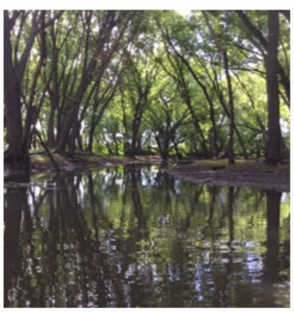
DEPARTMENT OF NATURAL RESOURCES

Nutrient Reduction Strategies for Stream and Gully Systems

Analysis for the Minnesota Nutrient Reduction Strategy (2025 update)



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Introduction

The 2014 Nutrient Reduction Strategy (NRS) (MPCA, 2014) provided a well-informed framework on nitrogen (N) and phosphorus (P) inputs, and strategies to reduce nutrients across Minnesota. The goal was to reduce nutrients from point and non-point sources and, ultimately, to restore and protect downstream waters such as the Gulf of Mexico, Lake Winnipeg and Lake Superior. Section 3.2 of the 2014 NRS indicated that streambank erosion represented 17%, 15% and 6% of the total phosphorus loads in the Mississippi River, Lake Superior Basin and Lake Winnipeg Basin, respectively. Section 5.4.1 of the report briefly discusses the contribution of streambank erosion on sediment and its associated phosphorus loading, as well as Best Management Practices (BMPs) within the near-channel area to reduce phosphorus. This report serves as a support document for the 2025 NRS update, providing additional information on what is known about nutrients and in-channel processes, as well as strategies that work to reduce their contributions to achieving the overall goals of reducing nutrient concentrations and loads in the nation's waters.

Several studies have recognized that streambank erosion can be a significant non-point source of phosphorus and nitrogen. Most studies have examined individual streams or small watersheds, finding that phosphorus loads from streambank erosion to total export load have ranged widely. A review by Fox et al. (2016) found that streambanks and other near-channel features contributed 7% to 94% of suspended sediment and 6% to 93% of phosphorus across studies. In Denmark, estimates for streambank contribution of phosphorus range from 15% to 93% (Laubel et al., 2003; Kronvang et al., 1997); in Iowa 3% to 38% (Beck et al., 2018); In the Blue Earth River in Minnesota 7% to 10% (Sekely et al., 2002); in the Kinnickinnic River in Eastern Wisconsin 13% (Blount, 2023); and in Oklahoma 31% to 100% (Miller et al., 2014; Purvis et. al., 2016). A study in Iowa estimated the statewide contribution of stream channel sources to the total phosphorus riverine export at 31% (Schilling et. al., 2022). A study in the Le Sueur River in Minnesota found a total of 23% of phosphorus derived from a combination of streambanks, bluffs and ravines (Baker, 2018).

Less work has been completed to estimate the contribution of streambank erosion sources to total nitrogen. Jiang et al. (2020) estimated that sediment-bound nitrogen from streambank erosion accounted for 26% of the total load in Big Elk Creek, PA. Noe et al. (2022) estimated the total load of nitrogen from streambanks to comprise 6% of the total load for Chesapeake Bay.

Modeling the total contribution of streambank sources of nutrients is difficult because of impacts and methods by which nutrients cycle in the stream corridor, whether processed or exported. Nutrients cycle between bound (less bioavailable) and dissolved (readily bioavailable) phases, through both biotic and abiotic pathways. This can involve being taken up and released by plants, microbes and phytoplankton (both nitrogen and phosphorus); undergoing equilibrium exchange with sediment or being released from sediment to bioavailable form under anaerobic reducing conditions (phosphorus); or being removed from the system under reducing conditions (nitrate, through denitrification). These processes of nutrient transformation impact nutrient transport and must be carefully considered in the assessment of the source and related targeting of management for nutrient load reduction. One such example is the Le Sueur River in Minnesota, where studies revealed the importance of near-channel sediment in modulating dissolved phosphorus concentrations (Baker, 2018) and in providing a vector for phosphorus to downstream waters (Baker, 2018, Grundtner et al., 2014).

In addition to these biogeochemical nutrient cycling processes that impact bioavailability, physical processes such as hyporheic exchange (surface and subsurface water and solute mixing at the sediment-water interface) and floodplain capture also impact processing and affect export. Noe et al. (2022) highlights the importance of including geomorphic processes when assessing or addressing nutrients in streams by noting, "Identification of the effects of streambank erosion and floodplain deposition on regional watershed mass balances, although notoriously difficult, is essential for improved understanding of stream geomorphic change and effective targeting of watershed management programs."

Background

The processes of stream channels and their relationships to water quality, watershed hydrology, and ecology are complex. Without a basic comprehension of these interrelationships, actions taken to address nutrient loading from stream channel sources may be unsuccessful or even detrimental. Successful implementation will address stream processes that drive nutrient release, storage and processing, which can differ from simply addressing the initial cause. This section introduces these processes, serving as a framework for the holistic evaluation of implementation strategies in the subsequent sections.

Nutrient Concentrations in Streambank Soils

It can be difficult to accurately quantify the amount of nutrients released by streambank erosion and exported. Phosphorus and nitrogen concentrations in soils vary by soil type, land cover and land use. For example, agricultural land use generally results in higher soil concentrations of nutrients than forest or prairie land cover, due to the use of fertilizers or manure (Zhou, 2022). The stratigraphy of the soil can also affect concentrations. Higher P concentrations tend to be found near the surface, due to accumulation from litter deposition or anthropogenic enrichment (i.e. manure, fertilizers; Fenton, 1983). Shengnan et al. (2022) attributed P concentrations in the top 30cm to 60 cm of soil to land use, while bedrock and soil sources influenced concentration below. Phosphorus concentrations in streambanks have been found to be highly variable with soil depth (e.g., 300-900 mg kg 1) and unpredictable (Ishee et al., 2015; Schilling et al., 2009). Different soil types have varying concentrations and forms of phosphorus (Cross and Schlesinger, 1995), depending on the age of the soils and past alluvial processes.

Quantifying nutrient export due to streambank erosion is further complicated by differences in the ways various forms of soil-bound nitrogen and phosphorus are mobilized, processed and stored when in contact with water. For example, the binding capability of soil particles to phosphorus varies with soil type and mineral content. Phosphorus binds well with clays and soils high in iron, aluminum and calcium (Zhou et al., 2022). Coarse materials like sand have reduced binding capacity, so phosphorus is rapidly released and mobilized following erosion of those particles from a streambank. Nitrogen, in most forms, is readily mobilized by water, regardless of soil type.

Stream Sediment Source

Nutrient release by soil erosion can be a primary driver of nutrient flux in rivers and streams. Due to this, sediment source assessment can serve as a relative indicator of nutrient sources. Methods to mitigate sediment loading in streams will also reduce nutrient export. Targeting the largest contributors of sediment should generally result in the greatest reduction in nutrient flux from sediment sources.

Many studies have shown that even in watersheds where agriculture is the dominant land use, the primary contributor of suspended sediment is near-channel sources (streambanks, ravines and bluffs). Wilcock et al. (2009) estimated sediment contribution sources to sub-watersheds in the Minnesota River watershed and estimated values between 10% and 40% from fields. In nine of the 11 sub-watersheds, the upper limit of the estimate of the total suspended sediment contribution from field sources was less than one-third of the total load. In the Well's Creek Watershed Assessment of River Stability and Sediment Supply (WARSSS) sediment source study, 89% of the total sediment was generated by streambank erosion (De Paz 2021). Schilling et al. (2011) found streambank erosion was the primary source of sediment in Walnut Creek (Iowa). Williamson et al. (2024) found that streambank erosion accounted for 54% to 96% of streambed sediment in streams with a contributing area larger than 2.7 km^2 in the Maumee River watershed. An assessment of sediment sources for streams spanning the Midwestern United States revealed that nine of 15 sites had suspended sediments with greater than 50% near-channel sources (Gellis et al., 2017). In Walnut Creek (Iowa), phosphorus source modeling attributed 54% to the stream channel (Beck et al. 2018). Similar findings have occurred in pastured streams. Sharpley and Syers (1979) found that while surface runoff from pastures contributes to sediment and P loading during storm events, annual P losses due to streambank erosion can be two to four times greater than those from surface runoff.

Streambank erosion and lateral migration rates vary considerably across streams. Geology, channel substrate type, density, and health of the riparian plant community, as well as channel form, all affect these rates. However, streams with annual high suspended sediment loads due to bank erosion and those that display rapid lateral migration are indicative of a channel that has become unstable.

Stream Channel Stability

A geomorphic definition of channel stability is the "ability of a stream to transport the water and sediment of its watershed in such a manner as to maintain its dimension, pattern and profile, over time, without either aggrading or degrading" (Rosgen and Silvey 1996). A way to visualize channel stability is through Lane's equation (Figure 1). It represents a balance between the energy of the flowing water and its ability to transport sediment and the amount of sediment available. When in balance, a channel will erode and laterally migrate at a very slow rate, maintaining its basic form over time while keeping its connection to the floodplain. A stable channel is in a state of dynamic equilibrium. Over time, the channel form, dimension (cross-sectional area, width, and depth), pattern (sinuosity, meander pattern), and profile (slope, pool, and riffle feature length and spacing) remain relatively static. In unstable channels, accelerated erosion and lateral accretion result in significant changes to the channel form.

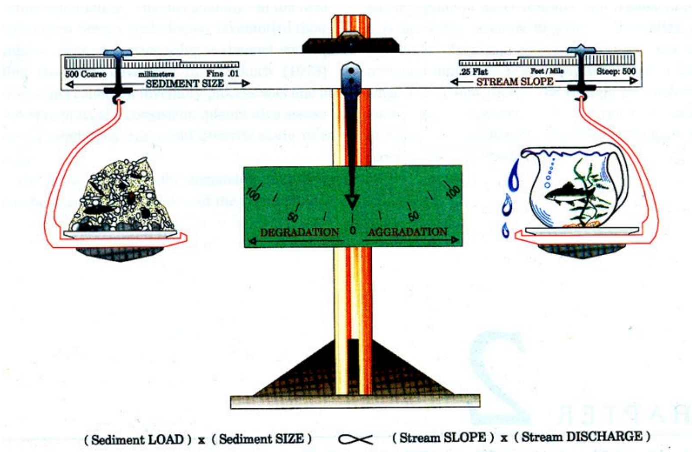

Figure 1. Lane's balance. Channels will remain stable and maintain their basic form over time when the hydraulic energy (stream power) to transport sediment equals the sediment volume being generated.

Channel form is determined by variables including valley morphology (slope and confinement), composition of streambank and channel bed sediment, riparian and in-stream vegetation community, and sediment loading rates from internal and external sources. Channel size in alluvial systems is determined by what is termed the effective discharge, also known as the dominant discharge or channel-forming flow. Effective discharge is the flow at which the combination of frequency of occurrence and volume of sediment transported per event results in the greatest transport of sediment over time (Figure 2). The channel cross-sectional area adjusts only to contain the effective discharge. Any higher flows will spill onto the adjacent floodplain in channels that are stable. For this reason, this flow event is also commonly referred to as the bankfull discharge. In incised streams, the effective discharge will not reach the floodplain elevation. Because discharge to a given point on a stream is directly correlated to the size of the upstream contributing watershed, channel area is correlated to drainage area, so channel dimensions increase as contributing watershed size increases.

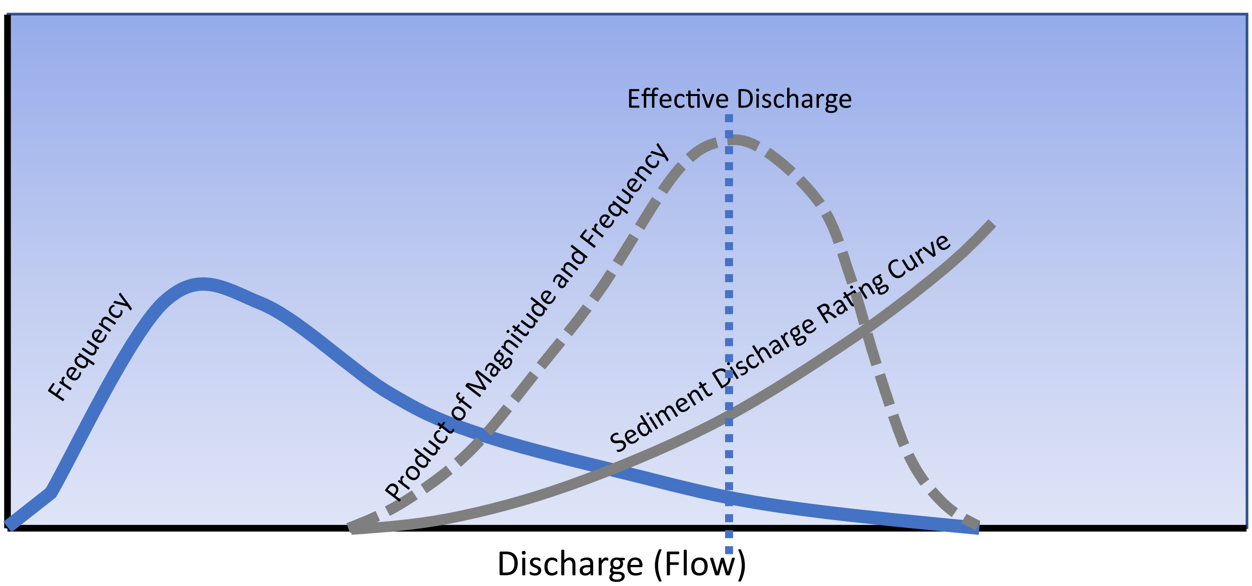

Figure 2. The effective discharge is the point at which the product of the frequency of various magnitudes of discharges and the volume of sediment transported at each discharge is highest. In other words, this is the discharge at which the most sediment transport that shapes a channel occurs. (From Wolman and Miller 1960).

