University of Minnesota | Extension

Fields to Streams

MANAGING WATER IN RURAL LANDSCAPES

Part One

Water Shaping the Landscape

PRINCIPAL AUTHORS

Ann Lewandowski, University of Minnesota Water Resources Center

Leslie Everett, University of Minnesota Water Resources Center

Chris Lenhart, University of Minnesota Department of Bioproducts and Biosystems Engineering

Karen Terry, University of Minnesota Extension

Mark Origer, ISG

Richard Moore, Minnesota Information Technology

CONTRIBUTORS

Patrick Belmont, Utah State University

Chuck Brandel, ISG

Brenda DeZiel, Minnesota Pollution Control Agency

Keith Harding, University of Minnesota Department of Soil, Water and Climate

Carrie Jennings, Geologist, Minnesota Department of Natural Resources

Kevin Kuehner, Minnesota Department of Agriculture

Martin Melchoir, Inter-Fluve, Inc.

Shawn Schottler, Minnesota Science Museum

Pat Baskfield, Minnesota Pollution Control Agency

ACKNOWLEDGMENTS

We are grateful to numerous reviewers, including

Craig Austinson, Blue Earth County

Jerad Bach, Blue Earth County SWCD

Brad Becker, Dakota County SWCD

David Bucklin, Cottonwood SWCD

Dan Engstrom, Minnesota Science Museum

Matthew Helmers, Iowa State University

Al Kean and Tim Gillette, Board of Water and Soil Resources

Beau Kennedy, Goodhue SWCD

Joe Magner, University of Minnesota Department of Bioproducts and Biosystems Engineering

Lee Thompson and Beth Kallestad, Cannon River Watershed Partnership

David Wall and Bill Thompson, Minnesota Pollution Control Agency

Cover photos courtesy of USDA NRCS

Layout, design and editing by Carissa Christenson and Gina Cooper, ISG.

This publication was funded by The McKnight Foundation.

Fields to Streams

PART ONE

Water Shaping the Landscape

A publication of the University of Minnesota Water Resources Center

University of Minnesota | Extension

Contents

Fields to Streams: Introduction

WHY THIS PUBLICATION?

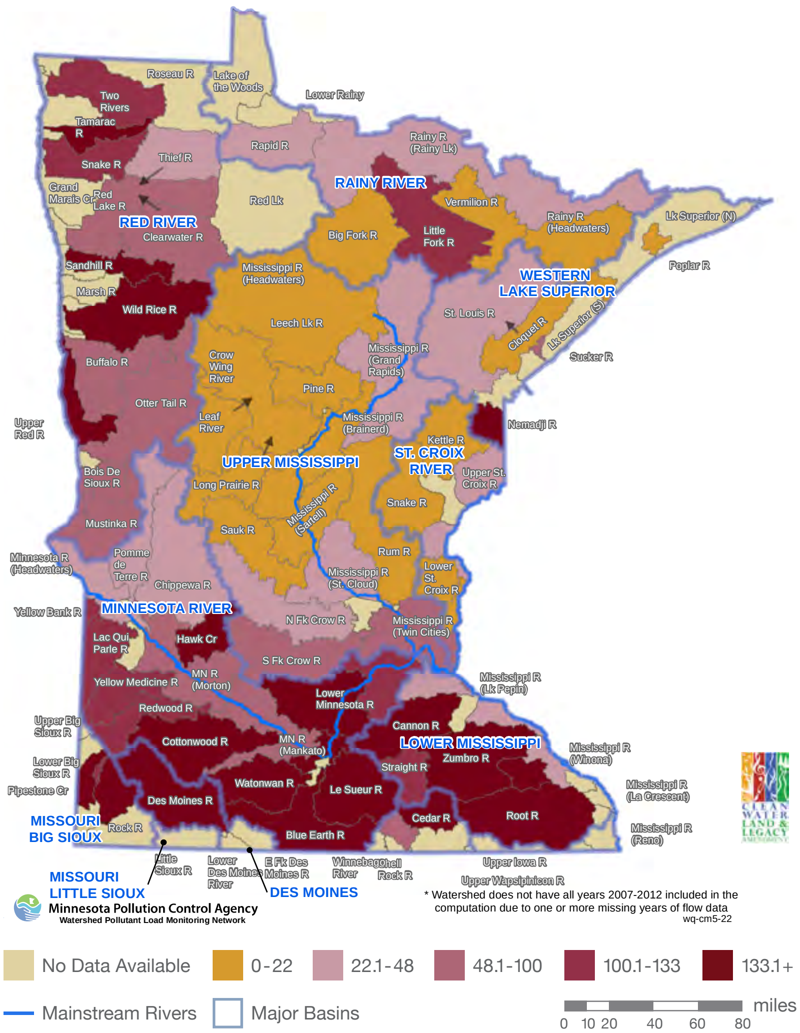
This document is designed to assist rural landowners, land managers, and conservation professionals in protecting rural streams. The emphasis is on land and water management practices that reduce streambank, bluff, and ravine erosion.

Many water-related concerns – including agricultural productivity, excess nutrients, high sediment levels, flooding, property loss, and habitat loss – are connected to the amount of water in streams. The last half century has seen substantial increases in the volume of water in streams, the width of stream channels, and the amount of sediment being transported downstream from streambanks, bluffs, and ravines, especially in southern Minnesota (Figure 1, and Chapter 12). These sources of sediment are primarily the result of higher stream and river flows. To protect rural streams, adjacent farmland, and wildlife habitat, more water needs to be transpired by plants or stored and slowly released using the land and water management practices described in this publication.

Figure 1: Watershed Sediment Loads

The amount of sediment in streams varies across the state. Total suspended solids (TSS) yield is the pounds of sediment in water at the watershed outlet, divided by the number of acres in the watershed, average for 2007 to 2012.

Source: MN Pollution Control Agency



Fields to Streams Summary

PART ONE: WATER SHAPING THE LANDSCAPE

Part One describes how Minnesota's landscapes were formed, how water continues to shape the landscape, and how land management affects water flows, shapes streams and rivers, and influences water quality.

Glaciers left a landscape that continues to be reshaped by flowing water. Most Minnesota watersheds are young in their development. In the Minnesota River Basin, the tributary watersheds are perched on a glacial plain much higher than the Minnesota River that flows in the deep valley created by the earlier Glacial River Warren. These tributaries are cutting back into the till plain at a rate related to tributary flows and delivering large amounts of sediment to the Minnesota and Mississippi Rivers. Large flows in other Minnesota watersheds are also delivering sediment from streambanks, bluffs, and ravines, as well as from upland fields.

Increases in channel-shaping flows are related to the interaction of:

- changes in precipitation,
- a decrease in spring transpiration with the shift to primarily summer annual crops (corn and soybeans), with less perennial and winter annual plant coverage,
- a decrease in surface water storage when ditches were constructed to connect previously unconnected depressions, including shallow lakes and wetlands, to streams,
- reduced evaporation of surface and near-surface water due to expanded subsurface drainage tile networks that lower the water table,
- changes in soil water holding capacity with reduction of soil organic matter.

Agricultural productivity has increased considerably with changes in cropping systems and drainage. However, moderating the combined effects of all of the above-listed changes on timing and volume of stream flows will be necessary to slow the rate of stream channel erosion and sediment movement downstream. Part Two of this publication addresses methods to moderate stream flows and protect streams.

In addition to sediment, changes in hydrology affect delivery of nitrate-nitrogen and phosphorus. These crop nutrients, when carried by surface runoff or tile water to lakes, streams, rivers, and the Gulf of Mexico, enhance production of algae and result in loss of oxygen in water when the algae decompose. A brief description of common pollutants and their pathways is included in Appendix A.

PART TWO: MANAGING SEDIMENT AND WATER

Part Two describes land and water management practices that can be combined to reduce stream degradation and improve water quality. The practices range from crop management to large scale water storage. All of the practices emphasize reducing peak flows and total volume of water reaching streams and rivers.

Since plant transpiration is the largest user of precipitation water, changes in the type, timing and duration of plants on the landscape determine the amount and timing of water that remains to run off the surface or through soil and tile. The absence of transpiring plants in spring leads to higher spring stream flows. Living plants also slow and infiltrate water, affecting the timing of runoff water reaching the stream. The use of cover crops and perennial plants in strategic locations can provide more spring and fall transpiration in row-crop areas.

Water storage can reduce peak flows, which drive the most streambank, bluff, and ravine erosion. Storage is especially effective in small watersheds that have a high sediment yield per amount of stream flow. Ravines and large gullies often supply large volumes of sediment eroded per unit of stream flow. Bypassing these areas or reducing and slowing the water flow can be effective in terms of cost per unit sediment reduced.

It is possible to directly protect areas of active streambank erosion and bluff collapse. In river segments with valuable infrastructure like buildings and bridges, direct protection with riprap or bio-engineered measures is often necessary. However, it is too expensive to undertake these engineering projects over long segments of streams and rivers.

Flows reaching streams and rivers are cumulative across the landscape, as are efforts by individual land managers to reduce those flows through practices that store and use water where it falls. This document describes a treatment train – a series of practices that treat or store water along its entire path from where rain falls on a field, through the soil or drainage system, over the land, and to the river.

The treatment train described in this book addresses:

- Soil Management: Enhancing the ability of the soil to infiltrate and store precipitation. Soil and crop management in agricultural fields affects infiltration rates and water holding capacity through effects on soil structure and soil organic matter.
- Transpiration: Managing the amount and distribution of crop transpiration throughout the year. Transpiration is the largest user of precipitation water, and its timing relative to rainfall distribution has a great influence on how much surplus water will move off the land.
- Surface Flow: Managing overland flow with crop residue, contour farming, and vegetated flow pathways like waterways and filter strips that slow, filter, and partially infiltrate surface runoff.
- Subsurface Drainage: Managing subsurface drainage flow by sizing, depth, and spacing of drainage pipe to control rates of drainage water leaving the field. Control structures can also be installed in the drainage system to allow temporary water storage for later crop use or timed release.
- Water Storage: Increasing water storage, including natural storage in wetlands and other depressions, and artificial storage with constructed wetlands, terraces, ponds, water and sediment control basins (WASCOBs), down-sized culvert retention, weirs, and large detention basins.
- Streambank Protection and Riparian Area Restoration: Although not the focus of this publication, a few measures to protect channels and restore riparian areas are briefly described, along with reference information for further information.

Note: References are provided at the end of most chapters. Many scientific journal articles are available as links from Google Scholar, through research libraries, or directly from authors.

Chapter One

Landforms: The Glacial Origin of Minnesota Landscapes

This chapter is abbreviated from the full version by Carrie Jennings, Geologist, Minnesota DNR. Full version available in Appendix B.

HIGHLIGHTS

Each region of Minnesota has a distinctive set of water management challenges due to its unique geological history.

The Red River of the North watershed, dominated by a flat glacial lake bottom and beaches, is prone to floods over broad areas.

The Minnesota River valley is much lower than the glacial plains in the rest of the watershed. Large amounts of sediment are mobilized as stream water accelerates from the glacial plains down to the valley bottom.

In southeastern Minnesota, porous limestone bedrock provides a rapid conduit for contamination of groundwater. The steep landscapes are susceptible to surface runoff and erosion.

Glaciers play a central role in explaining today's soils, shape of the landscape, and movement of water in Minnesota. The ice sheets exposed bedrock in some areas, created rivers that cut the landscape in other areas, and imported material from hundreds of miles away, grinding it up, and spreading it unevenly across all of Minnesota.

1.1 ORIGIN OF MINNESOTA SOILS

The soils of Minnesota developed in glacial sediment deposited during many glacial periods between 2.5 million and 13,000 years ago. Several patterns of deposits were left on which soils were formed.

- Where the ice sheets last flowed, the land tends to be level. As ice melted, it covered the landscape with a layer of till – a mixture of clay, silt, sand and stones.
- A series of ice advances were followed by stagnation and retreat. At the margins of the ice, the land is irregular with curved hills of deposited till. An example is the Central Lakes Region of Minnesota.
- Where the ice melted into streams and lakes, coarse sand and gravel was deposited in broad, braided meltwater streams.
- Silt and clay settled out in glacial lakes, including those in the Blue Earth River basin and the Red River valley (Figure 2).
- After the ice sheets retreated, strong winds picked up silt and sand from the unvegetated landscape and blanketed some regions in silty dust or loess. The southeastern and southwestern corners of the state include loess-draped areas today.

The Des Moines lobe of the last glacier is particularly important to Minnesota, eastern North Dakota, and northern Iowa. It ground up shale and limestone from Manitoba and Saskatchewan to create a gray, loamy clay. It spread this till as far south as Des Moines, Iowa (Figure 3). These clay-rich Des Moines lobe deposits and glacial lake bottoms, plus the large amount of organic matter later deposited by tall grass prairie and wetlands, are the sources of the highly productive agricultural soils of that region, including Lester, the official Minnesota state soil. These soils hold moisture well, but often have poor natural drainage, requiring artificial drainage for row crop agriculture.

Figure 2: Glacial Lakes

Clay-rich soils were left behind by glacial lakes Agassiz, Benson, and Minnesota. The lakes are shown here at their maximum extents, but were present at different times.

