

Aligning Conservation Efforts with the Geologic Legacy of the Snake River Watershed

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Introduction

All of the rivers in Minnesota are still responding to the most recent glacial period 12,000 years ago that rearranged the terrain by filling in old river valleys and creating the conditions for new ones to form. This happened repeatedly during the many glaciations that occurred in the last 2.5 million years. Prior to this time period, profound continent-scale events included Mid-continent rift formation (1.1 billion years ago) and continental crust formation and deformation (2-3 billion years ago). The primary legacy of these ancient times is the distribution of bedrock of varying ages and erodibility. These rock layers are shallowly buried by the glacial sediment in places but still control aspects of the modern river and its watershed. The shape of the land and nature of the sediment and rock also controls soil type which in turn controls vegetation and land use. That is why it is important for everyone to understand this history.

It is also important to understand how rivers work to adjust their gradients and channel form to changes in flow and local base level. The ongoing response of a river and its tributaries is inexorable. By appreciating the control of seemingly distant geologic events, land and water conservation professionals and residents can learn to align their restoration efforts with the course that the river and its watershed are on for the best return on investment. The geologic history defines what is possible and which modifications to the land and water will be resilient.

Geologic History

This section summarizes an immense span of geological time—almost 3 billion years—in just a few paragraphs. For a more detailed understanding of these events, please refer to [*Contributions to the Geology of Pine County, 2002*](#). Figures with non-sequential numbering are from this report and simply reproduced here.

Ancient Crust Formation

Most bedrock in the watershed is of Precambrian age (2.5. to 1 billion years old), commonly subdivided into the Archean and Proterozoic. The rock surface is low relief and generally buried. It is exposed where glacial sediment is thin or along the Snake River. The relative hardness of the rock helps shape the lay of the land and impacts the profile of the river locally, creating rapids.

The Archean McGrath Gneiss is the oldest rock in the watershed and forms low-lying exposures in the northern watershed in Aitkin County. However unassuming the outcrops, this rock is the product of multiple rounds of intense deformation and ancient mountain building. The specific rock type present is controlled by the original minerals present when the melted rock cooled

underground but varies on a local scale with the history of deformation and recrystallization (metamorphism). In that way, the initial igneous crystalline rock, generally referred to as granite, deformed with new minerals created and oriented with the stresses to form a gneiss or schist, depending on the degree of deformation and heating. These rocks along with associated metamorphosed sediments that were deposited in shallow seas and extrusive volcanic rocks form parts of the ancient continental crust and are collectively referred to as basement rocks.

Rifting

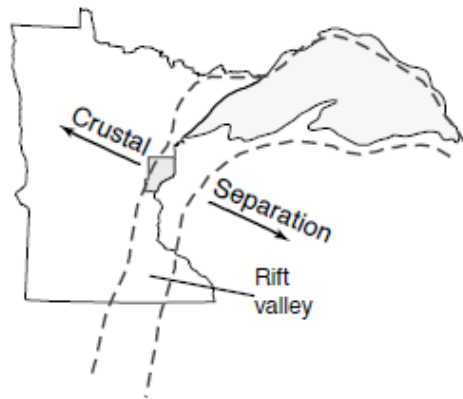
The basement rocks were rifted apart owing to convection deep in the earth's interior during the Proterozoic. The basement rocks of the crust were thinned and forced apart by upwelling basaltic lava. Layer upon layer of lava flows filled the widening and subsiding rift zone with up to 20 km of basalt ultimately emplaced. A modern analog is the Red Sea Rift. Basalt flows are exposed along both banks of the Snake River from above the dam at Cross Lake downstream for about a mile.

Eventually, the low area formed through rifting became extensive enough to allow sea water to enter. If rifting had continued, an ocean would exist between Minnesota and Wisconsin. The Fond du Lac Formation and Hinckley Sandstones were deposited during this ocean incursion and resulted in up to 2km of sandstone. The basal Fond du Lac Formation is a coarse, pinkish conglomerate and it crops out on the Kettle River; cobbles of basal Fond du Lac conglomerate can be found on the Snake River. The Hinckley Sandstone lies above the Fond du Lac Formation stratigraphically and is a tan to pink quartz sandstone exposed in quarries in Robinson Park in Sandstone, Minn. It is easy to distinguish between two distinct layers of the Hinckley Sandstone: thin layers with ripple marks alternate with thick, more indurated trough-cross-bedded sandstone. The thin strata are more susceptible to erosion. Vertical joints in the rock have been enlarged in places to form caves and sinkholes.

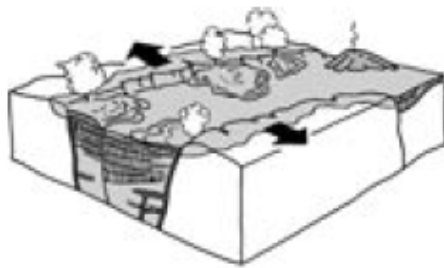
Major reverse (compressional) faults uplifted the Hinckley Sandstone and put it into fault contact with the basalt. The faults that uplifted basalt and sandstone were a result of compression events on the east coast of what we now refer to as North America and may have been responsible for the ultimate failure of the rift. The abrupt contrast of rock properties on either side of the faults exerts fundamental control on the river profile, localizing steps in the profile and creating rapids.