One of the main characteristics of a stable stream channel is lateral connectivity to the floodplain. Floodplains are relatively flat areas adjacent to the stream channel that are formed through erosional and depositional processes. In a stable stream system, lateral connectivity means that any floods greater than the effective discharge will access the floodplain. Floodplains serve many functions for stream stability, water quality, hydrology and hydraulics, and ecology. During floods, continuous, high-capacity floodplains allow high flows to spread out across the stream's valley, reducing the erosive force of the flows on the channel bed and banks. Natural floodplains provide roughness due to depressions and vegetation, which further slow velocities. These slower velocities equate to reduced sediment transport capacity, resulting in the deposition of sediment and associated nutrients on the floodplain while promoting infiltration on the descending limb of the flood event. Slower floodplain velocities also facilitate the migration of fish and other aquatic organisms.

Unstable streams can be actively aggrading (i.e. stream bed raising) or incising/degrading (i.e. stream bed lowering). Aggradation occurs when there is an upstream source of sediment that exceeds the channel's stream power to transport it. Examples include a significant reduction in stream power due to a reduced valley slope (such as an alluvial fan or delta), a decrease in the overall volume of water (through diversions), or more localized impacts of an increase in channel or floodplain roughness (including vegetation and large woody debris). Excess sediment sources can include external sources but, in many cases, the primary source is bank and ravine erosion from upstream reaches. A stream can, therefore, have both sections that are incising and that are aggrading (Figure 3).

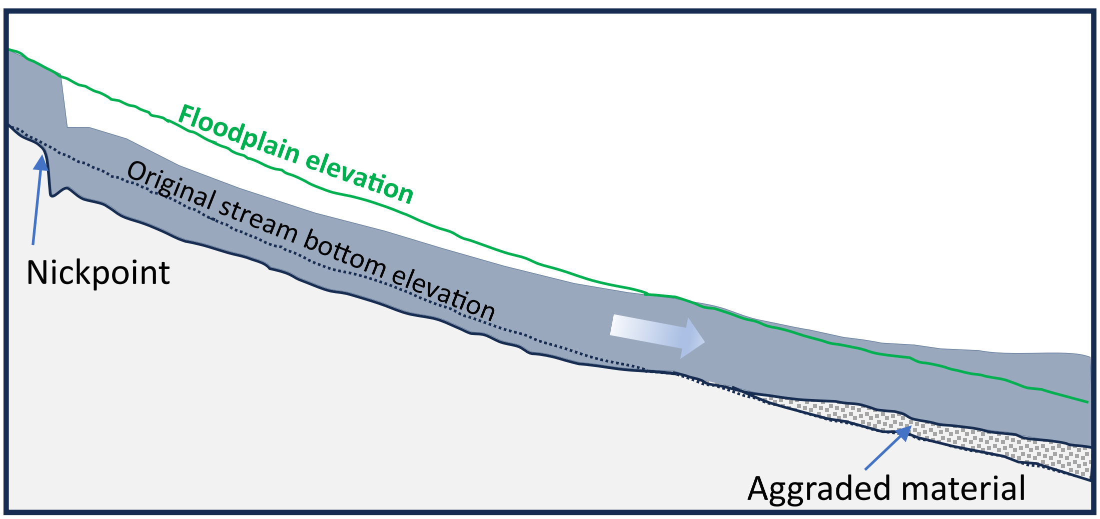

Figure 3. Representation of incision occurring in upstream reach leading to aggradation of downstream reach. The water surface represents a bankfull discharge and the green line represents bankfull/floodplain elevation prior to destabilization.

Incised channels are the predominant form of unstable channels in Minnesota. These are streams that have cut into their beds and no longer reach the floodplain at effective discharge flows. As the degree of incision (i.e. bank-height ratio) increases, relative velocities and shear stress on the channel during flood events increases, resulting in higher streambank sediment contributions. Even during smaller floods, comparing an incised Cascade Creek to the same reach after restoration, a two-fold increase in velocities and a five-fold increase in shear stress was modeled when comparing the unrestored, incised channel to the restored, laterally connected channel (Figure 4). Incised channels are often characterized by their extensive eroding banks, not only on the outside of bends where shear stress is highest, but on both sides of straight reaches. In some areas of the state, especially in agricultural regions, these channels have been artificially manipulated to be incised by channelization and ditching for drainage purposes.

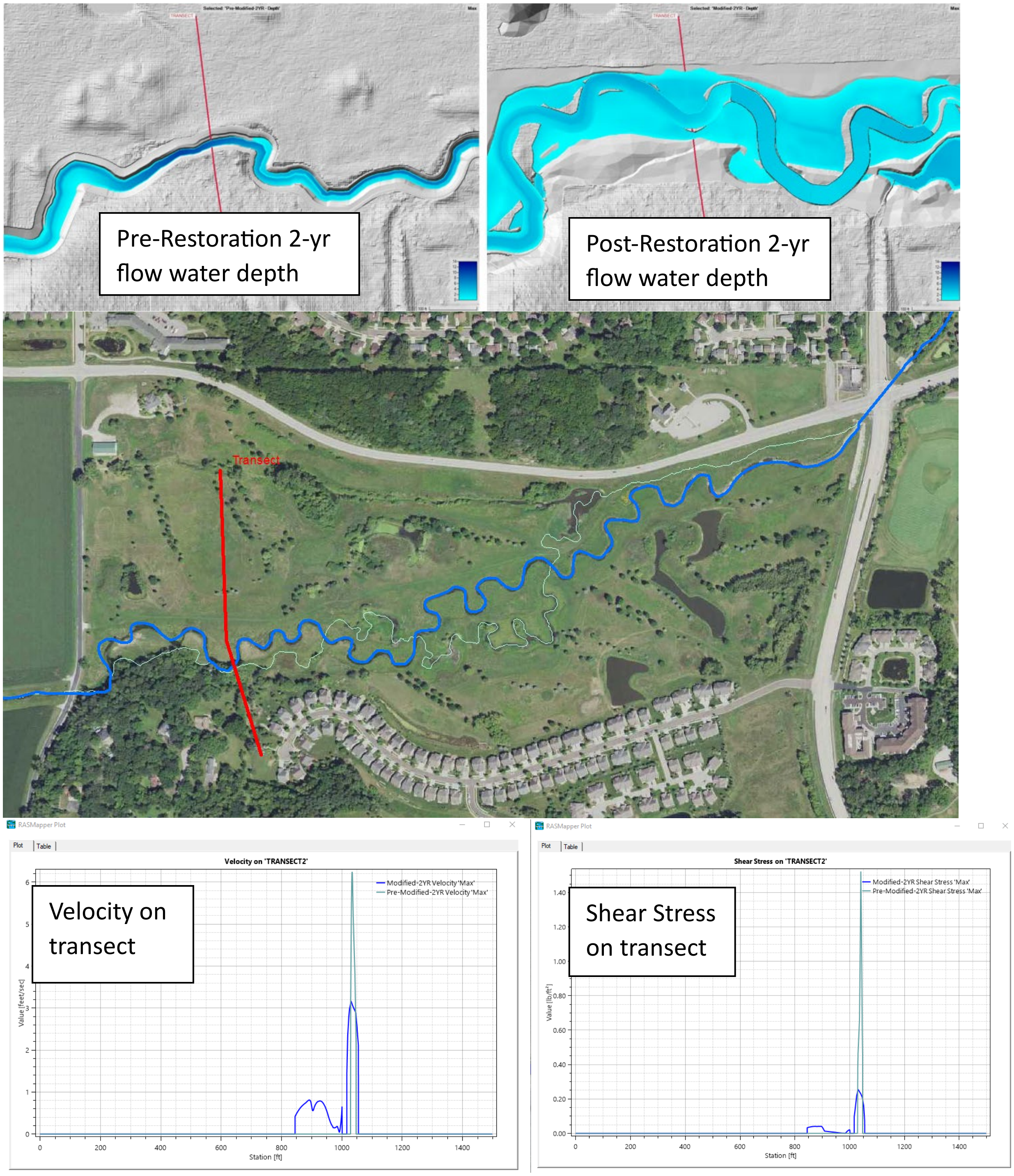

Figure 4. Cascade Creek Restoration before and after modeled conditions. Top images show modeled water depths during 2-yr frequency flow event in similar relative location. The middle image shows the new channel pattern (in blue) with the original channel visible in the photo. The red line represents the location of the transect modeled in the bottom two charts. Bottom charts show modeled velocities (left) and shear stress (right) for the original channel (grey) and the restored (laterally connected) channel (blue) at a 2-year discharge. (Reinartz and Murtada, Minnesota Department of Natural Resources in press 2025)

Causes of Channel Instability

Altered Hydrology

There are many causes that can lead to channel instability. Altered hydrology (changes to the natural magnitude, duration or frequency of hydrological events) is one of the main drivers of instability in Minnesota streams. Altered land use leading to increased runoff rates that amplify the magnitude and duration of a given precipitation event is one of the primary causes of altered hydrology. Increased run-off rates have been demonstrated to lead to channel enlargement, both through incision and widening. Schottler et al. (2014) correlated the widening of agricultural streams in Minnesota with an increase in annual water yield between the periods of 1940-1974 versus 1975-2009 (Figure 5).

In agricultural areas, peak flows and annual runoff have been increasing for as long as gaging has been in existence (Novotny and Stefan 2007). In Minnesota, there are over 19,000 miles of surface ditches, and it is estimated that 21% of the land area has some density of subsurface drainage (Nakagaki and Wieczorek, 2016). In some agricultural watersheds, it is estimated that more than 50% of the land has some sort of tile drainage (Sugg 2007).

It is estimated that half of the historic wetlands in Minnesota have been lost, while in the prairie region, wetland loss exceeds 90% (MRCACPR, 1995). Schottler et al. (2014) found that a reduction in evapotranspiration loss caused by the loss of wetland depressions, combined with an increase in other drainage methods, is a primary driver of increased runoff in agricultural areas, exceeding the contribution of increased precipitation (Figure 6).

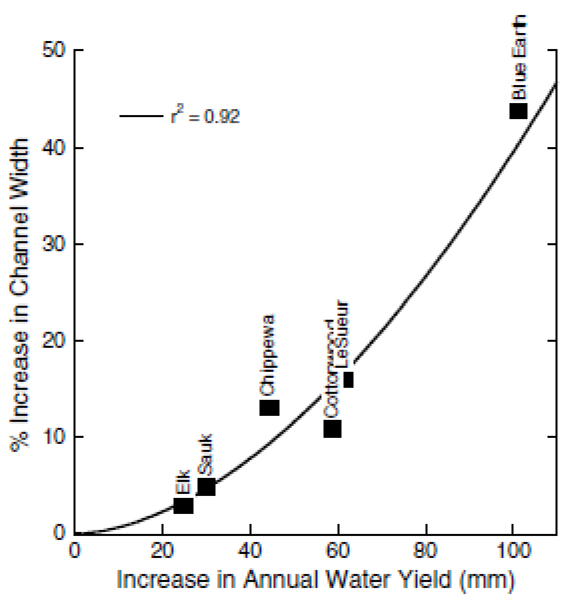

Figure 5. Percent change in channel mean width between periods of 1940-1974 vs 1975 -2009 compared to increase in water yield (Shottler et. al., 2014).

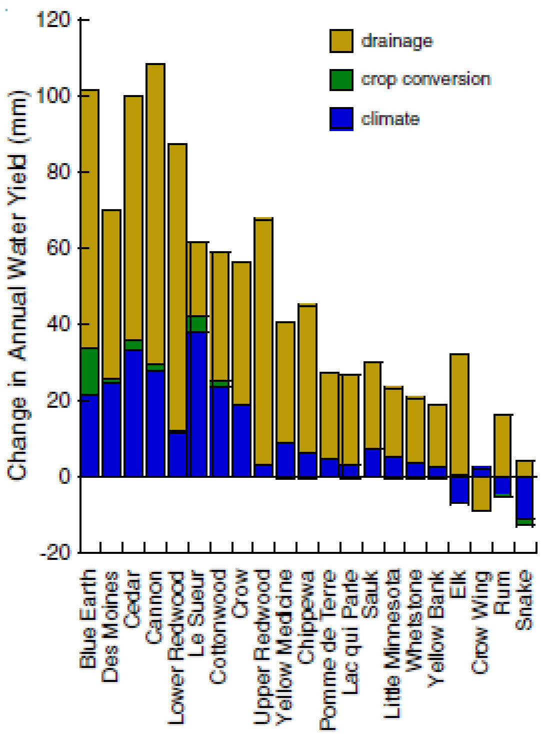

Figure 6. Apportionment of changes in mean annual water yield for watersheds in the Minnesota River watershed. (Schottler et. al., 2014).

