factors (soil texture, pH, metals concentrations, and the geology of the soil parent material; Brady and Weil, 2002) and are often highly variable, even in a single reach (e.g. Bledsoe et al., 2000; Nellesen et al., 2011; Schilling et al., 2009). Individual laboratory methods may differ in their ability to extract adsorbed phosphorus from soils, leading to potentially different results depending on the extraction method used and complicating direct comparison of data from various sites (Kleinman et al., 2001). Figure 1 shows the variability in bank phosphorus concentrations reported in 12 studies from around the U.S. and the world. Uncertainty in bank phosphorus concentrations can lead to significant uncertainty in estimated loading rates. While direct quantification through field sampling and analysis is the best approach for quantifying phosphorus concentrations, coarse estimates may be obtained based on regional soil phosphorus data. Recently, the U.S. Geological Survey published coarse scale soil phosphorus data for the conterminous U.S. (Smith et al., 2013). We compared bank phosphorus concentrations from various studies to upland surface soil phosphorus concentrations within a 50 mile radius. There appears to be a strong correlation between these two data sets, although uncertainty analysis suggests there remains significant variability (Figure 2; R² = 0.501, 95% CI: 0.114-0.677, p < 0.005). Correlation coefficients for A-horizon soil phosphorus concentrations are similar (data not shown; R² = 0.459, 95% CI: 0.126-0.647, p < 0.008). Regression results using data from the C-horizon are not statistically significant (p > 0.01). It should be noted that points on Figure 2 fall well below the 1:1 line, indicating that while the two data sets are correlated,
ufland phosphorus concentrations tend to be higher than in streambanks. While estimating actual streambank phosphorus concentrations based on this relationship is not advisable, this correlation can at least be used to assess relative bank phosphorus levels in a preliminary assessment of phosphorus loading potential.
Table 1. Summary of sediment and phosphorus loading rates from select studies. *Tonne is a metric tonne (1,000 kg). †Reported nitrogen concentrations of 400 – 2,100 mg/kg and nitrogen loading rates of 447 – 6,113 kg/km-yr.

<table>
<thead>
<tr>
<th>Paper</th>
<th>Location</th>
<th>Bank P Concentrations [mg/kg] (lb/ton)</th>
<th>Sediment Loading Rate [tonne/km-yr]* (ton/mi-yr)</th>
<th>Phosphorus Loading Rate [kg/km-yr] (lb/mi-yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>DeWolfe et al. (2004)</td>
<td>Vermont, USA</td>
<td>369 – 740 (0.74 – 1.48)</td>
<td>10 - 1,333 (71 – 9439)</td>
<td>10 – 840 (35 – 2,974)</td>
</tr>
<tr>
<td>Hubbard et al. (2003)</td>
<td>Mississippi, USA</td>
<td>168 – 237 (0.34 – 0.47)</td>
<td>7,574 - 17,604 (53,630 – 124,650)</td>
<td>1,170 – 2,719 (4,142 – 9,626)</td>
</tr>
<tr>
<td>Kronvang et al. (2012b)</td>
<td>Funen, Denmark</td>
<td>400 – 1,400 (0.8 – 2.8)</td>
<td>NA</td>
<td>4.2 – 167 (15 – 591)</td>
</tr>
<tr>
<td>Langendoen et al. (2012)</td>
<td>Vermont, USA</td>
<td>422 – 973 (0.84 – 1.95)</td>
<td>0.1 - 3,266 (0.7 – 23,126)</td>
<td>0.1 – 2,970 (0.4 – 10,515)</td>
</tr>
<tr>
<td>Miller et al. (2014)</td>
<td>Oklahoma, USA</td>
<td>239 – 427 (0.48 – 0.85)</td>
<td>300 - 12,857 (2,124 – 91,038)</td>
<td>320 – 4,104 (1,133 – 14,530)</td>
</tr>
<tr>
<td>Nellesen et al. (2011)</td>
<td>Iowa, USA</td>
<td>184 – 347 (0.37 – 0.69)</td>
<td>NA</td>
<td>3.4 – 20.7 (12 – 73)</td>
</tr>
<tr>
<td>Peacher (2011)</td>
<td>Missouri, USA</td>
<td>197 – 637 (0.39 – 1.27)</td>
<td>9.2 - 447.5 (65 – 3,169)</td>
<td>2.9 – 114 (10 – 404)</td>
</tr>
<tr>
<td>Thoma et al. (2005)</td>
<td>Minnesota, USA</td>
<td>249 – 452 (0.5 – 0.9)</td>
<td>9,147 (64,768)</td>
<td>3,589 (12,706)</td>
</tr>
<tr>
<td>Tufekcioglu (2010)</td>
<td>Iowa, USA</td>
<td>246 – 349 (0.49 – 0.7)</td>
<td>58 – 664 (411 – 4,702)</td>
<td>20 – 183 (71 – 648)</td>
</tr>
<tr>
<td>Walter et al. (2007)†</td>
<td>Pennsylvania, USA</td>
<td>339 – 958 (0.68 – 1.92)</td>
<td>510 - 2,800 (6,311 – 19,826)</td>
<td>298 – 2,680 (1,055 – 9,488)</td>
</tr>
<tr>
<td>Zaimes et al. (2008b)</td>
<td>Iowa, USA</td>
<td>303 – 555 (0.61 – 1.11)</td>
<td>5 – 304 (35 – 2,153)</td>
<td>2 – 123 (7 – 435)</td>
</tr>
</tbody>
</table>
Figure 1. Box plot of bank phosphorus concentrations for 12 studies from the U.S. and the world. Box plots indicate the median, quartiles, and non-outlier maximum and minimums (1.5 times the interquartile range). Open circles are outliers. The solid red line is the mean of the composite data set and the dotted lines are the 95th and 5th percentiles. [A] Bledsoe et al. (2000); [B] Howe et al. (2011); [C] Thompson and McFarland (2007); [D] Hubbard et al. (2003); [E] Veihe et al. (2011); [F] Nellesen et al. (2011); [G] Schilling et al. (2009) [H] Tufekcioğlu (2010); [I] Peacher (2011); [J] Kerr et al. (2011); [K] Hongthanat (2010); [L] Walter et al. (2007).

Figure 2. Mean bank phosphorus concentrations versus mean surface soil (top 5 cm) phosphorus concentrations. Solid line is a simple linear regression. Error bars are the 80 percent confidence intervals of individual points. Gray lines are bootstrap-estimated regression lines, indicating the range of uncertainty.
3.2 Riparian Buffers

Riparian buffers, undisturbed and/or managed vegetated areas along stream margins, have long been recognized for their potential to remove pollutants in surface and subsurface flow before they reach the stream. Under the right conditions, properly functioning riparian buffers (typically consisting of intact forest) can remove >90% of inflowing nitrate (Jordan et al., 1993; Peterjohn and Correll, 1984; Pinay et al., 1993; Spruill, 2000). Even under less-optimal conditions, nitrate removal is often significant. A comprehensive review of published removal rates found an average removal effectiveness of 74.2 ± 4.0% (Mayer et al., 2005). The majority of this removal takes place in the subsurface (Hill, 1996; Peterjohn and Correll, 1984) where conditions amenable for denitrification are often found (low dissolved oxygen and available organic carbon). However, primarily due to organic carbon limitation at depth, deep groundwater flow may not experience the same level of nitrate removal (Spruill, 2000). This can also lead to temporal variability in denitrification and nitrate removal rates; seasons with high water tables (e.g. spring snowmelt) see greater denitrification (Baker and Vervier, 2004). Often, denitrification rate per unit width is consistent, suggesting that increasing buffer width may not increase the rate of denitrification, but will increase the total removal efficiency (Mayer et al., 2007). However, others have found that most nitrate removal occurs in a relatively small portion of the buffer where high groundwater tables allow for denitrification and plant uptake (Clausen et al., 2000). In addition, buried layers of organic-rich soil may be hot spots of denitrification (McClain et al., 2003), especially if groundwater tables are low (Gold et al., 2001).

Subsurface hydrology is an important driver in denitrification potential in riparian zones. Denitrification removal efficiencies are typically higher in riparian zones with higher water tables and longer residence times (Kaushal et al., 2008). However, this relationship can be complicated by the fact that shallower soil layers typically have higher hydraulic conductivities and therefore shorter groundwater residence times than deeper soils. Generally, buffers wider than 50 m removed more nitrate than those 0-25 m (Mayer et al., 2007). However, buffers as narrow as 30 m have shown 100% removal efficiency (Pinay et al., 1993). While plot-scale studies of large, intact buffers demonstrate significant nutrient retention potential, there have been far fewer analyses on the potential impacts of narrower buffers (< 10 m wide) that are more commonly restored in practice (Hickey and Doran, 2004). Buffer age can also be an important control on nutrient removal efficiency. In-stream nitrate concentrations were shown to decrease with increasing buffer age, and buffers greater than 10 years old had significantly lower observed nitrate levels than younger buffers (Orzetti et al., 2010). As buffers mature, root density and organic carbon availability are expected to increase, leading to more conducive conditions for denitrification. Buffer age can also impact in-stream nutrient uptake by influencing light and carbon availability (McMillan et al., 2014). Short term manipulation of riparian buffers may be effective at increasing subsurface nitrate removal, giving buffers a chance to establish. Construction of a denitrification wall, a trench filled with a sawdust-soil mix, provided a labile carbon source and resulted in significant reductions in groundwater nitrate concentrations (from 5-16 mg/L to 0.6-2 mg/L) (Schipper and Vojvodić-Vuković, 1998). Even 14 years after installation, nitrate removal efficiency in this denitrification wall exceeded 90% (Long et al., 2011). Efforts have even been made to incorporate these bioreactors into bank stabilization projects. A trench modified with mulch and aluminum sulfate
reduced nitrate and phosphorus loads from an adjacent agricultural field by encouraging denitrification and phosphorus immobilization (Carlson et al., 2010; Son et al., 2011). However, these bioreactors are not conducive to large scale application, and should instead be targeted to areas known to be large contributors of nutrients (e.g. confined feeding operations or septic systems; Robertson and Cherry, 1995)

Denitrification is an important nitrogen removal mechanism but plant uptake is also a dominant process (Hill, 1996). There have been some studies that explore the relative uptake potential of different plant types. Some results indicate that trees may be more effective at uptake than grasses, possibly due to differences in root distributions (Hill, 1996). A meta-analysis found that grass buffers had significantly lower nitrate removal efficiencies compared to forest buffers (Mayer et al., 2005). However, others have found no statistical difference between buffer vegetation type (Groffman and Crawford, 2003; Mayer et al., 2007; Schoonover and Williard, 2003). A mixed forest-grass buffer is recommended by both the U.S. Forest Service and Natural Resources Conservation Service as the most effective buffer design (Natural Resources Conservation Service, 2003; Welch, 1991). This buffer design consists of an upland grassed strip to slow overland flow and trap sediment, a managed forest where tree harvesting is permitted, and a mature forest zone adjacent to the stream. Although this buffer design does effectively remove nutrients (Schultz et al., 1995), there are no studies comparing the performance of this type of buffer with other designs.

Although these studies illustrate the potential for riparian buffers to remove dissolved and particulate nutrients from both surface and subsurface flow, the effects of these features on in-stream nutrient concentrations at the watershed scale are less clear. Restored riparian buffers in a New Zealand watershed increased dissolved oxygen and reduced turbidity but had no impact on nutrient concentrations (Collins et al., 2013). Similarly, no change in in-stream nutrient concentrations was observed in watersheds with restored buffers in the Chesapeake Bay basin (Sutton et al., 2010). In both instances, the authors cite narrow buffer width and significant gaps along the streams which allow unimpeded nutrient loading which cannot be offset by the restored buffer sections. Contrasting these results, a broad scale modeling effort suggested that existing riparian buffers in the Chesapeake Bay watershed result in a 0.41 mg/L reduction in in-stream nitrate concentrations. Furthermore, fully restoring riparian buffers may result in an additional 0.68 mg/L reduction, although this is likely an overestimate (Weller et al., 2011). These studies suggest that a more comprehensive riparian buffer restoration program, beginning in headwater streams and moving downstream, would be more effective at improving water quality than the piecemeal restoration that typically occurs (Collins et al., 2013; Parkyn et al., 2005).

Most studies focus on nitrate removal in riparian buffers, often ignoring phosphorus removal. However, this may be partially due to evidence that these buffers are not effective for phosphorus retention. Although buffers may effectively trap particulate and dissolved phosphate in surface runoff (Lee et al., 2003; Newbold et al., 2010), groundwater phosphate concentrations often increase (Peterjohn and Correll, 1984; Spruill, 2000), potentially due to reduction of iron oxyhydroxides with bound phosphate (Jordan et al., 1993). These offsetting processes can result in little or no net change in phosphorus loading through buffers (Newbold et al., 2010). However, riparian buffers may impact stream dynamics
and thus reduce phosphorus loading indirectly. Vegetated streambanks tend to have lower erosion rates than non-vegetated banks (e.g. Simon and Collison, 2002; Smith, 1976). While narrow riparian buffers may not trap nutrients as effectively as wide buffers, they may still be important for bank stabilization (Carline and Walsh, 2007). Although there is conflicting evidence on the relative impact of grass versus forested banks (Anderson et al., 2004; Lyons et al., 2000), the beneficial impacts of some sort of bank vegetation is clear. Additionally, riparian buffers may be significant sources of in-stream wood and organic carbon to streams (Stanley et al., 2012), both of which can increase in-stream nutrient uptake (Bernhardt and Likens, 2002; Roberts et al., 2007).

Other stream restoration activities can negatively impact riparian buffer performance. Channel reconstruction projects often lead to reduced organic matter, higher bulk density, and lower root density in riparian soils (Gift et al., 2010; Laub et al., 2013; Unghire et al., 2011). Significant regrading often occurs during restoration, potentially burying topsoil and exposing lower soil horizons, reducing organic matter availability (Gift et al., 2010). Furthermore, removal of riparian vegetation and soil compaction are common side-effects of channel reconstruction projects with deleterious ecological consequences (Sudduth et al., 2011; Unghire et al., 2011). These impacts to riparian soils can persist for over a decade after restoration and may limit the ecological benefits claimed by restoration practitioners (Laub et al., 2013). Riparian planting, on the other hand, has little or no impact on soil composition and structure and may be a less invasive stream restoration technique (Laub et al., 2013).

3.3 Floodplain Reconnection

Floodplain reconnection promotes similar removal mechanisms as riparian buffers; encouraging subsurface denitrification in the riparian zone while retaining particulate and dissolved nutrients in surface flow. Because nitrate removal efficiency is dependent on groundwater hydrology, disruptions in groundwater levels and flows caused by land use change have significant implications for the denitrification potential of riparian zones. Channel incision, often caused by direct modification such as channelization or by hydrologic alteration such as watershed urbanization, can lower riparian groundwater tables, thereby reducing denitrification potential by creating a disconnect between the relatively anoxic, nitrate-laden groundwater and available organic carbon in the upper soil horizons. Incision may also increase the relative hydraulic head gradient between the groundwater and streamwater, increasing inflow of nutrient-laden groundwater. Urban streams tend to have lower riparian groundwater tables than rural or forested streams (Groffman et al., 2002; Hardison et al., 2009; Watson et al., 2010). This incision results in higher nitrate loading to streams (Schilling et al., 2006) and higher in-stream nitrate concentrations (Böhlke et al., 2007; Groffman et al., 2002). This can be explained by reduced denitrification, but also by increased nitrate production via nitrification as a deeper, oxygenated unsaturated zone in the riparian zone encourages oxidation of ammonium to nitrate (Groffman et al., 2003). Forested and urban riparian soils may have similar denitrification potential (Groffman and Crawford, 2003), indicating that under the right conditions, namely high water tables, floodplain denitrification will occur even in developed areas. However, suburban and agricultural riparian areas may have lower organic carbon availability compared with forested sites, a potential limitation on denitrification (Watson et al., 2010). In addition to potentially increasing denitrification
potential, floodplain reconnection also permits overbank flooding, allowing for deposition of nutrient laden sediment and biological processing of dissolved constituents.

Floodplain reconnection aims to restore optimal conditions for denitrification and nutrient retention by raising the channel bed level, removing or breaching levees, and/or re-grading and lowering banks. Natural floodplains have been demonstrated to be important areas for nitrate removal (e.g. Forshay and Stanley, 2005) and reconnected floodplains may have the potential to be significant nitrate sinks (Fink and Mitsch, 2007; Sheibley et al., 2006; Valett et al., 2005). Estimates for a reconnected floodplain in California predict 0.6-4.4% removal of the total river nitrogen load in wet years, but up to 23.7% removal in dry years (Sheibley et al., 2006). A constructed two-stage ditch in an agricultural watershed has the potential to remove 10% of the nitrate load during storms (Roley et al., 2012a). A reconnected oxbow wetland in Ohio saw annual reductions in nitrate, total nitrogen, and total phosphorus of 74%, 41%, and 31% by mass, respectively (Fink and Mitsch, 2007). In Denmark, both restored and natural floodplains removed small but significant (4-7%) portions of river’s total phosphorus load via overbank deposition (Kronvang et al., 2007). On the Rio Grande River, a reconnected floodplain saw a four-fold reduction in nitrate concentrations, although much smaller reductions in ammonium and phosphate (Valett et al., 2005). Conversely, denitrification rates in a reconnected Wisconsin floodplain were not significantly different from pre-restoration (Orr et al., 2007). However, this study examined only the rate of denitrification, not actual nutrient removal potential. While disconnected or degraded floodplains may have similar denitrification potential to reference floodplains (Groffman and Crawford, 2003), it is the total amount of nitrate removal that occurs that is of most interest. Contrasting the results of Orr et al. (2007), inundation of a newly constructed floodplain did significantly increase denitrification rates, likely due to increased supply of nitrate (Roley et al., 2012b). However, total nitrate removal in the restored floodplain and in the hyporheic zone only accounted for 5% and 2% of the total river load during baseflow and stormflow, respectively, indicating these removal mechanisms may be relatively insignificant in streams with high nutrient loads (Roley et al., 2012b). Nitrate removal in floodplains may be limited due to infrequent inundation (Azinheira et al., 2014), although most studies do not consider increased groundwater nutrient removal as a result of higher water tables.

Although reconnected floodplains have the potential to serve as nutrient sinks, the impact on in-stream nutrient concentrations and loads has only received limited attention. A small restored stream with graded banks and a reconnected floodplain had lower in-stream nitrate concentrations than a downstream unrestored reach (Kaushal et al., 2008). This was likely the result of higher nitrate removal in the restored floodplain which was highly correlated to groundwater residence time; indicating hydraulic retention is an important consideration for nitrate removal. Restored streams with connected riparian wetland complexes increase hydraulic retention and these systems showed net nitrogen retention (Filoso and Palmer, 2011). Reconnecting the stream to off-channel ponds also resulted in significantly higher nitrate removal compared with restoration designs without enhanced lateral connectivity (Browning, 2008). A significant decrease in total dissolved nitrogen concentrations was observed immediately downstream from in-line stormwater ponds and wetlands (Sivirichi et al., 2011). A reconstructed channel with in-line and off-line wetland complexes successfully reduced nutrient concentrations and loads; nitrate and phosphorus loads were reduced by 64% and 28%, respectively.
during a storm event (Richardson et al., 2011). Even when not a part of the restoration design, floodplain backwater areas may be responsible for a significant fraction of observed denitrification (Bukaveckas, 2007). These results are limited and further research is needed to assess the impact of floodplain reconnection on in-stream nutrient concentrations and loads at a larger spatial scale.