Paleozoic Rocks

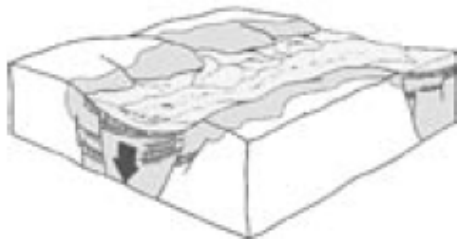
Younger rocks of oceanic origin lie on top of the basement and uplifted rift rocks. These sedimentary rocks (sandstone and siltstone) are more erodible and there are only a few remnants of the younger, more extensive ocean sediment in the eastern part of the watershed. They are exposed on the lower Snakes below the Million Dollar Bridge, are tan to white, and were deposited 510–450 million years ago during the Paleozoic.



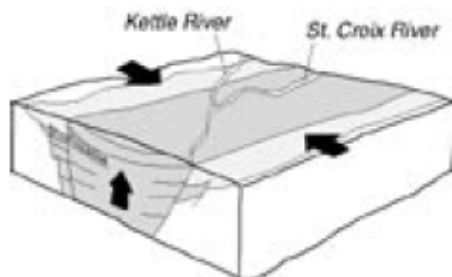
A. About 1,110 million years ago, the North American continent began to separate along a 2,000-kilometer-long arc-shaped path through what is now the Lake Superior area.



B. During the first 20 million years of the Midcontinent rift's history, layer after layer of lava was erupted into the ever-widening rift valley. By the time volcanic activity and crustal separation ended, hardened lavas had accumulated to a thickness of 20 kilometers (12.5 miles) in the Lake Superior area.



C. After volcanic activity and crustal separation ended, dense lavas caused the rift valley to continue to sag. Sediment (sand, gravel and silt) washed in, filling the valley and, ultimately, burying the lavas beneath many kilometers of sandstone.



D. Compression of the earth's crust reversed the movement along the earlier normal faults, forcing the previously deeply buried volcanic strata upward. Subsequent weathering and glaciation have eroded the sandstone in the central uplifted block (horst), resulting in the present-day distribution of bedrock types.

Figure 5. Development of the Midcontinent rift system in the northern midcontinent of North America. Stages A–C are modified from the Tettegouche State Park Interpretive Plaque of the Minnesota Department of Natural Resources. The Minnesota Geological Survey provided the geologic interpretation. Arrows on the diagrams above indicate the general direction of rock-body movement.

Gaps in the Rock Record

There are two, nearly 500 million-year long gaps in this history, from 1.1 billion to 510 million years ago, and from 410 million to 2.5 million years ago, when global glaciations commenced. These were periods of non-deposition or erosion. From what geologists can reconstruct from surrounding areas, the continental crust now called Minnesota moved slowly from south of the equator to north of the equator, through tropical climates that subjected all exposed rocks to deep weathering. Crystalline rocks slowly turned to clay and grit in these conditions and even quartz eventually dissolved. The Hinckley Sandstone shows multiple episodes of being cemented by silica-rich waters, then having the cement dissolve again. This not only explains the large gaps in the rock record, the thick weathering profiles preserved in the subsurface, and the low-relief expression of the rocks but also the varying strength of the rock layers today.

Quaternary Glaciations

The watershed has been glaciated repeatedly during the last 2.5 million years but was most recently shaped by the advance and wasting of two ice lobes during the last glaciation from about 25,000 to 12,000 years ago. Both ice lobes had multiple advances into the area. The sediment deposited by glaciers includes till deposited directly by the ice as well as sediment derived from winnowing of the till by meltwater streams, wind, and lakes. Glaciers erode as well as deposit and despite the multiple advances and long period of glaciation, only an average of 50' of glacial sediment buries the bedrock surface. This is thin compared to other parts of the state where glacial sediment thickness is hundreds of feet or more.

The Superior lobe advanced into this area from the north–northeast conveying rock fragments from the Midcontinent Rift and as far away as Hudson Bay in Canada. The Grantsburg sublobe advanced from the southwest as an offshoot the Des Moines lobe which conveyed rock fragments from northwest of Minnesota from the Dakotas and Canadian provinces of Manitoba, Saskatchewan and Alberta. These include carbonate and shale resulting in a finer-grained calcareous glacial till.

These two differently sourced ice advances have strongly contrasting deposits with different color, texture and pH resulting in the distinct soils and land use in the northern and southern part of the watershed. Mille Lacs, Aitkin and northern Pine counties have Superior lobe deposits at the surface; southern Pine County has primarily Grantsburg sublobe deposits at the surface. The Superior lobe deposits, when winnowed, produce high quality aggregate. The Grantsburg sublobe sediments are more appropriate for farming.

Glacial Lakes

The relief and slope of the bedrock surface not only guided the ice advances into the low-lying region, but after the area was vacated by ice, resulted in water being trapped against the ice front forming large, temporary lakes. The lake sediment deposited in front of the retreating Superior lobe and Grantsburg sublobe is also strongly contrasting in color, texture and pH. Glacial Lake Lind (Superior lobe) is in the subsurface, but the thin alternating layers of red clay and gray silt form an

impermeable layer that perches water. The lake existed for 1,000 years and eventually filled with red sand as it shallowed. This sand is near the surface south of Pine City. Glacial Lake Grantsburg deposited yellowish gray silt and clay that also slows water infiltration. Where present at the surface, it results in different plant communities and land-use practices. The calcareous nature (high pH) makes it more suitable for row-crop agriculture.