Increased impervious land cover in urban areas also contributes locally to increased runoff. Impervious surfaces reduce infiltration and evapotranspiration, which can significantly increase the magnitude of runoff to urban streams. This is all exacerbated by an increase in the frequency of large rain events and the magnitude of the heaviest rainfalls.

In the forested northeastern section of the state, historic logging, which began in the mid-1800s and continued into the early 1900s, denuded much of the land of its mature forests, resulting in increased snowmelt rates. This, combined with a corresponding loss of riparian buffers and impacts on larger streams due to logs floating downstream, the creation of splash-dams, and large-scale fires that often followed harvest, initiated channel instabilities in many streams (Reidel et al. 2002).

Direct Channel Alterations

Another primary cause of channel instability is the direct alteration of channel form through physically ditching and/or realigning streams. Almost 50% of Minnesota's streams have been altered in some way (Figure 7). Ditching tends to create incised channels, disconnecting streams from their floodplain. Channels straightened by ditching will begin to erode, taking time to get back to a stable meandering form.

Disrupting the continuity of sediment transport affects channel stability. Dams cause instability by capturing sediment in their reservoirs while creating sediment-starved water below the dam, which leads to increased erosion or scouring. Similarly, diversions can disrupt sediment transport, leading to aggradation.

Road crossings can have localized impacts on channel stability that cumulatively can have a significant impact on the health of a stream system. Road prisms across a floodplain with undersized culverts impact sediment transport similarly to a dam. Aggradation occurs upstream, while downstream velocities are increased, and channel scour occurs. In three northern Minnesota counties, culvert inventories identified that culverts were undersized (<80% of the bankfull width) at 43% to 93% of the crossings (Minnesota Department of Natural Resources data). When culverts are not properly aligned with the channel, at high flows, water directed into streambanks accelerates erosion.

Excess sediment loading is another cause of channel instability, leading to aggradation. Erosion of gravel road surfaces at stream crossings, cattle hoof-shear on streambanks, improper stormwater control measures, and the removal of riparian and streambank vegetation can all contribute to localized channel instability.

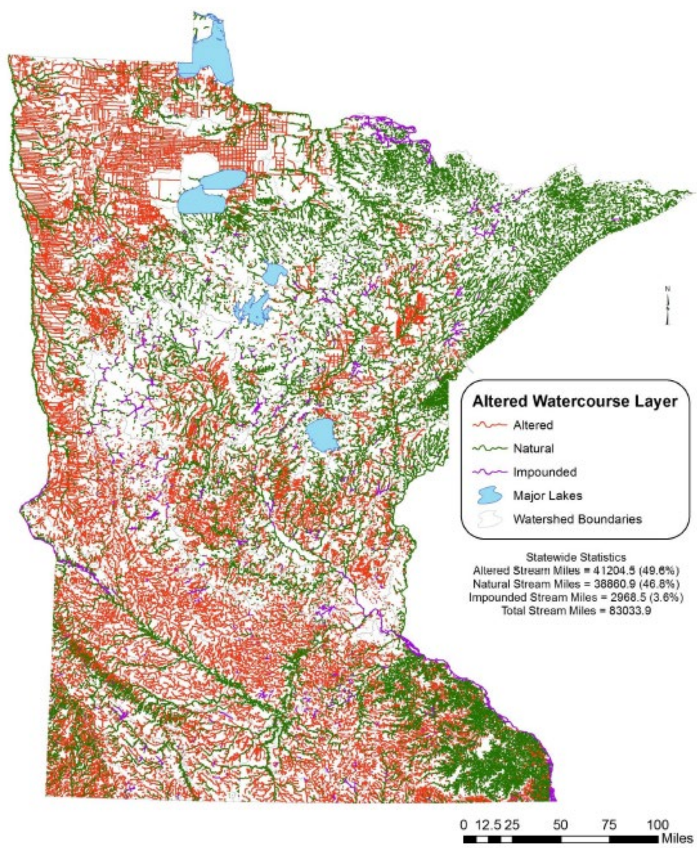

Figure 7. Map of altered streams in Minnesota. (Image from Minnesota Pollution Control Agency https://www.pca.state.mn.us/sites/default/files/wq-bsm1-05.pdf)

Channel Evolution

When a stream channel becomes destabilized in response to disturbance, a channel evolution process is often initiated. Channel evolution is a series of sequential changes in the width-to-depth ratio and floodplain connectivity, resulting in increased erosion and deposition rates as the stream moves toward developing a new stable form, typically at a new elevation. The initial model of channel evolution (Figure 8) was developed by Schumm et al. (1984), and Simon (1989) modified the model to specifically address the evolution initiated by channelization. In both models, the stream degrades (incises) into its bed, reducing lateral floodplain connectivity and increasing stress on the bed and banks. As the channel continues to incise, the steepened banks begin to collapse and the channel widens. As the channel widens and water depths decrease, the channel's capacity to transport sediment (stream power) decreases, resulting in aggradation. Eventually, in the final stage of evolution, a stable channel form is achieved with a floodplain developed at the new lower elevation (Figure 9). The abandoned floodplain is now referred to as a terrace. There are other channel evolution models in the literature (Rosgen and Silvey 1996, Cluer and Thorne 2014), but all represent accelerated rates of erosional processes when not in the stable first or final stage.

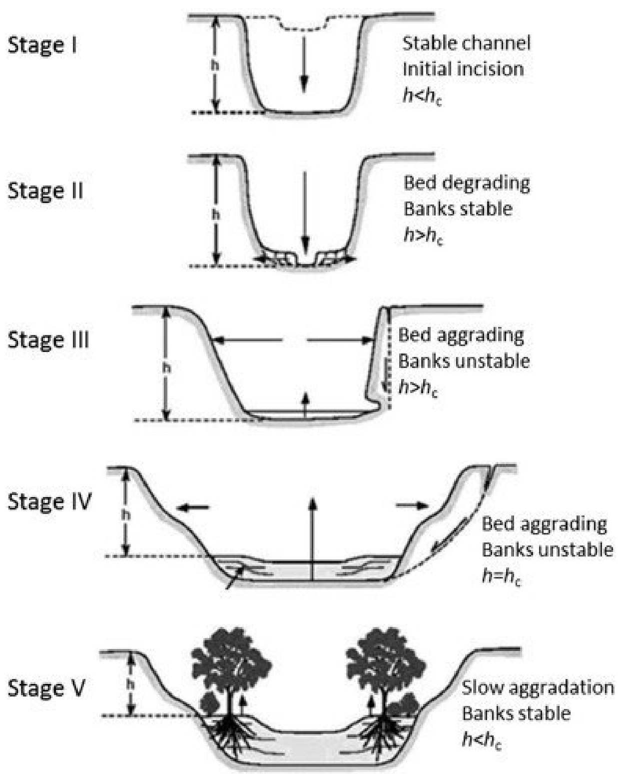

Figure 8. Channel evolution model (Schumm, 1984). Arrows represent the direction of bed or bank movement. (Hc = critical bank height). The rate of channel evolution can be a matter of years or can take decades or more. Typically, high sediment loads are an indication that a stream is in the middle of a channel evolution process.

Figure 9. Example of stage 5 in the channel evolution process on Rush River, Sibley County, Minnesota. Note that the high terrace on the left side was the floodplain elevation prior to channel evolution initiation. (Photo Minnesota Department of Natural Resources).

The lowering of the base-level elevation of a stream channel during channel evolution creates a difference in elevation between tributaries or gullies, driving headcuts up both. Headcuts disconnect tributaries or gullies from their floodplains, thereby accelerating instability and increasing the export of sediment and associated nutrients.

The increased rate of lateral migration observed during channel evolution not only increases bank erosion rates but also increases the likelihood of the channel migrating against a steeper valley wall. Once a stream is flowing against a valley wall (bluff), the increased lateral scour in the widening stages of channel evolution can increase the rate of toe erosion and, therefore, slumping. Sediment and nutrient contribution from large bluffs is often episodic, with large loads coming in the form of slumps, and can be of separate soil types (i.e. glacial clay, compared to alluvial sands and silts) with different nutrient concentrations.

Consequences of Channel Instability and Channel Evolution

When evaluating stream functions and processes, the 'five components of riverine systems' developed by the Instream Flow Council (Annear et al. 2004) provides a useful model for assessing stream functions systemically (Figure 10). The consequences of channel instability impact the functions of each of these components. It should be recognized that while having distinct components aids in defining stream processes, these components are all correlated, and impacts to functions in one component can, in turn, affect processes and functions in other components.

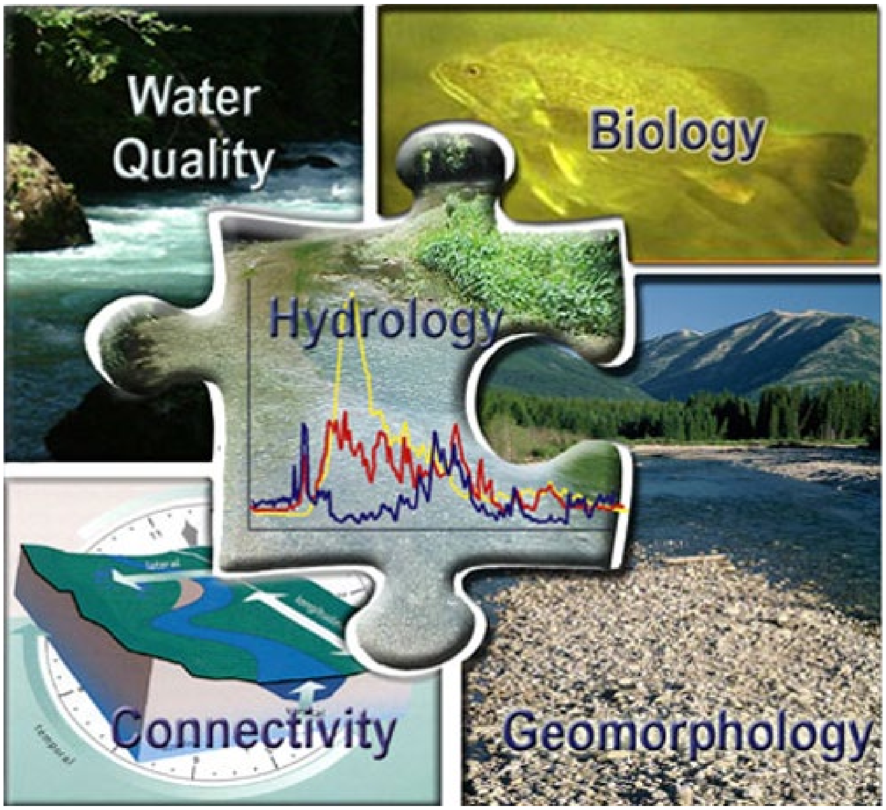

Figure 10. The Instream Flow Council's five components of riverine systems.

Water Quality

A primary consequence of channel instability that affects the ecological health of the system, as well as receiving waters, is the increased rate of bed and bank erosion, resulting in higher sediment and nutrient export. The total suspended sediment load is relatively low in stable channels compared to unstable channels that can have an order of magnitude or higher sediment loads (Figure 11). Therefore, restoring channel stability can be the most effective strategy for reducing sediment and nutrients in sediment-impaired systems. Water temperature is another component of water quality that can be affected by stream stability. Water temperature can increase when channels are in a widening stage of evolution.

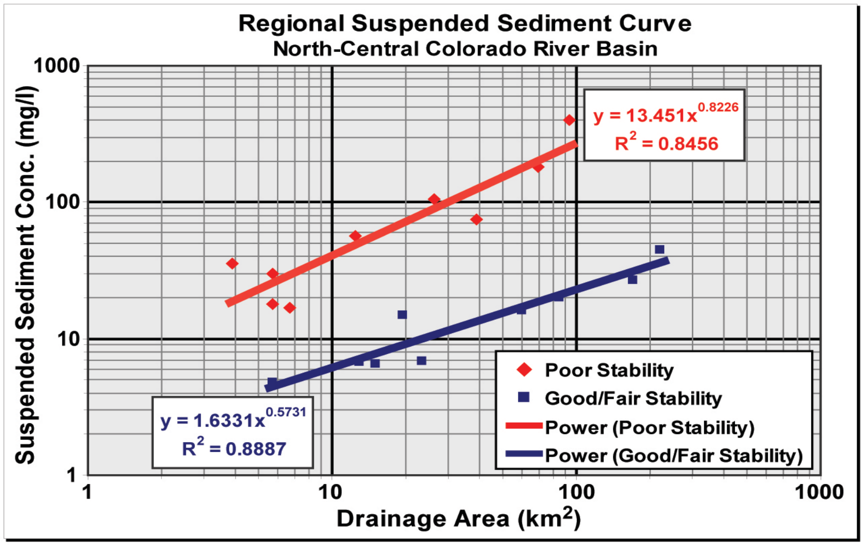

Figure 11. Regional Suspended Sediment Curves (Drainage area vs. Suspended Sediment Concentration) for North-Central Colorado River Basin. Stable streams versus unstable streams.

Connectivity

Connectivity refers to exchange pathways of water resources, sediment, nutrients and organisms between the channel, the aquifer and the floodplain (Ward 1995). There are four elements to the connectivity component: lateral, vertical, longitudinal and temporal. Each component of connectivity can be impacted by channel instability.