Source: MN DNR 2007, Teller et al. 1983, Hobbs and Goebel 1982

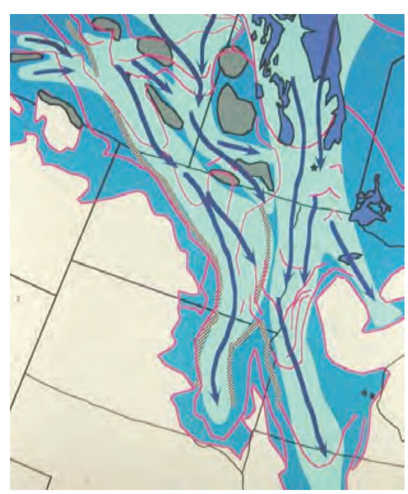


Figure 3: Advance of the Des Moines lobe of the Wisconsinan glaciation.

Source: C. Jennings, MN DNR

1.2 RED RIVER OF THE NORTH: THE BROAD VALLEY

The Big Stone moraine (Figure 4) impounded glacial melt water, creating the massive Glacial Lake Agassiz in what is now western Minnesota, eastern North Dakota, Manitoba and Ontario. Fine-grained silt and clay sediments settled to the lake bed, becoming the parent material for the heavy soils of today's agriculturally productive Red River Valley. The modern Red River slopes gently to the north at less than one foot per mile, and loses a small amount of gradient every year as the land to the north continues to rebound from its thicker glacial ice cover.

The Red River channel is incised only at a local scale, and floods spread over wide distances with no deep valleys to confine them. Floods are also exacerbated because in a north-flowing river, spring flooding comes first to the southern part of the watershed and may encounter still-frozen parts of the river as it flows north.

The flat lake plain portion of the valley is large, but is not the whole of the Red River watershed, which extends beyond the beach ridges of the former glacial lake and is drained by tributaries originating in higher elevation glacial deposits (Figure 5).

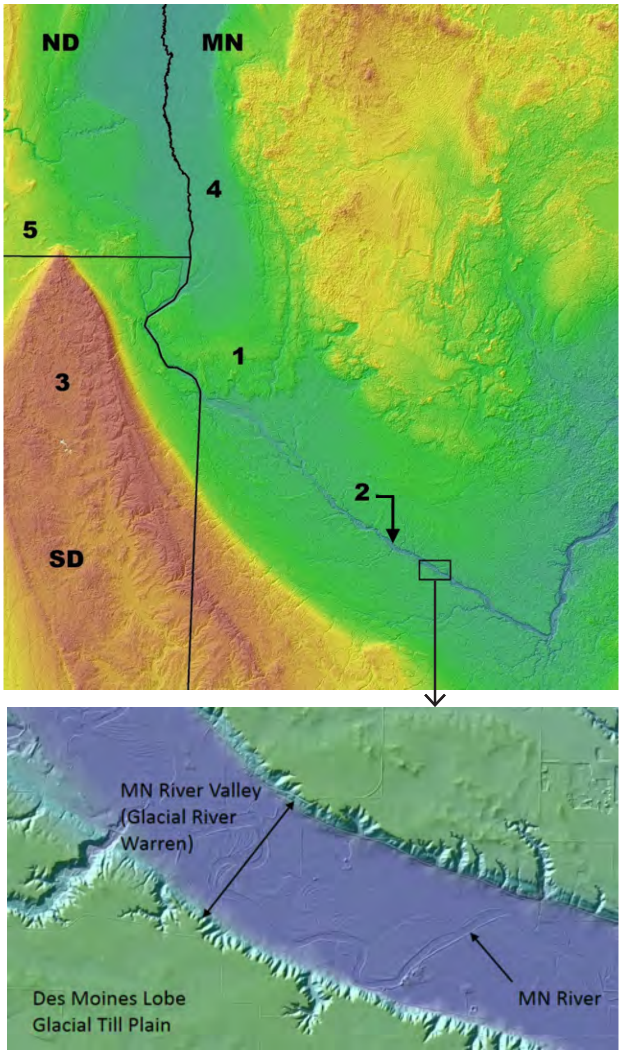


Figure 4: Topography of western Minnesota and the eastern Dakotas

Glacial Lake Agassiz was impounded by the Big Stone moraine (1) that separates the Red River watershed from the Minnesota River watershed. Glacial River Warren, an outlet channel created by the draining of glacial Lake Agassiz (2), follows the centerline of the glacial trough south of the Big Stone moraine. The Minnesota River now only partially occupies the valley created by Glacial River Warren (enlargement). The Prairie Coteau (3) with the narrow Buffalo Ridge separates the troughs of the Des Moines glacial lobe (4) and the James lobe (5) in the Dakotas.

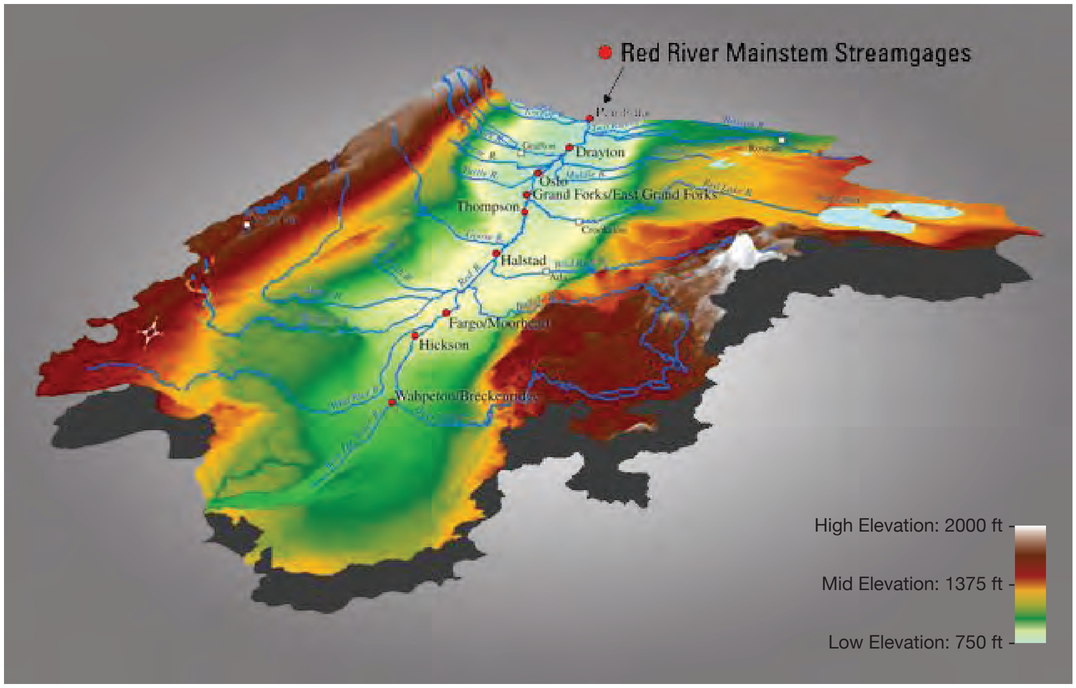


Figure 5: Elevation of the Red River of the North watershed in the U.S.

The Red River watershed is larger than the flat lake plain portion of the valley.

Source: USGS

1.3 MINNESOTA RIVER BASIN: INCISING TRIBUTARIES

About 13,400 years ago, Glacial Lake Agassiz began to drain across the Big Stone Moraine, forming the valley now occupied by Lake Traverse and Big Stone Lake. Glacial River Warren, as it is known to distinguish it from the modern Minnesota River, flowed episodically during the next 2000 years, creating the deep, mile wide valley as it cut through up to 200 feet of glacial sediment and in places, exposed the bedrock. This had a profound effect on the Minnesota River watershed because the newly deepened valley meant that all of the tributaries to the river had to adjust their gradients to match. They are still adjusting to this event today and are not very far along in the process.

The tributaries would have instantaneously become waterfalls or very steep steps in the river profile known as nick points or knick points. Where bedrock is present, nick points work their way upstream by the turbulence at the base of a falls undercutting the ledge causing it to break off. In sediment or till (as in the Minnesota River Basin), there is no bedrock to support waterfalls so instead, steep reaches with rapids and boulder beds stretch over the actively eroding zone. The landscapes above and below the nick zone are distinctly different (Figure 6).

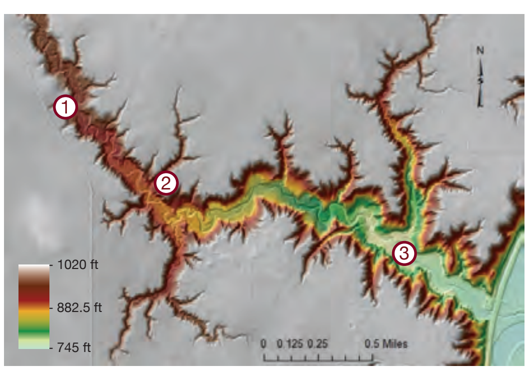


Figure 6: Geography of nick zones

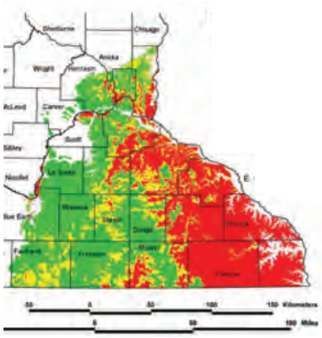
This map shows the incision of Seven Mile Creek from the Minnesota River (bottom right). The elevation changes more than 200 feet from the valley floor to the uplands.

1 - Above the nick zone, the streams are relatively shallow and slow moving with little slope. Sediment in these upper reaches primarily derives from field, ditch and stream erosion.

2 - As the nick zone moves up the stream, its smaller side tributaries experience a sudden drop at their mouths and they similarly become oversteep ravines. In this way, tributaries, ravines and newly formed bluffs increase the supply of sediment to the river related to flows.

3 - Below the nick zone, the stream bed has already adjusted or at least begun adjusting to the lower level of the outlet into the Minnesota River. The river here has steep bluffs along the valley walls, and stream sediment primarily derives from high bluffs and ravines.

Incision and migrating nick zones have contributed sediment to the Minnesota River since Glacial River Warren first flowed. The rate of incision has accelerated in recent decades in response to higher stream flows. Streambanks, bluffs, and ravines are now the source of the majority of sediment reaching the Mississippi River from the Minnesota River. See Chapter 11 for an explanation of the relationship between stream flow and amount of sediment.



Covered Karst

Transition Karst

Active Karst

Figure 7: Minnesota karst lands

Limestone bedrock runs as far west as Faribault County, but is overlain by an increasingly thick layer of glacial till. The active exposed karst areas and the transition areas with only a thin layer of till are susceptible to groundwater contamination.

Covered Karst - Areas underlain by carbonate bedrock but with more than 100 ft. of sediment cover.

Transition Karst - Areas underlain by carbonate bedrock with 50-100 ft. of sediment cover.

Active Karst - Areas underlain by carbonate bedrock with less than 50 ft. of sediment cover.

Source: E. Calvin Alexander Jr., Yongli Gao, and Jeff Green, 2006

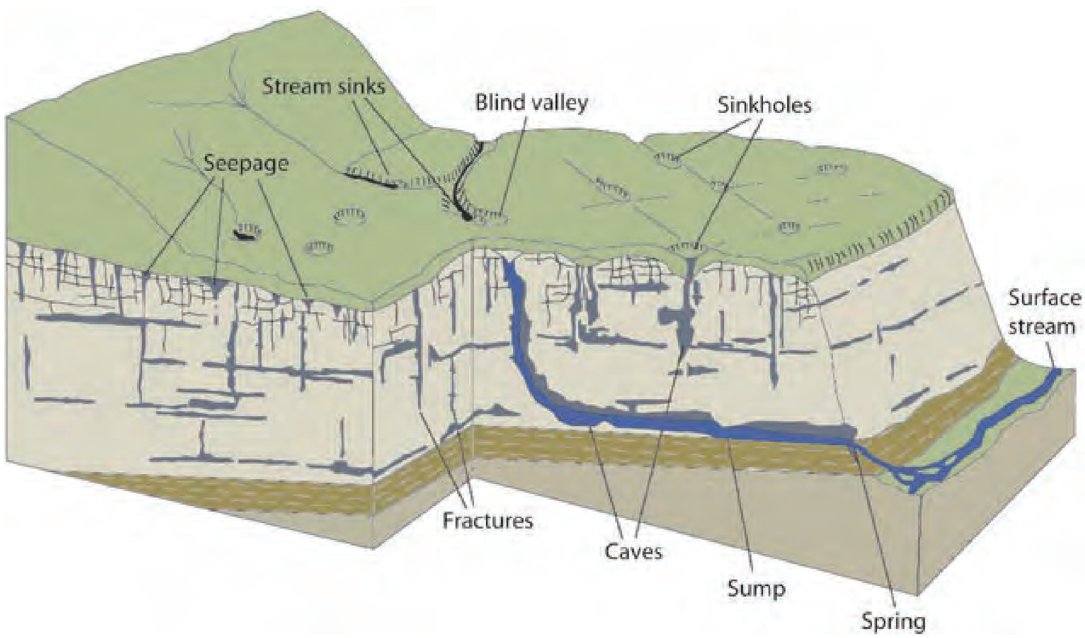
Figure 8: Karst topography

Source: Adapted from Wisconsin Geological Survey

1.4 SOUTHEASTERN MINNESOTA: KARST LANDSCAPE

Southeastern Minnesota was bypassed by the last glaciation but all of Minnesota has been glaciated at some point in time. The long history of glacial meltwater draining through the Mississippi River has allowed the tributary rivers in southeastern Minnesota to become deeply incised, highly evolved rivers that control the relief. They expose gently sloping layers of limestone, shale, and sandstone bedrock that were originally deposited in shallow seas two to five hundred million years ago. Away from the valleys, these layers may be shallowly buried by older glacial till and windblown loess. Glacial sediment cover generally thickens westward (Figure 7).