### 3.4 Channel Reconfiguration

Channel reconstruction and/or planform readjustment are common restoration strategies for highly altered streams. Channel straightening or channelization to increase flood conveyance was widespread during the first half of the 20th century. Later, the detrimental impacts of these “improvements” on stream function, ecology, and infrastructure were recognized. Since then, efforts have been ongoing to reverse these impacts, primarily through restoring a more “natural” channel structure and planform. As channelization creates a simplified stream system, channel reconstruction should increase complexity and ecological function, including nutrient processing. Channelization has been shown to increase velocities and nutrient concentrations compared to reference reaches, likely due to increased slope, reduced channel complexity, and undercutting of riparian zone water tables (Kuenzler et al., 1977). Channel re-meandering subsequently decreases slope and velocity, increasing hydraulic retention time and nutrient uptake rates (Bukaveckas, 2007). However, since channel reconstruction is typically used in conjunction with other restoration strategies, it is difficult to isolate individual effects. Channel reconstruction and grade control resulted in successful nutrient retention in a previously incised stream (Claushulte, 2015), although a lack of pre-restoration monitoring makes a full evaluation difficult. A complete channel reconstruction (including floodplain reconnection and bank stabilization) led to 33-42% reductions in nitrogen loads and 43-60% reductions in phosphorus loads (Stewart, 2008). Slightly higher nitrate uptake rates were observed in streams restored by reconstructing the channel to a “natural and stable” planform. However, these higher uptake rates were likely the result of higher primary productivity from increased water temperature and light availability due to removal of riparian vegetation during construction (Sudduth et al., 2011), a side-effect that likely has other detrimental ecological impacts. Hines and Hershey (2011) also found higher in-stream temperatures, greater algal biomass, and increased ammonium processing in restored reaches due to lower canopy cover, leading to the suggestion that riparian zones be managed to allow for both shaded and unshaded portions to improve nutrient retention. However, this runs counter to many stream temperature management objectives aimed at improving fish habitat and may not be a viable strategy in all systems. Re-creation of channel meanders and point bars may also stimulate lateral hyporheic exchange (Kasahara and Hill, 2007), presumably increasing nutrient processing. Significant denitrification and net nitrogen removal have been observed in the hyporheic zones of natural gravel bars (Zarnetske et al., 2011) suggesting that nutrient processing in constructed gravel bars may also be important. Although increasing hydraulic retention time is important, restoring conditions that enhance uptake processes (e.g. habitat heterogeneity) will likely be more effective at increasing nutrient retention rather than simply decreasing velocity and depth (Doyle et al., 2003). The high cost of channel reconstruction projects (Bernhardt and Palmer, 2007; Bernhardt et al., 2005) may make their use as a nutrient reduction strategy undesirable. However, these projects are often constructed to meet other restoration objectives and may also provide fortuitous nutrient retention benefits.
Improving in-stream habitat is one of the most common stream restoration objectives (Bernhardt et al., 2005) and typically consists of installing permanent or transient structures within a stream. In-stream structures are also used to reduce bed and bank erosion, reduce velocities, and trap sediment. While these structures may not be designed to enhance nutrient removal, they may significantly impact in-stream processing by increasing hydraulic retention time, enhancing habitat and increasing biotic nutrient demand, and improving lateral and vertical connectivity. Removal of in-stream wood and vegetation can increase velocities and reduce nutrient uptake (Ensign and Doyle, 2005). Conversely, in-stream wood addition can have the opposite effect (Roberts et al., 2007). Velocities were lower and ammonium uptake rates were higher in reaches with in-stream wood compared to wood-deficient reaches (Weigelhofer et al., 2012). However, phosphate uptake was not different, possibly due to phosphate release from sediments in reducing environments of backwater areas upstream of debris dams. Other forms of restoration (step-pool creation and floodplain reconnection) can reduce water velocities, increasing hydraulic residence time and nutrient uptake rates (Klocker et al., 2009).

In the Chesapeake Bay watershed, three different restoration strategies showed decreased nitrate concentrations; however, the design with riffle weirs and floodplain pond construction had the greatest removal compared with the designs that consisted of cross vanes, j-hooks, re-meandering, and riparian plantings (Browning, 2008). Features typically associated with NCD (cross-vanes and j-hooks) can significantly increase surface transient storage, although overall residence time may be shorter than in reference reaches due to less hyporheic exchange (Becker et al., 2013). However, in other systems hyporheic exchange may dominate in NCD restored reaches due to greater bedslope variability while unrestored reaches show predominately in-stream storage due to the presence of in-stream wood (Mueller Price et al., 2015a). Despite differences in transient storage dynamics in this system, overall nitrate uptake was not significantly different between reaches. Even structures not typically associated with stream restoration can increase in-stream nutrient uptake. In straightened streams, small (<5 m) weirs can increase transient storage and nutrient uptake by increasing channel complexity and reducing velocities (Pohlon et al., 2007). While dam removal is an increasingly common restoration practice, this may have unintended consequences on nutrient dynamics if additional effort is not made to increase channel complexity. A dam removal on a moderately sized river in Wisconsin reduced phosphorus uptake and increased concentrations by 40% (Doyle et al., 2003). Dams may create conditions conducive to nutrient retention and processing (i.e. sediment and phosphorus deposition, anoxic bed sediments where denitrification can occur). After dam removal, the channel adjusts its form and nutrient processing will be altered over time. The impact of changing geomorphology (even in less extreme situations) is often unaccounted for in nutrient retention studies (Stanley and Doyle, 2002).

Beaver reintroduction has been proposed as a viable stream restoration technique (Pollock et al., 2014; Roni and Beechie, 2013). Beaver dams can increase geomorphic complexity, serve as grade control, and are more resilient than engineered structures (i.e. are rebuilt after floods). A beaver dam and downstream man-made log dam induced significant hyporheic flux, although the individual impact of the beaver dam was not assessed (Fanelli and Lautz, 2008). While beaver dams may have similar effects
on in-stream hydraulics and nutrient dynamics as other in-channel structures (i.e. debris dams), more research is needed to accurately assess their impact.

Experimental baffle installation significantly increased nutrient uptake in low gradient streams and results indicated in-stream transient storage, rather than hyporheic exchange, was the primary control (Ensign and Doyle, 2005). In-stream storage was also shown to be more significant than hyporheic storage in steeper gradient urban and rural streams in Colorado (Baker et al., 2011). However, hyporheic denitrification may play an important role in nitrate removal. Hyporheic exchange is often driven by hydraulic head gradients induced by in-stream structures, including structures installed for stream restoration (Azinheira et al., 2014; Crispell and Endreny, 2009; Hester and Doyle, 2008; Kasahara and Hill, 2006b). Only a small fraction (<1%) of the total stream discharge may be exchanged at a given structure (Azinheira et al., 2014; Gordon et al., 2013), although this could be higher in more hydraulically conductive bed material (Hester and Doyle, 2008). Structure design can also have an impact on the hyporheic flux dynamics. Generally, channel spanning structures induce the most hyporheic exchange (Hester and Doyle, 2008) and modifying cross vanes to have higher and more abrupt drops can increase downwelling (Crispell and Endreny, 2009).

Nutrient processing around restoration structures may be important. Both constructed and natural riffles stimulate significant hyporheic flux and nitrate removal below these structures may be significant (29-90% efficiency) (Kasahara and Hill, 2006a). In fact, constructed riffles may have greater hyporheic exchange due to generally steeper slopes and coarser substrates than natural riffles (Kasahara and Hill, 2006b). Reaches with constructed riffles had significantly hydraulic retention times compared to unrestored reaches, an observation attributed to greater hyporheic flux. Modeling also suggested that this type of restoration could result in significant denitrification and that in-stream nitrate concentrations would decrease as the length of restoration increased (Knust and Warwick, 2009). Structure installation can promote formation of streambed biogeochemical hotspots that were not present in unrestored channels (Lautz and Fanelli, 2008). Denitrification can be significant if the streambed is anoxic, but nitrate production via nitrification can occur in other, oxic bed sediments. However, even in this case, net nitrogen removal still occurs (Lautz and Fanelli, 2008; Zarnetske et al., 2011). Installation of cross vanes can lead to greater downwelling compared to reference streams which likely encourages hyporheic zone denitrification (Daniluk et al., 2013). However, while these types of in-stream features may result in greater surface transient storage, hyporheic flux may still be greater overall in reference reaches, potentially due to bed compaction and blockage by large footer boulders in the restored stream (Becker et al., 2013). Residence times in the hyporheic zone under constructed cross vanes may be too short for significant nutrient processing to occur (Gordon et al., 2013). Even if retention times are long, conditions in these constructed features may not be conducive to denitrification and therefore natural riffle structures may be more effective nitrate removal zones (Smidt et al., 2014).

Indirect effects of constructed structures on hyporheic flux may be more significant than direct impacts. Both cross vanes and log dams create secondary geomorphic features (i.e. pools and riffles) and hyporheic exchange in these features may be more significant than in the restoration structures themselves (Fanelli and Lautz, 2008; Gordon et al., 2013). Direct modification of subsurface hydraulic
conductivity has also been suggested as a potential restoration strategy to enhance hyporheic exchange (Hester and Cranmer, 2014; Hester and Gooseff, 2010). Vaux (1968) proposed construction of high or low conductivity structures below the streambed to engineer hyporheic flow paths. Modeling has suggested that these constructed features function similarly to natural geomorphic features in driving subsurface flux and may be viable stream restoration tools (Ward et al., 2011). The importance of hyporheic zone processing has led to the suggestion that hyporheic zone restoration should be incorporated into the larger stream restoration context (Hester and Gooseff, 2010; Merill and Tonjes, 2014). Hester and Gooseff (2010) suggest in-stream enhancement, such as construction of morphological features, introduction of large wood, and sediment coarsening to increase hydraulic conductivity are the best approaches to hyporheic restoration. However, Merill and Tonjes (2014) focus more on out of channel improvements, including enhancements to agricultural ditches, construction of wetlands, and riparian planting and restoration to increase subsurface denitrification and nutrient removal. Different restoration strategies may be appropriate depending on local nutrient sources, delivery pathways, and location in the stream network (Craig et al., 2008). Whatever strategy is used, restoring vertical connectivity should be a component of stream restoration projects and may lead to increased nutrient removal.

While in-stream restoration may increase transient storage and hyporheic flux, denitrification may not be significantly different overall in restored and unrestored reaches (Groffman et al., 2005; Harrison et al., 2012; Tuttle et al., 2014). In fact, restored reaches may have lower denitrification rates due to coarser bed sediment (Weigelhofer et al., 2013) and lower organic carbon availability (Gift et al., 2010), side effects of construction activities. Lower nitrification rates have been observed in restored streams (potentially because of increased ammonia immobilization), indicating restoration can reduce conversion of ammonia to nitrate (Groffman et al., 2005). Although increased hydraulic retention can lead to increased nutrient removal, other factors (notably organic carbon availability) control actual removal/uptake rates. Organic carbon is an essential component for denitrification but also stimulates microbial and plant growth, thus increasing nutrient assimilation by these organisms. There are a variety of sources of organic carbon, originating from within the stream and from the watershed, including leaf litter, fallen riparian trees, aquatic vegetation, and dissolved constituents in runoff (Stanley et al., 2012). In many urban streams, abundance of in-stream wood has decreased due to direct removal, washout during higher peak flows, and supply reduction from clearing of riparian areas (Booth et al., 1996; Segura and Booth, 2010). However, in regions with significant reforestation, abundance of in-stream wood has increased, a trend that is expected to continue (Warren et al., 2009).

Installed or natural log structures trap organic matter (Quinn et al., 2007; Wallace et al., 1995) and these organic debris dams have higher denitrification potential compared to other geomorphic features such as gravel bars, pools, and riffles (Groffman et al., 2005; Harrison et al., 2012). Although nitrogen is often considered a limiting nutrient, in systems with high nitrogen concentrations, organic carbon may be the limiting factor for both denitrification and uptake (Johnson et al., 2009; Lefebvre et al., 2004; Newcomer et al., 2012), indicating that addition of organic carbon sources may increase in-stream nitrogen removal. Significant reductions in nitrate concentrations were observed following organic carbon addition; however, denitrification was unchanged, indicating all nitrate removal was occurring through
assimilation (Bernhardt and Likens, 2002). Addition of organic carbon sources can also increase phosphorus uptake rates (Aldridge et al., 2009), although others have found no change in phosphorus retention (Wallace et al., 1995). Even in un-amended streams, natural leaf-fall in autumn can significantly increase phosphate and ammonium uptake velocities (Argerich et al., 2008; Mulholland et al., 1985).

While increasing carbon availability can increase biotic demand for phosphorus, abiotic uptake (i.e. sediment adsorption) may be the dominant removal pathway in some systems and is limited by the saturation potential of the sediment (Aldridge et al., 2010). The bioavailability of the carbon source is likely a controlling factor for biotic uptake. For example, highly labile and available forms such as acetate that are used experimentally (Bernhardt and Likens, 2002) may have large effects on nutrient processing but may not be representative of natural carbon sources. Even in natural systems, leaf litter (Aldridge et al., 2009) is often decomposed much more rapidly into bioavailable compounds than coarser in-stream wood (Wallace et al., 1995). However, while in-stream wood may not be a significant source of bioavailable carbon, it is effective at reducing velocities, increasing hydraulic residence time (Ensign and Doyle, 2005; Roberts et al., 2007), and trapping other sources of more labile organic carbon (Quinn et al., 2007; Wallace et al., 1995). Noting the importance of dissolved organic carbon for nutrient processing and ecological function, Stanley et al. (2012) suggest riparian planting to restore more sustainable organic carbon fluxes to streams.

As noted previously, riparian buffers will be most effective on small, headwater streams where organic debris is more effectively retained (Quinn et al., 2007) and where there is significant potential for nutrient retention (e.g. Peterson et al., 2001). In addition, increased coarse substrate availability can create more stable habitat for algae and biofilms which can lead to enhanced nutrient demand and uptake (Hines and Hershey, 2011; Hoellein et al., 2012). Statistical modeling based on nutrient tracer experiments suggested that a forested riparian buffer increased nitrate assimilative capacity by 20-23% compared to an upstream unrestored reach (Faulkner, 2008); however, the specific mechanisms controlling nitrate uptake were not studied. Despite this potential for increasing in-stream nutrient uptake and removal, addition of in-stream wood may not be feasible in highly urbanized systems due to concerns of reduced flood capacity and damage to infrastructure.

Noting that nitrate removal is carbon limited in agricultural systems with high nitrate concentrations, Robertson and Merkley (2009) constructed an in-stream bioreactor (a woodchip-filled trench in the streambed) to enhance hyporheic zone denitrification. Mean in-stream nitrate concentrations were reduced from 4.8 mg/L to 1.04 mg/L and observed mass removal rates were 40 times that of nearby constructed wetlands. Although relatively intrusive, these bioreactor systems may be inexpensive nutrient treatment options in agricultural systems with high nutrient loads (Schipper et al., 2010).

3.6 Watershed Processes

Degraded streams may have high nutrient uptake rates, comparable to or greater than reference systems (Bernhardt and Palmer, 2007; Johnson et al., 2009; Mulholland et al., 2008). However, this is largely the result of higher nutrient loading to these streams, and the removal efficiency in these
systems is often much lower than undisturbed streams (Mulholland et al., 2008). Based on these results, there appears to be some maximum uptake rate in streams that limits nutrient removal, at least under certain conditions. This potential constraint on in-stream nutrient processing has led to the suggestion that stream restoration alone may be insufficient for reducing nutrient concentrations to desired levels if no upland best management practices are incorporated (Bernhardt and Palmer, 2007; Walsh et al., 2005). One of the better studied urban stream restoration success stories on Strawberry Creek in Berkeley, CA resulted in improved water quality and recovery of the stream ecosystem, largely due to concerted efforts to reduce pollutant loading to the stream (Charbonneau and Resh, 1992). In a watershed in Scotland, riparian buffers did not result in statistically significant improvements in water quality, but source control (i.e. removal of a septic system) resulted in measurable reductions in ammonium and phosphate concentrations (Bergfur et al., 2012). Others have suggested that failure of specific stream restoration projects to improve water quality on their own could be attributed to lack of stormwater controls to augment in-channel improvements (Selvakumar et al., 2010).

The high cost of channel reconfiguration relative to other stream restoration strategies, and the common practice of piecemeal, reach-scale implementation of these projects, led Bernhardt and Palmer (2007) to suggest that this technique is not a cost-effective approach to stream restoration. Instead, they propose riparian buffer planting and stormwater management that both reduce peak flows and flashiness and retain pollutants as more appropriate, watershed-scale restoration strategies. One of the major critiques of stream restoration in practice is that the commonly used analog approach often does not adequately take into account watershed conditions (e.g. Lave, 2009; Simon et al., 2007). Designs that explicitly account for contemporary fluxes of water, sediment, and nutrients, have a higher likelihood of meeting stability and water quality objectives (Roni and Beechie, 2013); however, analog approaches sometimes focus almost exclusively on restoring form with instream structures of uncertain persistence (Miller and Kochel, 2009), often without regard to the full range of water and sediment fluxes. This possibly explains why many of these projects have resulted in no observable improvement in water quality (Selvakumar et al., 2010) or ecological condition (Violin et al., 2011). Understanding how water and sediment fluxes have been altered, and designing restoration projects that explicitly account for these new conditions, is an essential component of sustainable restoration.

Distributed stormwater retrofits installed throughout a watershed can reduce erosive forces, reestablish flow patterns that support aquatic life, and improve water quality (Walsh et al., 2005); however, this is often impractical given constraints imposed by contemporary land uses. In addition, controlling surface runoff can raise local groundwater tables (Ku et al., 1992), and may increase groundwater flux to the stream, potentially exacerbating nutrient loading in certain watersheds. To achieve water quality objectives, a thorough watershed assessment is recommended to identify major nutrient sources and potential restoration projects, both within and outside of the stream channel (Roni and Beechie, 2013). A mix of restoration strategies, including those detailed in this review and conventional upland best management practices has the highest potential to achieve meaningful water quality improvements. Although true watershed-scale restoration is the ideal approach, there are few, if any, practical examples of where this type of restoration planning and implementation has been attempted.
Noting the integrative and sensitive nature of streams, the eminent river engineer Hans Albert Einstein said:

“If we change a river we usually do some good somewhere and good in quotation marks. That means we achieve some kind of a result that we are aiming at but sometimes forget that the same change which we are introducing may have widespread influences somewhere else [...] we must look at a river or a drainage basin or whatever we are talking about as a big unit with many facets. We should not concentrate only on a little piece of that river unless we have some good reason to decide that we can do that.” (Einstein, 1972)

It is important to recognize that stream restoration projects do not exist in a vacuum and they can significantly influence other parts of the watershed. For example, a channel stabilization project may successfully eliminate bank erosion and incision in a restored reach, but the reduction in sediment supply could subsequently cause instability and erosion in downstream reaches that become sediment starved. This underscores importance of a systems perspective rather than a piecemeal amalgamation of individual stream reaches.

4.0 Summary and Recommendations

While the number of studies with sufficient data to confidently assess the performance of stream restoration projects is increasing, there is still comparatively little information for quantitatively evaluating the relative efficacy of different restoration methods for achieving nutrient reduction goals. The complexity of stream ecosystems and the significant variability among regions, watersheds, and sites further complicates comparisons. Despite these concerns, Palmer et al. (2014) reported success rates of various restoration methods in achieving various self-reported objectives. They found that riparian restoration had the highest success in increasing nutrient uptake rates and reducing fluxes (88%), followed by in-stream structure installation (63%), wetland creation (25%), and channel reconstruction (14%). However, sample sizes were small and reported improvements were not necessarily statistically significant. Based on these results and the findings summarized in this literature review, some qualitative recommendations can be made on general approaches to stream restoration for nutrient management:

- Bank Stabilization: In unstable channels with high soil nutrient concentrations, bank erosion may be a significant source of sediment, phosphorus, and potentially nitrogen to receiving waters. Bank stabilization could therefore be a relatively simple way to reduce nutrient loading and is already a common practice to increase channel stability and protect infrastructure. Although estimating historic or present erosion rates is possible, quantification of future channel evolution, and therefore load reduction, is more challenging.
- In-Stream Enhancement: Structures that are already incorporated into stream restoration designs can be constructed to encourage hyporheic exchange and nutrient processing through enhanced geomorphic complexity and bedforms, especially during low discharges.
- Riparian Buffers: Buffers remove groundwater nitrate, protect streambanks, supply in-stream wood and organic carbon to increase in-stream processing and are generally less intrusive and
more cost-effective than channel reconstruction projects. Additionally, when groundwater conditions are amenable, organic carbon soil amendments can encourage denitrification and addition of metal oxides can enhance phosphorus retention.

- **Upland Controls**: Managing flows of water and sediment and reducing nutrient loading through source controls remains an essential strategy for improving water quality. Although complete stormwater retrofits is likely not feasible in many developed watersheds, steps to reduce streamflow amplification and flashiness can reduce the risk of channel erosion and potentially improve in-channel nutrient processing. Additionally, controlling non-point nutrient sources can reduce nutrient loading to streams and may improve the efficiency of in-channel nutrient processing. As stated previously, a combination of restoration strategies that reduce nutrient inputs to streams, reestablish riparian functions, provide balanced water and sediment regimes, and increase in-stream nutrient processing and retention will likely be most effective for improving water quality.