Lateral connectivity refers to the degree of connection between a channel and the floodplain. Stream channels are considered fully connected when water reaches the incipient point of flooding at the effective flow. The loss of lateral connectivity affects numerous processes related to the channel's hydraulics, as well as its water quality and biological health. When a channel is incising, it takes larger and larger floods to access its floodplain. When these large flow events are contained within the channel, there is increased stress on the bed and banks, resulting in higher erosion rates. Hence, an increase in suspended sediment loads is observed in unstable systems (Figure 11).

Floodplains also play a critical role in the flux of nutrients and sediment. During large floods, flows that inundate the floodplain encounter lower shear stress due to a decrease in depth and an increase in roughness. This results in the deposition of sediment and associated nutrients on the floodplain. Beck et al. (2019) tracked the incision process on an Iowa stream and found the cross-sectional area of the channel below the bank increased 16.8% over a 16-year period as the channel incised and widened (Figure 12). Over this 16-year period, the resulting reduction in floodplain inundation was estimated to reduce floodplain storage of suspended sediment (SS) and TP, 61% and 62%, respectively. As a result, the export of SS and TP was estimated to increase 9% and 18%, respectively.

Biologically, laterally connected streams and floodplains are considered more functional. For example, some plants, such as cottonwoods, rely on floods to disperse seeds in the floodplain and the deposition of sediment on the floodplain to create ideal germination and growing conditions. During larger floods, laterally connected streams will have lower mean velocities, reducing stress on fish. The slower velocity flows in floodplains are often used by fish as passage corridors to avoid the high velocities in the channel.

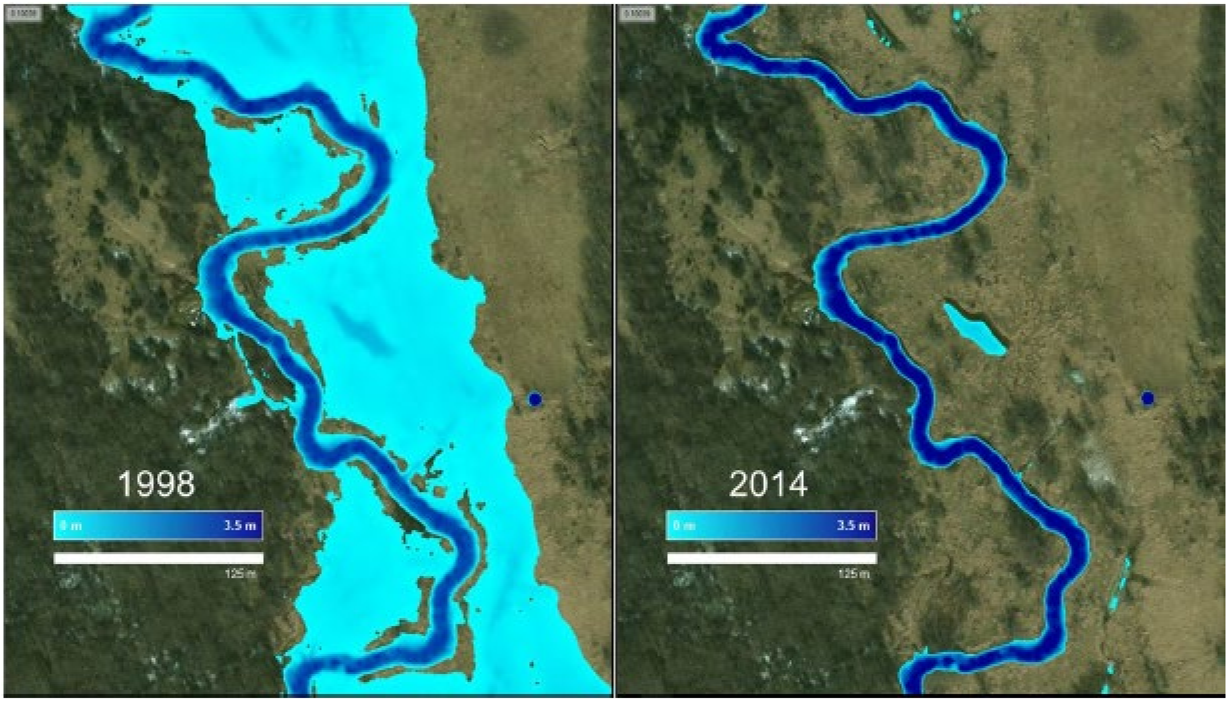

Figure 12. Extent of floodplain inundation on Walnut Creek (Iowa) for 1998 and 2014 with same modeled discharge. This depicts the amount of loss of lateral floodplain connectivity as the channel becomes further incised (Beck et al., 2019).

Fluvial depressional features like oxbows (waterbodies formed by cutting off a meander loop) provide critical habitat for special concern species, such as the Topeka shiner. These floodplain features have also been found to reduce nitrate exports by 45% (Schilling et al. 2019). Unstable streams with high sediment loads can fill these depressions during floods in the earlier stages of channel evolution, reducing their effectiveness. As channels become more incised, the oxbows and depressions become less hydrologically connected, reducing flood storage. This filling or abandoning reduces the benefits to water quality, water quantity and biology.

Vertical connectivity refers to the connection between channel hydrology and the groundwater table. This connection affects hyporheic exchange and water table elevations. Riparian floodplains play a role in reducing groundwater nitrate-nitrogen levels through denitrification and vegetative assimilation. The lowering of the groundwater table due to channel incision can reduce the health of riparian vegetation and reduce carbon and nitrate supply. It can also create aerobic soil conditions that reduce the effectiveness of riparian denitrification to the point that, at some times of year, the buffer can become a net source for nitrate rather than a sink (Schilling et al. 2006). In cold-water streams, the reduction of groundwater input due to a lowering of the water table can also affect stream temperatures.

Hyporheic exchange (movement of water between a stream channel and underlying sediment - the hyporheic zone) can facilitate denitrification in streams. Generally, the greater the hyporheic exchange, the greater the nitrogen processing (Kasahara and Wondzell 2003). The amount of heterogeneity in channel geomorphological features, such as pool-riffle or step-pool complexes, affects the amount of hyporheic exchange that can occur (Wondzell et al. 2009). Unstable channels typically demonstrate decreasing heterogeneity as pools fill with sediment. In later stages of evolution, riffles become embedded with fine sediments. This lack of geomorphological features decreases hyporheic exchange rates and, therefore, denitrification rates.

Longitudinal connectivity is a measure of the ability of water and sediment to move downstream and of aquatic organisms to move freely up and downstream. Longitudinal connectivity plays a crucial role in maintaining channel stability and ecological health, although its direct impact on nutrient levels is less clear. Obstacles to longitudinal connectivity (i.e., dams, undersized culverts, road prism constricting the floodplain) affect the hydrology of a stream system and sediment transport. When an obstruction blocks flow, stream power drops, and the channel aggrades upstream. Downstream of the obstruction, the sediment-hungry water (water with sufficient energy to transport sediment that lacks sediment) can lead to incision through scouring of the streambed. This process can lead to localized instability and increased bank erosion. The blocking of aquatic organism passage can limit species' ability to reach critical habitat, thus reducing ecological function.

Longitudinal connectivity also plays a complex role in nutrient spiraling, the process by which organisms take up nutrients and eventually release them. The increased residence time of water in the stream results in increased nutrient uptake, although transient storage in the hyporheic zone appears to be the primary driver (Ensign and Doyle, 2006). Therefore, unstable streams with more homogenous profiles may be less efficient at nutrient cycling.

Geomorphology

Fluvial geomorphology is the science describing the hydraulic and sediment transport processes that shape a channel. Shear stress is a measure of force on the channel bed, which increases with slope and depth. As the channel dimension changes through the evolution process described above, shear stress and, consequently, erosion rates and sediment transport rates are affected. Likewise, as the pattern changes, so does the slope and, therefore, the shear stress. Throughout most stages of evolution, there is an acceleration of erosional processes, resulting in an increase in sediment and nutrient export. These geomorphic changes can affect all the other stream components. For example, as channel evolution progresses and sinuosity is reduced, or when channels are mechanically straightened or ditched, sediment and nutrient storage and export are directly impacted. Beck (2018) measured 61% more storage of P in sinuous channels compared to straightened channels. The reduction in slope and point bar deposition/storage in sinuous channels likely explains much of this difference.

Changes that occur to form (dimension, pattern and profile) when a channel becomes destabilized and channel evolution is initiated directly affect channel-forming processes, and channel form will continue to change until a new equilibrium is reached. Hence, implementation actions that don't address restoring a stable channel form will have a limited ability to achieve major reductions in sediment and, therefore, nutrient export.

Hydrology

Hydrology is the study of how water moves and interacts with the landscape. The primary impact of channel evolution to hydrology is on the hydraulics in the channel and floodplain. As channels incise, they become further disconnected laterally, meaning larger and larger floods are required to reach the floodplain. This increases velocities within the channel and increases shear stress on the channel bed and banks. Accelerated erosion leads to increased sediment and nutrient export. Higher velocities during floods also increase stress on aquatic organisms.

Channel incision can also have an influence on downstream hydrology. As channels incise, the adjacent ground water table elevation is lowered, reducing the capacity for bank storage. The corresponding reduction in floodplain inundation frequency reduces the amount of water storage the floodplain can provide, as well as the frequency at which floodplain depressions and oxbows can capture floodwaters and process nutrients.

Biology

Biological processes are influenced by changes in the processes of all other components. The increased erosion rates and a corresponding increase in suspended sediment and nutrients in unstable stream channels can have significant direct impacts on the ecological function of receiving waters. Increased nutrient release leads to eutrophication, which can result in trophic shifts within aquatic communities. High suspended sediment concentrations can directly impact the survival of fish and invertebrates. High turbidity can lead to increased water temperatures, reduced photosynthesis and impaired fish feeding ability. Larger suspended sediment particles can damage fish and invertebrate gills and eggs through physical abrasion. Many of the direct impacts of high sedimentation rates are episodic, being most severe during high flows.

The indirect impacts of channel instability can persist continuously as long as the channel remains unstable. Loss of habitat heterogeneity and quality can occur as pools fill with sediment, becoming shallower, and riffle substrate becomes embedded with fines (Shields et al., 1998). Different species and life stages of fish require different water depths, substrate and velocities. For example, young-of-year brook trout tend to occupy habitats with larger substrate for cover from predators, while adults prefer deeper pools with overhead cover and slower velocities to avoid avian predators (Raleigh 1982). When cobble and gravel substrate become embedded with finer sediment, invertebrate production can be decreased, and the spawning success of gravel spawning fish species is reduced (Figure 13).

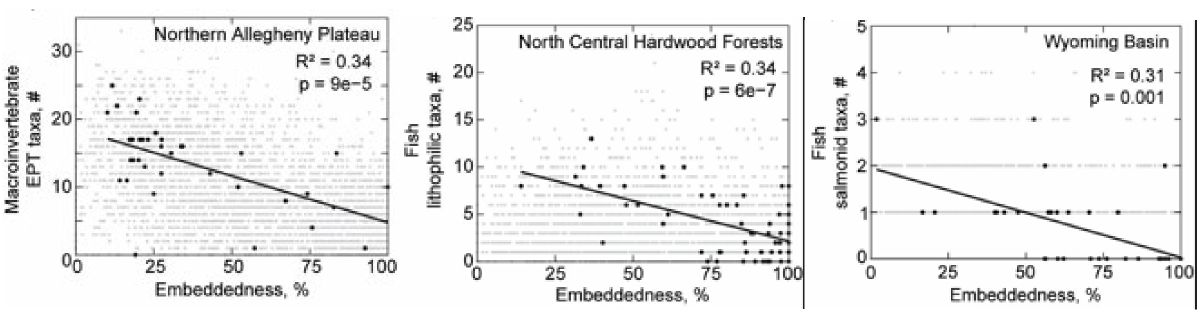

Figure 13. Correlation between percent embeddedness of substrate and abundance of various invertebrate and fish taxa. (EPT refers to sensitive invertebrates' orders of Ephemeroptera, Plecoptera and Trichoptera. Lithophilic fish are obligate gravel/rock spawners.) (Smith et al., in review).

Listed species, such as the Topeka shiner, can also be affected by indirect impacts. This species depends on oxbow habitats that can be filled with sediment more quickly when suspended sediment loads are high. As channels incise, the loss of lateral connectivity to oxbows could reduce the frequency they can access this critical habitat.

Riverine Components Interconnections

The consequences of channel instability are systemic, affecting multiple physical and ecological processes within each component simultaneously. A paired watershed study (F. Douglas Shields Jr. et al. 2009) compared water quality and biological parameters between an incised stream and one that was laterally connected. In the incised channel, turbidity and suspended solids were sampled at two to three times the rate of the unimpaired channel. Total P, Kjeldahl N, and chlorophyll a were also significantly higher, although nitrate levels were lower (lower nitrate levels may be attributed to the urban setting of the unimpaired stream). The incised channel had half the biodiversity and less than one-fourth the fish biomass. The study concluded that "channel incision is associated with a complex of ecological stressors that includes channel erosion, hydrologic perturbations, and water quality and physical habitat degradation." Understanding the interrelatedness of the various riverine components and processes is crucial when evaluating the effectiveness of proposed corrective actions. Single-objective strategies, aimed at impacting one component, can alter the functions of other components. Therefore, when considering nutrient reduction strategies, it is best to consider the holistic effects on all riverine processes.