The limestone layers dissolve in slightly acidic rainwater over time, and cracks have enlarged to form caves and sinkholes (Figure 8). These conduits allow surface water to quickly enter the groundwater system. This water may resurface lower in the landscape in the incised valleys as springs and streams. This karst topography, where it is overlain with relatively thin sediment on the eastern side of the region, is very susceptible to groundwater contamination. Natural drainage is usually good in this region. The dissected and steeply sloping landscape created by incision of tributaries from the much lower Mississippi River valley makes the eastern side susceptible to high rates of erosion when exposed by tillage.



REFERENCES

Hobbs HC, Goebel JE. 1982. Geologic map of Minnesota, Quaternary geology [map]. 1:500,000. Map S-1. St. Paul: Minnesota Geological Survey, University of Minnesota.

Minnesota Department of Natural Resources. 2007. Native plant communities and rare species of The Minnesota River Valley counties. Biological Report No. 89 http://files.dnr.state.mn.us/eco/mcbs/mn_river_report.pdf

Teller JT, Thorleifson LH, Dredge LA, Hobbs HC, Schreiner BT. 1983. Maximum extent and major features of Lake Agassiz. In Glacial Lake Agassiz, ed. Teller JT, Clayton L. p. 43–45. Special Paper 26. St. John' s, Newfoundland: Geological Association of Canada.

Chapter Two

The Water Cycle

HIGHLIGHTS

Most precipitation goes back to the atmosphere as evaporation and transpiration.

If water doesn't evaporate or transpire, it will eventually become stream flow.

70% - 90% of precipitation ends up back in the atmosphere through transpiration or evaporation

Water continuously moves through the soil, over land, through plants, into the atmosphere, and carried in air masses across the continent. Along this path water changes forms and pauses for hours or centuries in lakes and groundwater aquifers. The local climate, soils, terrain, and plants determine the routes and rates of the water cycle. Effective management decisions are based on understanding these local patterns.

TYPICAL WATER BUDGETS

Precipitation has three potential fates (Figure 9):

- It returns to the atmosphere through evapotranspiration or ET. This is the combination of transpiration from plants plus evaporation from soil and water surfaces. This is the fate of most precipitation.
- It infiltrates to deep groundwater aquifers.
- It flows to streams, sometimes pausing in lakes or wetlands, or moving slowly through soil.

Typically in Minnesota, about three-quarters of precipitation becomes evapotranspiration and one-quarter reaches streams via surface and subsurface flow (Baker et al., 1979). Less than 1% of precipitation seeps down to confined groundwater aquifers. A much larger proportion reaches unconfined aquifers near the surface, but this water flows relatively rapidly to streams, lakes, and wetlands (Delin and Falteisek, 2007).

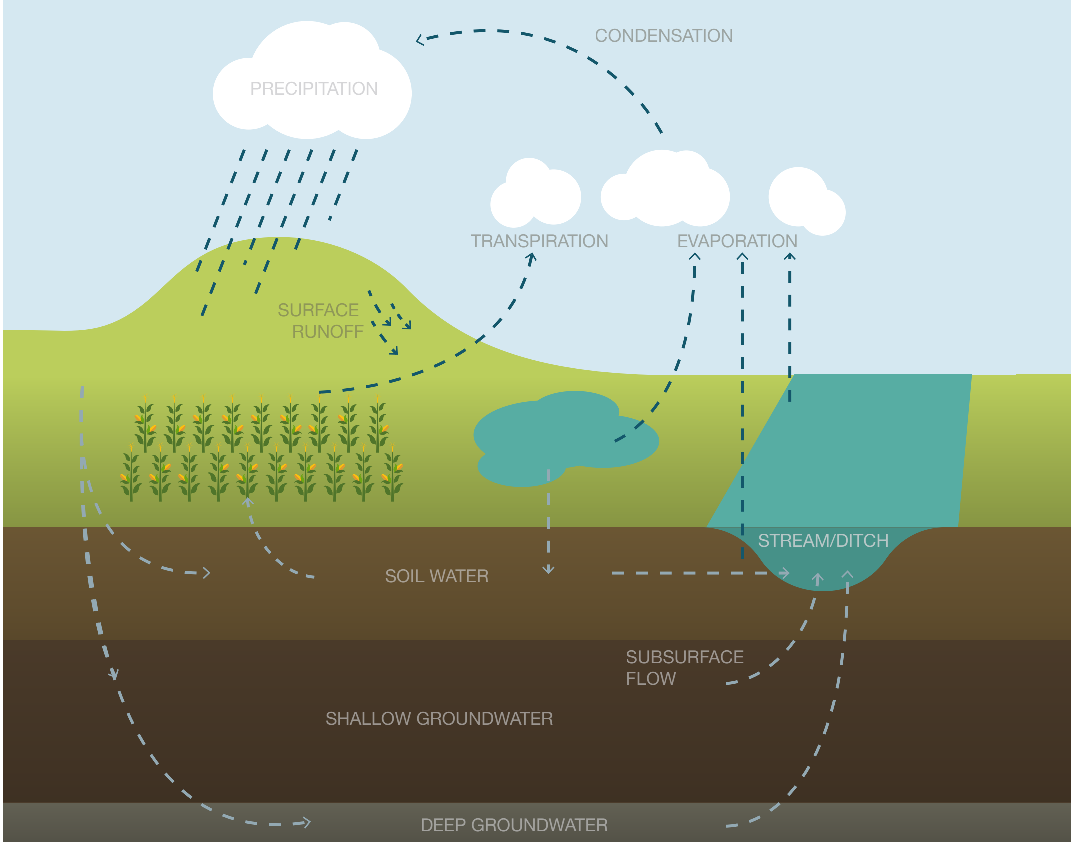


Figure 9: Movement of rainfall and snowmelt through the watershed to a stream

Source: ISG

Figure 10: Average annual precipitation in inches, 1981-2010

Source: MDNR climate website

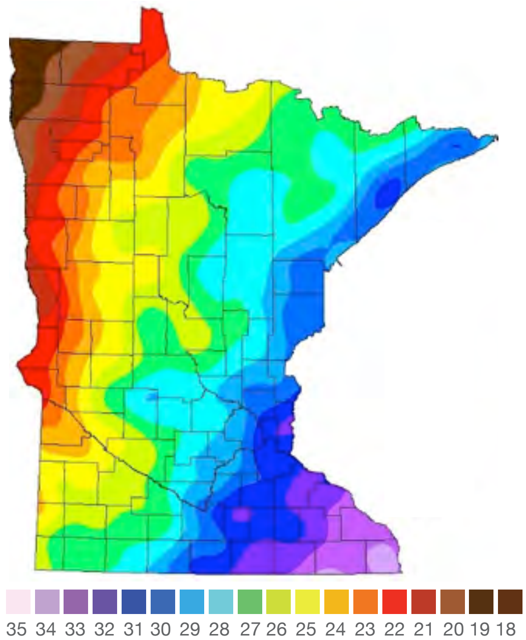
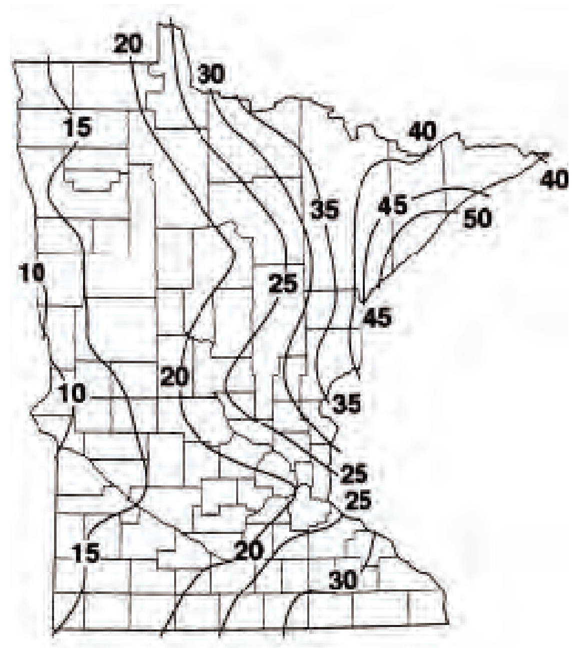


Figure 11: Stream flow as a percent of total precipitation, 1971-2000

Stream flow is the sum of surface and subsurface runoff through the watershed. The balance of precipitation returns to the atmosphere as ET.

Source: MDNR climate website



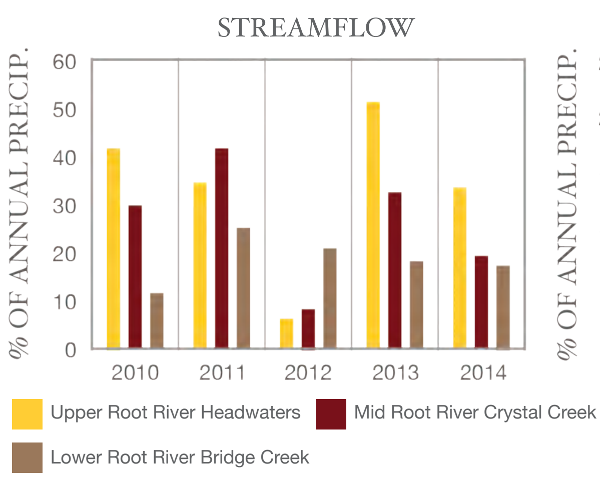
LOCAL VARIATION IN WATER BUDGETS

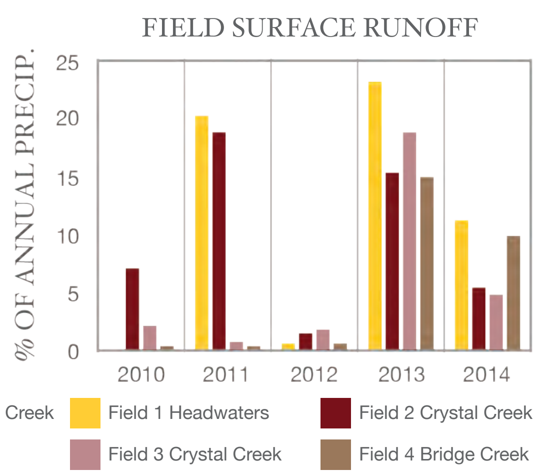
The typical water budget hides substantial regional and annual variation. Regionally, streamflow may be more than 40% of precipitation in northeast Minnesota where soils are thin and rainfall is high; and less than 10% in the west where soils are thick and flat and rainfall is lower (figure 11). Seasonally, runoff from frozen soil, typically snow melt or rain on frozen ground, can be significant.

The Root River watershed in southeast Minnesota provides an example of how water budgets vary year-to-year and between the local and watershed scale (Figure 12). Water from the stream and from fields was monitored in three subwatersheds (<5,000 acres) from 2010 through 2013. Stream flow (surface plus subsurface runoff) across all three subwatersheds averaged 27% of precipitation, and in one subwatershed ranged from 6% in 2012 to 51% in 2013. Edge-of-field (EOF) overland runoff monitoring from representative farming systems within these same sub-watersheds ranged from <1% in 2012 to 23% in 2013 in one field. Variation in the water budget is even higher for individual events. On average, 44% of the annual EOF surface runoff occurred when the soil was frozen, typically in the months of February and March.

Figure 12: Streamflow and surface runoff in the Root River Watershed

Source: Root River Field to Stream Partnership, Kevin Kuehner, Minnesota Department of Agriculture





REFERENCES

Baker DG, Nelson WW, Kuehnast EL. 1979. Climate of Minnesota: Part XII – The Hydrologic Cycle and Soil Water. University of Minnesota Agricultural Experiment Station Technical Bulletin 322. http://purl.umn.edu/109293

Delin BN, Falteisek JD. 2007. Groundwater Recharge in Minnesota. USGS Fact Sheet 2007-3002. http://pubs.usgs.gov/fs/2007/3002/pdf/FS2007-3002_web.pdf

Minnesota Department of Natural Resources (MDNR). (website) Water Year Data Summary: 1999-2000. http://www.dnr.state.mn.us/publications/waters/water_year_1999-2000.html

Minnesota Department of Natural Resources (MDNR). (website) Minnesota Normal Precipitation Maps: 1981-2010. http://www.dnr.state.mn.us/climate/summaries_and_publications/precip_norm_1981-2010.html

Chapter Three
Watersheds

HIGHLIGHTS

A *watershed* is the area of land that drains water from the landscape to a stream or lake. All land is part of a watershed.

The rain and meltwater flowing through a watershed links all the land within that watershed - both in space and over time. Thus, the characteristics of a stream or lake depend on the characteristics of the watershed.

Significant characteristics of a watershed include the type of soil, topography, and the quantity and type of water storage.

Water storage slows the movement of water across the landscape. Storage occurs at many locations including within the soil, surface roughness, temporary ponds, permanent wetlands, stream meanders, and lakes.