Even with the increase in published stream restoration monitoring studies, there remains a lack of consistent methodology and reported metrics, making direct comparisons challenging. While an increase in monitoring is a promising trend, there also needs to be an improvement in the quality of monitoring programs. Restoration monitoring should focus on metrics that are specific to project objectives (Palmer et al., 2005). Furthermore, monitoring should be pre-planned and hypothesis driven (e.g. bank stabilization will reduce phosphorus loads by 10%) rather than an afterthought. There may be significant lag time between completion of restoration projects and observed improvements (Meals et al., 2010), requiring long-term monitoring that may be perceived as impractical and cost-prohibitive. Monitoring of control, reference, and restored sites can provide critical information on how restored channels may have evolved over time in the absence of restoration interventions. In addition, uncertainty remains on details of in-stream nutrient dynamics and processing. Given these shortcomings, we have identified the following areas of need in addition to improved restoration strategies and implementation:

- **Improved design of sampling methodologies and more rigorous data collection are required to more accurately and effectively assess performance of stream restoration projects.** Monitoring plans must be designed with sufficient statistical power to assess changes in water quality. Sampling frequency can radically alter the length of monitoring required to detect changes and trends (Meals et al., 2010). Paired watershed and before-after-control-impact (BACI) experimental designs may be more robust than simple before/after restoration monitoring by accounting for climatic and hydrologic variability and are structured to assess whether significant differences exist between reference, control, and restoration sites. However, in practice BACI designs may be limited by use of a single control site (Underwood, 1994) and paired watershed designs often have insufficient sample sizes and monitoring periods (Loftis et al., 2001).
- **Controlled experiments arguably have the greatest potential to assess relative impact of different restoration strategies.** Ideally these would be conducted on one or more streams.
in a single watershed with similar impairment to adequately quantify the individual and cumulative impacts of restoration methods.

- A better understanding of the chemical fate and transport of phosphorus in streams is required. LINX / LINX-II and other experiments have provided important insight into in-stream processing and cycling of ammonium and nitrate and a similar effort should be made for phosphorus. It has likely been relatively neglected up to this point because there is no mechanism for permanent removal from stream systems (e.g. denitrification), but burial in bed or floodplain deposits may serve as effective removal mechanisms at engineering time scales and these processes deserve further examination.

- Additional monitoring and reporting of the potential successes of stream restoration projects for nutrient management are needed from diverse geographic locations. While the studies summarized in this review cover most of the U.S. as well as international locations, there are some more highly represented regions (e.g., the Chesapeake Bay watershed). This is largely a function of where nutrient management issues are of most concern, but it is important to note that these observations from one region may not be representative of stream-nutrient dynamics in other environments. To account for these potential differences, it is essential to expand the understanding of stream restoration and nutrient dynamics in other locations.

Existing studies suggest that certain restoration strategies may enhance nutrient retention and removal in stream and riparian systems. However, this is still an emerging science with insufficient evidence to precisely quantify the effects of different restoration strategies across regions and various hydrologic, geologic, and land use contexts. While efforts have been made to develop nutrient crediting programs for stream restoration projects (e.g. Berg et al., 2013), the complexity of nutrient dynamics in stream systems and limited current understanding of this topic will likely require these programs to initially employ safety factors and knowledge updating in a “learning by doing” approach. Given adequate expert knowledge, a conservative nutrient crediting program may be successfully developed based on current science, as long as the significant uncertainty associated with this problem is explicitly incorporated. Factor of safety values would likely be decided upon based on expert knowledge and could be reduced as additional research provides more defensible stream restoration performance metrics. Given the increasing attention stream restoration has been receiving, an increasing emphasis on improved effectiveness monitoring, and the growing number of published studies on the impact of stream restoration on nutrient dynamics, the future looks promising for improved understanding of the efficacy of stream restoration as a nutrient management tool.
5.0 References


moments at the interface of terrestrial and aquatic ecosystems. Ecosystems 6, 301–312. doi:10.1007/s10021-003-0161-9


Appendix C. 2016 Stream Restoration Database Study Summary

**Study ID:** 2016014 Carline and Walsh 2007  
**State/Country:** PA US  
**Category:** Riparian zone  
**Exp. Design:** Before-After with Control

**Project Purpose Statement:**
Quantify the effects of stream bank fencing with narrow grass buffer strips on channel morphology, stream substrate composition, and macroinvertebrate communities at the reach scale and sediment loads at the catchment scale in two second-order streams with unrestricted grazing by cattle and horses.

**Outcomes:**
Riparian buffers (3-4 m) and bank armoring essentially eliminated bank erosion and reduced suspended sediment concentrations 47-87%.

**Abstract:**
Riparian treatments, consisting of 3- to 4-m buffer strips, stream bank stabilization, and rock-lined stream crossings were installed in two streams with livestock grazing to reduce sediment loading and stream bank erosion.

**Project Purposes:**

<table>
<thead>
<tr>
<th>Practice</th>
<th>Aes_Rec_Ed</th>
<th>Bank_Stab</th>
<th>Chan_Reconfig</th>
<th>Chan_Incis_Stab</th>
<th>Sed_Bal</th>
<th>Dam_Retro</th>
<th>Fish_Pass</th>
<th>Flood_Convey</th>
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<th>Hab_veg</th>
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**Data Types Provided in Research Report:**

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</table>

Suspended solids concentrations. Storm and base flow TSS concentrations, Volumetric flow rates, macroinvertebrate abundance and richness data, stream physical characteristics including widths and depths as well as bed substrate details.

**WS_ID** 201601403 Cedar_Run_SubWatershed  
**Drainage Area (ha):** 4600  
**Land Use:** Mixed

**Stream ID/Stream Setting:** 20160140302 Cedar_Run_Post  
**Condition:** Post-Restoration (Agriculture)

**Practices Implemented:**

<table>
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<th>Redirect Practice</th>
<th>Resistant Practice</th>
<th>Grade Control</th>
<th>Flow Control</th>
<th>Riparian Condition/Buffer Reestab</th>
<th>Floodplain Connectivity/Reconfiguration</th>
<th>Habitat Enhance/Instream Features</th>
<th>Channel Reconfig/Planform Changes</th>
<th>Barrier Removal/Fish Passage</th>
<th>Passive Approaches</th>
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**Project Description:**

Fluxes_Managed

**Goals/Performance Standards**
Prevent bank erosion and livestock access to riparian area and streambank in order to assess channel morphology, stream substrate composition, suspended sediments, and macroinvertebrate communities.

**Bank Stabilization:**
Construction of animal crossings and animal accesses (14) including rock-lined ramps, and bank stabilization using 15-cm limestone rocks (245m).
Bed Stabilization:

Riparian Improvements: Streambank fencing including electric fences were installed to protect buffer areas. No plantings were made in the buffer strip; all vegetation colonized naturally.

Floodplain Connectivity:

Habitat Enhancement:

Channel Reconfiguration:

Barrier Removal/Fish Pass:

Infrastructure Protection:

Other Approaches: Streambank fencing (2,000 m) including the use of electric fences. Some electric fences were also installed across stream crossings.

### Practices Implemented:

<table>
<thead>
<tr>
<th>Practice</th>
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<th>Resistive Practice</th>
<th>Grade_Control</th>
<th>Flow_Control</th>
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<td>Passive Approaches</td>
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</tbody>
</table>

### Project Description:

Fluxes_Managed

Goals/Performance Standards

Prevent bank erosion and livestock access to riparian area and streambank in order to assess channel morphology, stream substrate composition, suspended sediments, and macroinvertebrate communities.

Bank Stabilization: Construction of animal crossings and animal accesses (26) including rock-lined ramps, and bank stabilization using 15-cm limestone rocks (1,875m).

Bed Stabilization:

Riparian Improvements: Streambank fencing including electric fences were installed to protect buffer areas. No plantings were made in the buffer strip; all vegetation colonized naturally.

Floodplain Connectivity:

Habitat Enhancement:

Channel Reconfiguration:

Barrier Removal/Fish Pass:

Infrastructure Protection:

Other Approaches: Streambank fencing (2,740 m) including the use of electric fences. Some electric fences were also installed across stream crossings.

### Study ID:

<table>
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<tr>
<td>Exp. Design:</td>
<td>Before-After</td>
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</table>

### Project Purpose Statement:

The primary project purpose was to improve water quality and reduce erosion to enhance habitat for newly introduced native fish species (Gasterosteus aculeatus).

Outcomes:

Restoration of Strawberry Cr. consisted of small (<45 cm) wood and rock grade control structures and bioengineered bank
Water quality in the urban downstream reaches of both the North and South Forks appeared to improve compared with pre-restoration conditions. Water clarity and aesthetic value noticeably improved on the central campus, indicated by decreases in downstream suspended and turbidity. Downstream nutrient and fecal bacterial concentrations both decreased since sewage contamination was eliminated.

**Abstract:**

Water quality in the urban downstream reaches of both the North and South Forks appeared to improve compared with pre-restoration conditions. Water clarity and aesthetic value noticeably improved on the central campus, indicated by decreases in downstream suspended and turbidity. Downstream nutrient and fecal bacterial concentrations both decreased since sewage contamination was eliminated.

**Project Purposes:**

- Aes_Rec_Ed: Yes
- Chan_Reconfig: NS
- Habitat: NS
- Infra_Prot: Yes
- Dam_Retro: NS
- Bank_Stab: Yes
- Flood_Convey: NS
- Species: Yes
- Permit_Req: NS
- Fish.Pass: NS
- Chan_Incis_Stab: Yes
- Floodplain_Recon: NS
- Rip_Veg: NS
- Pub_Safety: Yes
- Other: Yes
- Sed_Bal: NS
- Flow_Mod: NS
- SW.Man: Yes
- WQ_Man: Yes

**Benefits Documented by Researcher:**

- Water Quality: Yes
- Biological: Yes
- Physical: No
- Infrastructure: Yes
- Aesthetic/Rec: Yes
- Other: Yes
- Hydrologic: No
- Public Safety: Yes
- Property Value: NS
- Data_Descp: Nitrogen and phosphorus concentration data and other water quality. Pre- and post-restoration macroinvertebrate data.

**Data Types Provided in Research Report:**

- Water Quality: Yes
- Hydrologic: No
- Physical: No
- Biological: Yes

**Project Description:**

The goal of this study was to highlight some of the methods that made previous restoration efforts as part of the 1987 Strawberry Creek Management Plan successful in the hope of providing a model to assist in implementing similar urban stream restoration projects. The original objectives of the 1987 water quality study were: to evaluate the Creek’s water quality and identify both point and non-point sources of pollution, develop creek and catchment management strategies, and produce a document upon which future evaluation and management decisions could be based. Management actions included: correct deficiencies identified in sanitary engineering investigations, address reports of spills and releases into the storm drain system, and address accelerated stream-bank erosion on central campus, especially at a top priority site with 5-m vertical eroding bank that was undercutting a transportation bridge. Also, the project aimed to prevent further downcutting of the stream and bank undercutting using check dams and making repairs to old check dams. Addressed upstream influences by addressing erosion control in headwater canyons of both forks.
Bank Stabilization:

Bed Stabilization: Grouted rock or wood check dams (still allowing for fish passage); check dam repair in various locations with riprap

Riparian Improvements:

Floodplain Connectivity:

Habitat Enhancement: Check dams were also designed to provide varied habitat for fish and aquatic insect in downstream plunge pools.

Channel Reconfiguration:

Barrier Removal/Fish Pass:

Infrastructure Protection: Redwood Cribwall biotechnical erosion control method

Other Approaches: Sanitary sewer rehabilitation projects; Installed floating oil-spill control booms to trap debris, trash, and oil; Labeling of drains that released into the creek; Erosion control activities were implemented in headwater canyons.


Practices Implemented:

Redirective_Practice No Riparian_Condition/Buffer_Reestab No Barrier_Removal/Fish_Passage No
Resistive_Practice Yes Floodplain_Connectivity/Reconfiguration No Passive_Approaches Yes
Grade_Control Yes Habitat_Enhance/Instream_Features Yes
Flow_Control No Channel_Reconfig/Planform_Changes No

Project Description:

Fluxes_Managed Sediment

Goals/Performance Standards

The goal of this study was to highlight some of the methods that made previous restoration efforts as part of the 1987 Strawberry Creek Management Plan successful in the hope of providing a model to assist in implementing similar urban stream restoration projects. The original objectives of the 1987 water quality study were: to evaluate the Creek’s water quality and identify both point and non-point sources of pollution, develop creek and catchment management strategies, and produce a document upon which future evaluation and management decisions could be based. Management actions included: correct deficiencies identified in sanitary engineering investigations, address reports of spills and releases into the storm drain system, and address accelerated stream-bank erosion on central campus, especially at a top priority site with 5-m vertical eroding bank that was undercutting a transportation bridge.

Also, the project aimed to prevent further downcutting of the stream and bank undercutting using check dams and making repairs to old check dams. Addressed upstream influences by addressing erosion control in headwater canyons of both forks.
Study ID: 2016018 Collins et al. 2013
State/Country: ZZ NZ
Category: Riparian zone
Exp. Design: Control/Treatment

Project Purpose Statement:
A paired-catchment design on four river reaches was used to compare restored riparian buffers with control sites upstream. Chemical water quality sampling was used in conjunction with a macroinvertebrate community assessment. Equivocal benefits of riparian restoration were observed, with improvements in some variables but not in others. The close relationship of the riparian zone with in-stream systems makes it a focus for restoration strategies to mitigate the effects of land use change.

Outcomes:
Riparian buffers increased DO and reduced turbidity but had no impact on nutrient concentrations. This can be partially explained by the narrow buffers and the many gaps in the riparian zone.

Abstract:
A paired-catchment design on four river reaches was used to compare restored riparian buffers with control sites upstream. Chemical water quality sampling was used in conjunction with a macroinvertebrate community assessment. Equivocal benefits of riparian restoration were observed, with improvements in some variables but not in others. Results of the initial principal components analysis suggested that river flow had a large influence on environmental variables, potentially masking effects of the treatment (i.e. the presence/absence of a riparian buffer). Dissolved oxygen and conductivity were found to be significantly higher, and turbidity was significantly lower at sites where planting had occurred. The increase in dissolved oxygen and a decrease in turbidity suggests that planted riparian buffers are having a slight positive impact on water quality. However, this positive impact is confounded by the significant increase in conductivity at planted sites. These mixed responses to the planting of riparian buffers are not uncommon in New Zealand.

Results of the initial principal components analysis suggested that river flow had a large influence on environmental variables, potentially masking effects of the treatment (i.e. the presence/absence of a riparian buffer). Dissolved oxygen and conductivity were found to be significantly higher, and turbidity was significantly lower at sites where planting had occurred. The increase in dissolved oxygen and a decrease in turbidity suggests that planted riparian buffers are having a slight positive impact on water quality. However, this positive impact is confounded by the significant increase in conductivity at planted sites. These mixed responses to the planting of riparian buffers are not uncommon in New Zealand.

Benefits Documented by Researcher:
Water Quality: Yes
Physical: Yes
Infrastructure: NS
Aesthetic/Rec: NS
Other: NS

Data Types Provided in Research Report:
Water Quality: Yes
Hydrologic: No
Physical: Yes
Biological: Yes

Data_Descp: Various chemical data parameters including nutrient (N&P) concentrations. Hydrological data were obtained for study, but not provided in report; Macroinvertebrate Community Index (MCI); streambed substrate and stream shading.

WS_ID: 201601801 Lake Ellesmere Catchment
Drainage_Area (ha): 256000
Land_Use: Agriculture

Stream_ID/Stream Setting: 20160180101 Boggy_Crk_(BC)_Buffer
Condition: Post-Restoration (2 yr)

Practices Implemented:
### Project Description:

**Fluxes Managed**

**Goals/Performance Standards**

Riparian buffer sites were pre-existing buffer areas that were selected for the study to evaluate the effectiveness of riparian planting on water quality. Buffers were not planted specifically for this study.

**Bank Stabilization:**

**Bed Stabilization:**

**Riparian Improvements:** Data collected 2-years after riparian buffer had been planted.

**Floodplain Connectivity:**

**Habitat Enhancement:**

**Channel Reconfiguration:**

**Barrier Removal/Fish Pass:**

**Infrastructure Protection:**

**Other Approaches:** Fences in place to exclude livestock from riparian buffer area.

### Stream_ID/Stream Setting:

20160180102 Harts_Crk_LakeRd_(HT)_Buffer  Condition: Post-Restoration (5 yr)

### Practices Implemented:

<table>
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<th>Practice</th>
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<th>Riparian Condition/Buffer Reestab</th>
<th>Yes</th>
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<td>No Erosion</td>
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</table>

Riparian buffer sites were pre-existing buffer areas that were selected for the study to evaluate the effectiveness of riparian planting on water quality. Buffers were not planted specifically for this study.

**Bank Stabilization:**

**Bed Stabilization:**

**Riparian Improvements:** Data collected 5-years after riparian buffer had been planted.

**Floodplain Connectivity:**

**Habitat Enhancement:**

**Channel Reconfiguration:**

**Barrier Removal/Fish Pass:**

**Infrastructure Protection:**

**Other Approaches:** Fences in place to exclude livestock from riparian buffer area.

### Stream_ID/Stream Setting:

20160180103 Harts_Crk_LochRd_(HL)_Buffer  Condition: Post-Restoration (20 yr)
Practices Implemented:

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<td>Habitat_Enhance/Instream_Features</td>
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<td>Barrier_Removal/Fish_Passage</td>
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<td>Passive_Approaches</td>
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</table>

Project Description:

Fluxes_Managed

Goals/Performance Standards

Riparian buffer sites were pre-existing buffer areas that were selected for the study to evaluate the effectiveness of riparian planting on water quality. Buffers were not planted specifically for this study.

Bank Stabilization:

Bed Stabilization:

Riparian Improvements: Data collected 20+ years after riparian buffer had been planted.

Floodplain Connectivity:

Habitat Enhancement:

Channel Reconfiguration:

Barrier Removal/Fish Pass:

Infrastructure Protection:

Other Approaches: No fences in place, but adjacent land was not utilized for livestock grazing.

Stream_ID/Stream Setting: 20160180104 Birdings_Brook_Buffer  Condition: Post-Restoration (4 yr)

Practices Implemented:

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<td>Floodplain_Connectivity/Reconfiguration</td>
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<td>Channel_Reconfig/Planform_Changes</td>
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<tr>
<td>Barrier_Removal/Fish_Passage</td>
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Project Description:

Fluxes_Managed

Goals/Performance Standards

Riparian buffer sites were pre-existing buffer areas that were selected for the study to evaluate the effectiveness of riparian planting on water quality. Buffers were not planted specifically for this study.

Bank Stabilization:

Bed Stabilization:

Riparian Improvements: Data collected 4-years after riparian buffer had been planted.

Floodplain Connectivity:

Habitat Enhancement:

Channel Reconfiguration:

Barrier Removal/Fish Pass:

Infrastructure Protection:

Other Approaches: Fences in place to exclude livestock from riparian buffer area.
**Stream_ID/Stream Setting:** 20160180110 Buffer_Sites_Combined  
**Condition:** Post-Restoration

**Practices Implemented:**
- Redirective_Practice
- Resistive_Practice
- Grade_Control
- Flow_Control
- Riparian_Condition/Buffer_Reestab
- Floodplain_Connectivity/Reconfiguration
- Habitat_Enhance/Instream_Features
- Channel_Reconfig/Planform_Changes
- Barrier_Removal/Fish_Passage
- Passive_Approaches

**Project Description:**

Fluxes_Managed

Goals/Performance Standards

Bank Stabilization:

Bed Stabilization:

Riparian Improvements:

Floodplain Connectivity:

Habitat Enhancement:

Channel Reconfiguration:

Barrier Removal/Fish Pass:

Infrastructure Protection:

Other Approaches:

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<th>Exp. Design</th>
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<tr>
<td>2016123 Cottonwood Creek Stabilization</td>
<td>Stream restoration (multiple)</td>
<td>Upstream/Downstream &amp; Before/After</td>
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**Project Purpose Statement:**

Control channel erosion and reduce phosphorus loading to Cherry Creek Reservoir. Stabilize 2.83 miles of stream bed and banks, increase baseflow and riparian fringe from about 5 to 25 acres, increase 2-year floodplain from 7 to 83 acres.

**Outcomes:**

Stabilized channel, reconnected floodplain and improved riparian habitat with reduced phosphorus loading to reservoir. As of 2016, the Cottonwood Creek Stream Reclamation project and the two PRF wetland ponds, have been very effective in reducing flow-weighted total TP concentration and TSS load to the downstream PRF. Since the completion of the project, the combination of these three PRFs (treatment train approach) has effectively reduced the flow-weighted TP concentration entering the Reservoir, via Cottonwood Creek, from a pre-project WY average of 143 µg/L to a postproject WY average of 78 µg/L, nearly a 46% reduction. The two wetland PRFs have shown mixed results in reducing TN, and the entire treatment train reach has shown an average increase in TN from upstream to downstream by approximately 20% since 2008. The stream reclamation projects can reduce phosphorus loads and concentrations to levels below the target flow-weighted concentration levels (i.e., 0.20 mg/l).