Nutrient Reduction Strategies for In-channel Sources

There are many methods and strategies used to address excess nutrients derived from in-channel sources such as streambank and gully erosion. As with any approach, there are tradeoffs to consider for each strategy. Below is a summary of the commonly used BMPs to address in-channel sources of excess erosion, which, as outlined above, is intrinsically correlated with the quantity and delivery of phosphorus and nitrogen to our river systems.

Water Storage

The systemic removal of wetlands across much of Minnesota's agricultural landscape has altered the local hydrology, primarily by increasing runoff rates and thus increasing the magnitude of each flood event. This increase in hydrology has resulted in destabilized streams, leading to an increase in streambank and gully erosion (Schottler et al. 2013). A goal of water storage practices is to mitigate the impacts of channel instability by stabilizing flows and reducing peak discharge, thereby, in theory, mitigating streambank erosion and sediment input.

There are multiple methods and practices used to increase water storage, which have a wide range of efficacy and consequences. Water storage practices generally fall into two categories: off-channel storage and on-channel storage.

Off-channel Storage

Off-channel storage methods collect water on the landscape. These methods are diverse and range from in-field drainage management (Figure 14) to water and sediment control basins (WASCOB) (Figure 15), cover crops (Figure 16), and off-channel impoundments, as well as constructed wetlands (Figure 17). The primary goals of many BMPs are to capture sediment and process nutrients from field sources, with flow attenuation and increased infiltration as secondary objectives. The benefits are similar to those of on-channel strategies, but the mechanisms for storing water, reducing peak flows and slowing the rate of water entering the stream are different. Alternative tile outlets and WASCOBs directly intercept field runoff, which includes excess water, sediment and nutrients. Cover crops and grassed waterways rely on increasing organic soil content, field roughness and nutrient uptake to manage both excess water and nutrients. Historic wetland restoration, or the creation of new wetlands to process nutrients through plant uptake, captures field sources of sediment, increases infiltration and provides some floodwater attenuation. The scale of flood attenuation with most off-channel methods tends to be relatively small compared to the overall hydraulic capacity of the system. At most, these BMPs might help mitigate the runoff impacts from additional drainage features and a changing climate or landscape.

Figure 14. Alternative tile intake (Hickenbottom) (Photo Swift SWCD).

Figure 15. Four recently constructed Water and Sediment Control Basins (WASCOB's), circled in yellow. (Photo Wright County SWCD).

Figure 16. Cover crops growing within a harvested corn field. (Photo University of Minnesota Extension Service).

Figure 17. Restored wetland in Carver County Minnesota. (Photo Board of Water and Soil Resources).

On-channel Storage

On-channel storage methods place a structure directly on a stream or river to hold back water. Examples include small and large impoundments and dams (Figure 18), undersized culverts (Figure 19) and ditch plugs (Figure 20). The footprint of these structures can vary. Still, they function similarly to retain water during flood events, reducing the magnitude of downstream flooding. The siting and constructability can be attractive due to the relatively small footprint of the treatment area and the utilization of existing infrastructure. For example, one large on-channel impoundment can treat a significant portion of the watershed. The resulting reservoirs can be sinks for nutrients, due to their ability to capture and store sediment.

The effectiveness and impacts of on-channel storage methods on stream processes can vary, depending on the location in the watershed, the size of the structure and the type of infrastructure. When located in headwaters of small streams or on constructed ditches where wetlands historically existed and where there are little to no upstream sources of fluvial sediments, these structures can mimic the functions of wetlands. However, when placed farther downstream, they can have negative impacts on ecological and biological functions, resulting in increased future maintenance costs. On-channel impoundments flatten water slope, reducing stream power and the stream's ability to transport sediment. This reduction in sediment transport capacity results in aggradation upstream of the structure. Sediment-hungry water discharged below the structure leads to downcutting and bank erosion. Over time, a steep gradient develops, due to the aggradation of the channel upstream and the degradation of the channel downstream of the structure. The aggradation upstream can be mitigated with regular dredging. However, if the structure is ever removed, the stored sediment above the dam will need to be addressed.

On-channel water storage structures can have a significant impact on a watershed's ecological health. Dams, undersized culverts and similar structures create jump and/or velocity barriers that hinder the movement of aquatic organisms. Aquatic organisms require varying habitats at different times of the year. Blocking access to critical habitat at critical times can result in a species' extirpation from a stream. Fish and mussels species are especially impacted by on-channel impoundments.

Figure 18. Aerial photo of an on-channel impoundment on Belle Creek. (Goodhue County, Minnesota).

Figure 19. On-channel water storage utilizing an existing road crossing, Traverse County (Photo Ag BMP Handbook).

Figure 20. Example of a ditch plug. (Minnesota Wetland Restoration Guide Board of Water and Soil Resources).

Water Storage and Stream Stability

While a primary goal with both on- and off-channel water storage BMP's is to reduce the rate and volume of water entering streams, several factors limit the effectiveness of these BMP's at reducing streambank erosion. First, the amount of land required for larger-scale water retention structures, combined with the associated cost of BMP construction to mitigate the lost storage, is likely unachievable in agricultural areas (MPCA 2024). However, the adoption of other water storage methods, such as cover crops, could mitigate these costs, both for the project construction and the land use change. Second, even if a measurable reduction in run-off could be achieved through water storage BMPs, excess sediment will continue to be an issue when floodplain access is limited until the stream reaches a dynamic equilibrium, as illustrated in the stream evolution model. This is demonstrated in many forested areas of the state. Forest clear-cutting at the turn of the 19th century led to a change in runoff rates, resulting in channel incision and stream widening. Currently, forest cover has been restored in many watersheds in the northeastern part of the state; however, the streams remain unstable. Although the rate of evolution has slowed, these streams are still adjusting, leading to sediment impairments in forested watersheds. These northeast watersheds teach us that simply reducing runoff rates and volume does not address stream instability and the input of sediment and nutrients into our rivers.

Water storage approaches that process nutrients and help stabilize a watershed's hydrology will have the most significant impact when paired with efforts to restore stream channels to a stable form, connected to their floodplains.

Bank Stabilization or Protection

One of the indications of channel instability is the presence of substantial streambank erosion. Directly addressing erosion is a common strategy for reducing the rate of sediment and associated nutrients entering the river. Bank stabilization methods can include rip rap, toe wood sod mats, revetments, re-sloping of banks, vegetated reinforced soil slopes (VRSS) and other similar strategies (Figure 21).

All these measures can effectively reduce localized bank erosion, if designed and constructed appropriately. Not all stabilization methods offer the same benefits. Riprap, VRSS or any other hard armoring strategies can have localized impacts on river and ecological processes. Methods that employ hard armoring, such as rock or concrete, create relatively smooth banks that do little to mitigate erosive forces and often initiate new erosion downstream. Approaches that incorporate wood protruding into the channel, like toe wood and revetments, increase stream bank roughness, reducing near bank shear stress, which can mitigate downstream erosion.

Methods that follow a hard armoring approach, which doesn't support native vegetation, can reduce the ecological function along that reach of the stream bank. Besides the loss of trees and brush habitat that results, there is a reduction in both shading and wood and leaf litter input to the stream. Boulders and riprap can also hinder the movement of turtles and other organisms that utilize both stream and riparian areas for feeding, reproduction and shelter. Methods that stabilize using root wads, logs and branches enable the re-establishment of riparian vegetation, creating cover and habitat for fish and invertebrates below the water surface.

Bank stabilization can include additional design elements, such as barbs, J-hooks and rock gabions, to help redirect flow to the center of the channel and away from the streambank. The placement, shape and materials determine the length of bank protection and the morphology of pool scour. These structures can cause erosion if not located and angled properly along the streambank.

Bank stabilization methods are most effective when deployed on stable streams that are connected to their floodplain with localized causes of streambank erosion as opposed to systemic instability. Examples include an otherwise stable stream that has meandered up against a valley wall, creating a large, eroding slump; erosion at the base of infrastructure that impinges upon a floodplain; or erosion of banks below a constriction (i.e., culvert outlet).

In streams with systemic instability, the success of bank stabilization is very limited. Incised streams experience much higher near-bank shear stress during larger floods than streams with a well-connected, continuous floodplain. Bank stabilization does not improve lateral floodplain connectivity in incised streams, so all banks that are not armored will continue to experience high erosive forces. If the channel remains incised, any bank stabilization method outlined above is likely to fail eventually.

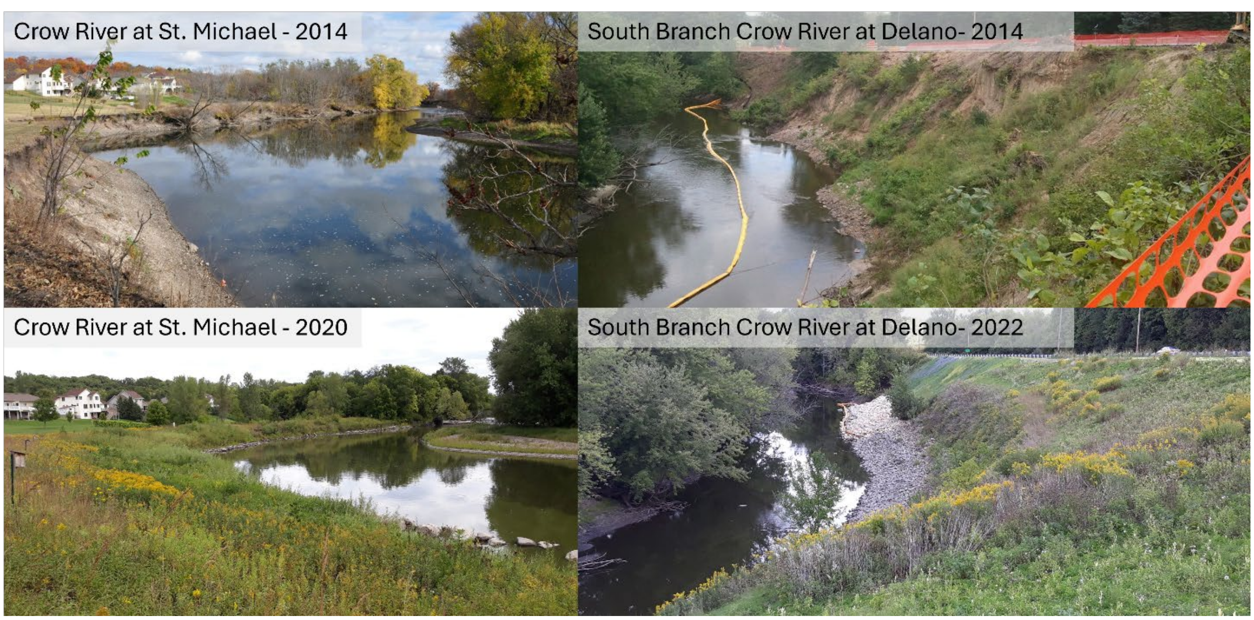

Figure 21. Bank stabilization methods; left, toe wood sod mat on the Crow River in St. Michael and, right, rip rap on the South Branch Crow River in Delano, Minnesota. During and after construction. (Photos Minnesota Department of Natural Resources).

Buffers

Perennial vegetation, particularly deep-rooted native plants, shrubs and trees, is crucial for maintaining long-term channel stability by preserving streambank structure and reducing near-bank shear stress. This recognized benefit has been codified within state statute. Minnesota's Buffer Law requires perennial vegetative buffers of up to 50 feet wide along lakes, rivers and streams, and buffers of 16.5 feet along ditches (Figure 22). The purpose of these buffers is to capture phosphorus, nitrogen and sediment, keeping them out of the river channel. Depending on the area, vegetation presence, and the degree of connectivity between the channel and the floodplain, these buffers can also help process nitrogen and phosphorus. Specifically, denitrification can occur in vegetated buffers and floodplains that are high in carbon, creating the conditions for microbial growth. Buffers also provide habitat for fish, invertebrates and other organisms that use aquatic and riparian habitats. According to data from the MPCA and analysis by BWSR, the greater the percentage of upstream stream channels with an intact buffer, the better the aquatic life score for fish and invertebrates (BWSR and MPCA, 2015).

Figure 22. Winter and summer vegetated buffer along a ditched segment of Cascade Creek in Olmsted County, Minnesota. (Photo Minnesota Department of Natural Resources).

As with many strategies designed to capture and process nutrients in the near channel area, channel condition or stability is an important factor in how effective a given BMP will be. Specifically, channel stability can affect the degree to which a channel is incised (i.e., connected to a floodplain). The more incised the channel, the less effective the buffers are at reducing streambank erosion. In incised systems, frequent flood events are contained within the channel, thereby reducing the frequency of sediment and nutrient deposition on the floodplain. Roots tend to be the largest and most dense nearer the soil surface and, therefore, provide the most soil cohesion and bank roughness near the top of the bank. The further a channel incises, the lower on the bank the greatest shear stress is directed, and the roots have less ability to stabilize banks, frequently resulting in bank failures or lateral erosion. For this reason, on already incised channels, restoring vegetative buffers may have a slowing effect on the channel evolution process but will not restore the stream to a stable form or restore lateral connectivity. Another limitation is related to scale, where larger rivers require a greater buffer than smaller streams and ditches. The current implementation of the buffer law does not require larger buffers on larger river systems. Vegetative buffers are most effective when combined with floodplain connectivity and scaled to the stream size.