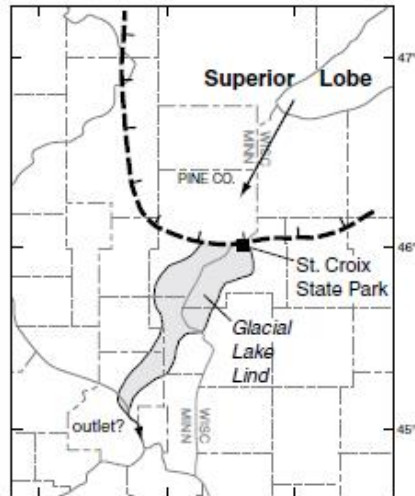


Figure 5. Location of Glacial Lake Lind in southwestern Pine County, showing the area once covered by the lake. The former lake bed is not expressed at the land surface; boundaries for it were determined by drilling and mapping exposures in surficial outcrops. In Pine County, red and gray laminated clay and silt are exposed in banks of the St. Croix River and in shallow gravel pits along terraces of the river. From Johnson and Hemstad (1998), and map D in Figure 1 of Plate 5 (Quaternary Stratigraphy) of the Pine County geologic atlas (Knaeble and others, 2001).



Figure 6. Varved lake sediment of Glacial Lake Lind, south-central Pine County, Minnesota. Reddish clay layers show in the photograph as very thin, dark horizontal lines; gray silt layers show as thicker, lighter layers. A single silt-and-clay layer, taken together, is called a varve couplet and represents deposits of a single year (Johnson and others, 1999). Glacial Lake Lind existed for more than 1000 years. Photograph by C.J. Patterson, Minnesota Geological Survey.

From Chapter 2, History of glaciation in Pine County, Minnesota by C.J. Patterson and A.R. Knaeble, In: Contributions to the Geology of Pine County, T. Boerboom, Project Manager, 2002.

Figure 7. An exposed section of Quaternary sediments showing pink fluvial sands that filled Glacial Lake Lind, southern Pine County, Minnesota. The sands are overlain by till of the Grantsburg sublobe of the Des Moines lobe. The pink to red sand is interpreted as fluvial and deltaic in origin (Johnson and others, 1999). The Grantsburg sublobe overrode the sands, shearing small amounts of it into the till. In other respects, the contact with Grantsburg-sublobe till is sharp and distinct. Also visible is the deformed lake sediment between two layers of Grantsburg till. The lake sediment represents a local deposit, most likely restricted to a low between the next older moraine and the ice front. The trenching shovel is about two and a half feet long. Photograph by C.J. Patterson, Minnesota Geological Survey.

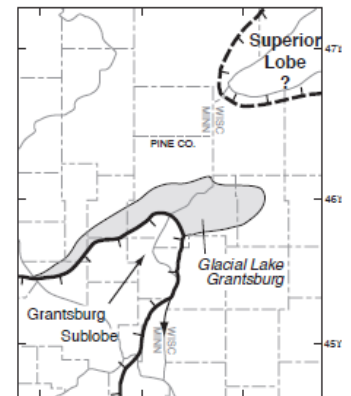
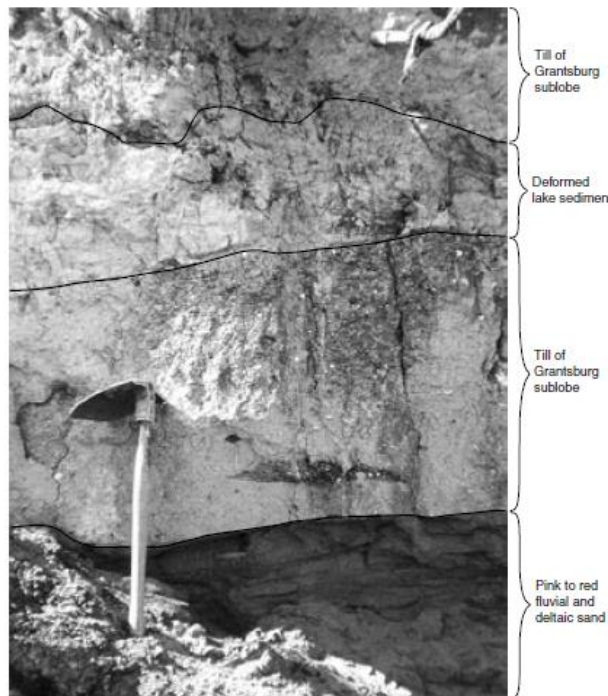