**Abstract:**

This reach of Cottonwood Creek exhibited substantial bank erosion at key gradient features as well as a deeply incised channel in the lower portions of the reach. Phase I of the reclamation project focused on the upper reach by widening the channel and increasing the meandering of the stream to reduce the velocity of flow and minimize erosion potential. Also, the main channel capacity was reduced to allow more frequent connection to the riparian zone and floodplain. Additionally, a mixture of geotextile fabrics and riparian vegetation were used to stabilize banks and to provide an infiltration zone during storm events. Phase II of the project relocated the lower portion of the stream to the historic channel, to provide a more suitable reach rather than the deeply incised channel that resulted when the stream was originally moved due historic farm practices or perhaps to roadway construction. The lower reach was similarly transformed to minimize velocity and to dissipate storm flows by creating a more expansive channel that allows for filtration and infiltration. The completion of Phase I and II effectively completed a “treatment train” of sediment and nutrient removal structures that have stabilized approximately three miles of
Cottonwood Creek upstream of the Reservoir. Cottonwood Creek’s pre-restoration condition was a highly incised (over 8 feet in some locations) with narrow channel widths (typically 8-feet) that had lost its connection to the floodplain. Approximately 2.16 miles of channel had actively eroding bed and banks, contributing sediment (and phosphorus) to Cherry Creek Reservoir. The Cottonwood Creek project increased sinuosity, provided about 20 riffle-pool drops (typically 9-inches), which reduced the overall main channel slope from about 0.6% to less than 0.2%. The baseflow channel width increased from an average of 8 feet to 23 feet and the width/depth ratio of the channel is greater than 50 over the first two vertical feet above the invert. Wetland vegetation and two wetland basins are part of the overall project. These improvements reduced erosion and sediment loading to Cherry Creek Reservoir.

Project Purposes:

| Aes_Rec_Ed | Chan_Reconfig | Habitat | Infra_Prot | Dam_Retro | Bank_Stab | Flood_Convey | Species | Permit_Req | Fish_Pass | Chan_Incis_Stab | Floodplain_Recon | Rip_Veg | Pub_Safety | Other | Sed_Bal | Flow_Mod | SW_Man | WQ_Man |
|------------|---------------|---------|------------|-----------|-----------|--------------|---------|------------|----------|----------------|------------------|---------|------------|       |         |         |        |         |
| Yes        | Yes           | Yes     | NS         | NS        | Yes       | Yes          | NS      | NS         | NS       | Yes            | Yes              | Yes     | Yes        | NS     | NS      | NS      | Yes    | Yes     |

Benefits Documented by Researcher:

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<th>Aesthetic/Rec</th>
<th>Other</th>
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Data Types Provided in Research Report:

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<th>Water Quality</th>
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<th>Physical</th>
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<tbody>
<tr>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>Instream monitoring of nutrients, sediment, bacteria and other parameters under baseflow and stormflow conditions. Interpretation of upstream-downstream data for restored segment must take into consideration the ACWWA WWTP discharge to Lone Tree Creek.</td>
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WS_ID: 201612301 Cottonwood
Drainage_Area (ha): 2201.5
Land_Use: Cottonwood_Channel_Post
Condition: Post-Restoration (other)

Stream_ID/Stream Setting: 20161230102 Cottonwood_Channel_Post
Condition: Post-Restoration (other)

Practices Implemented:

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<tr>
<th>Redirective_Practice</th>
<th>Riparian.Condition/Buffer_Reestab</th>
<th>BarrierRemoval/Fish_Passage</th>
<th>Resistive_Practice</th>
<th>Floodplain.Connectivity/Reconfiguration</th>
<th>Passive_Approaches</th>
<th>Grade_Control</th>
<th>Habitat.Enhance/Instream_Features</th>
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<td>No</td>
<td>Yes</td>
<td>Channel_Reconfig/Planform_Changes</td>
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</table>

Project Description:

Fluxes_Managed: Nutrients, Sediment

Goals/Performance Standards:

Bank Stabilization: The channel was stabilized using three levels of bio-engineering techniques, ranging from light-duty geotextile and seeding, to a more heavy duty technique employing rock-reinforced willow bundles combined with geotextile. The channel was widened and meanders were increased to reduce the velocity of flow and minimize erosion potential. The improved stream increases the length from 11,600 linear feet with a sinuosity of 1.37 to 14,260 feet with a sinuosity of 1.74.

Bed Stabilization: 20 riffle-pool drops (typically 9 inches), which reduce the overall main channel slope from about 0.6% to less than 0.2%.

Riparian Improvements: Increase base flow and riparian fringe area from about to 25 acres (20 acres), Pre-restoration channel riparian wetlands were primarily associated with limited channel bottom. The project widened the channel and increased the frequency of riparian flooding. These improvements were expected to increase riparian wetland areas by 20-acres.

Floodplain Connectivity: The main channel capacity was reduced to
allow more frequent connection to the riparian zone and floodplain. Pre-restoration 2-year floodplain width was 5.3 acres, which increased to over 80 acres. This increases the riparian corridor area from 4.4 to 24.9 acres and provides for greater infiltration and filtration by vegetation.

**Habitat Enhancement:** 20 riffle-pool drops (typically 9 inches).

**Channel Reconfiguration:** Phase I of the reclamation project focused on the upper reach by widening the channel and increasing the meandering of the stream to reduce the velocity of flow and minimize erosion potential. Also, the main channel capacity was reduced to allow more frequent connection to the riparian zone and floodplain. Phase II of the project relocated the lower portion of the stream to the historic channel, to provide a more suitable reach rather than the deeply incised channel that resulted when the stream was originally moved due to historic farm practices or perhaps to roadway construction. The lower reach was transformed to minimize velocity and to dissipate storm flows by creating a more expansive channel that allows for filtration and infiltration. The improved stream increases the length from 11,600 linear feet with a sinuosity of 1.37 to 14,260 feet with a sinuosity of 1.74.

**Barrier Removal/Fish Pass:** NA

**Infrastructure Protection:**

**Other Approaches:**

**Stream_ID/Stream Setting:** 20161230103 Cottonwood_Peoria_Wetland    **Condition:** Post-Restoration (other)

**Practices Implemented:**

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<th>Practice Type</th>
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<td>Resistive Practice</td>
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<td>Grade Control</td>
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<td>Channel Reconfig/Planform Changes</td>
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**Project Description:**

**Fluxes Managed:** Nutrients, Sediment, Water

**Goals/Performance Standards:** Flood control and phosphorus reduction.

**Bank Stabilization:**

**Bed Stabilization:**

**Riparian Improvements:**

**Floodplain Connectivity:**

**Habitat Enhancement:**

**Channel Reconfiguration:**

**Barrier Removal/Fish Pass:**

**Infrastructure Protection:**

**Other Approaches:** Detention with wetlands

---

**Stream_ID/Stream Setting:** 20161230104 Cottonwood_Cott_Wetland    **Condition:** Post-Restoration (other)

**Practices Implemented:**

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<tr>
<th>Practice Type</th>
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**Project Description:**

- **Fluxes Managed:** Nutrients, Sediment, Water
- **Goals/Performance Standards:** Flood control and phosphorus reduction.

**Bank Stabilization:**

**Bed Stabilization:**

**Riparian Improvements:**

**Floodplain Connectivity:**

**Habitat Enhancement:**

**Channel Reconfiguration:**

**Barrier Removal/Fish Pass:**

**Infrastructure Protection:**

**Other Approaches:** Detention with wetlands

**Stream ID/Stream Setting:** 20161230105 Cottonwood System

**Condition:** Post-Restoration (other)

**Practices Implemented:**

- **Redirective Practice:** No
- **Resistive Practice:** Yes
- **Grade Control:** Yes
- **Flow Control:** Yes
- **Riparian Condition/Buffer Reestab:** Yes
- **Floodplain Connectivity/Reconfiguration:** Yes
- **Habitat Enhance/Instream Features:** Yes
- **Channel Reconfig/Planform Changes:** Yes
- **Barrier Removal/Fish Passage:** No
- **Passive Approaches:** No

**Fluxes Managed:** Nutrients, Sediment

**Goals/Performance Standards:** Channel stabilization, phosphorus reduction and flood control.

**Bank Stabilization:**

**Bed Stabilization:**

**Riparian Improvements:**

**Floodplain Connectivity:**

**Habitat Enhancement:**

**Channel Reconfiguration:**

**Barrier Removal/Fish Pass:**

**Infrastructure Protection:**

**Other Approaches:**

**Project Purpose Statement:**

The major goals were to implement actions under the Bear Creek Reservoir TMDL by reducing phosphorous loadings from bank erosion and stormwater runoff into Bear Creek Reservoir, improve wetlands habitat, provide informational and educational opportunities, and measure the post-construction phosphorus reduction efficiency of the channel improvements.

**Outcomes:**
Coyote Gulch is a tributary to Bear Creek Reservoir and is a substantial contributor of phosphorus to the reservoir. There were four main project objectives: Design, Construction, Monitoring and Education. This project entailed design and construction of bank and channel stabilization features. Returning the channel to a stable environment utilized five enhanced drop structures to correct severe bank erosion, encourage wetland growth and reduce the quantity of total phosphorous entering Bear Creek Reservoir. The ongoing Monitoring Program is designed to provide measurable results by establishing pre and post-construction trends for wet and dry weather events, thereby determining phosphorus removal efficiencies for the improvements. The monitoring program measures total phosphorus into Bear Creek Reservoir and within the water column. The total phosphorus target for the reservoir is to maintain the water column average below 60 ug/L. Controlling total phosphorus source inputs is also a control strategy for reducing chlorophyll levels in the reservoir and meeting the reservoir narrative standard.

Channel stabilization effort successfully reducing nutrient and sediment loading to reservoir. Total phosphorus loading during baseflow conditions before stabilization averaged 20 lbs/year, whereas post-construction loading has ranged from 4.4 to 8 lbs/year. The project withstood the historic September 2013 flood.

Abstract:
Coyote Gulch is a tributary to Bear Creek Reservoir and is a substantial contributor of phosphorus to the reservoir. There were four main project objectives: Design, Construction, Monitoring and Education. This project entailed design and construction of bank and channel stabilization features. Returning the channel to a stable environment utilized five enhanced drop structures to correct severe bank erosion, encourage wetland growth and reduce the quantity of total phosphorous entering Bear Creek Reservoir. The ongoing Monitoring Program is designed to provide measurable results by establishing pre and post-construction trends for wet and dry weather events, thereby determining phosphorus removal efficiencies for the improvements. The monitoring program measures total phosphorus into Bear Creek Reservoir and within the water column. The total phosphorus target for the reservoir is to maintain the water column average below 60 ug/L. Controlling total phosphorus source inputs is also a control strategy for reducing chlorophyll levels in the reservoir and meeting the reservoir narrative standard.

Project Purposes:
- Aes_Rec_Ed: NS
- Chan_Reconfig: NS
- Habitat: NS
- Infra.Prot: NS
- Dam_Retro: NS
- Bank_Stab: Yes
- Flood_Convey: NS
- Species: NS
- Permit_Req: NS
- Fish_Pass: NS
- Chan_Incis_Stab: Yes
- Floodplain_Recon: NS
- Rip_Veg: Yes
- Pub_Safety: NS
- Other: NS
- Sed_Bal: NS
- Flow_Mod: NS
- SW_Man: Yes
- WQ_Man: Yes
- Infra_Prot: NS
- Permit_Req: NS
- Pub_Safety: NS
- Other: NS
- Project Purposes: Water Q: Yes
- Biological: No
- Physical: No
- Floodplain Mod: NS
- Public Safety: NS
- Property Value: NS
- Aesthetic/Rec: Yes
- Other: Yes
- Benefits Documented by Researcher:
- Water Quality: Yes
- Physical: Yes
- Infrastructure: NS
- Aesthetic/Rec: Yes
- Other: Yes
- Biological: No
- Physical: No
- Biological: No
- Data Types Provided in Research Report:
- Water Quality: Yes
- Hydrologic: Yes
- Physical: No
- Biological: No
- Drainage Area (ha): 259
- Land Use: Urban
- Stream ID/Stream Setting: 20161250102 Coyote_Gulch_Post
- Condition: Post-Restoration (other)
- Practices Implemented:
  - Redirective Practice: No
  - Resistive Practice: Yes
  - Grade_Control: Yes
  - Flow_Control: No
  - Riparian_Condition/Buffer_Reestab: Yes
  - Floodplain_Connectivity/Reconfiguration: Yes
  - Habitat_Enhance/Instream_Features: No
  - Channel_Reconfig/Planform_Changes: No
- Project Description:
  - Fluxes_Managed: Nutrients, Sediment
  - Goals/Performance Standards: This Project's objective was to design and construct bank stabilization, five (5) enhanced drop structures and wetlands habitat improvements to correct severe bank erosion and reduce the quantity of total phosphorus entering Bear Creek Reservoir.
  - Bank Stabilization: Bank armororing as necessary to resist erosion.
  - Bed Stabilization: Installation of five grade control (drop) structures using boulders.
  - Riparian Improvements: Revegetation with native grasses.
  - Floodplain Connectivity: Fill in the existing deep, eroded channel and re-establish a new stabilized channel at the surface, near the grade of the existing top of channel banks. The reconstructed channel emulates a natural stream system and would be armored as necessary and provided with grade controls to resist
erosion on the relatively steep slope down to the lake.

Habitat Enhancement:

Channel Reconfiguration:

Barrier Removal/Fish Pass:

Infrastructure Protection:

Other Approaches:

<table>
<thead>
<tr>
<th>Study ID:</th>
<th>2016023 Doyle et al. 2003</th>
<th>State/Country:</th>
<th>WI US</th>
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<tr>
<td>Category:</td>
<td>In-stream processing</td>
<td>Exp. Design:</td>
<td>Upstream/Downstream</td>
</tr>
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</table>

**Project Purpose Statement:**
Study to analyze the affects of geomorphic controls and dynamic reestablishment on nutrient retention metrics following dam removal in Wisconsin. Attempts to isolate the relative influences of biochemical process, background nutrient concentration and hydrogeomorphology on MRP retention in streams.

**Outcomes:**
Dam removal may reduce phosphorus retention capacity, leading to an ~40% increase in downstream P concentrations. Changes to channel hydrogeomorphology (i.e. velocity and depth) likely have much less of an effect on uptake and retention than uptake processes. Therefore, restoration should focus on restoring conditions to increase uptake processes rather than simply reducing velocity and depth.

**Abstract:**
The authors compared the relative influences of biochemical uptake processes and dynamic hydrology and geomorphology (hydrogeomorphology) on molybdate reactive phosphorus (MRP) retention within a stream. MRP concentrations were measured upstream and downstream of a 4.5-km reach undergoing dynamic channel adjustment in response to downstream dam removal. Geomorphic adjustments following removal produced measurable changes in velocity and depth, and decreases in MRP retention. Paired upstream and downstream measurements of MRP concentration were used to compute three retention metrics: uptake rate, mass transfer coefficient, and uptake length, which were used as model parameters. Modeling results showed that changes in channel morphology alone following dam removal could result in an approximate 40% increase in downstream MRP concentrations compared with conditions with the dam in place. However, empirical and modeling results indicate that hydrogeomorphology can control nutrient retention on the reach scale only when uptake processes are either sufficiently great or when uptake rates have limited variability. Review of published phosphorus retention values revealed greater variability in biochemical uptake rates than in hydrogeomorphology. Thus uptake rates should exert a stronger control on reach-scale MRP retention than changing channel morphology or hydrology. These results suggest that maintaining or restoring channel conditions that are conducive to biochemical uptake are of greater priority than restoration of hydrologic or geomorphic conditions alone.

**Project Purposes:**

**Benefits Documented by Researcher:**

**Data Types Provided in Research Report:**

**WS_ID:** 201602301 koshkonong_ws

**Drainage_Area (ha):** 36000

**Land_Use:**
Stream_ID/Stream Setting: 20160230101 koshkonong_river

Practices Implemented:

- Redirective_PRACTICE: No
- Resistive_PRACTICE: No
- Grade_Control: No
- Flow_Control: No
- Riparian_Condition/Buffer_Reestab: No
- Floodplain_Connectivity/Reconfiguration: No
- Habitat_Enhance/Instream_Features: No
- Channel_Reconfig/Planform_Changes: No
- Barrier_Removal/Fish_Passage: Yes
- Passive_Approaches: No
- Fluxes_Managed

Goals/Performance
Standards
Bank Stabilization:
Bed Stabilization:
Riparian Improvements:
Floodplain Connectivity:
Habitat Enhancement:
Channel Reconfiguration:
Barrier Removal/Fish Pass: dam removal
Infrastructure Protection:
Other Approaches:

Study conducted in the coastal plain of western Maryland on two portions of the watershed, upper stream reaches with a control and lower stream reaches with a control. Primary purpose of study was to assess the performance of stream restoration on reducing nutrient transport to downstream reaches. Controls in the context of this study represented degraded stream reaches in their respective locations within the watershed.

The degradation of headwater streams is common in urbanized coastal areas, and the role these streams play in contributing to downstream pollution is a concern among natural resource managers and policy makers. Thus, many urban stream restoration efforts are increasingly focused on reducing the downstream flux of pollutants. In regions that suffer from coastal eutrophication, it is unclear whether stream restoration does in fact reduce nitrogen (N) flux to downstream waters and, if so, by how much and at what cost. The authors evaluate whether stream restoration implemented to improve water quality of urban and suburban streams in the Chesapeake Bay region, USA, is effective at reducing the export of N in stream flow to downstream waters. The authors assessed the effectiveness of restored streams positioned in the upland vs. lowland regions of Coastal Plain watershed during both average and stormflow conditions. The authors found that, during periods of low discharge, lowland streams that receive minor N inputs from groundwater or bank seepage reduced in-stream N fluxes. Furthermore, lowland streams with the highest N concentrations and lowest discharge were the most effective. During periods of high flow, only those restoration projects that converted lowland streams to stream–wetland complexes seemed to be effective at reducing N fluxes, presumably because the design promoted the spillover of stream flow onto adjacent floodplains and wetlands. The observed N-removal rates were relatively high for stream ecosystems, and on the order of 5% of the inputs to the watershed. The dominant forms of N entering restored reaches varied during low and high flows, indicating that N...
uptake and retention were controlled by distinctive processes during different hydrological conditions. Therefore, in order for stream restoration to effectively reduce N fluxes exported to downstream waters, restoration design should include features that enhance the processing and retention of different forms of N, and for a wide range of flow conditions. The use of strategic designs that match the dominant attributes of a stream such as position in the watershed, influence of groundwater, dominant flow conditions, and N concentrations is crucial to assure the success of restoration.

Project Purposes:

| Aes_Rec_Ed | Chan_Reconfig | Yes | Habitat | NS | Infra.Prot | NS | Dam_Retro | NS |
| Bank_Stab | Yes | Flood_Convey | NS | Species | NS | Permit_REQ | NS | Fish_Pass | NS |
| Chan_Incис_Stab | Yes | Floodplain_Recon | Yes | Rip_Veg | Yes | Pub_Safety | NS | Other | NS |
| Sed_Bal | NS | Flow_Mod | NS | SW_Man | NS | WQ_Man | Yes |

Benefits Documented by Researcher:

| Water Quality | Yes | Physical | NS | Infrastructure | NS | Aesthetic/Rec | NS | Other | NS |
| Biological | NS | Floodplain Mod | NS | Public Safety | NS | Property Value | NS |

Data Types Provided in Research Report:

| Water Quality | Yes | Hydrologic | Yes | Physical | No | Biological | No |
| Data_Descp | TN, particulate N, dissolved org N, ammonium N and nitrate N. Storm-event data for various nitrogen species but only available graphically. Upstream/downstream nutrient fluxes.

WS_ID 201602701 Coastal_plain_upland Drainage_Area (ha): Land_Use: Urban

Stream_ID/Stream Setting: 20160270101 weems_cr_bristol Condition: Post-Restoration (other)

Practices Implemented:

| Redirective_Practice | No | Riparian.Condition/Buffer_Reestab | No | Barrier_Removal/Fish_Passage | No |
| Resistive_Practice | Yes | Floodplain_Connectivity/Reconfiguration | No | Passive_Approaches | No |
| Grade_Control | Yes | Habitat_Enhance/Instream_Features | No |
| Flow_Control | No | Channel_Reconfig/Planform_Changes | Yes |

Project Description:

Fluxes_Managed

Goals/Performance Standards

Bank Stabilization: (Bristol [BRI], Moreland [MOR], and Mall [MAL]; were “geomorphically restored” using channel design methods (e.g., Gillilan 1996, Rosgen 1996, Federal Interagency Stream Restoration Working Group 1998) commonly employed to reduce streambed and bank erosion including some level of channel reconfiguration, bank armoring, boulder placement, and grade controls to increase hydraulic resistance.

Bed Stabilization: (Bristol [BRI], Moreland [MOR], and Mall [MAL]; were “geomorphically restored” using channel design methods (e.g., Gillilan 1996, Rosgen 1996, Federal Interagency Stream Restoration Working Group 1998) commonly employed to reduce streambed and bank erosion including some level of channel reconfiguration, bank armoring, boulder placement, and grade controls to increase hydraulic resistance.