Two-Stage Ditch

The anthropogenic alteration of rivers and streams began in the late 19th to early 20th centuries. In Minnesota, 41,204.5 miles, or 49.6% of stream miles, have been impacted (MPCA 2013). These altered streams continue to play a significant role in managing water across the state's agricultural areas.

Two-stage ditches are a practice typically implemented when space is limited, leveraging the benefits of floodplains. The concept is to create a small floodplain bench by either pulling back and re-sloping the bank or physically removing the excess sediment. The general rule of thumb is to make the first bench roughly seven times wider than the bankfull channel width at the riffle, to allow room for the stream to meander or laterally migrate over time. The horizontal width needed to meet this rule of thumb is not typically feasible for most ditched systems. The first stage is the channel itself, which is designed using dimensions appropriate for its drainage area, preferably a reference reach. The second stage is a constructed floodplain at the bankfull elevation (Figure 23, Figure 24).

The benefits of the small, connected floodplain are that it provides areas for sediment to deposit, plants and microbes to process nutrients, and plants to act as roughness, slowing the erosive forces of water. The benches increase the vegetative cover within the ditch, adding stability to the side slopes. Over time, these systems can evolve into a more stable condition, when the stream is allowed to naturally meander within the overwide ditch, or meanders can be constructed (Figure 25). This creates additional and higher-quality in-channel habitats, such as pools, riffles and overhead cover, while moderating water temperature. The meandered channel is also more efficient at transporting sediment, reducing the need for ditch maintenance.

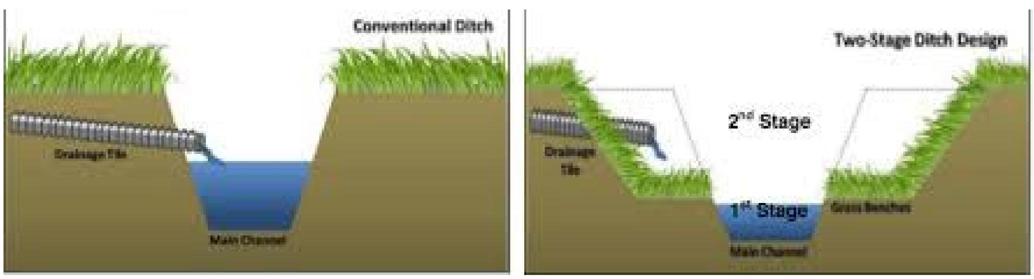

Figure 23. Two-stage ditch design diagrams. (Board of Water and Soil Resources 2020).

Figure 24. Two-stage ditch without meanders and recently constructed (Board of Water and Soil Resources 2020).

Figure 25. Two-stage ditch with meandering (Board of Water and Soil Resources 2020).

Two-stage ditches offer an improvement over traditional ditches, which often require ongoing maintenance. However, there are limitations. Meandered channels provide better habitat, nutrient processing and water quality benefits compared to non-meandered channels (Beck 2018). Overall, the biggest constraint for both meandered and non-meandered two-stage systems within existing watercourses is the floodplain's relatively small size compared to the wide valleys most of these ditches flow through. This limits the stream's function and can impact channel stability, given the degree to which large flow events are confined within the ditch. There isn't simply enough belt width to properly address the channel pattern and profile. Ditch law can erase the benefits of two-stage ditches by cleaning them out of aggraded sediment, returning them to the original ditch bottom elevation, and removing meanders and any habitat features created.

Near Channel Gully or Ravine Stabilization

Gullies and ravines are deeply incised channels formed by concentrated flowing water and steep slopes that contain highly erodible soil and/or lack vegetation (Figure 26Figure 27). The terms "gully" and "ravine" are commonly used interchangeably and can contribute to excess nutrient delivery to a stream channel through bed and bank erosion. The excess sediment and nutrients derived from active gully erosions vary greatly depending on the underlying soils, the condition of the watershed and the receiving channel's stability. Studies in the Minnesota River basin indicate around 10% of the sediment is generated by unstable gullies and ravines (Wilcock 2009; Gran et al. 2011), while in another Minnesota study, ravines were responsible for up to 50% of the sediment budget in the Little Fork River watershed (Fitzpatrick 2023). The impact of gully erosion on the river itself is highly dependent on longitudinal connectivity. Specifically, the more connected the receiving channel is to the gully, the greater the potential for excess sediment and nutrient loads to reach the channel and be transported downstream.

The stabilization of gullies can include a wide range of methods and materials. The most common is to create a pond, wetland, or WASCOB at the start or top of the forming gully. This addresses the concentrated flow by retaining runoff and allowing it to be slowly released. A water drop structure can be added to the impoundment to bypass the gully's steepest terrain, where it will discharge near the elevation of the receiving channel. The gully is then allowed to stabilize on its own. The other common method is to use grade control structures within the gully itself, creating a step-pool morphology where energy is dissipated by pools (Figure 28). A wide range of materials, including rock, trees, vegetation and commercially available propitiatory materials, are used for grade control. Like bank stabilization, stabilizing gullies will reduce the amount of sediment and nutrients delivered to the stream.

While gullies and ravines can account for a significant portion of sediment and associated nutrient loading into a watershed, stabilizing these features may only provide localized improvements in channel stability.

Figure 26. Stable ravine in Franconia Bluffs SNA (photo Minnesota Department of Natural Resources).

Figure 27. Unstable ravine in Franconia Bluffs SNA (photo Minnesota Department of Natural Resources).

Figure 28. Check dam and rip rap stabilization method near Taylors Falls, Minnesota (photo Minnesota Department of Natural Resources).

Grade Control Structures

Grade controls are natural or man-made structures that regulate the elevation and slope of the streambed. They are typically the shallowest point on the stream profile and help dissipate stream energy by regulating flow and creating pools upstream to slow velocities. Their elevation determines the amount of connectivity to the floodplain. In natural meandering riffle-pool river systems, the hydraulic grade control is typically located at the transition point from the glide to the riffle. On step-pool systems, it is the step. Artificial grade control structures can be installed to arrest head cuts, reconnect a stream to its floodplain, reduce streambed erosion, create pool habitats and/or raise the groundwater elevation.

Constructed grade controls reduce erosion by decreasing the slope and improving floodplain connectivity. Arresting channel incision and providing floodplain relief reduces bed erosion. Using an appropriate structure and design is critical for success. Structures that simply block flow, such as check dams and beaver dam analogs (BDAs), can lead to channel avulsions around the structure, which generate more sediment. Constructed riffles and rock arch rapids, and some weir designs, direct flow away from banks. If the grade control slope is steeper than what is typically found in the stream system, it will cause a hydraulic jump, creating strong circulatory flows downstream of the structure. This can induce undercutting and failure of the structure, create a passage barrier for aquatic organisms and even pose a safety risk to recreational users on larger systems. Depending on the spacing and design, grade control structures can function more like a dam, capturing sediment and increasing the risk of lateral channel migration.

Stream Channel Restorations

Definitions of stream restoration vary considerably. Variations include returning to a pre-disturbance condition to primarily focusing on addressing species-specific habitat needs. The definition of restoration discussed below involves restoring the channel and floodplain to a stable form, allowing the natural physical, biological and chemical stream processes to self-regulate within the current constraints of the landscape.

Unlike many other strategies to address stream bank sources of sediment and nutrients, channel restoration is a systemic approach that can improve functions within all five riverine components: water quality, biology, geomorphology, hydrology and connectivity.

Restoring channel stability is at the center of successful stream restoration. Stability is achieved by restoring a form (dimension, pattern and profile) that will create a balance between the hydraulic energy of the stream and the sediment load being generated and transported. Lateral connection to the floodplain at flows that exceed the effective discharge is critical to achieving stability and should be one of the primary objectives of restoration. Floodplain connectivity is crucial in mitigating shear stress on streambanks, particularly during flood events (Figure 29). The channel dimension determines the hydraulic and sediment transport capacities of a channel. A channel that is too wide will aggrade (Figure 8 – Stage 3); while one too narrow will down-cut and degrade and incite bank erosion (Figure 8 – Stage 2 and 3). The profile is dictated by the valley and stream and is tied to the channel pattern. Profile, including both the overall slope and the sequencing of pools and riffles or steps, affects the hydraulic energy directed at the stream bed and can impact hyporheic exchange. Changes in profile can occur through intentional straightening or channel evolution. Finally, the pattern is dictated by the valley, slope and underlying geology. Pattern affects overall channel slope, sediment and nutrient storage, habitat diversity, and hydraulic energy dissipation. The pattern is one element that is typically not addressed in most restoration efforts, and the rationale varies from a lack of technical expertise to additional regulatory hurdles.

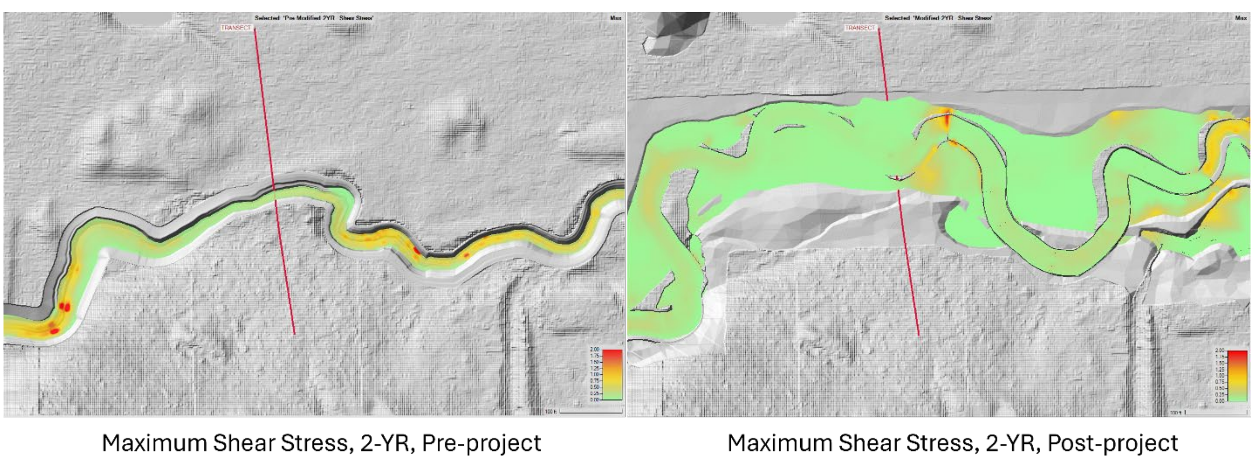

Figure 29. Pre and post-restoration shear stress estimates at a two-year flood event. Cascade Creek, Rochester, Minnesota. (Reinartz and Murtada Minnesota Department of Natural Resources in press 2025)

When done holistically considering and incorporating all five riverine processes, stream restoration restores the dimension, pattern and profile of a river system, allowing it to self-maintain over time without active management. Using reference or analog sites that are stable in the current hydro-physiographic regime to inform the design parameters is a preferred methodology called Natural

Channel Design (NCD) (Rosgen 2011) (Figure 30, Figure 31). This approach relies heavily on empirically derived data to inform the design. Restoration, as defined above, requires knowledge of the channel's position within the stream succession scenario and an understanding of the causes of instability. Understanding the evolution sequence helps identify and design the appropriate final equilibrium form that suits the current conditions and constraints. Accounting for channel evolution and causes of instability, along with basic watershed science, will help prioritize and target potential restoration sites. The scope, scale and design of a project must account for the underlying causes of instability.

Figure 30. Before (upper) and after (lower) construction of a restoration based on Natural Channel Design Principles. Channel dimension, pattern and profile were informed by a reference reach. Sand Creek, Coon Rapids, Minnesota. (photo Minnesota Department of Natural Resources).

Figure 31. Aerial photos of Cascade Creek, Rochester, Minnesota, before (upper left) and after (lower left) restoration at 45th Ave. The after-restoration aerial photo was taken shortly after the floodplain was reconnected to the channel. The drone image (right) was captured during a flood event when the newly constructed floodplain was activated and can be compared to the upstream incised stream channel, also at 45th Ave.

Sediment and nutrient reductions using this method can be substantial. Stream restoration encompasses elements of several of the BMPs outlined above, including the reconnection of the floodplain (riparian buffer) for both sediment capture and nutrient processing, water storage, grade control to maintain connectivity, and streambank and bed stabilization. It is not uncommon to observe a reduction of more than 80% in streambank erosion rates following restoration, provided that effectiveness monitoring has been completed (Table 1). Additional benefits include improved habitat for both aquatic and semi-aquatic organisms, increased recreational value and improved aesthetics. Pierce et al. (2022) monitored a natural channel design project for more than ten years. The project restored channel stability (reduction in bank erosion), improved habitat diversity and quality (pool depths, cover, and substrate), and increased baseflow (by raising the water table - Figure 32). This resulted in decreased water temperatures and increased diversity of fish species and trout abundance (Figure 33).

Table 1. Cascade Creek pre- (2011 and 2015) and post-restoration (2019 and 2022) long-term monitoring streambank erosion results using the Bank Assessment for Non-point source Consequences of Sediment (BANCS) model. Percent difference from previous sampling event.