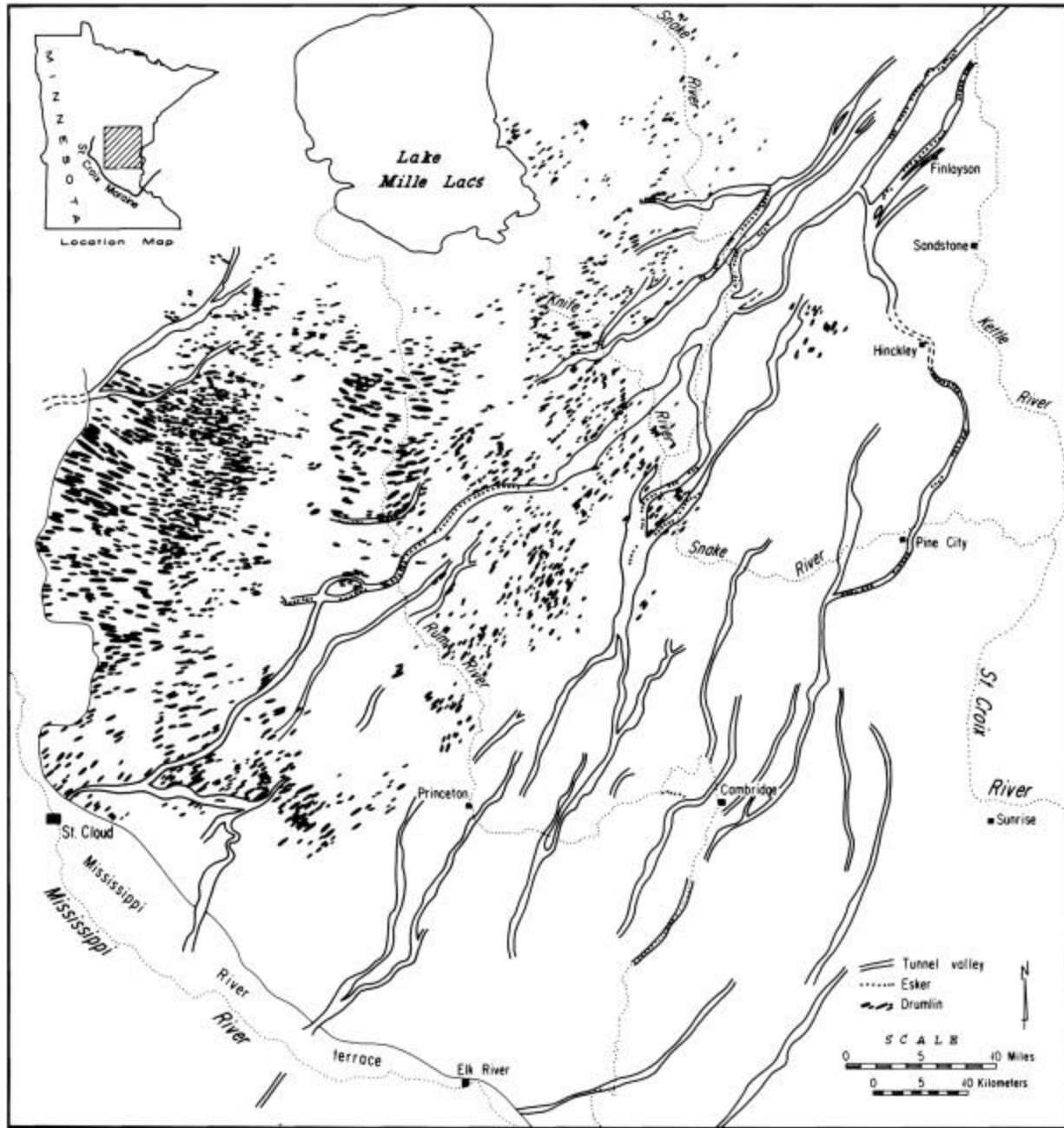
Figure 13. The location of Glacial Lake Grantsburg. Both Glacial Lakes Lind and Grantsburg occupied a similar basin, referred to by Meyer (1998) as the Stacy Basin. Glacial Lake Grantsburg developed because of the blockage of south-draining rivers at the time of the maximum advance of the Grantsburg sublobe. It was a much shorter lived lake than Glacial Lake Lind. From Johnson and Hemstad (1998) and map I in Figure 1 of the Quaternary Stratigraphy plate (Plate 5; Knaeble and others, 2001) of the Pine County geologic atlas.

From Chapter 2, History of glaciation in Pine County, Minnesota by C.J. Patterson and A.R. Knaeble, In: Contributions to the Geology of Pine County, T. Boerboom, Project Manager, 2002.