People have multiple interests in the same water. Water management goals may conflict.

3.1 WATERSHEDS LARGE AND SMALL

A watershed is the area of land within which all surface water converges to a common point.

The Mississippi River basin is an example of a very large watershed covering much of the continent and converging at the outlet in New Orleans (Figure 13). The rain and snow that falls on the state flows outward in three directions: north through the Red River of the North and Lake Winnipeg to Canada's Hudson Bay, south through the Mississippi River to the Gulf of Mexico, or east through the Great Lakes and St. Lawrence Seaway to the Atlantic Ocean. Minnesota is distinctive for being at the headwaters of three large watersheds. Because very little water flows into the state from elsewhere, Minnesota has a unique opportunity to protect its own water quality.

Figure 13: Continental drainages

Source: B. Knudsen, MN DNR, 2015; Data from Lehner et al., 2006

The three major drainages can be divided into 10 basins (Figure 14).

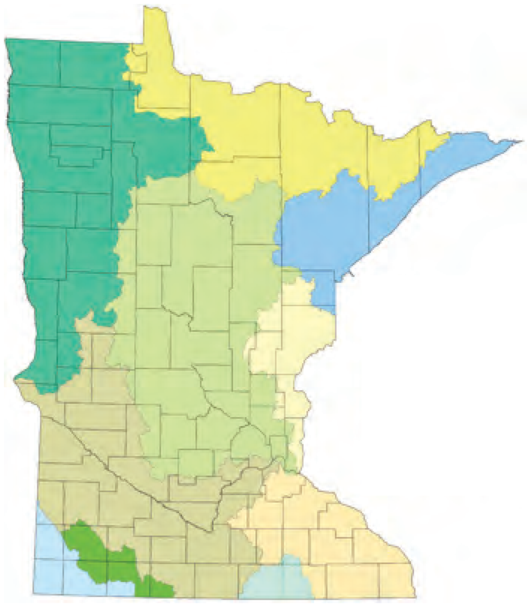


Figure 14: Minnesota basins

Figure 15: Minnesota major watersheds

In turn, the 10 major basins comprise 81 major watersheds (Figure 15). This is the scale of planning for the Minnesota Pollution Control Agency and for many watershed districts and projects.

The major watersheds can be further divided into smaller and smaller sub-watersheds. The portion of a field that converges on a waterway is an example of a small watershed (Figure 16).

Many ways to say "watershed"

Drainage, basin, major watershed, sub-watershed, and catchment are all just some of the words that mean "watershed". The terms are not used consistently, so look out for what size watershed is meant in a particular context.

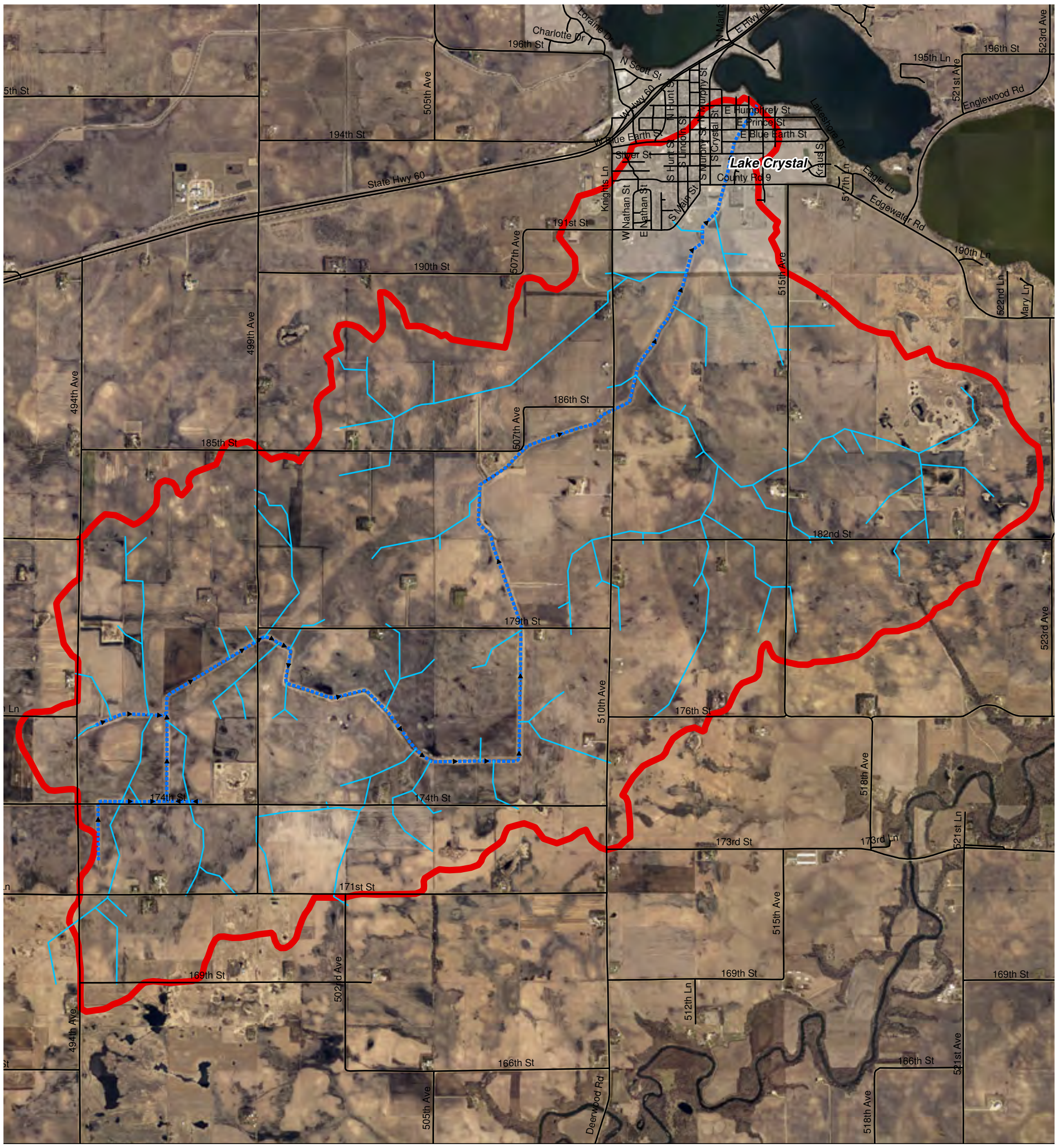
See the DNR watershed page www.dnr.state.mn.us/watersheds for more definitions and an explanation of the Hydrologic Unit Codes (HUC) used to uniquely label every watershed.

Figure 16

Source: USDA NRCS

Figure 17: Ditch system watershed

Source: ISG



A DITCH SYSTEM IS A WATERSHED

Storm sewers and agricultural drainage systems can change the boundaries of watersheds by transferring water across topographic features that originally defined the watersheds. Some city storm water systems drain into an agricultural drainage system. Figure 17 shows the boundary of the watershed drained by the Ditch 56 system in Blue Earth County, Minnesota.

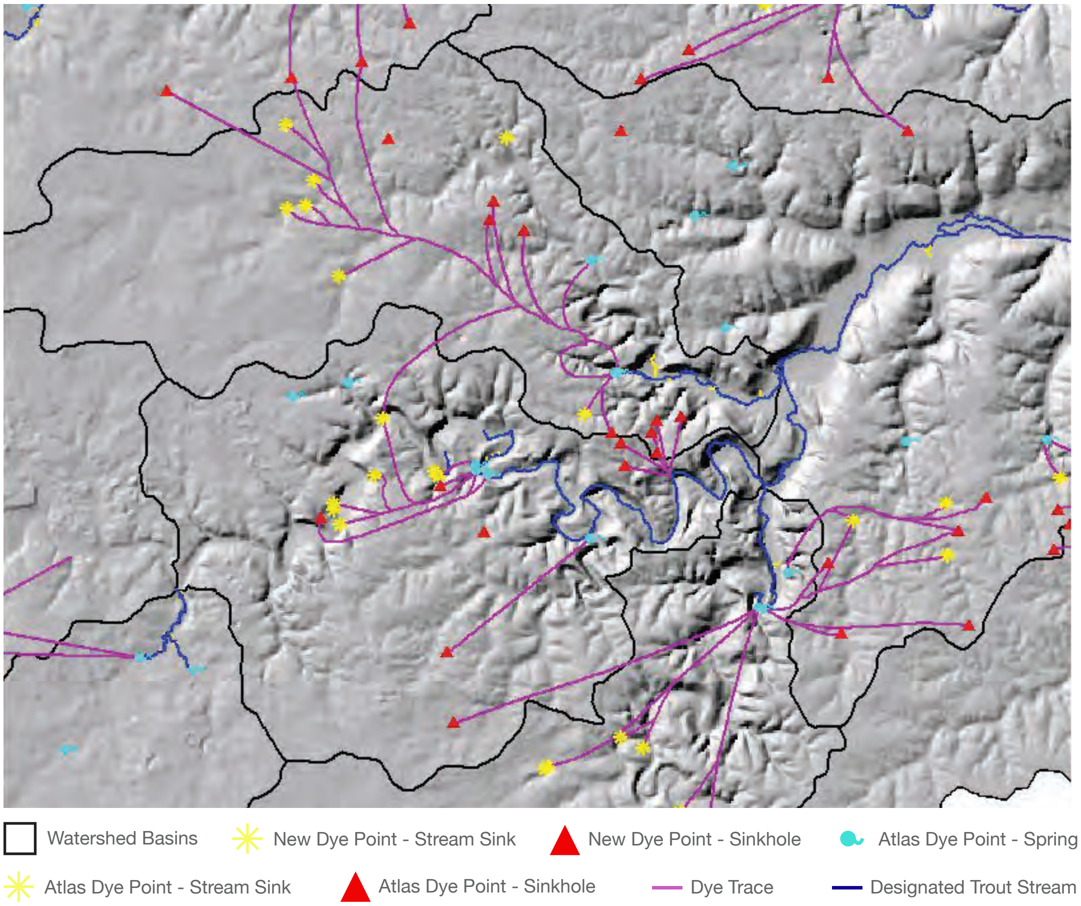


Figure 18: Underground movement of water

Source: Jeff Green, Minnesota Department of Natural Resources

GROUNDWATER HAS DIFFERENT BOUNDARIES

The water below the surface forms a second system of flows and storage in deep and shallow aquifers. Groundwater moves more slowly, following different patterns than surface water. In Figure 18 of the South Branch of the Root River, purple lines show the underground direction of dye tracers from where they were added to sink holes (red triangles) to where they reappeared in a spring (blue symbol). Notice how the underground paths cross the black boundaries of surface watersheds.

3.2 WATERSHED CHARACTERISTICS

Each watershed has its unique shape, topography, soils, climate, geology, vegetation, and land use activities, making water flow differently through each one.

Water moves quickly through the steep, rocky North Shore watersheds, and very slowly across the flat, deep-soils of the Red River watersheds. Long, narrow watersheds (e.g., Pomme de Terre River watershed, Figure 19) generally have fewer natural storage basins and shorter tributary streams so rainwater or snowmelt gets to the river quickly. For a given landscape, water moves slower through meandering than straight rivers because it is traveling a much longer distance to drop the same elevation. Slower moving water has less energy and therefore carries less sediment.

Water flows more slowly through vegetation with dense stems, like grasses, than over bare soil with sparse vegetation, like trees or row crops. Slower-moving water has more time to infiltrate into the ground and less energy to move sediment.

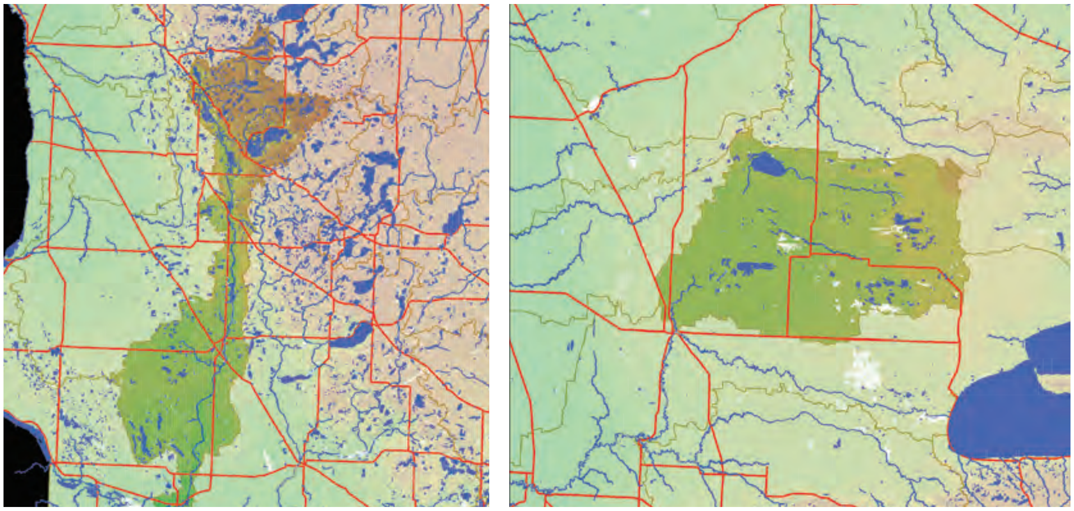


Figure 19: Pomme de Terre and Thief River watersheds

Water reaches the river more quickly in narrow watersheds, like the Pomme de Terre, than in broader watersheds, like the Thief River.