Riparian Improvements:

Floodplain Connectivity:

Habitat Enhancement:

Channel Reconfiguration: (Bristol [BRI], Moreland [MOR], and Mall [MAL]; were “geomorphically restored” using channel design methods (e.g., Gillilan 1996, Rosgen 1996, Federal Interagency Stream Restoration Working
Group 1998) commonly employed to reduce streambed and bank erosion including some level of channel reconfiguration, bank armoring, boulder placement, and grade controls to increase hydraulic resistance.

Barrier Removal/Fish Pass:
Infrastructure Protection:
Other Approaches:

Stream_ID/Stream Setting: 20160270102 weems_cr_morland

Practices Implemented:

Redirective_Practice No Riparian_Condition/Buffer_Reestab No Barrier_Removal/Fish_Passage No
Resistive_Practice Yes Floodplain_Connectivity/Reconfiguration No Passive_Approaches No
Grade_Control Yes Habitat_Enhance/Instream_Features No
Flow_Control No Channel_Reconfig/Planform_Changes Yes

Project Description:
Fluxes_Managed
Goals/Performance Standards
Bank Stabilization: (Bristol [BRI], Moreland [MOR], and Mall [MAL]; were “geomorphically restored” using channel design methods (e.g., Gillilan 1996, Rosgen 1996, Federal Interagency Stream Restoration Working Group 1998) commonly employed to reduce streambed and bank erosion including some level of channel reconfiguration, bank armoring, boulder placement, and grade controls to increase hydraulic resistance.

Bed Stabilization: (Bristol [BRI], Moreland [MOR], and Mall [MAL]; were “geomorphically restored” using channel design methods (e.g., Gillilan 1996, Rosgen 1996, Federal Interagency Stream Restoration Working Group 1998) commonly employed to reduce streambed and bank erosion including some level of channel reconfiguration, bank armoring, boulder placement, and grade controls to increase hydraulic resistance.

Riparian Improvements:
Floodplain Connectivity:
Habitat Enhancement:
Channel Reconfiguration: (Bristol [BRI], Moreland [MOR], and Mall [MAL]; were “geomorphically restored” using channel design methods (e.g., Gillilan 1996, Rosgen 1996, Federal Interagency Stream Restoration Working Group 1998) commonly employed to reduce streambed and bank erosion including some level of channel reconfiguration, bank armoring, boulder placement, and grade controls to increase hydraulic resistance.

Barrier Removal/Fish Pass:
Infrastructure Protection:
Other Approaches:

Stream_ID/Stream Setting: 20160270103 weems_cr_mall

Practices Implemented:

Redirective_Practice No Riparian_Condition/Buffer_Reestab No Barrier_Removal/Fish_Passage No
Resistive_Practice Yes Floodplain_Connectivity/Reconfiguration No Passive_Approaches No
Grade_Control Yes Habitat_Enhance/Instream_Features No
Flow_Control No Channel_Reconfig/Planform_Changes Yes
Fluxes_Managed

Goals/Performance Standards

Bank Stabilization: (Bristol [BRI], Moreland [MOR], and Mall [MAL]; were “geomorphically restored” using channel design methods (e.g., Gillilan 1996, Rosgen 1996, Federal Interagency Stream Restoration Working Group 1998) commonly employed to reduce streambed and bank erosion including some level of channel reconfiguration, bank armoring, boulder placement, and grade controls to increase hydraulic resistance.

Bed Stabilization: (Bristol [BRI], Moreland [MOR], and Mall [MAL]; were “geomorphically restored” using channel design methods (e.g., Gillilan 1996, Rosgen 1996, Federal Interagency Stream Restoration Working Group 1998) commonly employed to reduce streambed and bank erosion including some level of channel reconfiguration, bank armoring, boulder placement, and grade controls to increase hydraulic resistance.

Riparian Improvements:

Floodplain Connectivity:

Habitat Enhancement:

Channel Reconfiguration: (Bristol [BRI], Moreland [MOR], and Mall [MAL]; were “geomorphically restored” using channel design methods (e.g., Gillilan 1996, Rosgen 1996, Federal Interagency Stream Restoration Working Group 1998) commonly employed to reduce streambed and bank erosion including some level of channel reconfiguration, bank armoring, boulder placement, and grade controls to increase hydraulic resistance.

Barrier Removal/Fish Pass:

Infrastructure Protection:

Other Approaches:

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<td>20160270201 howards_branch</td>
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Project Description:

Fluxes_Managed

Goals/Performance Standards

Bank Stabilization:

Bed Stabilization: (Howard’s Branch [HBR] and Wilelinor [WIL]) were restored with less-conventional methods that involved sculpting a combination of back-watered “step-pools” of varied sizes connected by small “riffles,” adding rock weirs in various places, and establishing vegetated floodplains.

Riparian Improvements:

Floodplain Connectivity: (Howard’s Branch [HBR] and Wilelinor [WIL]) were restored with less-conventional methods that involved sculpting a combination of back-watered “step-pools” of varied sizes connected by small
“riffles,” adding rock weirs in various places, and establishing vegetated floodplains.

Habitat Enhancement:
Channel Reconfiguration:
Barrier Removal/Fish Pass:
Infrastructure Protection:
Other Approaches:

**Stream_ID/Stream Setting:** 20160270202 wilelinor_str_valley  

**Practices Implemented:**
- Redirective_Practice: No
- Resistive_Practice: No
- Grade_Control: Yes
- Flow_Control: No

**Project Description:**
Fluxes_Managed
Goals/Performance Standards
Bank Stabilization:
Bed Stabilization: (Howard’s Branch [HBR] and Wilelinor [WIL]) were restored with less-conventional methods that involved sculpting a combination of back-watered “step-pools” of varied sizes connected by small “riffles,” adding rock weirs in various places, and establishing vegetated floodplains.

Riparian Improvements:
Floodplain Connectivity: (Howard’s Branch [HBR] and Wilelinor [WIL]) were restored with less-conventional methods that involved sculpting a combination of back-watered “step-pools” of varied sizes connected by small “riffles,” adding rock weirs in various places, and establishing vegetated floodplains.

Habitat Enhancement:
Channel Reconfiguration:
Barrier Removal/Fish Pass:
Infrastructure Protection:
Other Approaches:

**Stream_ID/Stream Setting:** 20160270203 spa_cr  

**Practices Implemented:**
- Redirective_Practice: No
- Resistive_Practice: No
- Grade_Control: No
- Flow_Control: Yes

**Project Description:**
Fluxes_Managed
Goals/Performance Standards
Bank Stabilization: (Spa Creek [SPA]) was restored by regrading its banks, planting riparian grasses, and placing small
cobbles and stones along the stream bed.

Bed Stabilization:
Riparian Improvements: (Spa Creek [SPA]) was restored by regrading its banks, planting riparian grasses, and placing small cobbles and stones along the stream bed.

Floodplain Connectivity: (Spa Creek [SPA]) was restored by regrading its banks, planting riparian grasses, and placing small cobbles and stones along the stream bed.

Habitat Enhancement:
Channel Reconfiguration:
Barrier Removal/Fish Pass:
Infrastructure Protection:
Other Approaches:

<table>
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<tr>
<th>Study ID</th>
<th>Fink and Mitsch 2007</th>
<th>State/Country</th>
<th>OH</th>
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<tr>
<td>Category</td>
<td>Floodplain reconnection</td>
<td>Exp. Design</td>
<td>Inflow/Outflow</td>
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</table>

**Project Purpose Statement:**
The objective of this project was to observe the function of a created river diversion wetland in the upper Ohio River basin. Focus was water quality functions and the development of herbaceous plant communities in a riparian wetland.

**Outcomes:**
A constructed floodplain wetland is a significant nutrient sink on an annual basis. However, it may be a net source of P and organic N, especially during large summer thunderstorms which are preceded by relatively dry periods.

**Abstract:**
Hydrological, successional, and water-quality dynamics are documented for a whole-ecosystem study involving a 3-ha created riparian wetland at the Schiermeier Olentangy River Wetland Research Park at The Ohio State University in Columbus during 2003 and 2004. Overall, the oxbow design is successful in ecological terms and the authors recommend that similar diversion wetlands be created in other locations to examine their function under different climatic and hydrological conditions.

**Project Purposes:**

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<thead>
<tr>
<th>Aes_Rec_Ed</th>
<th>Chan_Reconfig</th>
<th>NS</th>
<th>Habitat</th>
<th>NS</th>
<th>Infra.Prot</th>
<th>NS</th>
<th>Dam_Retro</th>
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<tbody>
<tr>
<td>Bank_Stab</td>
<td>Flood_Convey</td>
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<td>Species</td>
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<td>Chan_Incis_Stab</td>
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<td>Rip_Veg</td>
<td>NS</td>
<td>Pub_Safety</td>
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<td>Sed_Bal</td>
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</table>

**Benefits Documented by Researcher:**

| Water Quality | Yes | Physical | Yes | Infrastructure | NS | Aesthetic/Rec | NS | Other | NS |
| Biological    | Yes | Floodplain Mod | NS | Public Safety | NS | Property Value | NS |        |    |

**Data Types Provided in Research Report:**

| Water Quality | Yes | Hydrologic: | Yes | Physical: | Yes | Biological: | No |
| Data_Descp | Nitrogen (TKN, NO3) and phosphorus, US/DS nutrient concentrations, nutrient retention. Also, TSS, flow, vegetative species diversity, vegetation diversity |

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<th>WS_ID</th>
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**Stream_ID/Stream Setting:**

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<th>Stream_ID/Stream Setting</th>
<th>2016001010101 All_Oxbow_Wetland</th>
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</table>

**Practices Implemented:**

| Redirective_Practice | No | Riparian_Condition/Buffer_Reestab | No | Barrier_Removal/Fish_Passage | No |
| Resistive_Practice   | No | Floodplain_Connectivity/Reconfiguration | Yes | Passive_Approaches | No |
| Grade_Control        | No | Habitat_Enhance/Instream_Features | No | | |

Friday, August 26, 2016
Flux Control No  Channel Reconfig/Planform Changes No

### Project Description:

**Fluxes Managed**  Flow Rates, Nutrients

**Goals/Performance Standards**  Analyzed constructed diversion wetland ecosystems in enough detail to determine if the various zones of the wetland are functioning similarly, and take into account rare but important hydrologic events such as spring floods, rainstorms, and ice melts.

**Bank Stabilization:**

**Bed Stabilization:**

**Riparian Improvements:**

**Floodplain Connectivity:**  Construction of river diversion wetland in 1996 noted to increase connectivity between rivers and floodplains.

**Habitat Enhancement:**

**Channel Reconfiguration:**

**Barrier Removal/Fish Pass:**

**Infrastructure Protection:**

**Other Approaches:**

### Study ID: 2016039 Harrison et al. 2012  State/Country MD US

#### Category: In-stream processing  Exp. Design: Inflow/Outflow with Control

#### Project Purpose Statement:

**Purposes:** (1) quantify and compare sediment denitrification potential (DEA) among and within stream features (pools, riffles, organic debris dams), across stream condition (forested, restored, degraded), and across seasons; (2) quantify and compare methane production among stream features (pools and riffles) and stream sites; and (3) determine the controls on denitrification in stream sediments and how they vary seasonally.

**Outcomes:**

Denitrification potential was higher in organic debris dams than in pools, riffles, and sloughs and was higher in forested than urban degraded and urban restored streams. Reach scale nitrification and denitrification rates were similar (157-344 and 97-230 mg N m⁻² d⁻¹) in both restored and degraded sites indicating that cycling between N types is common and these sites can be N sinks.

**Abstract:**

In-stream geomorphic features in urban restored and degraded sites have the potential to function as N sinks by maintaining anaerobic conditions and microbial biomass and activity that stimulate denitrification.

### Project Purposes:

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<tr>
<th>Aes_Rec_Ed</th>
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<th>Habitat</th>
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#### Benefits Documented by Researcher:

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#### Data Types Provided in Research Report:

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<td>Data_Descp</td>
<td>Nitrogen, denitrification potential. Microbial biomass and activity among geomorphic stream features over all sites, sampling dates, and land uses. Physical geomorphic parameters.</td>
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Drainage Area (ha): 847  Land Use: Urban

Stream_ID/Stream Setting: 20160390401 MBOR_MineOldRest  Condition: Post-Restoration (other)

Practices Implemented:
- Redirective Practice: No
- Resistive Practice: No
- Grade Control: Yes
- Flow Control: No
- Riparian Condition/Buffer Reestab: Yes
- Floodplain Connectivity/Reconfiguration: Yes
- Habitat Enhance/Instream Features: No
- Channel Reconfig/Planform Changes: Yes
- Barrier Removal/Fish Passage: No
- Passive Approaches: No

Project Description:
Fluxes_Managed
Goals/Performance Standards
Bank Stabilization:
Bed Stabilization: creation of pool-riffle sequences
Riparian Improvements: re-vegetation of the riparian zone
Floodplain Connectivity: regrading the stream banks to hydrologically reconnect the stream to the riparian zone.
Habitat Enhancement:
Channel Reconfiguration:
Barrier Removal/Fish Pass:
Infrastructure Protection:
Other Approaches:

Stream_ID/Stream Setting: 20160390402 MBNR_MineNewRest  Condition: Post-Restoration (other)

Practices Implemented:
- Redirective Practice: No
- Resistive Practice: No
- Grade Control: Yes
- Flow Control: No
- Riparian Condition/Buffer Reestab: Yes
- Floodplain Connectivity/Reconfiguration: Yes
- Habitat Enhance/Instream Features: No
- Channel Reconfig/Planform Changes: Yes
- Barrier Removal/Fish Passage: No
- Passive Approaches: No

Project Description:
Fluxes_Managed
Goals/Performance Standards
Bank Stabilization:
Bed Stabilization: creation of pool-riffle sequences
Riparian Improvements: re-vegetation of the riparian zone
Floodplain Connectivity: regrading the stream banks to hydrologically reconnect the stream to the riparian zone.
Habitat Enhancement:
Channel Reconfiguration:
Barrier Removal/Fish Pass:
Infrastructure Protection:
Other Approaches:
Study within the North Carolina Piedmont region on urban streams to assess the uptake of ammonium and affect on benthic macroinvertebrates related to restoration efforts and instream structures. WQ metrics based on injections and subsequent sampling.

Outcomes:
Restored sites had higher percentage of coarse substrate, lower riparian cover, and higher in-stream temperatures compared to unrestored sites. These factors led to an increase in algal biomass at these sites. Ammonium uptake lengths were significantly shorter in restored reaches. Ammonium concentrations did not differ between sites.

Abstract:
Comparisons of ammonium uptake parameters in restored and unrestored urban streams suggest that sufficient light penetration to areas where hard substrates have been installed should be an important management consideration to enhance biofilm accumulation and subsequent ammonium removal to the streambed. The authors studied ammonium uptake parameters and macroinvertebrate communities in 3 types of restoration structures (riffle, cross vane, and step pool) in restored streams and in unrestored urban streams in Greensboro, North Carolina, USA, where urbanization has led to high nutrient concentrations, degraded channel conditions, and low biotic diversity in streams. Restored streams had a significantly higher percentage of large substrates (boulder, cobble, and gravel) and less canopy cover compared to unrestored streams (P = 0.029; t-test), providing substrates and sufficient light penetration for biofilm growth. Benthic chlorophyll a was higher in restored compared to unrestored streams. Significantly shorter ammonium uptake length (P = 0.02) was observed in restored compared to unrestored sites. This effect was probably related to greater biofilm development and therefore more assimilation sites for removal of ammonium from the stream water. Differences in uptake velocity (P < 0.07) and areal uptake (P < 0.06) were not significant. Despite the shorter ammonium uptake length in restored streams, there was little improvement in measures of macroinvertebrate-based water quality classifications between restored and unrestored streams (P = 0.545). Because this study was completed 2 years post restoration, continued, longer-term monitoring of restored streams is needed for full evaluation of the effects of the restoration approaches used in these streams.

**Project Purposes:**

Aes_Rec_Ed | NS | Chan_Reconfig | NS | Habitat | NS | Infra.Prot | NS | Dam_Retro | NS
Bank_Stab | Yes | Flood_Convey | NS | Species | NS | Permit Req | NS | Fish_Pass | NS
Chan_Incis_Stab | Yes | Floodplain_Recon | NS | Rip_Veg | Yes | Pub_Safety | NS | Other | Yes
Sed_Bal | NS | Flow_Mod | NS | SW_Man | NS | WQ_Man | NS

**Benefits Documented by Researcher:**

Water Quality | Yes | Physical | Yes | Infrastructure | NS | Aesthetic/Rec | NS | Other | NS
Biological | Yes | Floodplain Mod | NS | Public Safety | NS | Property Value | NS

**Data Types Provided in Research Report:**

Water Quality: Yes Hydrologic: No Physical: Yes Biological: Yes

Data_Descp: Nitrogen, nutrient uptake rates. Initial stream injection concentrations for ammonium-N for each stream (averaged per locations) and uptake metrics. Additional data presented in charts and likely more available.
Flow_Control No  Channel_Reconfig/Planform_Changes No

**Project Description:**

Fluxes_Managed

Goals/Performance Standards

Bank Stabilization: specific type not indicated, Benbow map indicates "rock bank" and root wad

Bed Stabilization: cross veins, riffles and step pools

Riparian Improvements: Riparian planting

Floodplain Connectivity:

Habitat Enhancement:

Channel Reconfiguration:

Barrier Removal/Fish Pass:

Infrastructure Protection:

Other Approaches:

**Stream_ID/Stream Setting:** 20160450102 brown_bark

**Condition:** Post-Restoration (2 yr)

**Practices Implemented:**

Redirective_Practice No  Riparian.Condition/Buffer_Reestab Yes  BarrierRemoval/Fish_Passage No

Resistive_Practice Yes  Floodplain.Connectivity/Reconfiguration No  Passive_Approaches No

Grade_Control Yes  Habitat_HasEnhance/Instream_Features No

Flow_Control No  Channel_Reconfig/Planform_Changes No

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Project Description:
Fluxes_Managed

Goals/Performance Standards
Bank Stabilization: specific type not indicated, Benbow map indicates "rock bank" and root wad
Bed Stabilization: cross veins, riffles and step pools
Riparian Improvements: Riparian planting
Floodplain Connectivity:
Habitat Enhancement:
Channel Reconfiguration:
Barrier Removal/Fish Pass:
Infrastructure Protection:
Other Approaches:

Stream_ID/Stream Setting: 20160450107 benbow_riff Condition: Post-Restoration (2 yr)

Practices Implemented:

Redirective_Practice
Resistive_Practice
Grade_Control
Flow_Control
Riparian_Condition/Buffer_Reestab
Floodplain_Connectivity/Reconfiguration
Habitat_Enhance/Instream_Features
Channel_Reconfig/Planform_Changes
Barrier_Removal/Fish_Passage
Passive_Approaches

Project Description:
Fluxes_Managed

Goals/Performance Standards
Bank Stabilization:
Bed Stabilization:
Riparian Improvements:
Floodplain Connectivity:
Habitat Enhancement:
Channel Reconfiguration:
Barrier Removal/Fish Pass:
Infrastructure Protection:
Other Approaches:

Stream_ID/Stream Setting: 20160450108 benbow_cv Condition: Post-Restoration (2 yr)

Practices Implemented:

Redirective_Practice
Resistive_Practice
Grade_Control
Flow_Control
Riparian_Condition/Buffer_Reestab
Floodplain_Connectivity/Reconfiguration
Habitat_Enhance/Instream_Features
Channel_Reconfig/Planform_Changes
Barrier_Removal/Fish_Passage
Passive_Approaches
Fluxes Managed

Goals/Performance Standards

Bank Stabilization:

Bed Stabilization:

Riparian Improvements:

Floodplain Connectivity:

Habitat Enhancement:

Channel Reconfiguration:

Barrier Removal/Fish Pass:

Infrastructure Protection:

Other Approaches:

**Stream_ID/Stream Setting:** 20160450109 benbow_step

**Condition:** Post-Restoration (2 yr)

**Practices Implemented:**

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**Project Description:**

Fluxes Managed

Goals/Performance Standards

Bank Stabilization:

Bed Stabilization:

Riparian Improvements:

Floodplain Connectivity:

Habitat Enhancement:

Channel Reconfiguration:

Barrier Removal/Fish Pass:

Infrastructure Protection:

Other Approaches:

**Stream_ID/Stream Setting:** 20160450110 brown_bark_riff

**Condition:** Post-Restoration (2 yr)

**Practices Implemented:**

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**Project Description:**

Fluxes_Managed
Goals/Performance
Standards
Bank Stabilization:
Bed Stabilization:
Riparian Improvements:
Floodplain Connectivity:
Habitat Enhancement:
Channel Reconfiguration:
Barrier Removal/Fish Pass:
Infrastructure Protection:
Other Approaches:

Stream_ID/Stream Setting: 20160450111 brown_bark_cv

Condition: Post-Restoration (2 yr)