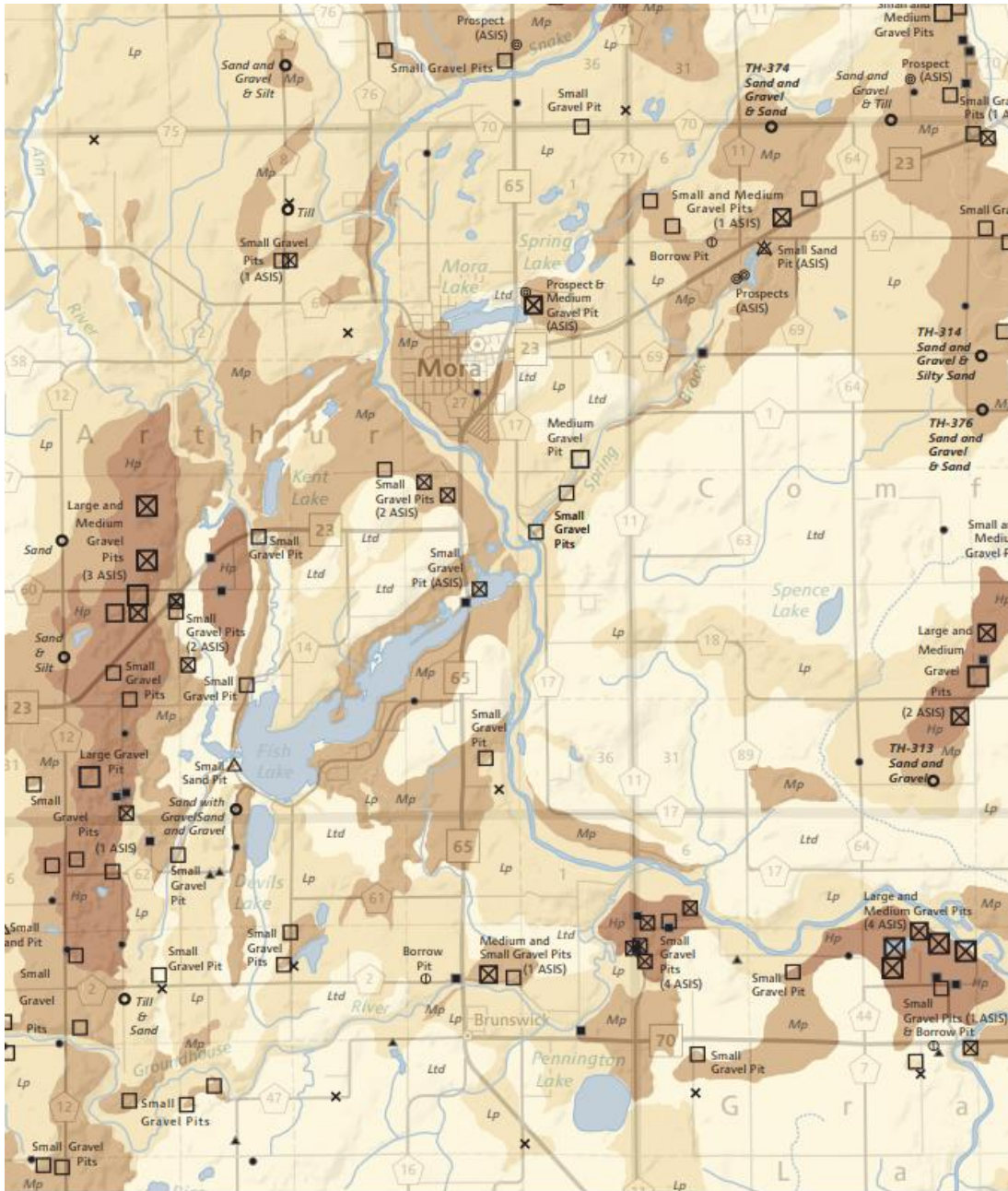
The Impact of Glacial Drainage Systems

Glaciers tend to level the landscape. So, a post-glacial landscape is generally low relief, even more so in areas that are subsequently blanketed with lake sediment. However, drainage from beneath the ice and from temporary lakes can cut deeply into the landscape, steepening slopes locally.

The drainage system that formed beneath the Superior lobe is a radial network of tunnel valleys that exert strong control on the watershed (see figure from Wright, 1972). The half mile-wide troughs are tens of miles long and formed episodically to carry large bursts of meltwater from beneath the ice to the ice margin. They created tunnels in the ice and eroded into the sediment and rock below. Where they exited the ice, they deposited large fans of the eroded material. As the water flow dissipated the pressure of the ice slowly closed the tunnels resulting in a narrow linear ridges of sand and gravel (eskers) within the broad trough that are like upside down river deposits.



Tunnel valleys (solid paired lines), eskers (dotted lines) and drumlins, streamlined hills, of the Superior lobe in the Snake River watershed and beyond. From Wright, 1972. Tunnel valleys, glacial surges and subglacial hydrology of the Superior lobe, Minn.



Excerpt from the Kanabec County Aggregate map showing the relationship between lakes confined by tunnels and sand and gravel deposits emanating from the tunnels in the Mora area. From Friedrich, 2012.

The adverse slope of the tunnel valleys creates basins that hold long lakes: Grass, Pokegama and Cross lakes are examples. Where the troughs and eskers cross modern rivers, they create boulder concentrations that form low rapids. Eskers appear on the lake floors in depth maps. Cross Lake has a clear esker that forms a peninsula on the north end and continues the length of the lake floor. The Grantsburg sublobe advance to Pine City partially obscures the Superior lobe tunnel but both tunnel and esker are still visible to the south.