3.3 LAND AND WATER CONNECTIONS

Land within a watershed is connected by the water that moves through it. Water moves in all directions (Figure 20).

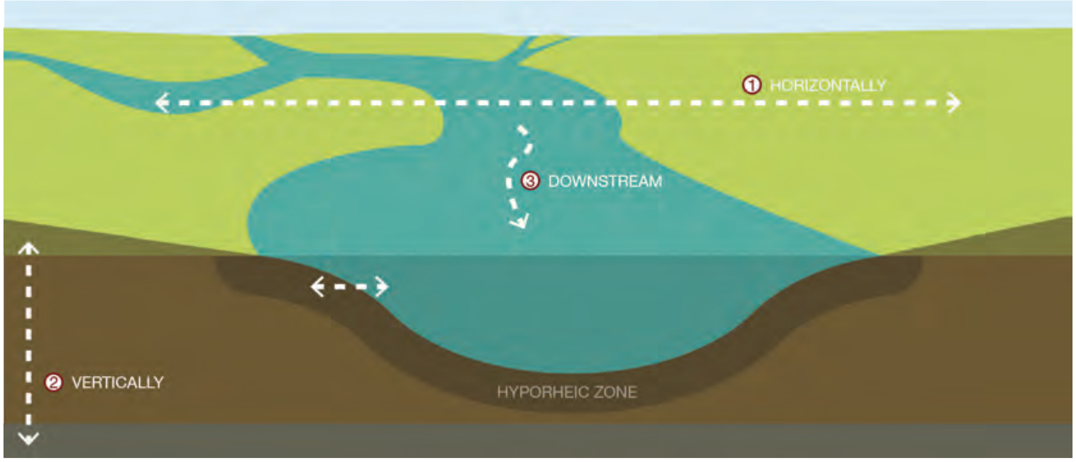


Figure 20: Directions of water movement connecting land and water

1 - horizontally over the surface as the stream spreads out over its flood plain, and horizontally through soil between groundwater and the stream

2 - vertically through the soil to groundwater aquifers

3 - downstream along the stream channel

Source: ISG

TIME MATTERS

Water moves over long and short time scales. Travel from the surface to a deep aquifer may take decades; travel from uplands to a stream channel may take days or hours (Figure 21); and travel down a stream channel from the top of the headwaters to the outlet may take hours.

Time is also important as water interacts with the constituents it carries. Sediment-bound phosphorus may become biologically available over long periods of time. Sediment moves downhill in spurts as it is alternately picked up and deposited over multiple events. Denitrification (the conversion of nitrate to N_2 gas) occurs in saturated (low oxygen) conditions – but only if the nitrate is in the low oxygen environment for enough time.

A flow, or discharge, **hydrograph** shows the amount of water flowing in a stream over time (Figure 22). It may show flow month-by-month or hour-by-hour after a storm. The hydrograph of a small tributary typically will show flow reaching a peak soon after a rainfall. In contrast, the mainstem reaches peak flow later, as water from all the tributaries collects in the larger stream.

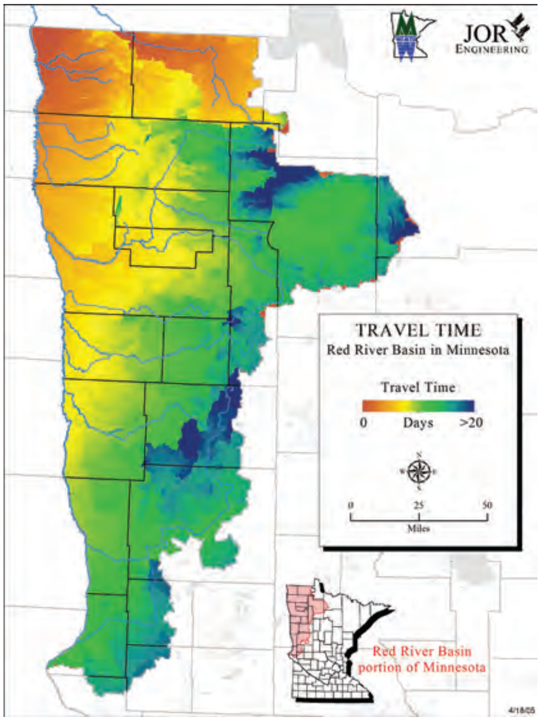


Figure 21: Travel time across the Red River Basin

Authorities in the Red River Basin use information about the travel time of water from the headwaters to the mainstem to strategize where to implement water retention practices and to estimate timing of flood peaks.

Source: Jim Solstad (MNDNR Waters), Charlie Anderson & Mark Reineke (JOR Engineering) for the Red River Watershed Management Board's (RRWMB) Flood Damage Reduction (FDR) committee.

Base flow is the sustained low flow in a channel. Base flow comes from sources such as water seeping into the streambed from near-surface groundwater, from lakes, or from drainage tile outlets which are transporting soil water. Greater flows following a storm or snowmelt are a combination of overland flow, which reaches the stream quickly, and water that flows through soil, which reaches the stream much later.

Lag time is the gap in time between a land management change and the resulting impact on infiltration, water flow, sediment loads, shape of a stream, or other characteristics of a watershed. Lag time varies greatly depending upon the size of the drainage area and the type and degree of land management changes.

Another use of the term lag time is for the gap between the bulk of a rainfall and the peak in the hydrograph (Figure 22).

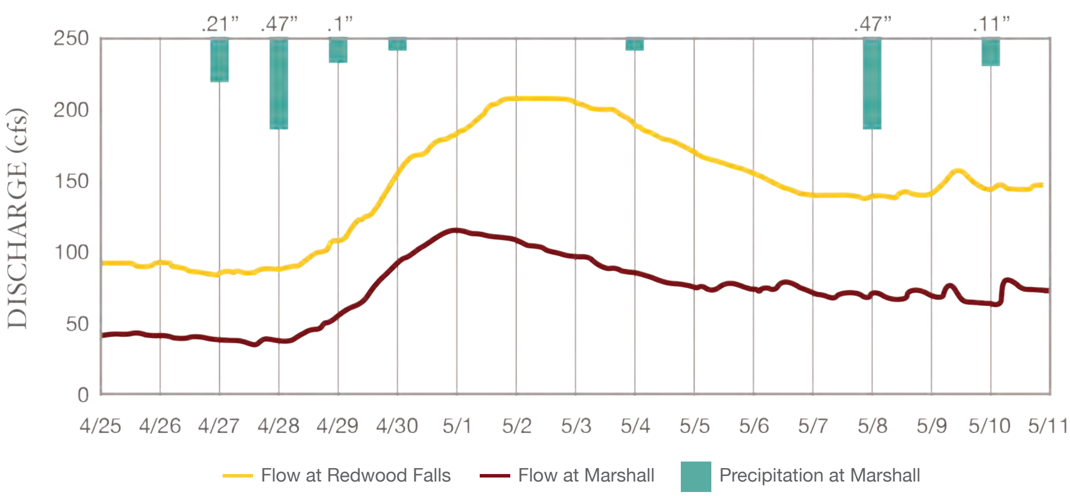


Figure 22: Hydrographs for the Redwood River

After rainfall on April 27th and 28th, 2014 stream flow at Marshall briefly peaks on May 1st while flow downstream at Redwood Falls has a longer peak starting on May 2nd. (Rainfall was measured at Marshall.)

Source: USGS Current Water Data

Expect the impacts of water management to cross property boundaries and political boundaries

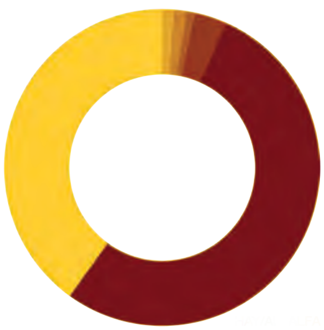


Figure 23: Pre-European settlement land cover in Martin County

This chart shows the estimated land cover based on soil type in Martin County, Minnesota before agricultural development and drainage installation. Less than half of the area was uplands, while the remainder was a variety of wetlands.

Source: Galatowitsch and Van der Valk, 1994. Matzdorf, 1984

MULTIPLE GOALS FOR WATER MANAGEMENT

People have many interests in water, how it moves, and what it carries. These interests relate to:

- agriculture,
- industry,
- recreation,
- habitat for wildlife and fish,
- nutrient cycling,
- drinking water and wash water,
- groundwater recharge,
- flood mitigation,
- pollutant mitigation,
- landscape aesthetics,
- and more.

Managing water always impacts more than one of these interests. People manage water for the purpose of getting more water in recreational lakes and waterfowl ponds, less water in farm fields and basements, lower water around bridge abutments, colder water in trout streams, cleaner water in the tap, and for keeping sediment and nutrients on the land. Management for one goal at one site affects other sites in a watershed. For example, enlarging a culvert to improve a road crossing may alter the timing and flow of water downstream. While it was installed to improve transportation, it may impact agriculture and wildlife habitat.

3.4 NATURAL WATER STORAGE

Along its path from uplands through tributaries to a large river, water pauses in wetlands, lakes, ponds, and other water storage basins. When water pauses, sediment settles out, nutrients can change form (e.g. through plant uptake or denitrification), water evaporates, and peak flows after storms are lower and spread out over time. Some watersheds have abundant natural storage while others have very little.

Each type of storage has different impacts on the watershed. Shallow lakes provide habitat for waterfowl, while deeper lakes can be great fisheries. Large wetlands provide large water storage capacity and nesting habitat for some ducks, while smaller wetlands provide food for shorebirds during migration and habitat for some amphibians.

Sedge meadows, wet prairies and ephemeral wetlands were abundant in south-central and western Minnesota prior to European settlement (Figure 23). Most of these occurred on dense clay loam soils with slow infiltration rates typical in this region. This type of shallow wetland contains ponded water for only a few weeks each year, enables evaporation, and stores large amounts of water in the soil.

FLASHY VS. SLOW RESPONSE STREAMS

Flashy streams are those with dramatic fluctuations in the volume of flow. Storage in a watershed slows down and spreads out the rate of rain and snowmelt flow to a stream outlet. For example, Figure 24 shows hourly flows in 2014 for two different watersheds. The Otter Tail River watershed above Elizabeth has substantial natural water storage (lakes and wetlands), while the Yellow Medicine River watershed above Granite Falls has very little. The Otter Tail River tends to be at low flows during the winter and gradually rises to its annual high flows in late spring in response to spring rains and snowmelt. Flows then slowly drop back down to low levels in the fall. In contrast, the Yellow Medicine River rises sharply in response to snowmelt and rainstorms and quickly drops back to low flows. The high flows and rapid changes in water level result in more streambank erosion.

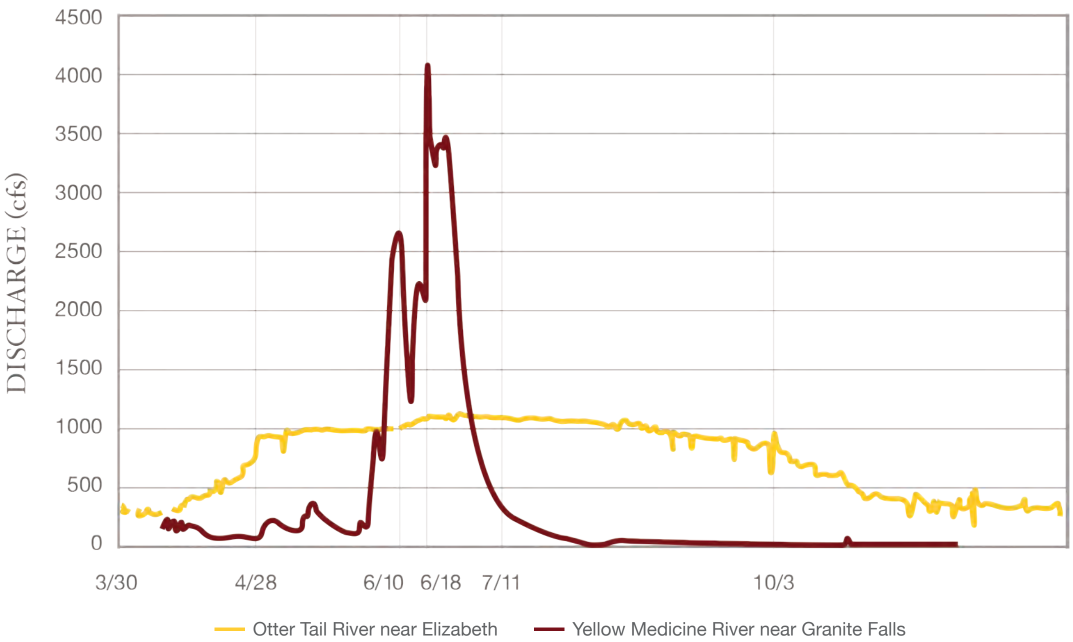


Figure 24: 2014 hydrograph of rivers with different water storage

Source: 2014 data from USGS Water Data for station 5030500 (Otter Trail River near Elizabeth) and 05313500 (Yellow Medicine River near Granite Falls.) http://waterdata.usgs.gov/nwis/rt

REFERENCES

Altena, ER. 2005. Stream Survey Report, Clearwater River. MDNR Division of Fish and Wildlife. http://files.dnr.state.mn.us/areas/fisheries/montrose/Clearwater%20River%20survey%20report%202005.pdf

Galatowitsch SM, Van der Valk AG. 1994. Restoring prairie wetlands: an ecological approach. Iowa State University Press.