Practices Implemented:
Redirective_Practice  Riparian_Condition/Buffer_Reestab  Barrier_Removal/Fish_Passage
Resistive_Practice  Floodplain_Connectivity/Reconfiguration  Passive_Approaches
Grade_Control  Habitat_Enhance/Instream_Features
Flow_Control  Channel_Reconfig/Planform_Changes

Project Description:
Fluxes_Managed

Goals/Performance
Standards
Bank Stabilization:
Bed Stabilization:
Riparian Improvements:
Floodplain Connectivity:
Habitat Enhancement:
Channel Reconfiguration:
Barrier Removal/Fish Pass:
Infrastructure Protection:
Other Approaches:

Stream_ID/Stream Setting: 20160450112 brown_bark_step

Condition: Post-Restoration (2 yr)

Practices Implemented:
Redirective_Practice  Riparian_Condition/Buffer_Reestab  Barrier_Removal/Fish_Passage
Resistive_Practice  Floodplain_Connectivity/Reconfiguration  Passive_Approaches
Grade_Control  Habitat_Enhance/Instream_Features
Flow_Control  Channel_Reconfig/Planform_Changes

Project Description:
Fluxes_Managed
**Goals/Performance Standards**

**Bank Stabilization:**

**Bed Stabilization:**

**Riparian Improvements:**

**Floodplain Connectivity:**

**Habitat Enhancement:**

**Channel Reconfiguration:**

**Barrier Removal/Fish Pass:**

**Infrastructure Protection:**

**Other Approaches:**

**Stream_ID/Stream Setting:** 20160450113 spring_valley_riff  

**Condition:** Post-Restoration (2 yr)

**Practices Implemented:**

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**Project Description:**

Fluxes.Managed

**Goals/Performance Standards**

**Bank Stabilization:**

**Bed Stabilization:**

**Riparian Improvements:**

**Floodplain Connectivity:**

**Habitat Enhancement:**

**Channel Reconfiguration:**

**Barrier Removal/Fish Pass:**

**Infrastructure Protection:**

**Other Approaches:**

**Stream_ID/Stream Setting:** 20160450114 spring_valley_cv  

**Condition:** Post-Restoration (2 yr)

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**Project Description:**

Fluxes.Managed
Goals/Performance Standards
Bank Stabilization:
Bed Stabilization:
Riparian Improvements:
Floodplain Connectivity:
Habitat Enhancement:
Channel Reconfiguration:
Barrier Removal/Fish Pass:
Infrastructure Protection:
Other Approaches:

Stream_ID/Stream Setting: 20160450115 spring_valley_step

Practices Implemented:
Redirective_Practice Riparian_Condition/Buffer_Reestab Barrier_Removal/Fish_Passage
Resistive_Practice Floodplain_Connectivity/Reconfiguration Passive_Approaches
Grade_Control Habitat_Enhance/Instream_Features
Flow_Control Channel_Reconfig/Planform_Changes

Project Description:
Fluxes_Managed

Goals/Performance Standards
Bank Stabilization:
Bed Stabilization:
Riparian Improvements:
Floodplain Connectivity:
Habitat Enhancement:
Channel Reconfiguration:
Barrier Removal/Fish Pass:
Infrastructure Protection:
Other Approaches:

Stream_ID/Stream Setting: 20160450116 restored_all

Practices Implemented:
Redirective_Practice Riparian_Condition/Buffer_Reestab Barrier_Removal/Fish_Passage
Resistive_Practice Floodplain_Connectivity/Reconfiguration Passive_Approaches
Grade_Control Habitat_Enhance/Instream_Features
Flow_Control Channel_Reconfig/Planform_Changes

Project Description:
Fluxes_Managed
Goals/Performance Standards

Bank Stabilization:

Bed Stabilization:

Riparian Improvements:

Floodplain Connectivity:

Habitat Enhancement:

Channel Reconfiguration:

Barrier Removal/Fish Pass:

Infrastructure Protection:

Other Approaches:

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Project Purpose Statement:
Quantify the influence of the change in benthic habitat on several metrics of ecosystem function. Evaluate the effects of creation of upstream sediment traps paired with downstream bank stabilization and habitat amendments as a type of habitat restoration on ecosystem function. Study was replicated in three adjacent headwater streams.

Outcomes:
Restored sites had slightly higher nutrient uptake rates that were positively correlated with the percent of coarse substrate (gravel, cobble, boulder). This suggests that this coarse substrate provides a stable structure for biofilm development, increasing nutrient demand.

Abstract:
The authors measured nutrient uptake of ammonium, nitrate and phosphate, as well as gross primary production and community respiration in three streams in Michigan, USA, each with an upstream reference and a downstream restored reach. The restoration included a 10-m sediment trap, paired with 40–60m of gravel and boulders added downstream and designed to retain sediment, stabilize banks and provide spawning habitat for trout. The authors sampled four times in the six stream reaches from May 2006 to September 2007. Across streams, restored reaches reflected the structural manipulation with increased predominance of coarse inorganic sediments, higher gas exchange rate and increased transient storage. However, nutrient uptake and community respiration rates were different between reaches at only one site. The ecosystem response by this stream was driven by the large differences in coarse inorganic habitat between reference and restored reaches. The authors concluded that restorations of benthic habitat which are visually conspicuous, such as creation of settling pools and gravel-filled reaches, did not universally affect stream ecosystem function. Initial conditions and magnitude of change may be key factors to consider in explaining functional responses, and predicting the influence of habitat restoration on ecosystem function remains a challenge.

Project Purposes:

Benefits Documented by Researcher:

Data Types Provided in Research Report:

Water Quality: Yes  Physical: Yes  Infrastructure: NS  Aesthetic/Rec: NS  Other: NS
Biological: Yes  Floodplain Mod: NS  Public Safety: NS  Property Value: NS

Water Quality: Yes  Hydrologic: Yes  Physical: No  Biological: Yes
Various chemical parameters including nitrogen and phosphorus, nutrient uptake rates, discharge flow rate and velocity, physical dimensions of stream

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**Stream_ID/Stream Setting:** 20160460102 State_Creek_Rest  
**Condition:** Post-Restoration (other)

### Practices Implemented:

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### Project Description:

**Fluxes_Managed:** Sediment  
**Goals/Performance Standards:** Quantify the influence of the change in benthic habitat on several metrics of ecosystem function. Because sediment maintenance was suspended 3 years prior to our measurements, the authors did not measure effects on fish. This study is not an analysis of the success or failure of the spawning habitat-restoration technique for fish and should not be viewed in that context.

**Bank Stabilization:** 40–60 m immediately downstream of the trap, the banks were lined with boulders and logs parallel to the direction of flow.

---

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### Project Description:

**Fluxes.Managed:** Sediment  
**Goals/Performance Standards:** Quantify the influence of the change in benthic habitat on several metrics of ecosystem function. Because sediment maintenance was suspended 3 years prior to our measurements, the authors did not measure effects on fish. This study is not an analysis of the success or failure of the spawning habitat-restoration technique for fish and should not be viewed in that context.

**Bank Stabilization:** 40–60 m immediately downstream of the trap, the banks were lined with boulders and logs parallel to the direction of flow.
Bed Stabilization:
Riparian Improvements:
Floodplain Connectivity:
Habitat Enhancement: Channel was filled with pea gravel (mean intermediate axis ~1–2 cm).
Channel Reconfiguration:
Barrier Removal/Fish Pass:
Infrastructure Protection:
Other Approaches: Sediment traps were maintained by removing sand and organic material once per year from 2000 until spring 2003, after which they were left unmanaged.

Stream_ID/Stream Setting: 20160460106 Walton_Creek_Rest  Condition: Post-Restoration (other)
Practices Implemented:

- Redirective_Practice No Riparian.Condition/Buffer_Reestab No Barrier Remo/ removing/Fish.Passage No
- Resistive_Practice Yes Floodplain_Connectivity/Reconfiguration No Passive_Approaches Yes
- Grade_Control No Habitat_Enhance/Instream_Features Yes
- Flow_Control No Channel_Reconfig/Planform_Changes No

Fluxes_Managed: Sediment
Goals/Performance Standards: Quantify the influence of the change in benthic habitat on several metrics of ecosystem function. Because sediment maintenance was suspended 3 years prior to our measurements, the authors did not measure effects on fish. This study is not an analysis of the success or failure of the spawning habitat-restoration technique for fish and should not be viewed in that context.

Bank Stabilization: 40–60 m immediately downstream of the trap, the banks were lined with boulders and logs parallel to the direction of flow.

Bed Stabilization:
Riparian Improvements:
Floodplain Connectivity:
Habitat Enhancement: Channel was filled with pea gravel (mean intermediate axis ~1–2 cm).
Channel Reconfiguration:
Barrier Removal/Fish Pass:
Infrastructure Protection:
Other Approaches: Sediment traps were maintained by removing sand and organic material once per year from 2000 until spring 2003, after which they were left unmanaged.


Project Purpose Statement:
Documents the assessment of potential water quality improvements and economic impacts associated with streambank-stabilization and phosphorus retention.

Outcomes:
Quantification of reductions in sediment and phosphorus loading from a ~2,900 m bank stabilization project (bendway weirs and willow plantings) on Harland Creek using historical photographs to estimate pre-stabilization erosion rates. The estimated value of phosphorus removal/retention was $612/m-yr compared to the $85.11/m cost of the bank stabilization project.

Abstract:
This study provides an example of how the benefits of bank stabilization and subsequent phosphorus loading reductions might be quantified using documented cost rates for total phosphorus removal and the potential volumes of sediment eroded from the banks over a period of time. The annual benefits of bank stabilization for Harland Creek Site 23 are estimated at $612,161 per km with respect to total phosphorus removal. This type of approach could have application nationwide to show the benefits of bank stabilization.

**Project Purposes:**

- Aes_Rec_Ed: NS
- Chan_Reconfig: NS
- Habitat: NS
- Infra_Prot: NS
- Dam_Retro: NS
- Bank_Stab: Yes
- Flood_Convey: NS
- Species: NS
- Permit_Req: NS
- Fish_Pass: NS
- Chan_Incis_Stab: NS
- Floodplain_Recon: NS
- Rip_Veg: NS
- Pub_Safety: NS
- Other: NS
- Sed_Bal: NS
- Flow_Mod: NS
- SW_Man: NS
- WQ_Man: Yes
- Infra_Prot: NS
- Permit_Req: NS
- Pub_Safety: NS
- Other: NS

**Benefits Documented by Researcher:**

- Water Quality: Yes
- Physical: Yes
- Infrastructure: NS
- Aesthetic/Rec: NS
- Other: NS
- Biological: NS
- Floodplain Mod: NS
- Public Safety: NS
- Property Value: NS

**Data Types Provided in Research Report:**

- Water Quality: Yes
- Hydrologic: No
- Physical: Yes
- Biological: No

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**Practices Implemented:**

- Redirective_Practice: Yes
- Riparian_Condition/Buffer_Reestab: No
- Barrier_Removal/Fish_Passage: No
- Resistive_Practice: Yes
- Floodplain_Connectivity/Reconfiguration: No
- Passive_Approaches: No
- Grade_Control: No
- Habitat_Enhance/Instream_Features: No
- Flow_Control: No
- Channel_Reconfig/Planform_Changes: No

**Project Description:**

**FluxesManaged**

**Goals/Performance Standards**

Design goals were directed at reducing the bank migration rate and erosion rate of Harland Creek, improving water quality by soil phosphorus retention. Design methodology and goals were cited from Raphelt et al. (1995) and Watson et al. (2001) from the 1993 stabilization efforts that were referenced in this study.

**Bank Stabilization:**

Bendway weirs were tested as bank protection on nine reaches. Six bendway weirs are sloped, fairly short (between 5.2 to 12.3 m (17 to 60 ft)) in length, and emergent except at very high flows.

**Bed Stabilization:**

Riparian Improvements:

Floodplain Connectivity:

Habitat Enhancement:

Channel Reconfiguration:

Barrier Removal/Fish Pass:

Infrastructure Protection:

Other Approaches:

**Stream_ID/Stream Setting:** 20160470104 Site_23_PostRest_R2

**Condition:** Post-Restoration (10 yr)
Design goals were directed at reducing the bank migration rate and erosion rate of Harland Creek, improving water quality by soil phosphorus retention. Design methodology and goals were cited from Raphelt et al. (1995) and Watson et al. (2001) from the 1993 stabilization efforts that were referenced in this study.

Bank Stabilization: Bendway weirs were tested as bank protection on nine reaches. Eight bendway weirs are sloped, fairly short (between 5.2 to 12.3 m (17 to 60 ft)) in length, and emergent except at very high flows.

Bed Stabilization: Bendway weirs were tested as bank protection on nine reaches. Five bendway weirs are sloped, fairly short (between 5.2 to 12.3 m (17 to 60 ft)) in length, and emergent except at very high flows.
**Infrastructure Protection:**

**Other Approaches:**

**Stream_ID/Stream Setting:** 20160470106 Site_23_PostRest_R4  
**Condition:** Post-Restoration (10 yr)

**Practices Implemented:**

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**Project Description:**

**Fluxes_Managed**

**Goals/Performance Standards**

Design goals were directed at reducing the bank migration rate and erosion rate of Harland Creek, improving water quality by soil phosphorus retention. Design methodology and goals were cited from Raphelt et al. (1995) and Watson et al. (2001) from the 1993 stabilization efforts that were referenced in this study.

**Bank Stabilization:**

Bendway weirs were tested as bank protection on nine reaches. One bendway weir is sloped, fairly short (between 5.2 to 12.3 m (17 to 60 ft)) in length, and emergent except at very high flows. Willow posts were also tested as bank protection during 1994 over 9000 willow posts were planted in selected bends. Three and five rows of willow posts were planted in 1994, with nearly 100% mortality by the time of the study in 2002.

**Bed Stabilization:**

**Riparian Improvements:**

**Floodplain Connectivity:**

**Habitat Enhancement:**

**Channel Reconfiguration:**

**Barrier Removal/Fish Pass:**

**Infrastructure Protection:**

**Other Approaches:**

**Stream_ID/Stream Setting:** 20160470107 Site_23_PostRest_R5  
**Condition:** Post-Restoration (10 yr)

**Practices Implemented:**

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<tr>
<td>Flow_Control</td>
<td>No</td>
</tr>
<tr>
<td>Riparian_Condition/Buffer_Reestab</td>
<td>No</td>
</tr>
<tr>
<td>Floodplain_Connectivity/Reconfiguration</td>
<td>No</td>
</tr>
<tr>
<td>Habitat_Enhance/Instream_Features</td>
<td>No</td>
</tr>
<tr>
<td>Channel_Reconfig/Planform_Changes</td>
<td>No</td>
</tr>
<tr>
<td>Barrier_Removal/Fish_Passage</td>
<td>No</td>
</tr>
<tr>
<td>Passive_Approaches</td>
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</table>

**Project Description:**

**Fluxes_Managed**

**Goals/Performance Standards**

Design goals were directed at reducing the bank migration rate and erosion rate of Harland Creek, improving water quality by soil phosphorus retention. Design methodology and goals were cited from Raphelt et al. (1995) and Watson et al. (2001) from the 1993 stabilization efforts that were referenced in this study.

**Bank Stabilization:**

Bendway weirs were tested as bank protection on nine reaches. One bendway weir is sloped, fairly short (between 5.2 to 12.3 m (17 to 60 ft)) in length, and emergent except at very high flows.
flows. Willow posts were also tested as bank protection during 1994 over 9000 willow posts were planted in selected bends. Supplemented with traditional longitudinal peaked stone toe dikes with tiebacks. Two rows of willow posts were planted in 1994, with nearly 100% mortality by the time of the study in 2002.

Bed Stabilization:
Riparian Improvements:
Floodplain Connectivity:
Habitat Enhancement:
Channel Reconfiguration:
Barrier Removal/Fish Pass:
Infrastructure Protection:
Other Approaches:

Stream_ID/Stream Setting: 20160470108 Site_23_PostRest_R6+7  Condition: Post-Restoration (10 yr)

Practices Implemented:

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<td>Riparian_Condition/Buffer_Reestab</td>
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<tr>
<td>Resistive_Practice</td>
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<td>Floodplain_Connectivity/Reconfiguration</td>
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Project Description:
Fluxes_Managed
Goals/Performance Standards: Design goals were directed at reducing the bank migration rate and erosion rate of Harland Creek, improving water quality by soil phosphorus retention. Design methodology and goals were cited from Raphelt et al. (1995) and Watson et al. (2001) from the 1993 stabilization efforts that were referenced in this study.

Bank Stabilization: Willow posts were tested as bank protection during 1994 over 9000 willow posts were planted in selected bends. Three rows of willow posts were planted in 1994, with nearly 100% mortality by the time of the study in 2002.

Bed Stabilization:
Riparian Improvements:
Floodplain Connectivity:
Habitat Enhancement:
Channel Reconfiguration:
Barrier Removal/Fish Pass:
Infrastructure Protection:
Other Approaches:

Stream_ID/Stream Setting: 20160470109 Site_23_PostRest_R8  Condition: Post-Restoration (10 yr)

Practices Implemented:

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Design goals were directed at reducing the bank migration rate and erosion rate of Harland Creek, improving water quality by soil phosphorus retention. Design methodology and goals were cited from Raphelt et al. (1995) and Watson et al. (2001) from the 1993 stabilization efforts that were referenced in this study.

Willow posts were tested as bank protection during 1994 over 9000 willow posts were planted in selected bends. Five rows of willow posts were planted in 1994, with nearly 100% mortality by the time of the study in 2002.

Bendway weirs were tested as bank protection on nine reaches. Seven bendway weirs are sloped, fairly short (between 5.2 to 12.3 m (17 to 60 ft)) in length, and emergent except at very high flows. Supplemented with traditional longitudinal peaked stone toe dikes with tiebacks.
Practices Implemented:

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Project Description:

Fluxes_Managed

Goals/Performance Standards

Design goals were directed at reducing the bank migration rate and erosion rate of Harland Creek, improving water quality by soil phosphorus retention. Design methodology and goals were cited from Raphelt et al. (1995) and Watson et al. (2001) from the 1993 stabilization efforts that were referenced in this study.

Bank Stabilization: Bendway weirs were tested as bank protection on nine reaches. Two bendway weirs are sloped, fairly short (between 5.2 to 12.3 m (17 to 60 ft)) in length, and emergent except at very high flows. Willow posts were also tested as bank protection during 1994 over 9000 willow posts were planted in selected bends. Five rows of willow posts were planted in 1994, with nearly 100% mortality by the time of the study in 2002.

Bed Stabilization:

Riparian Improvements:

Floodplain Connectivity:

Habitat Enhancement:

Channel Reconfiguration:

 Barrier Removal/Fish Pass:

Infrastructure Protection:

Other Approaches:

Stream_ID/Stream Setting: 20160470112 Site_23_PostRest_R11 Condition: Post-Restoration (10 yr)

Practices Implemented:

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Project Description:

Fluxes_Managed

Goals/Performance Standards

Design goals were directed at reducing the bank migration rate and erosion rate of Harland Creek, improving water quality by soil phosphorus retention. Design methodology and goals were cited from Raphelt et al. (1995) and Watson et al. (2001) from the 1993 stabilization efforts that were referenced in this study.

Bank Stabilization: Bendway weirs were tested as bank protection on nine reaches. Twelve bendway weirs are sloped, fairly short (between 5.2 to 12.3 m (17 to 60 ft)) in length, and emergent except at very high flows.

Bed Stabilization:

Riparian Improvements:

Floodplain Connectivity:
Design goals were directed at reducing the bank migration rate and erosion rate of Harland Creek, improving water quality by soil phosphorus retention. Design methodology and goals were cited from Raphelt et al. (1995) and Watson et al. (2001) from the 1993 stabilization efforts that were referenced in this study.

Bank Stabilization: Bendway weirs were tested as bank protection on nine reaches. Seven bendway weirs are sloped, fairly short (between 5.2 to 12.3 m (17 to 60 ft)) in length, and emergent except at very high flows.

Bank Stabilization: Willow posts were also tested as bank protection during 1994 over 9000 willow posts were

Design goals were directed at reducing the bank migration rate and erosion rate of Harland Creek, improving water quality by soil phosphorus retention. Design methodology and goals were cited from Raphelt et al. (1995) and Watson et al. (2001) from the 1993 stabilization efforts that were referenced in this study.
planted in selected bends. Supplemented with traditional longitudinal peaked stone toe dikes with tiebacks. Four and five rows of willow posts were planted in 1994, with nearly 100% mortality by the time of the study in 2002.

Bed Stabilization:
Riparian Improvements:
Floodplain Connectivity:
Habitat Enhancement:
Channel Reconfiguration:
Barrier Removal/Fish Pass:
Infrastructure Protection:
Other Approaches:

**Stream_ID/Stream Setting:** 20160470115 Site_23_PostRest_R14  
**Condition:** Post-Restoration (10 yr)

**Practices Implemented:**

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**Project Description:**
Fluxes Managed

**Goals/Performance Standards**
Design goals were directed at reducing the bank migration rate and erosion rate of Harland Creek, improving water quality by soil phosphorus retention. Design methodology and goals were cited from Raphelt et al. (1995) and Watson et al. (2001) from the 1993 stabilization efforts that were referenced in this study.