<table>
<tr><th>Year</th><th>Total Erosion (tons/year)</th><th>Total Erosion (tons/yr/ft)</th><th>Mean Percent Reduction (tons/year)</th></tr>
<tr><td>2011 (pre-restoration)</td><td>545</td><td>0.08</td><td rowspan="4">82%</td></tr>
<tr><td>2015 (pre-restoration)</td><td>750</td><td>0.11</td></tr>
<tr><td>2019 (post-restoration)</td><td>160</td><td>0.024</td></tr>
<tr><td>2022 (post-restoration)</td><td>68</td><td>0.0096</td></tr>
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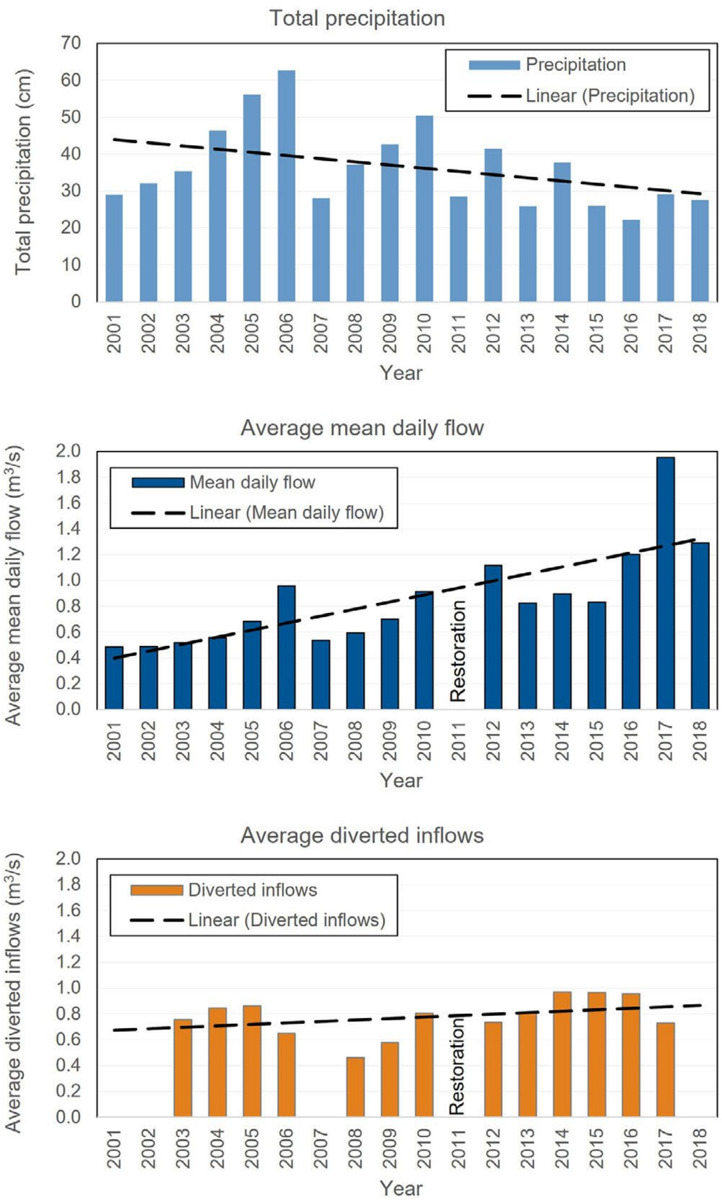

Figure 32. The average mean daily flow, total precipitation, and diverted inflows per year, along with their associated trends, indicate an increase in average mean daily flows despite lower precipitation and no significant increase in diverted flows. (Pierce et al. 2022).

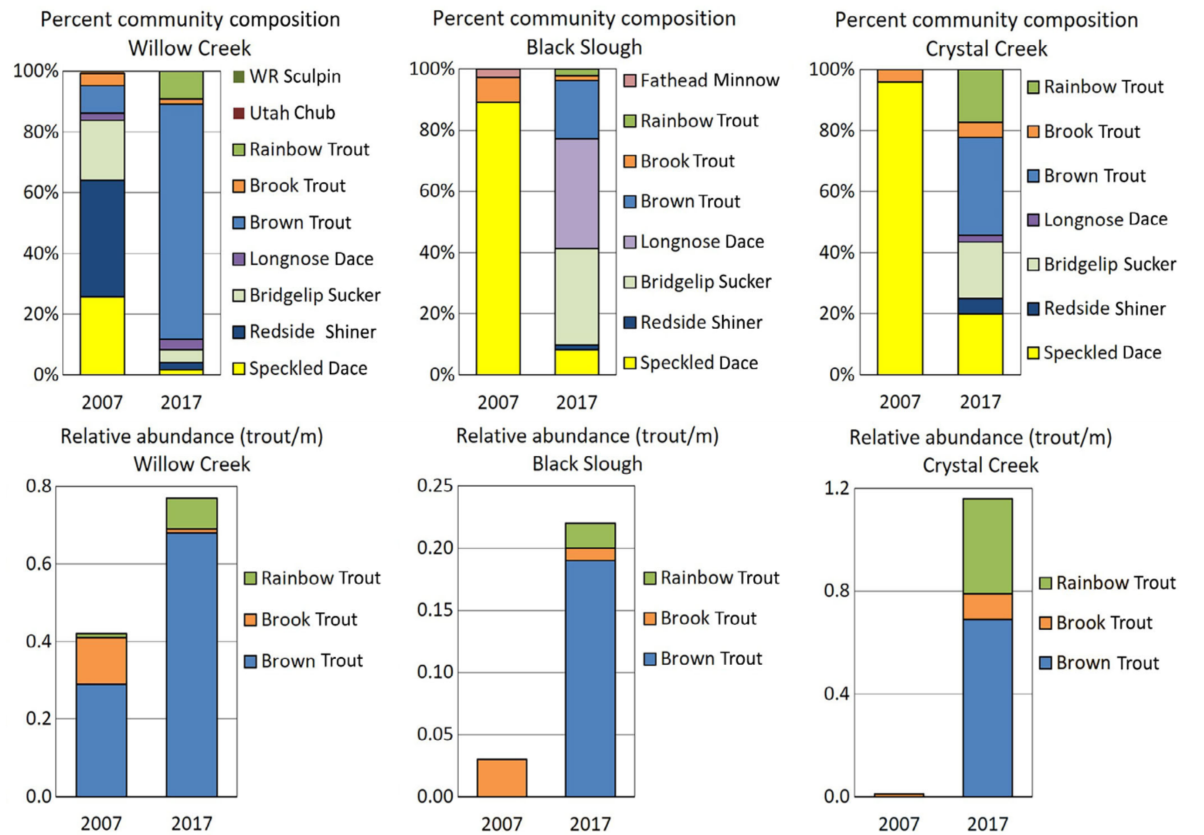

Figure 33. Percent community composition and trout relative abundance before (2007) and after (2017) restoration by reach (Pierce et al. 2022). Blackfoot River Basin, Montana.

There are many reasons cited for not pursuing channel restoration, which should be balanced with the benefits achieved. First, watershed and stream processes are complex, so successful restorations require a diverse team of technical experts of varied backgrounds to design, manage, oversee construction, obtain funding, and complete permitting and environmental review requirements. Channel restoration projects can require more time and are more expensive ($100-$400 per linear foot) than traditional agricultural BMPs. Larger restoration projects have a significant footprint and may necessitate collaboration with multiple landowners. While cost and working at a larger scale may appear to be a limitation, spending equivalent time on numerous smaller projects often does not achieve as much functional ecological benefit. The BMPs described above tend to address specific objectives for a single component. Off-channel storage treats field sources of nutrients and sediment but does not address in-channel sources or improve stream habitat. Bank stabilization methods address channel sources of sediment and nutrients but don’t restore stability or address habitat limitations. Each BMP has its pros and cons, as described above. Still, only channel restoration addresses the physical and biological processes of the stream channel that determine whether a stream is impaired.

Implementation Summary

There are multiple strategies and methods for reducing excess phosphorus and nitrogen generated from in-channel sources (Table 2). All best management practices, no matter their benefits or limitations, require effective targeting, prioritization, project-level scaling, and proper design and construction. A project will eventually fail to meet its intended goals if it is not targeted or poorly constructed. Understanding the underlying processes that drive channel instability can provide insight not only into where but also which method to employ.

A multifaceted approach is necessary when addressing streambank and gully erosion with the goal of reducing nutrients. Combining approaches can be effective when the strategies work in concert and not at cross purposes. For example, water storage projects that process nutrients and help to stabilize the hydrology of a watershed will have the most impact when paired with efforts that restore stream channels to a stable form that is connected to the floodplain.

All best management practices can have feasibility constraints related to scalability. A cost-benefit analysis will be useful for project planning at the watershed scale. Costs should include planning, permitting, design, construction, nutrient removal potential and/or prevention, ongoing nutrient processing and long-term maintenance.

Table 2. Summary of nutrient reduction strategies for in-channel and gully sources. Note that this table represents the performance of each BMP in reducing nutrients originating from streambank erosional processes and does not reflect its effectiveness for other sources.

Practice Type	Water Quality		Biology	Connectivity	Geomorphology		Hydrology	Comments
	Nutrient release prevention [1]	Nutrient processing [2]	Ecological functional lift – habitat diversity	Longitudinal connectivity	Stability - form diversity	Lateral/floodplain connectivity	Hydrology stabilization	
Off-Channel Water Storage	+	+++	NA	NA	NA	NA	+	Treats field sources but doesn't restore channel stability
On-Channel Water Storage	+	+	-	- - -	-	NA	++	Can be effective in headwaters but detrimental to ecology and stability elsewhere
Bank Stabilization or Protection	++	NA	+/NA*	NA	NA	NA	NA	Only effective where channel connected to floodplain *some methods can provide habitat
Buffers	+	++	+	NA	NA	NA	+	Most effective when the channel connected to a floodplain
Two Stage Ditch	++	+	NA	NA	NA	+++	NA	Does not address ecological function but partially reduces erosion rates
Near Channel Gully or Ravine Stabilization	+++	+	NA	NA	NA	NA	NA	Large reduction in sediment from ravines possible, but limited impact on receiving channel stability
Grade Control Structures	++/- -*	++	+/-*	+/-*	+/-*	+++	+	*Style and design of structures determine success, as well as existing channel condition – improper design can increase erosion
Stream Channel Restorations	+ + +	+ + +	+ + +	+ + +	+ + +	+++	+ +	Addresses all stream functions - greatest reduction in sediment and nutrients – scale design and location critical to success

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[1] Practices that directly keep nutrients associated with sediment in place, e.g., streambank stabilizations.

[2] Practices that process or bind nutrients, keeping them from being mobile, e.g., wetland creation.

+, ++, +++ slight, moderate, high positive outcome

- , --, --- slight, moderate, high negative outcome

NA – not applicable

Conclusions

Channel erosion has been identified as a significant source of excess sediment in Minnesota's streams and rivers. The release of soil-bound nutrients from eroded stream bank soils can significantly impact water quality and the amount of nutrients exported from a system. High streambank erosion rates, high suspended sediment loads and rapid lateral migration are indicators of channels that have become unstable. Once destabilized, the channel form will continue to evolve through accelerated erosional processes until a form is established in which the hydraulic energy of the stream is in equilibrium with its sediment transport capacity and a connected and continuous floodplain has been established. As the channel is moving through an evolution sequence, not only is there an increase in sediment and nutrient release, but consequences can also include impacts on ecological function (i.e., acute impacts to organisms, reduced habitat quality, decreased riparian health), hydrology, and other water quality parameters (i.e., temperature). The loss of floodplain connectivity reduces the floodplain's capacity to capture sediment and process nutrients. At the same time, the loss of channel bedform diversity can also reduce nutrient processing through a reduction in hyporheic exchange. In summary, channel instability affects all components of stream systems, including the physical, chemical and biological processes.

Project funding and partners can be limiting factors in completing this work, which might hinder the successful implementation of nutrient reduction activities at a scale large enough to demonstrate improvement using standard water quality monitoring strategies. Using these resources wisely is critical, and while there are multiple implementation methods to choose from, selecting those that maximize numerous benefits and minimize unintended consequences should be the primary focus. While various strategies exist to mitigate the release of sediment and nutrients from streambanks, most efforts to reduce streambank erosion have narrow objectives. Success can be limited if stream processes are overlooked. In such cases, this can lead to project failure or create unintended negative consequences that affect other components, such as creating a barrier to fish movement or altering sediment transport. Stream restoration addresses the processes that drive instability, aiming to restore a stable form and reconnect the floodplain, thereby restoring functions in all components.

While it is recognized that the primary goal of nutrient reduction strategies is to reduce nutrients that cause problems in local waters within our watershed, these strategies also aim to reduce the export of nutrients from our watersheds. The 1972 Clean Water Act requires that states address more than just the reduction of individual water quality constituents (McCall, 2007). The key objective of the Clean Water Act is to “restore and maintain the chemical, physical, and biological integrity of the nation’s waters.” The Act states, “due regard shall be given to the improvements which are necessary to conserve such waters for the protection and propagation of fish and aquatic life and wildlife, relational purposes...” The Clean Water Act requires practitioners to use the most holistic and systemically sound methods and strategies to restore the nation’s waters. An increasing emphasis in Minnesota’s Nutrient Reduction Strategy is to utilize limited resources to achieve nutrient reductions in ways that yield multiple ecosystem benefits.