Lehner, B., Verdin, K., and Jarvis, A. (2006): HydroSHEDS Technical Documentation. World Wildlife Fund US, Washington, DC. Available at http://hydrosheds.cr.usgs.gov.

Matzdorf, K. 1984. Soil Survey of Martin County, MN. USDA NRCS

Chapter Four

Soil and the Water Cycle

HIGHLIGHTS

Soil does not hold water like a bucket holds water. Small scale forces like surface tension hold water in small pores around soil particles.

Soils vary greatly in how quickly water can enter and how much water can be held. This depends on soil texture, soil structure, and the amount of organic matter.

Management practices impact soil structure and soil organic matter, and therefore the amount of water available to plants or running off the surface.

The type of soil and its condition impact how water is stored and moves through a watershed.

4.1 FOUR TYPES OF SOIL WATER

Water is held in soil four different ways (Figure 25). Each moves through soil differently.

- **Surface water** is stored in the depressions of a rough surface.
- **Hygroscopic water** is held tightly by soil particles and cannot be accessed by plants.
- **Plant available water** is the amount held by soil against the pull of gravity.
- When soil is saturated, all soil pores are filled. This is the **drainable water** that will flow down or laterally if it has an outlet.

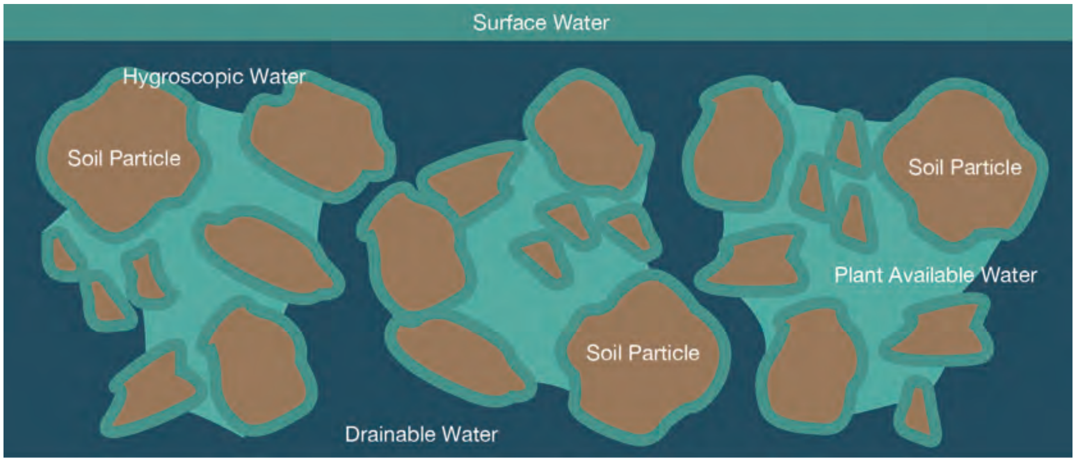


Figure 25: Four types of soil water

Source: adapted from Charles Fritz, International Water Institute.

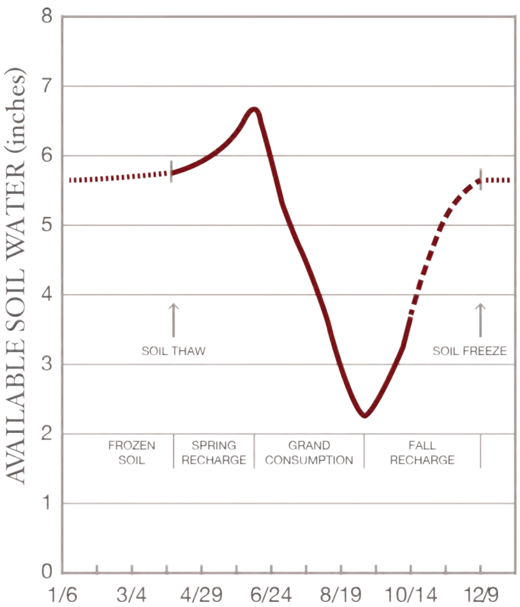


Figure 26: Four periods of soil water storage

Graph shows the average total plant available water to a depth of five feet under continuous corn over the course of a year in southwestern Minnesota.

Source: Baker et al 1979

4.2 FOUR PERIODS OF WATER STORAGE

The amount of water in agricultural soils drops sharply in the middle-to-late summer as crops grow vigorously and draw up large amounts of water. Water levels are recharged in the fall, freeze in the winter, and continue to recharge in the spring (Figure 26).

4.3 SOIL TEXTURE AFFECTS HOW MUCH WATER SOIL HOLDS

Figure 27 shows how much water can be held in a foot of soil. Medium textured soils hold the greatest amount of plant available water (water holding capacity).

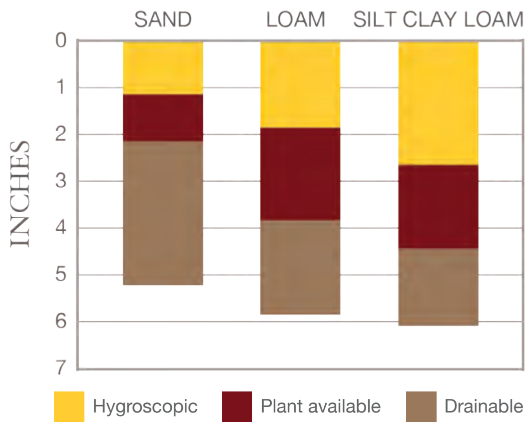


Figure 27: Soil texture affects how much water soil holds

Source: University of Nebraska, 1999

4.4 ORGANIC MATTER AND MANAGEMENT AFFECT HOW MUCH WATER SOIL HOLDS

Infiltration into soil and water holding capacity depend not just on the type of soil particles (texture), but also on how those particles are held together and structured. Soil structure is influenced by soil organic matter, tillage practices, vegetation type, and compaction – all of which are influenced by soil management practices.

Soil organic matter (SOM) increases plant available water because it influences soil structure, and absorbs and holds water for plant use. A soil with 3% SOM may have twice the plant available water of a soil with 0.5% SOM, especially in coarser soils (Figure 28).

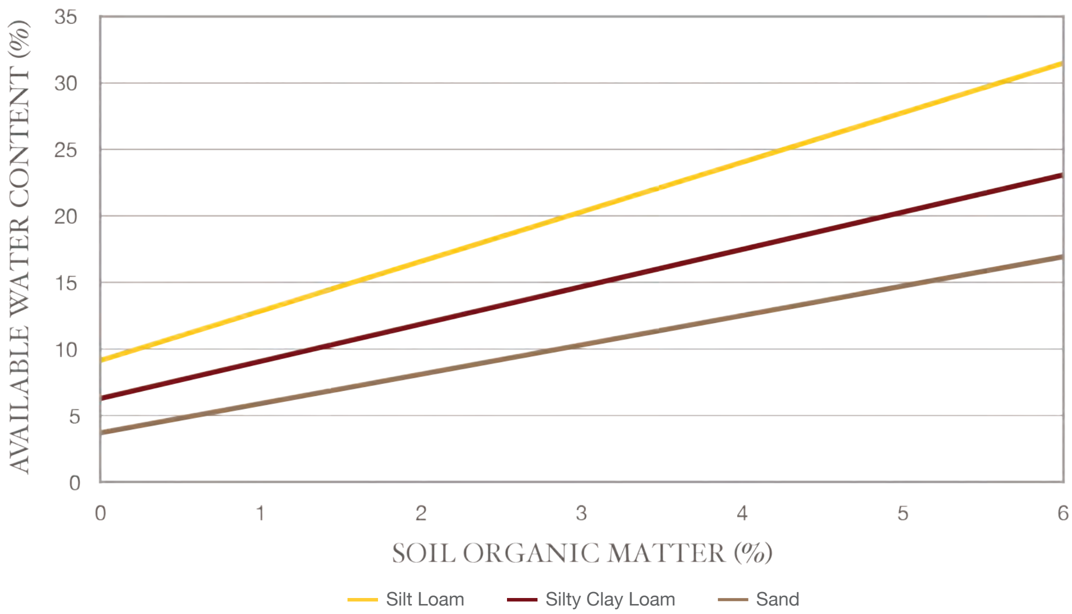


Figure 28: Soil organic matter affects how much water soil holds

Source: Based on Hudson 1994

REFERENCES

Baker DG, Nelson WW, Kuehnast EL. 1979. Climate of Minnesota: Part XII – The Hydrologic Cycle and Soil Water. University of Minnesota Agricultural Experiment Station Technical Bulletin 322. http://purl.umn.edu/109293

See figure 19 for graphs showing year-by-year variation in the four stages of soil water.

Hudson BD. 1994. Soil organic matter and available water capacity. Journal of Soil and Water Conservation 49:189-194.

University of Nebraska Cooperative Extension. 1999. Soils – Part 2: Physical Properties of Soil and Soil Water. Plant & Soil Sciences eLibrary. http://passel.unl.edu/pages/informationmodule.php?idinformationmodule=1130447039&topicorder=10&maxto=10

Chapter Five

Precipitation Trends

HIGHLIGHTS

For the past several decades, annual precipitation has generally increased.

The frequency of extreme events may be increasing.

Increases in both precipitation and frequency of large events (e.g. greater than two inches) are occuring primarily in summer and early fall.

5.1 PRECIPITATION HAS INCREASED

Annual precipitation has increased since the early 1930s across the state (Figures 29 and 30), but not as strongly when compared to the early 1900s. The increase has been less in the northeast than in other regions of the state.

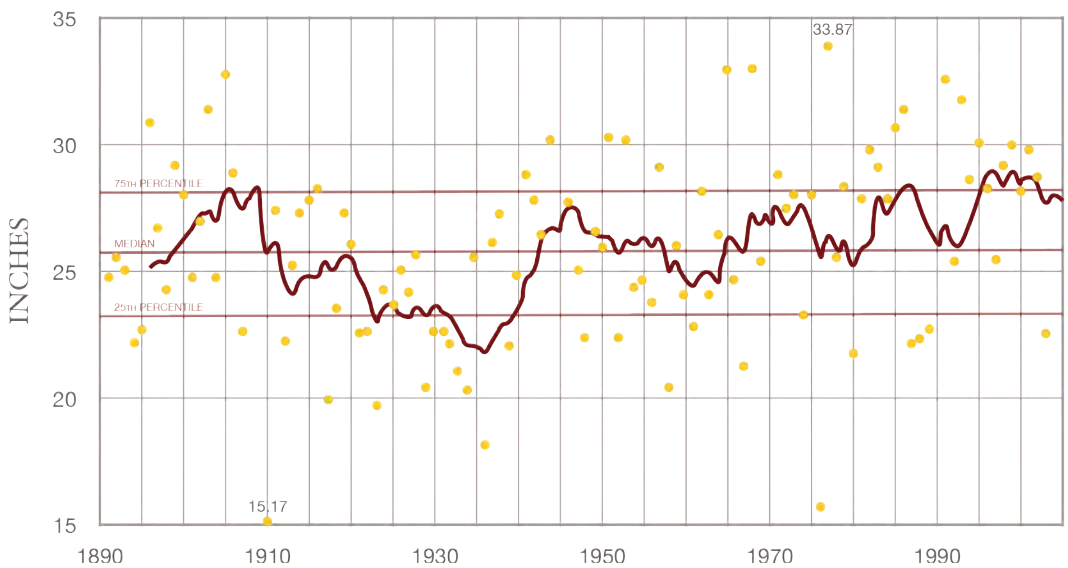


Figure 29: Minnesota annual precipitation trends

Variability is high from year to year (dots) and somewhat dampened in the seven year moving average (solid line).

Source: Zandlo, 2008

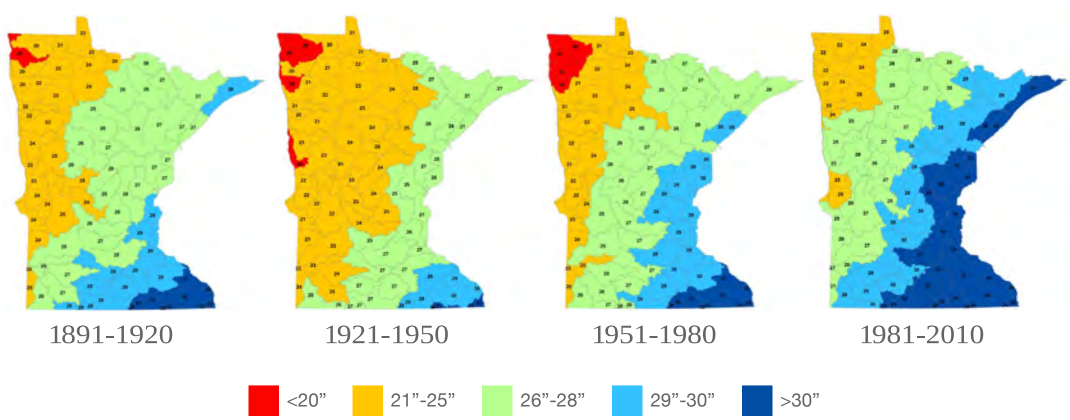


Figure 30: Minnesota annual precipitation patterns in four periods

Source: Gupta et al. 2014, based on data generated by Greg Spoden, Climatologist, Minnesota Department of Natural Resources

5.2 SUMMER AND FALL PRECIPITATION HAS INCREASED MORE

Much of the increase in annual precipitation is coming during summer and early fall. In the graphs below, the bold line shows the 5-year running average. Notice how much of the fall trend line is above the 20th century average (the light, straight line).