Bank Stabilization:
Willow posts were also tested as bank protection during 1994 over 9000 willow posts were planted in selected bends. Supplemented with traditional longitudinal peaked stone toe dikes with tiebacks. Longitudinal Peaked Stone Toes were constructed to repair bank toe.

Bed Stabilization:
Riparian Improvements:
Floodplain Connectivity:
Habitat Enhancement:
Channel Reconfiguration:
Barrier Removal/Fish Pass:
Infrastructure Protection:
Other Approaches:

**Stream_ID/Stream Setting:** 20160470116 Site_23_PostRest_All  
**Condition:** Post-Restoration (10 yr)

**Practices Implemented:**

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<th>Implementation</th>
<th>Riparian Condition/Buffer Reestab</th>
<th>Habitat Enhance/Instream Features</th>
<th>Channel Reconfig/Planform Changes</th>
<th>Barrier Removal/Fish Passage</th>
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<tbody>
<tr>
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<td>Grade Control</td>
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<td>Flow Control</td>
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</tbody>
</table>
Design goals were directed at reducing the bank migration rate and erosion rate of Harland Creek, improving water quality by soil phosphorus retention. Design methodology and goals were cited from Raphelt et al. (1995) and Watson et al. (2001) from the 1

### Project Description:

**Fluxes Managed**

**Goals/Performance Standards**

Bank Stabilization:

Bed Stabilization:

Riparian Improvements:

Floodplain Connectivity:

Habitat Enhancement:

Channel Reconfiguration:

Barrier Removal/Fish Pass:

Infrastructure Protection:

Other Approaches:

### Study ID:

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<th>2016050</th>
<th>Kasahara and Hill 2006</th>
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<tbody>
<tr>
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<tr>
<td>Exp. Design:</td>
<td>Upstream/Downstream</td>
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### Project Purpose Statement:

Study of the effects on hyporheic zone chemistry and nutrient removal for naturally occurring and constructed riffle in lowland streams in southern Ontario. Related study (Kasahara and Hill, 2006) studies the hyporheic exchange and residence time at same sites.

### Outcomes:

Hyporheic zone nitrate removal was observed in both constructed and natural riffles. Removal may actually be higher in constructed riffles (as total mass, although removal efficiency is lower) due to steeper slopes and coarser sediment size which creates a larger hyporheic zone (including a larger aerobic zone which is detrimental to denitrification). Clogging due to high watershed sediment inputs may impact hyporheic zone exchange long-term.

### Abstract:

**Project Purposes:**

| Aes_Rec_Ed | NS | Chan_Reconfig | NS | Habitat | NS | Infra_Prot | NS | Dam_Retro | NS |
| Bank_Stab | NS | Flood_Convey | NS | Species | NS | Permit_Req | NS | Fish_Pass | NS |
| Chan_Incis_Stab | NS | Floodplain_Recon | NS | Rip_Veg | NS | Pub_Safety | NS | Other | Yes |
| Sed_Bal | NS | Flow_Mod | NS | SW_Man | NS | WQ_Man | NS |

### Benefits Documented by Researcher:

| Water Quality | Yes | Physical | NS | Infrastructure | NS | Aesthetic/Rec | NS | Other | Yes |
| Biological | NS | Floodplain Mod | NS | Public Safety | NS | Property Value | NS |

### Data Types Provided in Research Report:

| Water Quality | Yes | Hydrologic | Yes | Physical | Yes | Biological | No |
| Data_Descp | Nitrogen, US/DS nutrient concentrations, nitrate removal rates |

### WS_ID

| 201605001 | Southern_Oakridge_Moraine |
| Drainage_Area (ha): | |
| Land Use: | Mixed |

### Stream_ID/Stream Setting:

| 20160500101 | Rouge_river_trib_1_riff |
| Condition: | Post-Restoration (2 yr) |

### Practices Implemented:

Friday, August 26, 2016
Redirective Practice No  Riparian Condition/Buffer Reestab No  Barrier Removal/Fish Passage No
Resistive Practice No  Floodplain Connectivity/Reconfiguration No  Passive Approaches No
Grade Control Yes  Habitat Enhance/Instream Features No
Flow Control No  Channel Reconfig/Planform Changes No

Project Description:
Fluxes Managed  Hyporheic exchange
Goals/Performance Standards
Bank Stabilization:
Bed Stabilization: Riffle constructed using cobbles ranging from 0.05 - 0.12 m with a total thickness of 0.25 m.
Riparian Improvements:
Floodplain Connectivity:
Habitat Enhancement:
Channel Reconfiguration:
Barrier Removal/Fish Pass:
Infrastructure Protection:
Other Approaches:

Stream ID/Stream Setting: 20160500102 rouge_river_trib_2_riff  Condition: Post-Restoration (2 yr)

Practices Implemented:
Redirective Practice No  Riparian Condition/Buffer Reestab No  Barrier Removal/Fish Passage No
Resistive Practice No  Floodplain Connectivity/Reconfiguration No  Passive Approaches No
Grade Control Yes  Habitat Enhance/Instream Features No
Flow Control No  Channel Reconfig/Planform Changes No

Project Description:
Fluxes Managed  Hyporheic exchange
Goals/Performance Standards
Bank Stabilization:
Bed Stabilization: A small step was constructed with a 0.17 m diameter log supported by boulders. A low hydraulic conductivity fabric was installed on the streambed upstream of the step to reduce erosion.
Riparian Improvements:
Floodplain Connectivity:
Habitat Enhancement:
Channel Reconfiguration:
Barrier Removal/Fish Pass:
Infrastructure Protection:
Other Approaches:

Stream_ID/Stream Setting: 20160500103 Silver_creek_riff  Condition: Post-Restoration (2 yr)

Practices Implemented:
Project Description:

Fluxes_Managed

Goals/Performance Standards

Bank Stabilization:

Bed Stabilization: Riffle constructed using cobbles and boulders ranging in diameter from 0.15 - 0.45 m to a depth of 0.6 m.

Riparian Improvements:
Floodplain Connectivity:
Habitat Enhancement:
Channel Reconfiguration:
Barrier Removal/Fish Pass:
Infrastructure Protection:
Other Approaches:

Stream_ID/Stream Setting: 20160500104 Silver_creek_control Condition: Post-Restoration (2 yr)

Practices Implemented:

Redirective_Practice No Riparian.Condition.Buffer.Reestab No Barrier_Removal/Fish_Passage No
Resistive_Practice No Floodplain_Connectivity_Reconfiguration No Passive_Approaches No
Grade_Control Yes Habitat_Enhance_Instream_Features No
Flow_Control No Channel_Reconfig/Planform_Changes No

Project Description:

Fluxes_Managed

Goals/Performance Standards

Bank Stabilization:

Bed Stabilization:
Riparian Improvements:
Floodplain Connectivity:
Habitat Enhancement:
Channel Reconfiguration:
Barrier Removal/Fish Pass:
Infrastructure Protection:
Other Approaches:

Quantified the effects of geomorphic stream restoration on rates of in-situ N removal via denitrification using 15 N-based "push-pull" methods along the riparian-zone-stream interface of a coastal stream. A secondary objective was to investigate the potential importance of the riparian-zone-stream interface as a site for mass removal of nitrate-N by coupling measured in situ denitrification rates with estimates of groundwater flow.

Outcomes:
Restored streams had lower in-stream nitrate concentrations and degraded sites. In general, the restored site with floodplain connection had the highest denitrification rate. Denitrification was positively correlated with groundwater residence time.

Abstract:
The authors hypothesized that stream restoration has the potential to increase denitrification rates at the riparian-zone-stream interface in an urbanizing watershed, but that restoration designs promoting low banks with increased hydrologic connectivity at the riparian-zone-stream interface would show the highest rates of denitrification. Results of the present study provide estimates of in situ denitrification along the riparian-zone-stream interface of a restored stream and make a further contribution toward the investigation of the importance of denitrification rates associated with degraded urban ecosystems and certain forms of stream restoration. Their results suggest that stream restoration associated with storm water management that increases hydrologic connectivity can increase denitrification rates, and it supports the idea that the riparian-zone-stream interface can be an active site for denitrification rates. Nitrate-N could be removed at the riparian-zone-stream interface due to high denitrification rates coupled with hydrologic flow and that hydrologic residence time in the riparian-zone-stream interface may be an important factor. Their results suggest that restoration practices for storm water management that foster "connectivity" between the stream and the riparian zone can increase rates of in situ denitrification in stream banks and that mass nitrate-N removal may be substantial at the riparian-zone-stream interface. The results also suggest that there can be substantial variability in denitrification rates among restoration designs based on hydrological connectivity and bank height and that continuing work is necessary to identify which types of stream restoration practices will be most effective at removing nitrogen.
Goals/Performance Standards

Bank Stabilization: One or more of the following techniques: reshaping slopes to reconnect the channel to the floodplain, embedding root wads, planting cover vegetation, and covering with erosion mats.

Bed Stabilization: Filling the channel with sediment, cobbles, and boulders.

Riparian Improvements: Planting of trees and shrubs in the riparian zone.

Floodplain Connectivity: In areas away from commercial properties, low banks were engineered to promote flooding over the banks and dissipation of erosive force, creating low, hydrologically "connected" riparian areas.

Habitat Enhancement:

Channel Reconfiguration: Constructing point bars, riffles, and meander features along the reach and creating step-pool sequence.

Barrier Removal/Fish Pass:

Infrastructure Protection: In some areas, incised, high banks prone to erosion were armored with rocks and channelized to keep water in the stream and rapidly transport water away from commercial properties, with less potential for overbank flooding.

Other Approaches:

<table>
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<tr>
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<td>Exp. Design: Post-restoration monitoring</td>
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**Project Purpose Statement:**
Assess the influence of restoration approach (e.g., construction of cross-vanes, riffle/pools) and restoration age, specifically riparian vegetation in various stages of maturity on nutrient retention across seasons. To better understand the influence of restoration age and restoration approach, the authors investigated the relationships among age, canopy cover, sediment C, and channel complexity with multiple sites representing ranges of restoration age. Assessed potential to reduce instream NO3-N and PO4-P concentrations by measuring reach-scale retention using the nutrient spiraling approach.

**Outcomes:**
The age of the restoration project controlled nutrient uptake rates. New restoration projects had more labile carbon, lower canopy cover, and higher temperature which was correlated to higher phosphorus uptake. On the other hand, older projects had greater canopy cover, lower temperature, and higher nitrate retention. Channel complexity was also correlated with nutrient uptake.

**Abstract:**
The results of this study show a similar trend of decreasing instream uptake (particularly phosphate) at restored streams with more mature vegetation and reflect similar trends observed following logging and removal of riparian forests. Restoration age controlled type and maturity of riparian vegetation and thereby temperature and sediment C, whereas the restoration design had the greatest influence on channel complexity and structure.

**Project Purposes:**

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<th>Yes</th>
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**Benefits Documented by Researcher:**

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<th>Property Value</th>
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**Data Types Provided in Research Report:**

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**NO3-N & PO4-P uptake length, velocity, and rates for each stream. Base flow rate, reach depth, wetted channel width, % canopy coverage, & habitat transitions/channel complexity.**

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**Practices Implemented:**

- **Redirective_Practice** | No |
- **Resistive_Practice** | Yes |
- **Grade_Control** | Yes |
- **Flow_Control** | No |

**Project Description:**

- **Fluxes_Managed**
- **Goals/Performance Standards**
- **Bank Stabilization:** Coir netting and live stakes planted at 1 m spacing.
- **Bed Stabilization:** Installation of large wood j-hooks and boulder cross-vanes.
- **Riparian Improvements:** A 50-70 m wide floodplain was planted with deciduous trees at 3 m spacing. Plantings occurred in spring 2011.
- **Floodplain Connectivity:** No details provided.
- **Habitat Enhancement:** Riffle/step/pool sequences using large wood J-hooks, boulder cross-vanes.
- **Channel Reconfiguration**
- **Barrier Removal/Fish Pass**
- **Infrastructure Protection**
- **Other Approaches**

<table>
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**Practices Implemented:**

- **Redirective_Practice** | No |
- **Resistive_Practice** | No |
- **Grade_Control** | Yes |
- **Flow_Control** | No |

**Project Description:**

- **Fluxes_Managed**
- **Goals/Performance Standards**
- **Bank Stabilization:** Coir netting and live stakes planted at 1 m spacing.
- **Bed Stabilization:** Installation of large wood j-hooks and boulder cross-vanes.
- **Riparian Improvements:** Plantings included herbaceous grasses, dogwood, and elderberry saplings planted as live stakes on 1 m spacing and newly planted deciduous trees.
- **Floodplain Connectivity:**

---

Friday, August 26, 2016
Habitat Enhancement: Crossvanes installed for flow variation and stabilization.

Channel Reconfiguration:

Barrier Removal/Fish Pass:

Infrastructure Protection:

Other Approaches:

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<tr>
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</table>

Practices Implemented:

- Redirective Practice: No
- Resistive Practice: No
- Grade Control: Yes
- Flow Control: No
- Riparian Condition/Buffer Reestab: No
- Floodplain Connectivity/Reconfiguration: Yes
- Habitat Enhance/Instream Features: Yes
- Channel Reconfig/Planform Changes: Yes
- Barrier Removal/Fish Passage: No
- Passive Approaches: No

Project Description:

- Fluxes Managed
- Bank Stabilization: Rock weirs were installed for grade control
- Riparian Improvements: Rock weirs were installed for grade control
- Floodplain Connectivity: Banks were graded to improve floodplain accessibility.
- Habitat Enhancement: Meandering pattern with riffle-pool sequences, rock weirs for grade control.
- Channel Reconfiguration:
- Barrier Removal/Fish Pass:
- Infrastructure Protection:
- Other Approaches:

---

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<thead>
<tr>
<th>WS_ID</th>
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Practices Implemented:

- Redirective Practice: No
- Resistive Practice: Yes
- Grade Control: No
- Flow Control: No
- Riparian Condition/Buffer Reestab: Yes
- Floodplain Connectivity/Reconfiguration: Yes
- Habitat Enhance/Instream Features: No
- Channel Reconfig/Planform Changes: Yes
- Barrier Removal/Fish Passage: No
- Passive Approaches: No

Project Description:

- Fluxes Managed
- Bank Stabilization: Boulder armoring was placed at the outside of one meander bend.
- Bed Stabilization:
Riparian Improvements: A 10-15 m wide riparian zone was re-planted and is composed of mostly deciduous trees and shrubs.

Floodplain Connectivity: Several intermittent wetlands between highly sinuous meander bends.

Habitat Enhancement: Lateral scour pool with armoring boulders at the outside margin of one meander bend.

Channel Reconfiguration:

Barrier Removal/Fish Pass:

Infrastructure Protection:

Other Approaches:

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</table>

**Project Description:**

Fluxes Managed

Goals/Performance Standards

Bank Stabilization:

Bed Stabilization: Installation of boulder cross-vanes and constructed riffles.

Riparian Improvements: Live stake plantings of willow.

Floodplain Connectivity:

Habitat Enhancement: Cross-vanes creating step-pool sequences and constructed riffles within a two-stage channel.

Channel Reconfiguration:

Barrier Removal/Fish Pass:

Infrastructure Protection:

Other Approaches:

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<td>Exp. Design: Paired Watershed</td>
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**Project Purpose Statement:**

Quantify effectiveness of livestock exclusion, streambank protection, and riparian restoration practices as tools to reduce sediment, nutrient, and bacteria runoff from agricultural land.

**Outcomes:**

Livestock fencing, streambank stabilization, and riparian protection led to reduced P concentrations (-25%) and export (-42%) in a watershed in Vermont.

**Abstract:**

The Lake Champlain Basin Agricultural Watersheds National Monitoring Program (NMP) Project evaluates the effectiveness of livestock exclusion, streambank protection, and riparian restoration practices in reducing concentrations and loads of nutrients, sediment, and bacteria in surface waters.

**Project Purposes:**
**Benefits Documented by Researcher:**

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**Data Types Provided in Research Report:**

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**WS_ID** 201606801 Missiquoi_Drainage_LC_Basin  
**Drainage Area (ha):** 2080000  
**Land Use:**

**Stream_ID/Stream Setting:** 20160680102 WS2_Treat_PostTreat  
**Condition:** Post-Restoration (1 yr)

**Practices Implemented:**

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<td>Flow Control</td>
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**Project Description:**

**Fluxes Managed**

**Goals/Performance Standards**

**Bank Stabilization:** Bioengineering bank stabilization including plantings and livestock exclusion.

**Bed Stabilization:** Planting of vegetation and livestock exclusion.

**Floodplain Connectivity**

**Habitat Enhancement**

**Channel Reconfiguration**

**Barrier Removal/Fish Pass**

**Infrastructure Protection**

**Other Approaches:** Created of protected riparian zones, improved or eliminated livestock crossings, revegetation of degraded streambanks.

**Stream_ID/Stream Setting:** 20160680104 WS3_Control_PostTreat  
**Condition:** Post-Restoration (other)

**Practices Implemented:**

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**Project Description:**
Fluxes_Managed

Goals/Performance Standards

Bank Stabilization:

Bed Stabilization:

Riparian Improvements:

Floodplain Connectivity:

Habitat Enhancement:

Channel Reconfiguration:

Barrier Removal/Fish Pass:

Infrastructure Protection:

Other Approaches:

Data collected represents conditions in the paired control wetland after restoration of the stream and watershed at WS2, and is the corresponding "Treatment Period".

Miller et al. quantified bank erosion sediment and phosphorus loading on Barren Fork Creek, OK using aerial photo analysis. Erosion rates were significantly lower on sections with a forested riparian buffer compared to unforested sites. Water soluble phosphorus loading from banks accounted for ~10% of total watershed P loading while total P loading exceeded the watershed total, indicating in-stream and floodplain storage of sediment-bound P was occurring.

Abstract:

Seven sites were historically protected (HP) including historic riparian forests, while 3 sites did not include riparian forests and were historically unprotected (HUP). It was hypothesized that HUP sites would have higher average total phosphorus (TP) and water soluble phosphorus (WSP) concentrations than HP sites due to a presumed potential history of fertilizer or poultry litter application at HUP sites. In total the ten sites contributed 2.2 × 10^2 kg of WSP and 1.7 × 10^4 kg TP to the BFC over the seven year study period. The WSP loading was dominated by erosion at the HUP sites while the TP loading was significantly greater at the HUP sites.

Data Types Provided in Research Report:

Water Quality: Yes

Physical: No

Hydrologic: Yes

Benefits Documented by Researcher:

Biological: Yes

Property Value: Yes

Public Safety: No

Infrastructure: No

Aesthetic/Rec: No

Other: Yes

HS предлагаем использовать для обучения модели на английском языке.
Stream_ID/Stream Setting: 20160701101 BFC_All_HP

Practices Implemented:

|| Practice Type | No | Yes |
|---|---|---|
| Redirective_Practice | No |  |
| Resistive_Practice | No |  |
| Grade_Control | No |  |
| Flow_Control | No |  |
| Riparian_Condition/Buffer_Reestab | Yes |  |
| Floodplain_Connectivity/Reconfiguration | No |  |
| Habitat_Enhance/Instream_Features | No |  |
| Channel_Reconfig/Planform_Changes | No |  |
| Barrier_Removal/Fish_Passage | No |  |
| Passive_Approaches | No |  |

Project Description:

Fluxes_Managed: Sediment, Nutrients

Goals/Performance Standards: No restoration designs were actively implemented, however, this study focused on the benefit of riparian management practices to prevent streambank erosion and quantify load of phosphorus from streambanks in the watershed.

Bank Stabilization:

Bed Stabilization:

Riparian Improvements: Combination of all Historically Protected (HP) sites.

Floodplain Connectivity:

Habitat Enhancement:

Channel Reconfiguration:

Barrier Removal/Fish Pass:

Infrastructure Protection:

Other Approaches:

Project Purposes:

Study ID: 2016078 Orzetti et al. 2010

Category: Riparian zone

Exp. Design: Post-restoration monitoring

Project Purpose Statement:

Evaluate benefits of restored forest riparian buffers along streams in the Chesapeake Bay watershed by examining habitat, selected water quality variables, and benthic macroinvertebrate community metrics in 30 streams with buffers ranging from zero to greater than 50 years of age. Data was pooled from all sites and divided into "young" (<10 years) and "old" (10 years and up) sites for the purpose of analysis and comparison.

Outcomes:

In-stream nitrate concentrations were significantly negatively correlated with buffer age, suggesting that the effectiveness of buffer nutrient removal increases with age. No trends in phosphorus concentrations were observed.