References

Annear, T., I. Chisholm, H. Beecher, A. Locke, P. Aarrestad, C. Coomer, C. Estes, J. Hunt, R. Jacobson, G. Jöbsis, J. Kauffman, J. Marshall, K. Mayes, G. Smith, R. Wentworth, and C. Stalnaker. 2004. Instream Flows for Riverine Resource Stewardship, Revised Edition. Instream Flow Council, Cheyenne, WY. 268 pp.

Baker, A. C. 2018. *Phosphorus-sediment interactions and their implications for watershed scale phosphorus dynamics in the Le Sueur River Basin* (Master's thesis, University of Minnesota).

Beck, William, J., Peter L. Moore, Keith E. Schilling, Calvin F Wolter, Thomas M. Isenhart, Kevin J. Cole, Mark D. Toner. 2019. Changes in lateral floodplain connectivity accompanying stream channel evolution: Implications for sediment and nutrient budgets. Science of the Total Environment. (660) 1015-1028.

Beck, William, J. 2018. Sediment and phosphorus dynamics within the channel and floodplain of Walnut Creek, Iowa. Dissertation for Doctor of Philosophy, Iowa State University, Ames Iowa 146pp.

Belmont, P., K. B. Gran, S. P. Schottler, P. R. Wilcock, S. S. Day, C. J. Jennings, J. W. Lauer, E. Viparelli, J. K. Willenbring, D. R. Engstrom, G. Parker. 2011. Large shift in source of fine sediment in the upper Mississippi River. Environmental Science and Technology 45(20): 8804-8810.

Blout, J., Lenoch, L, Fitzpatrck, F. 2023. Stream corridor sources of suspended sediment and sediment-bound phosphorus from an urban tributary to the Great Lakes. USGS Publications Warehouse. https://pubs.usgs.gov/publication/70242719

Cluer, B. and C. Thorne 2014. A stream evolution model integrating habitat and ecosystem benefits. River Research and Applications, 30, 135-154.

Cross, A., Schlesinger, W. H., 1995. A literature Review and evaluation of the Hedley fractionation: Applications to the biogeochemical cycle of soil phosphorus in natural ecosystems. Geoderma 64 (3-4), 197-214

Ensign, S. H., and M. W. Doyle 2006, Nutrient spiraling in streams and river networks, J. Geophys. Res., 111, G04009, doi:10.1029/2005JG000114.

Fenton, T.E., 1983. Chapter 4 Mollisols. Elsevier, pp. 125-163.

Fitzpatrick, F., Sterner, S., Baker, A., Soderman, S., Gran, K., Kasun, A., Kennedy, M., Norvitch, P., Anderson, J., and Gutzmann, M. 2023. Stream Corridor Sediment Budget for Watershed Sediment Source Apportionment for the Forested Little Fork River, Minnesota. SEDHYD Conference Proceedings. https://www.sedhyd.org/2023Program/1/71.pdf

Gran, K., Belmont, P, Day S., Jennings C., Lauer J.W., Viparelli, E., Wilcock, P., and G. Parker. 2011. An Integrated Sediment Budget for the Le Sueur River Basin. http://www.pca.state.mn.us/index.php/view-document.html?gid=16202

Jiang G, Lutgen A, Mattern K, Sienkiewicz N, Kan J and Inamdar S 2020. Streambank legacy sediment contributions to suspended sediment: bound nutrient yields from a Mid-Atlantic, Piedmont watershed J. Am. Water Resour. Assoc. 56 820–41

Juracek, K. E. and A. C. Ziegler. 2009. Estimation of sediment sources using selected chemical tracers in the Perry Lake basin, Kansas, USA. International Journal of Sediment Research 24: 108-125.

Kasahara, T., and S. M. Wondzell 2003. Geomorphic controls on hyporheic exchange flow in mountain streams, Water Resour. Res., 39(1), 1005, doi:10.1029/2002WR001386.

Lenhart, C. F., E. S. Verry, K. N. Brooks, and J. A. Magner. 2011. Adjustment of prairie pothole streams to land use, drainage and climate changes and consequences for turbidity impairment. River Research and Applications 28:1609-1619.

McCall, D.K. 2007. The Clean Water Act. Pages 299-364 in T.F.P. Sullivan, editor. Environmental Law Handbook. 19th Edition. Government Institutes, Lanham, Maryland.

Minnesota Board of Water and Soil Resources. (BWSR) and Minnesota Pollution Control Agency (MPCA). 2015. Buffers Improve Water Quality. 6pp. https://bwsr.state.mn.us/sites/default/files/2023-07/MPCA%20Buffers%20Improve%20Water%20Quality%20Article.pdf

Minnesota Board of Water and Soil Resources (BWSR). 2020. Two-Stage Drainage Ditch Fact Sheet. https://www.bwsr.state.mn.us/sites/default/files/Two-stage%20Ditch%20Fact%20Sheet%20access.fixed_.pdf

Minnesota Department of Natural Resources, Reinartz, D. and Murtada, S. in press 2025. Hydrologic Hydraulic Analysis of Cascade Creek, Rochester MN between 60th Ave SW to West Circle Drive. Minnesota Department of Natural Resources, Saint Paul, MN.

Minnesota Department of Natural Resources. 2021. Blue Earth River Watershed Characterization Report. 152pp. https://wrl.mnpals.net/islandora/object/WRLrepository%3A3745

Minnesota Department of Natural Resources. 2021. De Paz, D., Carlson, J., Northwick, R., Proulx, N. Wells creek watershed assessment of river stability and sediment supply (WARSSS). Ecological and Water Resources. 2021. Pg 82.

Minnesota Pollution Control Agency (MPCA). 2013. The impact of altered watercourses. Retrieved from https://www.pca.state.mn.us/air-water-land-climate/the-impact-of-altered-watercourses

Minnesota Pollution Control Agency (MPCA). 2024. Water Storage in the Minnesota River Basin Water Storage Options Assessment (Report 1A): https://wrl.mnpals.net/node/4305

Minnesota Groundwater Association. 2018. Drain tiles and groundwater resources: Understanding the relations. Retrieved from www.mgwa.org/documents/white-papers/Drain_Tiles_and_Groundwater_Resources.pd

Minnesota Pollution Control Agency. *Minnesota River Citizens' Advisory Committee Progress Report*. January, 1994.

Nakagaki, N. and Wieczorek, M.E., 2016. Estimates of subsurface tile drainage extent for 12 Midwest states, 2012: U.S. Geological Survey data release, http://dx.doi.org/10.5066/F7W37TDP.

Noe, G.B., K G Hopkins, P R Claggett, E R Schenk, M J Metes, L Ahmed, T R Doody and C R Hupp. 2022. Streambank and floodplain geomorphic change and contribution to watershed material budgets. Environmental Research Letters 17 (6)

Novotny EV, Stefan HG. 2007. Stream flow Minnesota: Indicator of climate change. Journal of Hydrology 334: 319–333.

Pierce, R., Podner, C., Carim, K. (2013). Response of Wild Trout to Stream Restoration over Two Decades of the Blackfoot River Basin, Montana. Transactions of the American Fisheries Society 142:68-81.

Pierce, R., Rosgen, D., Geenen, D., and Rosgen, B. 2021. Wild trout and hydrologic response to restoration of incised streams with improved water use for ranching and fisheries. Ecosphere 13(3): e3986. https://doi.org/10.1002/ecs2.3986.

Raleigh, R. F., U.S. Fish and Wildlife Service. Division of Ecological Services. 1982. *Habitat suitability index models: brook trout.* Washington, D.C.: Western Energy and Land Use Team, Fish and Wildlife Service.

Rosgen, D. 2006. Watershed Assessment of River Stability and Sediment Supply (WARSSS). Ft. Collins, Colo.: Wildland Hydrology

Rosgen, D.L. and Silvey, H.L., 1996. Applied River Morphology. Wildland Hydrology, Pegosa Springs, Colorado.

Riedel, Mark S., Elon.S. Verry and Kenneth N. Brooks. 2002. Land use impacts on fluvial processes in the Nemadji River watershed. Hydrological Science and Technology, 18 (1-4): 197-205.

Schottler, S. P., D. R. Engstrom, and D. Blumentritt. 2010. Fingerprinting sources of sediment in large agricultural river systems, Final Report to Minnesota Pollution Control Agency CFMS # A94798. http://www.smm.org/static/science/pdf/scwrs-2010fingerprinting.pdf.

Schottler, S. P., J. Ulrich, P. Belmont, R. Moore, J. W. Lauer, D. R. Engstrom, J. E. Almendinger. 2013. Twentieth century agricultural drainage creates more erosive rivers. Hydrological Processes 28(4):1951-1961.

Schumm, S. A., Harvey, M. D., and Watson, C. C. 1984. *Incised channels: morphology, dynamics and control*. Water Resources Publications, Littleton, Colo.

Sekely, A. C., D. J. Mulla, D. W. Bauer. 2002. Streambank slumping and its contribution to phosphorus and suspended sediment loads of the Blue Earth River, Minnesota. Journal of Soil and Water Conservation 57(5):243-250.

Shields Jr., F.D., et al., The stream channel incision syndrome and water quality. Ecol. Eng. 2009. doi:10.1016/j.ecoleng.2009.09.014

Shields, F.D., Knight, S.S. & Cooper, C.M. Rehabilitation of aquatic habitats in warmwater streams damaged by channel incision in Mississippi. *Hydrobiologia* **382**, 63–86 (1998). https://doi.org/10.1023/A:1003485021076

Schilling, K. E., Zhongwei Li, You-Kuan Zhang. 2006. Groundwater-surface water interactions in the riparian zone of an incised channel, Walnut Creek, Iowa. Journal of Hydrology. 327: 140-150.

Schilling, K.E.; Isenhart, T.M.; Palmer, J.A.; Wolter, C.F.; Spooner, J. 1998. Impacts of Land-Cover Change on Suspended Sediment Transport in Two Agricultural Watersheds. J. Am. Water Resour. Assoc. 2011, 47, 672–686.

Schilling, K. E., Isenhart, T. M., Wolter, C. F., Streeter, M. T., & Kovar, J. L. 2022. Contribution of streambanks to phosphorus export from Iowa. *Journal of Soil and Water Conservation*, *77*(2), 103–112. https://doi.org/10.2489/jswc.2022.00036

Simon, A. 1989. The discharge of sediment in channelized alluvial streams. *Water Resources Bulletin*, 25(6), 1177-1188.

Sharpley, A.N., Syers, J.K., 1979. Phosphorus inputs into a stream draining an agricultural watershed. Water Air soil Pollution 11 (4) 417-428.

Shengnan Zhou, Nan Li, Andrew J. Margenot. 2022. Soil meets stream: Vertical distribution of soil phosphorus in streambanks. Geoderma 424 - The Global Journal of Soil Science.

Skaggs, R. W., Brevé, M. A., & Gilliam, J. W. 1994. Hydrologic and water quality impacts of agricultural drainage∗. *Critical Reviews in Environmental Science and Technology*, *24*(1), 1–32. https://doi.org/10.1080/10643389409388459

Sugg Z. 2007. Assessing U.S. Farm Drainage: Can GIS Lead to Better Estimates of Subsurface Drainage Extent. World Resources Institute. Washington D.C. 1–8. August.

Thoma, D. P., S. C. Gupta, M. E. Bauer, C. E. Kirchoff. 2005. Airborne laser scanning for riverbank erosion assessment. Remote Sensing of Environment 95(4):493-501.

Ulrich, J.S. 2023. The varying effects of climate and landscape changes on increased river flows in Minnesota watersheds. University of Minnesota Dissertations and Theses. 30524793. Pg 98.

Ward, J. V. and J. A. Stanford. 1995. Ecological Connectivity in alluvial river ecosystems and its disruption by flow regulations. Regulated Rivers: Research and Management, Vol. 11, 105-119.

Williamson, T.N., Fitzpatrick, F.A., Kreiling, R.M. *et al.* Sediment budget of a Maumee River headwater tributary: how streambank erosion, streambed-sediment storage, and streambed-sediment source inform our understanding of legacy phosphorus. *J Soils Sediments* **24**, 1447–1463 (2024). https://doi.org/10.1007/s11368-023-03713-6

Wilson, C. G., D. D. Kuhnle, D. D. Bosch, J. L. Steiner, P. F. Starks, M. D. Tomer, G. V. Wilson. 2008. Quantifying relative contributions from sediment sources in conservation effects assessment project watersheds. Journal of Soil and Water Conservation 63(6):523-531.

Wolman, M. G. and Miller, J. P. 1960. Magnitude and Frequency of Forces in Geomorphic Processes. *Journal of Geology, 68,* 54-74.

Wondzell, S. M., J. LaNier, R. Haggerty, R. D. Woodsmith, and R. T. Edwards 2009. Changes in hyporheic exchange flow following experimental wood removal in a small, low-gradient stream, Water Resour. Res., 45, W05406,doi:10.1029/2008WR007214.

Zaimes, G. N. and R. C. Schultz. 2012. Assessing riparian conservation land management practices impacts on gully erosion in Iowa. Environmental Management 49:1009-1021.

Zhou S., Li, N., Margenot, A. J., 2022. Soil meets stream: Vertical distribution of soil phosphorus in streambanks. Geoderma 424.