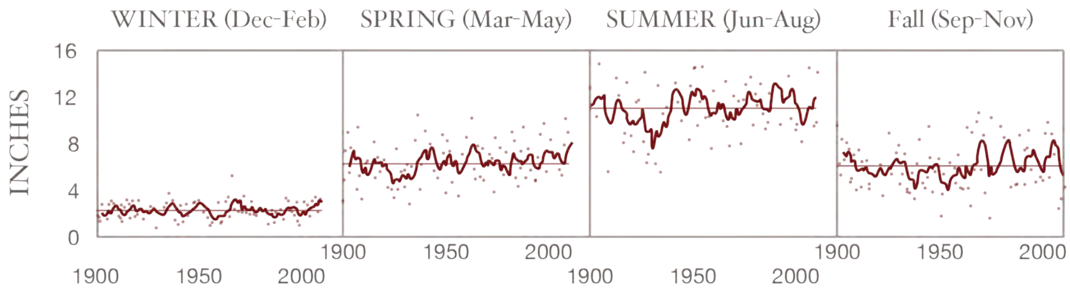


Figure 31: Seasonality of Minnesota precipitation trends

The straight light lines indicate the 20th century average precipitation. In the fall, episodes of wetter than average precipitation are higher and more persistent than in other seasons. Dots are single season precipitation, and heavy lines are the 5-year running average for Minnesota.

Source: Data from the National Climate Data Center http://www.ncdc.noaa.gov/cag

5.3 EXTREME EVENTS ARE MORE COMMON

Stream flow is not only determined by the total amount of precipitation but also the intensity, duration, frequency, and seasonality of precipitation. Each of these factors impacts the proportion of rainfall infiltrating into soil, running over the surface, or running through sewers or tile lines.

The proportion of annual precipitation that falls during large events (e.g. greater than 2 inches) is important to stream flow because soil has a limited capacity to absorb water depending on the soil type, vegetation, and previous saturation (antecedent conditions). Once that limit is reached, additional precipitation will run over the surface or pond in low spots. Watersheds also have a limited capacity to absorb rainfall depending on the amount of water storage in lakes, ponds, wetlands, floodplains, and soil. Thus, larger events yield proportionally more surface runoff than smaller events which can be entirely absorbed by the watershed.

Summarized across the whole state, the increase in number of large rainfall events (e.g. greater than 2 inches) has not been statistically significant. However, large rainfall events have been increasingly common at smaller scales (Figures 32 and 33).

Anecdotally, "mega-events" and flood events have been more common in recent years. The timeline in Figure 34 shows a concentration of mega-rain events in recent decades.

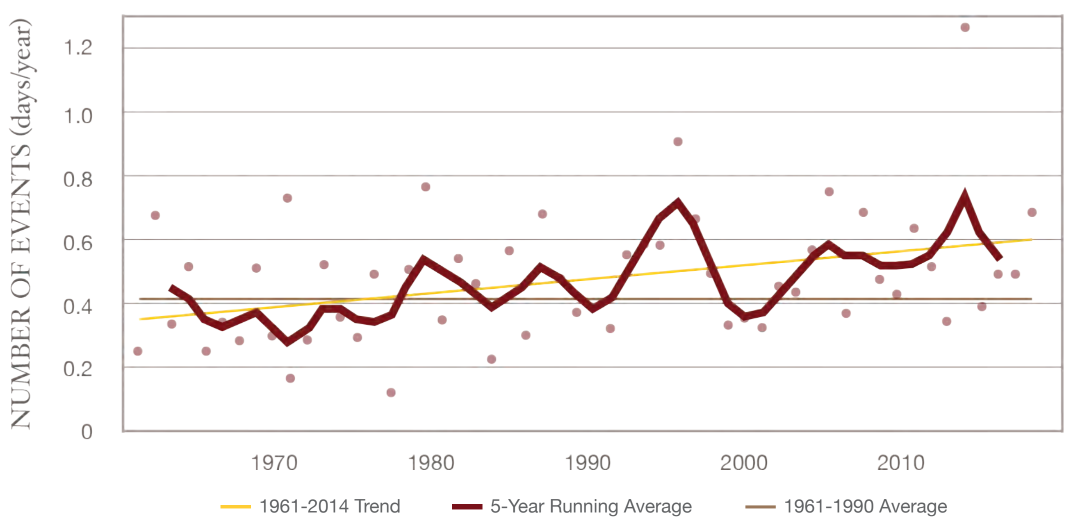


Figure 32: Number of days per year with >2" rainfall

The Minnesota statewide average number of days with greater than two inches of rainfall has increased more than 50% in the last half century from about 0.3 days to more than 0.5 days per year. Graph includes April through September data.

Source: Harding and Snyder, 2015

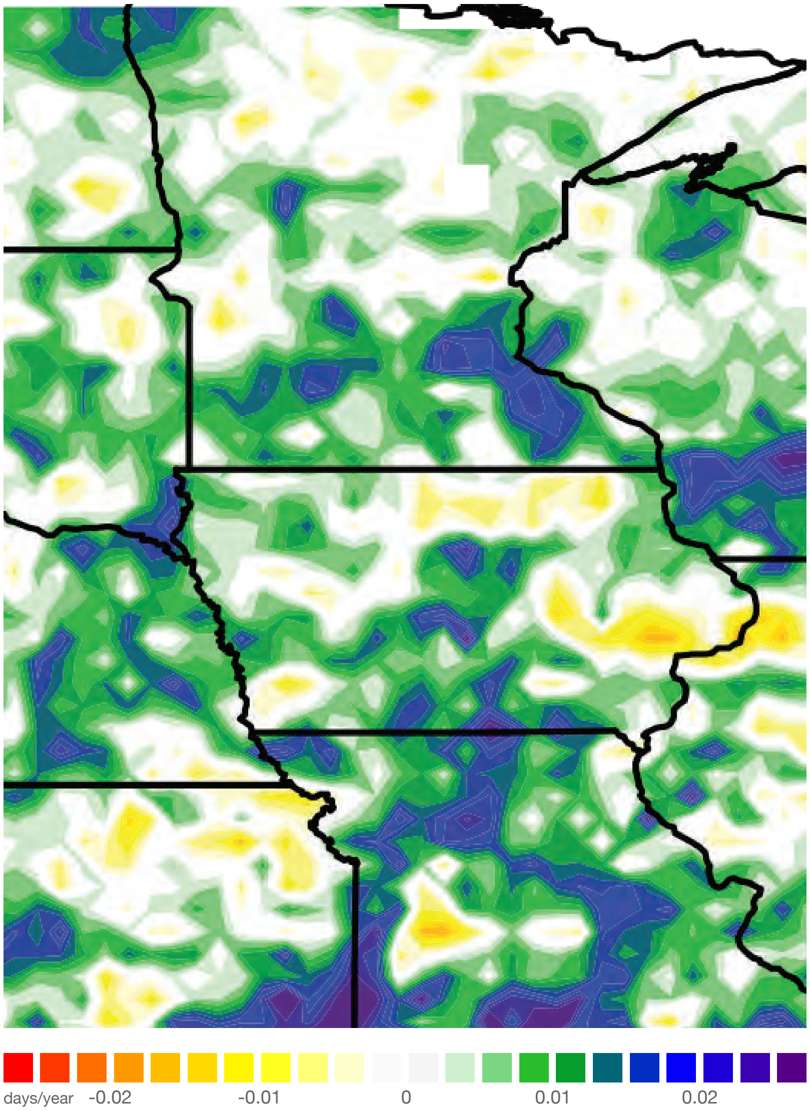


Figure 33: Half-century increase in number of days per year with >2” rainfall

This map shows the uneven distribution of large events, demonstrating the difficulty of identifying trends. Map includes April through September data.

Source: Harding and Snyder, 2015

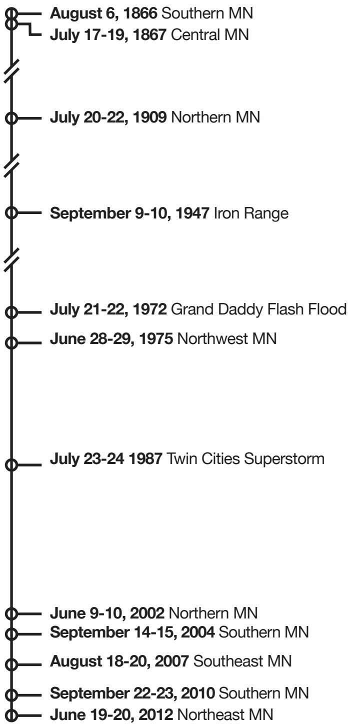


Figure 34: All “mega-events” in Minnesota since 1858

Mega-events are defined here as events where six-inch rainfall totals covered more than 1000 square miles, and the core of the event topped eight inches.

Source: Compiled by the DNR State Climatology Office

REFERENCES

Gupta SC, Kessler AC, Brown MK. 2014. Climate effects on annual river discharge and annual baseflow from different watersheds in Minnesota. A final report submitted to the Minnesota Corn and Soybean Growers Association.

Harding KJ, Snyder PK. 2015. Using dynamical downscaling to examine mechanisms contributing to the intensification of Central U.S. heavy rainfall events, J. Geophys. Res. Atmos.,120, doi:10.1002/2014JD022819.

Map and graph of trends in extreme events were generated by Keith Harding, based on the analysis in Harding and Snyder (2015), using CPC US Unified Precipitation data provided by the NOAA/OAR/ESRL PSD, Boulder, Colorado, USA, from their Web site at http://www.esrl.noaa.gov/psd/.

Saunders S, Findlay D, Easley T. 2012. Doubled trouble: more Midwestern extreme storms. The Rocky Mountain Climate Organization. http://www.rockymountainclimate.org/images/Doubled%20Trouble.pdf

Zandlo, J. 2008. Climate Change and the Minnesota State Climatology Office: Observing the climate. Web page. http://climate.umn.edu/climateChange/climateChangeObservedNu.htm

Chapter Six

A History of Vegetation

HIGHLIGHTS

The original prairie and brushland, and part of the hardwood forest were converted largely to agriculture beginning with the European settlement in the 1800's.

Over the past 60 years, row crops (corn and soybeans) have replaced much of the forages and small grains that were grown on agricultural lands.

The type and timing of green vegetation on the landscape determine how much of the annual precipitation will return to the atmosphere as transpiration, and how much will leave the watershed as stream flow or percolate to groundwater. Vegetation in agricultural and urban areas has changed considerably since European settlement in the 1800s, and with it, timing and amounts of stream flow.

Coniferous forests, mainly pine, spruce, and fir, once covered most of northeastern and northcentral Minnesota. Deciduous forests—predominantly oak, hickory, maple, beech, and birch—extended in a broad band from around Brainerd southeastward to the Iowa border. The rest of the state—the south and the west—was tallgrass prairie. Wetlands and wetland vegetation were scattered throughout the glaciated areas where shallow bedrock in the northeast, or heavy glacial till soils elsewhere, restricted drainage (Figure 35).

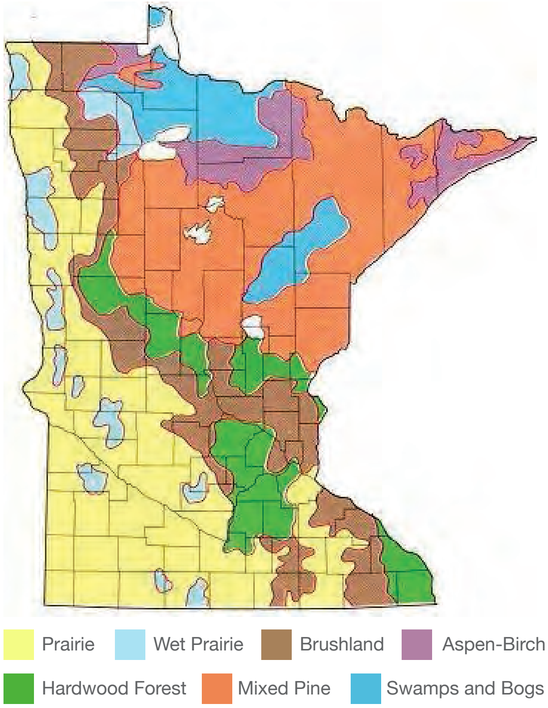


Figure 35: Original vegetation of Minnesota

Source: Abstracted from Marschner, 1974

Very little of Minnesota's natural vegetation remains. The coniferous forests of northeastern and northcentral Minnesota were cleared by loggers and in most areas have been replaced by poplar, aspen, birch, second-growth conifers, and various types of shrubs. The wetlands of that region remained in relatively good condition (Genet et al. 2012). The deciduous forests were largely cleared, and agriculture now occupies much of the former hardwood forest area. The former brushland and prairie areas are the most intensively cropped areas of the state.