Abstract:

This study investigates the change in water quality, habitat conditions, and benthic macroinvertebrate community recovery in streams with restored and naturally regenerated buffer zones varying in age from 0 to 25 years. The authors hypothesized that as a restored or naturally recolonizing forest riparian buffer matures, both water quality and habitat conditions will improve facilitating an increase in the diversity and decrease of pollution tolerance of stream macroinvertebrate assemblages. If the authors' hypothesis is true, then there will be a positive correlation between stream buffer age and improvements in water quality, habitat conditions, and benthic macroinvertebrate community metrics.
Benefits Documented by Researcher:

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Data Types Provided in Research Report:

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WS_ID 201607801 Chesapeake_Bay_Watershed_Piedmo Drainage_Area (ha): 3260000 Land_Use: Mixed

Stream_ID/Stream Setting: 20160780101 Old_Sites_10+ Condition: Post-Restoration (20 yr)

Practices Implemented:

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Fluxes_Managed

Goals/Performance Standards

By proving hypothesis hope to demonstrate a positive correlation between stream buffer age and improvements in water quality, habitat conditions, and benthic macroinvertebrate community metrics.

Bank Stabilization:

Bed Stabilization:

Riparian Improvements: Unknown, buffers were established 10-50 years prior to study. The forest riparian buffer zone width was then measured at three areas within the sampling reach and averaged to obtain approximate buffer widths for each side of the stream.

Floodplain Connectivity:

Habitat Enhancement:

Channel Reconfiguration:

Barrier Removal/Fish Pass:

Infrastructure Protection:

Other Approaches:

Stream_ID/Stream Setting: 20160780102 Young_Sites_10- Condition: Post-Restoration (10 yr)

Practices Implemented:

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Fluxes_Managed

Goals/Performance Standards

By proving hypothesis hope to demonstrate a positive correlation between stream buffer age and improvements in water quality, habitat conditions, and benthic macroinvertebrate community metrics.
Bank Stabilization:  
Bed Stabilization:  
Riparian Improvements: Unknown, buffers were established 10 years or less before study. The forest riparian buffer zone width was then measured at three areas within the sampling reach and averaged to obtain approximate buffer widths for each side of the stream.

Floodplain Connectivity:  
Habitat Enhancement:  
Channel Reconfiguration:  
Barrier Removal/Fish Pass:  
Infrastructure Protection:  
Other Approaches:  

Richardson et al. 2011

Three phased restoration project within the Duke University stream and wetland assessment management park (SWAMP) attempting to quantify water quality improvements.

Project Purpose Statement:

Outcomes:
Prior to restoration, the stream was incised and nutrient concentrations increased through the study reach. After restoration, mean nutrient concentrations decreased through the reach and were significantly lower than pre-restoration. During a storm event, nitrate loads were reduced by 64% and TP loads by 28%. Sediment retention in the wetlands and stormwater pond totaled 500 metric tonnes per year.

Abstract:

Water quality in Upper Sandy Creek, a headwater stream for the Cape Fear River in the North Carolina Piedmont, is impaired due to high N and P concentrations, sediment load, and coliform bacteria. The creek and floodplain ecosystem had become dysfunctional due to the effects of altered storm water delivery following urban watershed development where the impervious surface reached nearly 30% in some sub-watersheds. At Duke University, an 8-ha Stream and Wetland Assessment Management Park (SWAMP) was created in the lower portion of the watershed to assess the cumulative effect of restoring multiple portions of stream and former adjacent wetlands, with specific goals of quantifying water quality improvements. To accomplish these goals, a three-phase stream/riparian floodplain restoration (600 m), storm water reservoir/wetland complex (1.6 ha) along with a surface flow treatment wetland (0.5 ha) was ecologically designed to increase the stream wetland connection, and restore groundwater wetland hydrology. The multi-phased restoration of Sandy Creek and adjacent wetlands resulted in functioning riparian hydrology, which reduced downstream water pulses, nutrients, coliform bacteria, sediment, and stream erosion. Storm water event nutrient budgets indicated a substantial attenuation of N and P within the SWAMP project. Most notably, (NO₂⁻ + NO₃⁻)–N loads were reduced by 64% and P loads were reduced by 28%. Sediment retention in the stormwater reservoir and riparian wetlands showed accretion rates of 1.8cmyear⁻¹ and 1.1cmyear⁻¹, respectively. Sediment retention totaled nearly 500MTyear⁻¹.

Project Purposes:

Benefits Documented by Researcher:

Data Types Provided in Research Report:  

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<table>
<thead>
<tr>
<th>Water Quality:</th>
<th>Yes</th>
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<th>No</th>
<th>Physical:</th>
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Data_Descp: nitrogen and phosphorus, nutrient concentrations, nutrient loads

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**Stream_ID/Stream Setting:** 20160860201 sandy_creek_phase1

**Practices Implemented:**

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**Project Description:**

Fluxes Managed

Goals/Performance Standards

Bank Stabilization:

Bed Stabilization:

Riparian Improvements: re-planting floodplain

Floodplain Connectivity: re-contouring

Habitat Enhancement:

Channel Reconfiguration:

Barrier Removal/Fish Pass:

Infrastructure Protection:

Other Approaches:

**Stream_ID/Stream Setting:** 20160860202 sandy_creek_phase2

**Condition:** Post-Restoration (other)

**Practices Implemented:**

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<tr>
<th>Practice Type</th>
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<tbody>
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**Project Description:**

Fluxes Managed

Goals/Performance Standards

Bank Stabilization:

Bed Stabilization:

Riparian Improvements:

Floodplain Connectivity:

Habitat Enhancement:

Channel Reconfiguration:

Regulate delivery to downstream water bodies and allow for additional retention and removal of excess nutrients and sediments from the stream.
Barrier Removal/Fish Pass:
Infrastructure Protection:
Other Approaches: Construction of an earthen dam and outflow system in conjunction with a 1.6 ha storm water/wetland reservoir to regulate flow and enhance nutrient removal.

Stream_ID/Stream Setting: 20160860203 sandy_creek_phase3  
Condition: Post-Restoration (other)

Practices Implemented:
Redirective_Practice No Riparian_Condition/Buffer_Reestab No Barrier_Removal/Fish_Passage No
Resistive_Practice No Floodplain_Connectivity/Reconfiguration No Passive_Approaches No
Grade_Control No Habitat_Enhance/Instream_Features No
Flow_Control No Channel_Reconfig/Planform_Changes No

Project Description:
Fluxes_Managed

Goals/Performance Standards
Intercept and improve water quality of a tributary impacted by high concentrations of N and P from the university campus.

Bank Stabilization:
Bed Stabilization:
Riparian Improvements:
Floodplain Connectivity:
Habitat Enhancement:
Channel Reconfiguration:
Barrier Removal/Fish Pass:
Infrastructure Protection:
Other Approaches: 0.5 ha surface flow treatment wetland.

Stream_ID/Stream Setting: 20160860204 sandy_creek_combined  
Condition: Post-Restoration (other)

Practices Implemented:
Redirective_Practice No Riparian_Condition/Buffer_Reestab Yes Barrier_Removal/Fish_Passage No
Resistive_Practice No Floodplain_Connectivity/Reconfiguration Yes Passive_Approaches No
Grade_Control No Habitat_Enhance/Instream_Features No
Flow_Control No Channel_Reconfig/Planform_Changes No

Project Description:
Fluxes_Managed

Goals/Performance Standards

Bank Stabilization:
Bed Stabilization:
Riparian Improvements:
Floodplain Connectivity:
Habitat Enhancement:
Channel Reconfiguration:
Barrier Removal/Fish Pass:

Infrastructure Protection:

Other Approaches:

**Study ID:** 2016120 Tuttle et al. 2014

**Category:** Stabilization

**State/Country:** NC US

**Exp. Design:** Treatment/Control

**Project Purpose Statement:**

Purposes: (1) quantify differences in denitrification rates in the vicinity of grade control structures and (2) identify environmental controls on rates of denitrification.

**Outcomes:**

Denitrification rates were highly variable and were not statistically significant between restored and unrestored reaches. Rates were correlated with nitrate concentration and channel complexity.

**Abstract:**

Measured denitrification rates in streambed sediments seasonally at eight streams in North Carolina, USA to characterize the physicochemical drivers of nitrogen transformations in restored urban streams. Mean denitrification rates were highly variable and most significantly influenced by nitrate concentrations. Observed significantly greater denitrification rates in more geomorphically complex streams, particularly near grade control structures and in deep pools. The results of this research suggest that natural and artificial geomorphic structures enhance denitrification rates through hydraulic mechanisms. Increased denitrification activity near grade control structures and riffles suggests that the hydraulics generated by streambed geomorphology can be a regulator of the richness, extent, or the affinity of the biofilm community for nitrate removal.

**Project Purposes:**

<table>
<thead>
<tr>
<th>Aes_Rec_Ed</th>
<th>Bank_Stab</th>
<th>Chan_Reconfig</th>
<th>Chan_Incis_Stab</th>
<th>Chan_Reconfig</th>
<th>Dam_Retro</th>
<th>Infra_Prot</th>
<th>Dam_Retro</th>
<th>Fish_Pass</th>
<th>Floodplain_Recon</th>
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**Benefits Documented by Researcher:**

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<th>Water Quality</th>
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<th>Infrastructure</th>
<th>Aesthetic/Rec</th>
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<td>Public Safety</td>
<td>Property Value</td>
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**Data Types Provided in Research Report:**

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<th>Physical</th>
<th>Biological</th>
<th>NS</th>
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</thead>
</table>

| Data_Descp | Denitrification rate, NO3-N concentrations, DOC, flow data, physical parameters including channel complexity and shading. |

**WS_ID** 201612001 MC_Watershed  
**Drainage_Area (ha):** 140  
**Land_Use:** Urban

**Stream_ID/Stream Setting:** 20161200101 MC_MuddyCreek  
**Condition:** Post-Restoration (other)

**Practices Implemented:**

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<tr>
<th>Redirective_Practice</th>
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<tbody>
<tr>
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<td>Floodplain.Connectivity/Reconfiguration</td>
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<td>Passive_Approaches</td>
<td>No</td>
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<tr>
<td>Grade_Control</td>
<td>Yes</td>
<td>Habitat_Enhance/Instream_Features</td>
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<td>Flow_Control</td>
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</table>

**Project Description:**

Fluxes_Managed

Goals/Performance Standards
Bank Stabilization: installation of structures (e.g., cross vanes, log weirs) for grade control and bank stabilization
Bed Stabilization: Installation of structures (e.g., cross vanes, log weirs) for grade control and bank stabilization
Riparian Improvements: Replanting of riparian zone vegetation.
Floodplain Connectivity: Floodplain regrading
Habitat Enhancement:
Channel Reconfiguration:
Barrier Removal/Fish Pass:
Infrastructure Protection:
Other Approaches:

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**Stream_ID/Stream Setting:** 20161200201 NC_NorthCreek

**Practices Implemented:**
- **Redirective Practice:** Yes
- **Resistive Practice:** Yes
- **Grade Control:** Yes
- **Flow Control:** No
- **Riparian Condition/Buffer Reestab:** Yes
- **Floodplain Connectivity/Reconfiguration:** Yes
- **Habitat Enhance/Instream Features:** Yes
- **Channel Reconfig/Planform Changes:** No
- **Barrier Removal/Fish Passage:** No
- **Passive Approaches:** No

**Condition:** Post-Restoration (other)

**Project Description:**
Fluxes_Managed

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**Stream_ID/Stream Setting:** 20161200301 DB_DairyBranch

**Practices Implemented:**
- **Redirective Practice:** Yes
- **Resistive Practice:** Yes
- **Grade Control:** Yes
- **Flow Control:** No
- **Riparian Condition/Buffer Reestab:** Yes
- **Floodplain Connectivity/Reconfiguration:** Yes
- **Habitat Enhance/Instream Features:** Yes
- **Channel Reconfig/Planform Changes:** No
- **Barrier Removal/Fish Passage:** No
- **Passive Approaches:** No

**Condition:** Post-Restoration (other)

**Project Description:**
Fluxes_Managed
**Goals/Performance Standards**

- **Bank Stabilization:** Installation of structures (e.g., cross vanes, log weirs) for grade control and bank stabilization
- **Bed Stabilization:** Installation of structures (e.g., cross vanes, log weirs) for grade control and bank stabilization
- **Riparian Improvements:** Replanting of riparian zone vegetation
- **Floodplain Connectivity:** Floodplain regrading
- **Habitat Enhancement:**
- **Channel Reconfiguration:**
- **Barrier Removal/Fish Pass:**
- **Infrastructure Protection:**
- **Other Approaches:**

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<td>20161200501 RB_RockyBranch</td>
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<th><strong>Floodplain Connectivity/Reconfiguration</strong></th>
<th><strong>Passive Approaches</strong></th>
<th><strong>Grade Control</strong></th>
<th><strong>Habitat Enhance/Instream Features</strong></th>
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<th><strong>Flow Control</strong></th>
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**Project Description:**
Fluxes Managed

**Goals/Performance Standards**

- **Bank Stabilization:**
- **Bed Stabilization:**
- **Riparian Improvements:**
- **Floodplain Connectivity:**
- **Habitat Enhancement:**
- **Channel Reconfiguration:**
- **Barrier Removal/Fish Pass:**
- **Infrastructure Protection:**
- **Other Approaches:**
**Project Description:**

Fluxes Managed

Goals/Performance Standards

Bank Stabilization: installation of structures (e.g., cross vanes, log weirs) for grade control and bank stabilization

Bed Stabilization: Installation of structures (e.g., cross vanes, log weirs) for grade control and bank stabilization

Riparian Improvements: Replanting of riparian zone vegetation

Floodplain Connectivity: Floodplain regrading

Habitat Enhancement:

Channel Reconfiguration:

Barrier Removal/Fish Pass:

Infrastructure Protection:

Other Approaches:

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<th>Condition: Post-Restoration (other)</th>
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</table>

**Practices Implemented:**

- Redirective_Practice: Yes
- Resistive_Practice: Yes
- Grade_Control: Yes
- Flow_Control: No

- Riparian_Condition/Buffer_Reestab: Yes
- Floodplain_Connectivity/Reconfiguration: Yes
- Habitat_Enhance/Instream_Features: Yes
- Channel_Reconfig/Planform_Changes: No

**Project Description:**

Fluxes Managed

Goals/Performance Standards

Bank Stabilization: installation of structures (e.g., cross vanes, log weirs) for grade control and bank stabilization

Bed Stabilization: Installation of structures (e.g., cross vanes, log weirs) for grade control and bank stabilization

Riparian Improvements: Replanting of riparian zone vegetation

Floodplain Connectivity: Floodplain regrading

Habitat Enhancement:

Channel Reconfiguration:

Barrier Removal/Fish Pass:

Infrastructure Protection:

Other Approaches:

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**Study ID:** 2016110 Wallace et al. 1995

**State/Country:** NC US

**Category:** In-stream processing

**Exp. Design:** Before-After with Control

**Project Purpose Statement:**

Paired sites study conducted at the USFS Coweeta Hydrologic laboratory looking at the effect of the addition of coarse woody debris on ecological, physical and nutrient uptake parameters.

**Outcomes:**

---

Friday, August 26, 2016
Log installation reduced velocities and greatly increased organic matter storage. Uptake lengths increased for ammonia, decreased for nitrate, and were unchanged for phosphorus.

Abstract:
Three pairs of cobble riffle study sites were established in a second-order stream in North Carolina and logs added to the downstream riffle at each site. At log addition transects, stream depth increased, current velocity decreased, cobble substratum was covered by sand and silt, and both coarse and fine particulate organic matter increased dramatically. Log additions had less dramatic effects on uptake lengths of ammonium, nitrate, and phosphate, but they had immediate and significant impacts on invertebrate community structure: abundances and biomass of scrapers and filterers decreased; collectors and predators increased; overall shredder biomass did not change, but biomass of trichopteran and dipteran shredders increased, while that of most plecopteran shredders decreased; and plecopteran predators also decreased despite greater abundances of potential prey. These observations suggest that physiological and morphobehavioral constraints preclude many animals from tracking resources among patches when patches display very different abiotic conditions. Secondary production of scrapers and filterers decreased, whereas that of collectors and predators increased. The shifts in functional group abundances, biomass, and production between reference and debris-dam transects, which differed considerably from those previously reported for Bow-gradient, sandy-bottom streams, accentuate the importance of localized abiotic factors in structuring invertebrate communities within patches.

Project Purposes:

<table>
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<tr>
<th>Aes_Rec_Ed</th>
<th>Chan_Reconfig</th>
<th>NS</th>
<th>Habitat</th>
<th>Yes</th>
<th>Infra_Prot</th>
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<th>Dam_Retro</th>
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<tbody>
<tr>
<td>Bank_Stab</td>
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<tr>
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<td>Flow_Mod</td>
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<td>WQ_Man</td>
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</table>

Benefits Documented by Researcher:

| Water Quality | Yes | Physical | Yes | Infrastructure | NS | Aesthetic/Rec | NS | Other | NS |
| NS | Physical | No | Public Safety | NS | Property Value | NS |

Data Types Provided in Research Report:

| Water Quality | Yes | Hydrologic | Yes | Physical | Yes | Biological | Yes |
| NS | Physical | No | Public Safety | NS | Property Value | NS |

Data_Descp: Nitrogen and phosphorus, nutrient uptake lengths

WS_ID: 201611001 Coweeta
Drainage_Area (ha): Land_Use: Condition: Post-Restoration (other)

Stream_ID/Stream Setting: 20161100101 Cunningham_Ref

Practices Implemented:

| Redirective_Practice | No | Riparian_Condition/Buffer_Reestab | No | Barrier_Remove/Fish_Passage | No |
| Resistive_Practice | No | Floodplain_Connectivity/Reconfiguration | No | Passive_Approaches | No |
| Grade_Control | Yes | Habitat_Enhance/Instream_Features | Yes |
| Flow_Control | No | Channel_Reconfig/Planform_Changes | No |

Project Description:

Fluxes_Managed

Goals/Performance Standards

Bank Stabilization:

Bed Stabilization:

Riparian Improvements:

Floodplain Connectivity:

Habitat Enhancement: Coarse woody debris inputs and channel spanning logs.
Implement stream restoration project to protect land, improve aquatic life and terrestrial habitat, and reduce sediment and nutrient loads to the West Fork White River.

Outcomes:
The implementation of the WFWR stream restoration at Brentwood has proven to be successful in protecting land, improving aquatic and terrestrial habitat, and reducing sediment and nutrients loads to the WFWR.

Abstract:
The implementation of the WFWR stream restoration at Brentwood has proven to be successful in protecting land, improving aquatic and terrestrial habitat, and reducing sediment and nutrients loads to the WFWR. The project has been effective in reducing streambank erosion for a range of flow events that have exceeded the design flow up to catastrophic floods during the spring of 2011.
Benefits Documented by Researcher:

Water Quality: Yes
Physical: Yes
Infrastructure: Yes
Aesthetic/Recreational: Yes
Other: NS

Data Types Provided in Research Report:

Water Quality: Yes
Hydrologic: No
Physical: Yes
Biological: No

Data_Descp: Nitrogen and phosphorus, streambank erosion rates, phosphorus loading rates, nitrogen loading rates

**WS_ID**: 201612201 Beaver_Lake
**Drainage_Area (ha)**: 4662
**Land_Use**: Forest

**Stream_ID/Stream Setting**: 20161220102 WestFork_PostRest
**Condition**: Post-Restoration (3 yr)

**Practices Implemented:**
- Redirective_Practice: Yes
- Resistive_Practice: Yes
- Grade_Control: Yes
- Flow_Control: Yes
- Riparian_Condition/Buffer_Reestab: No
- Floodplain_Connectivity/Reconfiguration: No
- Habitat_Enhance/Instream_Features: No
- Channel_Reconfig/Planform_Changes: Yes
- Barrier_Removal/Fish_Passage: No
- Passive_Approaches: No

**Project Description:**

**Fluxes_Managed**

**Goals/Performance Standards**
Utilized "natural channel design" with constructed boulder and wood toe bank and bench construction. Reduce sediment, phosphorus, and nitrogen loadings, an improve local ecology through aquatic and terrestrial habitat restoration. Also, reduce land loss and protect infrastructure.

**Bank Stabilization:**
Bank Stabilization was a main focus of NCD design approach. The primary component of the stabilization design was the construction of a multi-level bench composed of boulders, trees, and gravel with a layer of topsoil encapsulated in coconut fiber fabric on top.

**Bed Stabilization:**

**Riparian Improvements:**

**Floodplain Connectivity:**

**Habitat Enhancement:**

**Channel Reconfiguration:**

**Barrier Removal/Fish Pass:**

**Infrastructure Protection:**

**Other Approaches**: Natural Channel Design
References


Hubbard, L.C., Biedenharn, D.S., Ashby, S.L. 2003. Assessment of environmental and economic benefits associated with streambank stabilization and phosphorus retention. USACE Research and Development Center, Vicksburg, MS.