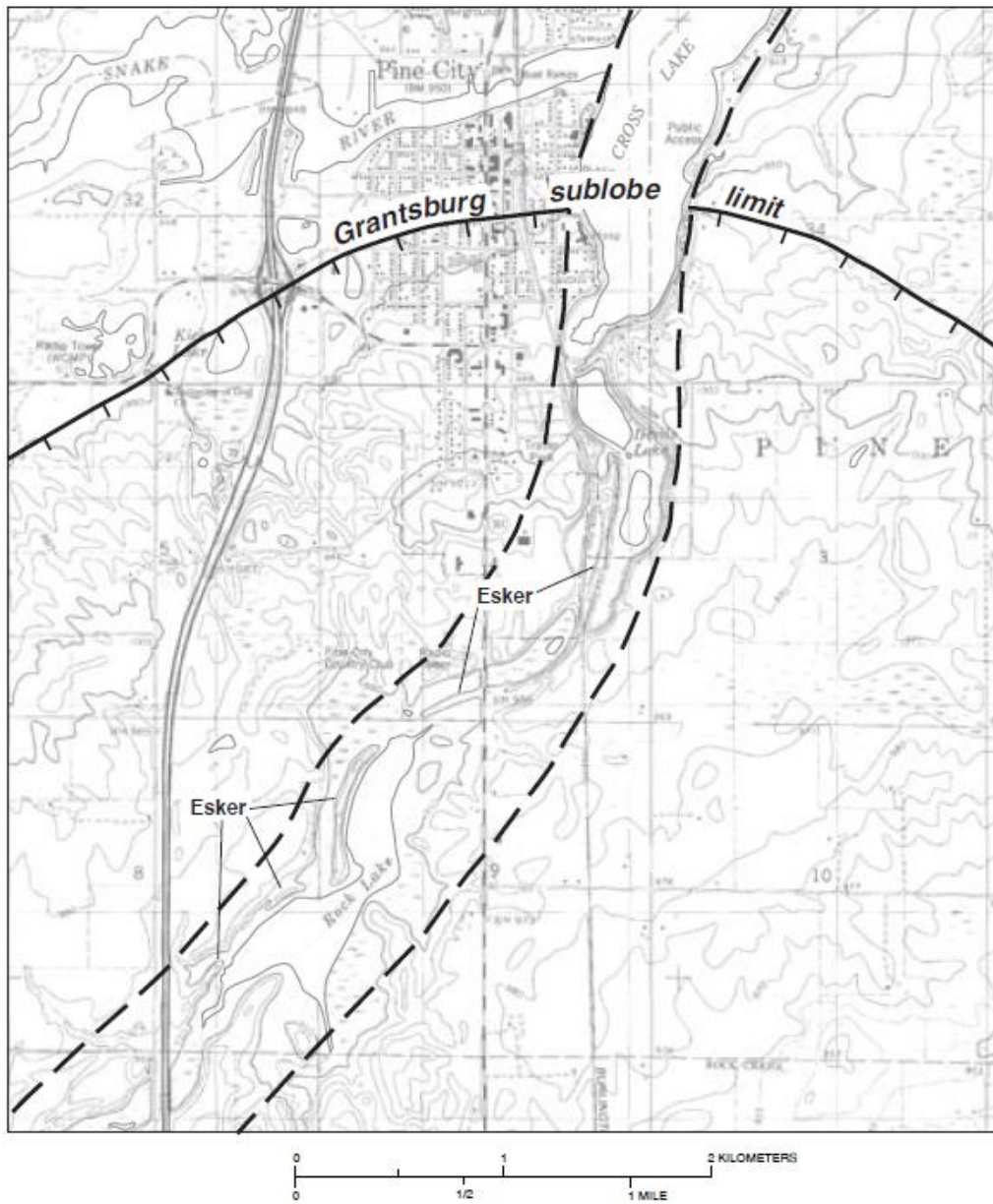
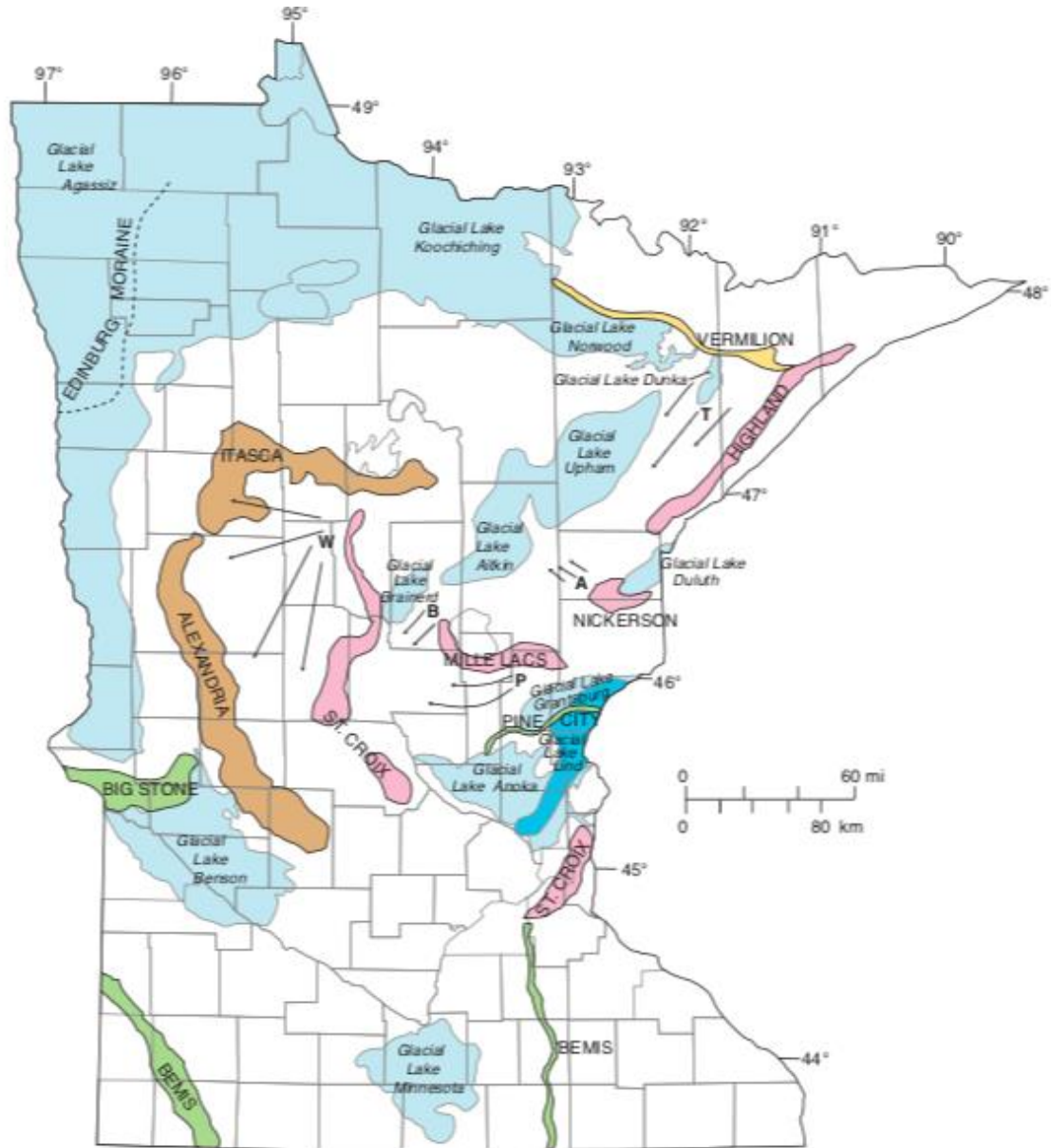


Figure 4. A tunnel valley of the Superior lobe runs north–south through Pine City in south-central Pine County, Minnesota. Contained within the tunnel valley is an esker partly buried by glacial sediment of the Grantsburg sublobe of the Des Moines lobe. The southwest-trending portion of Cross Lake lies within the tunnel valley, and an esker is preserved on the lake bottom (not visible on the figure). The tunnel and esker are preserved even where buried by thick glacial sediment deposited by the Grantsburg sublobe, a condition that requires no ice in the valley to protect these features during the advance of the Grantsburg sublobe. Modified from U.S. Geological Survey Pine City 7.5-minute topographic quadrangle map.

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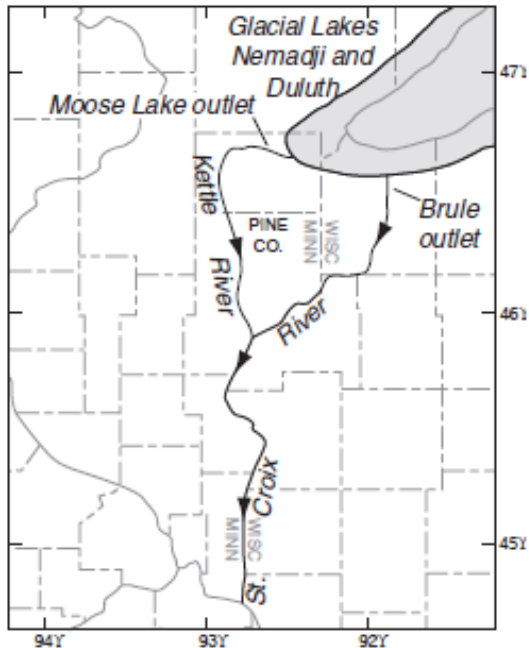
Glacial Lake Drainage Events

Other, more distant drainage events also exert control on the Snake River watershed. A glacial lake that formed in the northern part of the watershed—glacial Lake Aitkin—created the level, poorly drained area that forms the low-gradient headwaters of the Snake and hosts wetlands and peat deposits. Its drainage helped form the channel now occupied by the upper Snake River.



Glacial Lakes and Moraines in Minnesota (not contemporaneous). [From Johnson et al. 2016, Quaternary Lithostratigraphy of Minnesota.](#)

A much larger glacial lake formed in front of the retreating Superior lobe in the basin now occupied at a lower level by the Lake Superior. Its catastrophic drainage created the Kettle and St. Croix valleys which lowered the elevation of the outlet for the Snake at the St. Croix.



From Chapter 2, History of glaciation in Pine County, Minnesota by C.J. Patterson and A.R. Knaeble, In: Contributions to the Geology of Pine County, T. Boerboom, Project Manager, 2002.

Figure 14. Glacial Lakes Nemadji and Duluth occupied approximately the same area in what is now the Lake Superior basin of Minnesota and Wisconsin. The proglacial lake developed as the Superior lobe retreated northeastward. It is referred to as Glacial Lake Nemadji for when it was at the highest level and drained out the Moose Lake outlet. The proglacial lake is called Glacial Lake Duluth for when it was at a lower level and draining out the Brule and St. Croix Rivers. Although the drainages appear to be confluent—and the modern streams occupying them are, the Kettle was created first, but lost most of its flow when the Brule outlet was created.

The Response of the Watershed to Geologic and Human Events

The base-level lowering of the St. Croix River by glacial lake drainage started the Snake on its current path of adjusting its gradient to that local base level. It adjusts by headward or upstream retreat of that break in slope, or nick point. The step in the river profile has moved upriver over the last 12,000 years. More resistant bedrock layers have slowed the progress of nick point retreat. There are steps in the Snake River profile marked by rapids where it encounters the Paleozoic sandstone, the basalt, the basal Fond du Lac and more cemented parts of the Hinckley Sandstone, boulders concentrated in eskers, and McGrath Gneiss. Any structure put in its path (e.g. dams) creates an artificial step.

As the mainstem Snake lowers, so do its tributaries and they begin to erode upstream into their subwatersheds. In the lower Snake, many small streams descend steeping and groundwater seeps out of exposed rock and sediment bluffs. It is in this way that the modern drainage network is

evolving. Given enough time, the headward erosion of the river and its tributaries will eventually reach all of the ponded water on the landscape. Lakes and wetlands are temporary features on a geologic timescale. Older glacial landscapes (for example, Illinois) do not have the number of lakes and wetlands that Minnesota has because they have been drained or filled.

The river flows in or crosses tunnel valleys at right angles from north of Mora to below Cross Lake. This creates the very unusual situation of a river crossing a lake. In other places the Snake River is confined to a broad meltwater channel from Grasston to Lake Pokegama. In that stretch it is flanked by broad wetlands that lie in the former glacial channel.

How Rivers Generally Work

Rivers are dynamic and naturally adjust not only to their gradients but to accommodate the amount of water and sediment they must convey. The geologic events described above overprint the typical evolution of a river channel but in some cases, the river may not be able to overcome the old channel it finds itself stuck in.

In general, where gradients are low, rivers meander more. Where the gradient is steep, rivers are straighter. The outer bends of meanders are eroded by swifter water; slower water deposits sediment on inner bends. Meanders translate downstream over time, shifting the concentrated areas of erosion and deposition. The broadly sinuous reaches of a river are subject to straightening by cutoff, especially during high-water events when steeper reaches are needed to convey the excess water.

Increases in sediment supply can lessen gradients and force channels to meander more or bifurcate around areas of sediment deposition in mid-channel. An increase in water can cause channels to enlarge, either widening or deepening or both, whichever the geologic material more easily accommodates.

The Role of People

Unlike geological timescale events, river events happen on a human timescale. Rivers respond in real time to precipitation and snow melt and also to human interventions such as drainage that increases water supply, vegetation changes that increase runoff, and construction of bridges or structures that pin meanders and do not allow the natural evolution of the channel.

The intervention of people can either accelerate or slow down the progression of the longer-scale geologic events but it is rare for people to completely reverse the course of the geologic events of river events. Where they do intervene, they may have unintended consequences. For example, the dam below Cross Lake has temporarily slowed the retreat of the nick point moving up the Snake River from the St. Croix. The river's gradient is much lower upstream of it with some reaches essentially ponded. These unnaturally slow reaches are depositing sediment as they slow, the water is warming and potentially subject to algal blooms if it has excess nutrients. The dam is built advantageously where the basalt outcrops in the channel but needs human intervention to remain in place.

The steeper reaches below Cross Lake appear to be much more active in comparison to the reaches above the dam. Places where the nick points are currently located at major faults are the most active parts of the channel. Human structures built in the river corridor near the nick points

were put there with the assumption that the river was a stationary object. These are most susceptible to being lost to river processes. Changes to the amount of water the river conveys might be accelerating the natural evolution of the river. Long-term gauging records may help determine if this is happening.

Observations from Canoeing and Kayaking

In June, 2025, Carrie Jennings and Mary Poelman canoed, kayaked or drove the length of the river from Mora to the confluence with the St. Croix. The flow was moderate from Mora to Pokegama and canoeing would have been possible at lower flows in these low-gradient reaches. We used the designated canoe landings indicated on the State Water Trail map and drove the very low-gradient reach from Lake Pokegama to Cross Lake. We used a shuttle service to kayak the reach downstream of Cross Lake. The flow was 600 cubic feet/second and most of the rapids were passable without getting out of the boat. We were advised that the river was not passable at flows lower than 400 cfs.

The river and land are well connected along the upper reaches of the river. Tunnel valleys that cross the channel have formed natural buffers for flood waters, and the wetlands along the riparian corridor play the same role. Where the channel is well connected to the land and access by roads is possible, there is more concentrated seasonal and permanent housing. There are some areas where landscaping and tree removal have made the banks vulnerable to erosion. Eroding banks would deliver mainly sandy sediment to the river. This could be addressed through education efforts emphasizing the preservation of buffer vegetation and the role of natural woody debris in deflecting water energy and protecting a bank. There were only a handful of places where row crop agriculture or cow pastures directly impacted the river. These could be addressed with better setbacks.

The general impression is of a river with low human impact but we did not sample for e-coli or dissolved nutrients and only casually observed transparency. Fishers were mainly onshore and noted an increase in game fish over the past decades.

The river below Cross Lake has naturally higher banks and is increasingly more deeply set in the landscape downstream. All land is either privately held or in a State Forest and the only access point is on the St. Croix after the confluence. Groundwater seeps, steep tributaries and the natural translation of meanders downstream will continue to make bluffs recede in places, especially in the nick zones. Increases in flow from altered hydrology or climate may accelerate this. Mainly this is a case of managing expectations of landowners, increasing setbacks from bluff tops, and removing structures that are in jeopardy of falling into the river. Fishers were in boats in the channel were after catfish and bass.

Recommendations

Use existing data sources to document changes in the river. State water trails have gauge data dating back to when the trail was established.

Document trends in flow and meander migration

It would be helpful to document any long-term trends in flow on the river. The gauge at Grasston appears to have data beginning in 2010. The Pine City gauge data extends to at least 1998. There may be older, less frequent river level measurements. All of these measurements could be analyzed and compared to precipitation data to determine if the river is responding to changes in precipitation or if altered hydrology is also having an impact.

Another way to determine if the river is changing over time is to look for changes in width on air photos. This is difficult in forested reaches, however. Air photos also afford the opportunity to look at the pattern of meander migration over time. The Borchert Map Library has collections of photos that can be accessed online. There are images from 1930, 1960 and the present that could be compared. It is important to compare reaches that are depicted in the center of the photo to avoid distortion from the lens (https://geo.lib.umn.edu/aerial_photos/pine.pdf; <https://apps.lib.umn.edu/mhapo/>)

Create a detailed profile of the river

An approximate profile of the river corridor was created using MnTOPO. However, because this is a LiDAR based elevation model, it does not accurately record the elevation of the channel because the light cannot penetrate water. Review other ways to create river profiles in order to locate the nick points in the profile. Most are demarcated by the location of rapids but identifying steeper reaches will help put current processes into context.

Review steep slope ordinances and educate landowners

Homeowners are generally unaware of the risks of locating structures too close to steep slopes. Floodplains are typically avoided because of their homeowner's insurance provisions or ordinances.

The Department of Natural Resources has created setbacks for steep slopes for rivers that they control zoning on. These rules have been adopted by some counties in Minnesota (Blue Earth and Winona, for example) and are zoning overlays. The DNR has a limited ability to help buyout structures vulnerable to slope failure. Talk to Ceil Strauss [Ceil Strauss](#), MN DNR State Floodplain Manager about setbacks and buyouts.

It is not recommended to intervene in areas of steep, eroding bluffs. These efforts are expensive, have little long-term impact and benefit only one or two landowners, while potentially negatively impacting others.

Test for human and animal pharmaceuticals and microbes

In high e-coli reaches of the river, it might be educational to test for other things that may accompany human or animal bacteria. Pharmaceuticals, hormones, antibiotic-resistant bacteria, and microbial source tracking with host-associated bacteria can elucidate if the problem is from septic systems, animal operations, and if there are other compounds affecting aquatic life (<https://www.usgs.gov/centers/upper-midwest-water-science-center/science/microbial-source-tracking>).

Orient people to the river

Orient new staff to the watershed by getting them on the river. Encourage residents to enjoy the river. The State Water Trail appears to not be well used; campsites are not mowed or kept up and landings not maintained and parking areas feel unsafe. Ask for DNR assistance to upgrade these amenities.

Promote the 15-mile long, annual Snake River canoe race (in early May). Get schools and clubs out on the water to boat or fish. More engagement will result in greater river stewardship. As former Gov. Arne Carlson put it, “float it, fish it, fix it.”

This river is an asset to the communities in your watershed.