In southern, central and western Minnesota, the transition was made from perennial forest and prairie to an agricultural patchwork of perennial pasture and hay crops, winter annual grains (winter wheat and rye), spring/early summer grains (oats, spring wheat and barley) and summer annual grains and oilseeds (corn and later soybeans). In recent years, major crop producing areas in the southern half of the state and much of the Red River Basin have converted largely to corn and soybean production. The principal sources of feed for livestock, now primarily in confined feeding and dairy operations, are corn silage, soybean meal, and corn and corn byproducts. The exceptions are beef cow-calf and smaller dairy operations, where pasture and hay are still major sources of forage. Figure 36 shows this cropping transition statewide, while Figure 37 shows wetland area loss along with the change in cropping areas in a representative watershed, Seven Mile Creek, in Nicollet County in the Minnesota River Basin. A similar trend was reported in Blue Earth County (Musser et al. 2009).

Figure 36: Agricultural crops in Minnesota from 1920-2007

Source: Graph L. Schmitt-Olabisi, UM

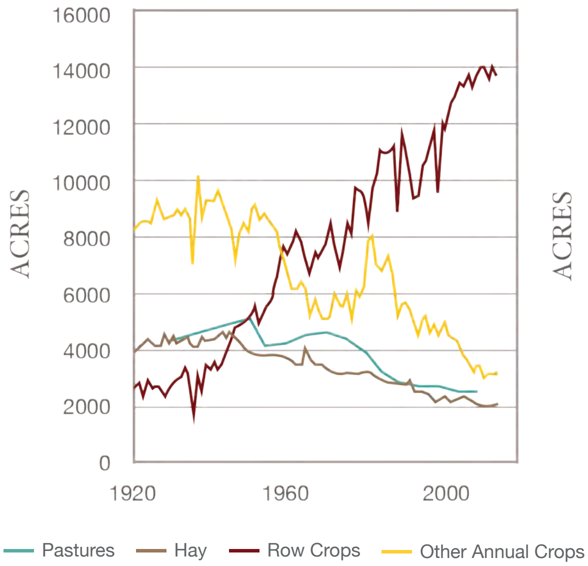
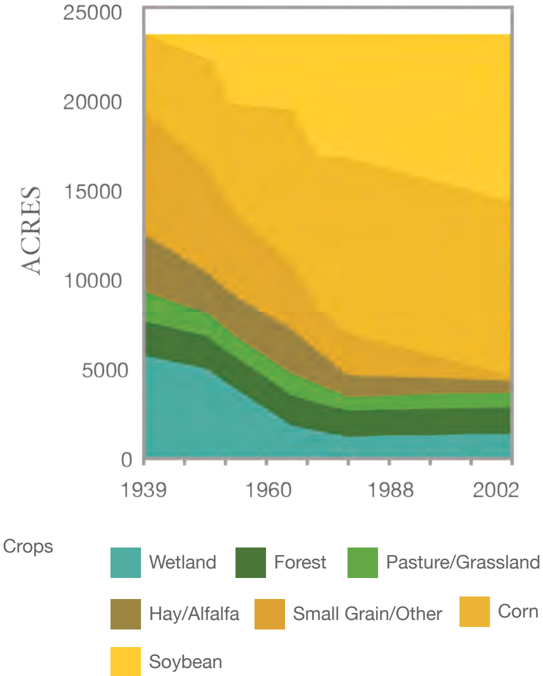


Figure 37: Land cover change from 1939-2002 in Seven Mile Creek watershed, Nicollet County Minnesota

Note that wetlands had covered 11,000 acres of the Seven Mile Creek watershed in 1872, declining to 5,863 acres by 1939, the beginning of the graph.

Source: Data from K. Kuehner, 2004



The change in plant cover from perennial trees, prairie, and wetlands with three seasons of transpiration and evaporation to corn and soybeans with primarily summer transpiration has resulted in more precipitation water in spring and fall available for surface and subsurface runoff. That, coupled with higher levels of precipitation in recent decades (Chapter 5) as well as surface and subsurface drainage to remove excess water (Chapters 8 and 9), is resulting in more water volume transported to streams and rivers.

More subtle changes have also affected hydrology. Invasive species have changed the composition of wetlands and riparian areas with reed canary grass displacing native grasses and trees particularly along streambanks, decreasing streambank stability especially on larger streambanks (Thomsen et al. 2012).

REFERENCES

Genet J. 2012. Status and trends in wetlands in Minnesota: Depressional wetland quality baseline. Report of the Minnesota Pollution Control Agency. http://www.pca.state.mn.us/index.php/view-document.html?gid=17741

Kuehner K J. 2004. An historical perspective of hydrologic changes in Seven Mile Creek Watershed. In: Self-Sustaining Solutions for Streams, Wetlands, & Watersheds. Conference Proceedings. American Society of Agricultural Engineers, St. Joseph, MI. 401 pp. Also found as report of the Brown Nicollet Cottonwood Water Quality Board, Minnesota. http://mrbdc.mnsu.edu/sites/mrbdc.mnsu.edu/files/public/org/bnc/sevenmile.html

Marschner F J. 1974. The original vegetation of Minnesota, a map compiled in 1930 by FJ Marschner under the direction of ML Heinselman of the US Forest Service. St. Paul, Minnesota, Cartography Laboratory of the Department of Geography, University of Minnesota.

Musser K, Kudelka S, Moore R. 2009. Minnesota River Basin Trends Report. http://mrbdc.mnsu.edu/mnbasin/trends

Thomsen M, Brownell K, Groshek M, Kirsch E. 2012. Control of Reed Canary grass promotes wetland herb and tree seedling establishment in an upper Mississippi River floodplain forest. Wetlands, 32(3), 543-555.

Chapter Seven

Vegetation and the Water Cycle

HIGHLIGHTS

The type of vegetation determines the seasonal pattern of transpiration.

Evapotranspiration changes when plant cover changes. If more precipitation transpires through plants, then less reaches streams through surface and subsurface runoff. Because transpiration is such a significant part of the water cycle, managing transpiration can be a significant way to manage surface and subsurface runoff. (See Crop Management section of Part 2 for information about practices that impact transpiration.)

Transpiration from row crops is minimal in springtime until mid to late June when leaf canopies close (dark green in Figure 38). By mid-summer a vigorous corn crop transpires more water than many other plant types. Transpiration from perennials and cover crops begins earlier in the season and ends later in the fall than from corn and soybeans. The different timing of plant coverage can be seen in Figure 38 by comparing areas of dominant row crops (western and southern Minnesota) to areas with a higher proportion of trees and other perennials (eastern Minnesota).

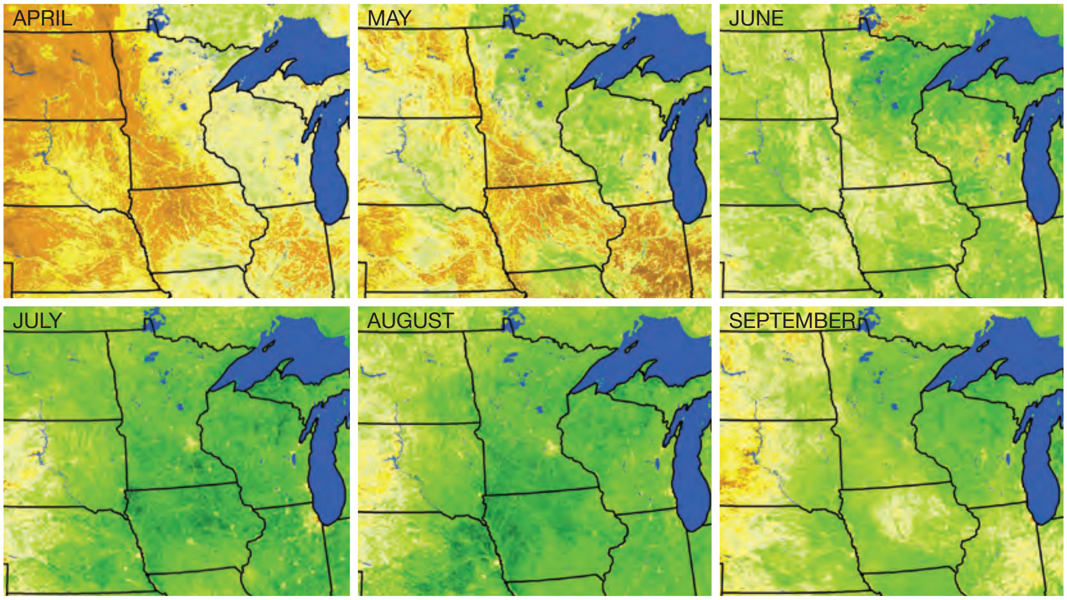


Figure 38: Mid-month greenness, 2010

Source: Nan An, Ecology & Agriculture Spatial Analysis Laboratory, Kansas State University

In the spring, when there is little or no transpiration from annual crop plants, and when precipitation exceeds the soil water holding capacity, the excess will leave the field in drainage tile, over the surface as runoff, or percolate to groundwater if the soil profile characteristics permit. The shaded area in Figure 39 represents the amount of transpiration from a perennial grass in the period before corn begins significant transpiration in mid-June. Tile flows from perennials are usually less than under summer row crop annuals because of spring and early summer transpiration by perennials (Figure 40).

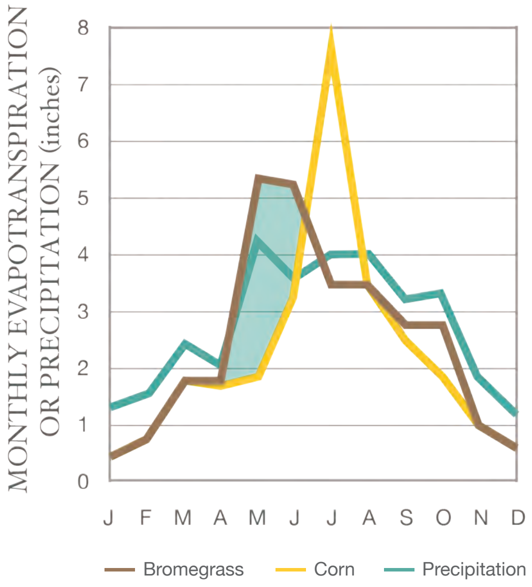


Figure 39: The seasonal evapotranspiration from annual and perennial crop

The shaded area shows the greater amount of ET from perennials in spring than from a field of annuals.

Source: M. Helmers, Iowa State University, pers. comm., based on estimates from WEPP model

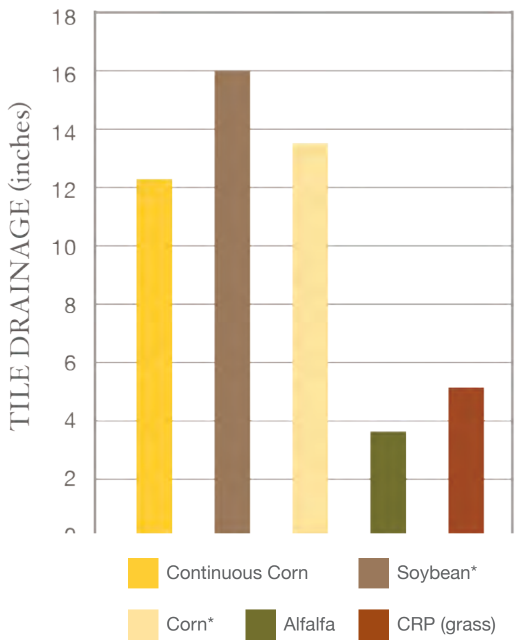


Figure 40: Total tile drainage volume in inches in 1991-1992 under five crops at Lamberton, Minnesota

Greater spring ET reduces annual tile flow under perennials compared to annuals. *Designates corn/soybean rotation

Source: Randall et al, 1997

REFERENCES

Randall GW, Huggins DR, Russelle MP, Fuchs DJ, Nelson WW, and Anderson JL. 1997. Nitrate Losses through Subsurface Tile Drainage in Conservation Reserve Program, Alfalfa, and Row Crop Systems. Journal of Environmental Quality. 26: 1240-1247

Chapter Eight

History of Agricultural Drainage in Minnesota

HIGHLIGHTS

A large proportion of Minnesota's agricultural ditch systems were constructed before 1930, connecting streams to depressions that were previously unconnected.

Sub-surface tile installations have continued up through the present, primarily in the Minnesota River Basin, and expanded rapidly in the past decade in the Red River of the North Basin.

Early tiling drained individual wet areas. More recently, "pattern" tiling has been used by individual landowners to systematically drain entire fields.

In geological age, the recent glaciation of most of Minnesota left large areas of glacial till containing depressional wetlands and shallow lakes, and other areas of very flat glacial lake sediment. Percolation of surface water was slow through the silt and clay soils that developed on these glacial materials. A stream network that would allow rapid surface drainage had not yet fully developed by the time of European settlement.

8.1 SURFACE DRAINAGE

In order to enable and enhance agricultural production, transportation, and economic development, construction of drainage ditches began even before Minnesota achieved statehood in 1858. The ditches connected the natural stream network to previously unconnected depressions and lowered the water table near the ditches. Precipitation water previously stored in the depressions and soil around them was now rapidly conveyed to streams and rivers. Many of the natural streams themselves were straightened and enlarged to increase transport capacity.

Each county has records of the public ditch systems, however no statewide record and map of historical ditch development has been compiled. Figure 41 shows the pace of public ditch development in four south central Minnesota counties.

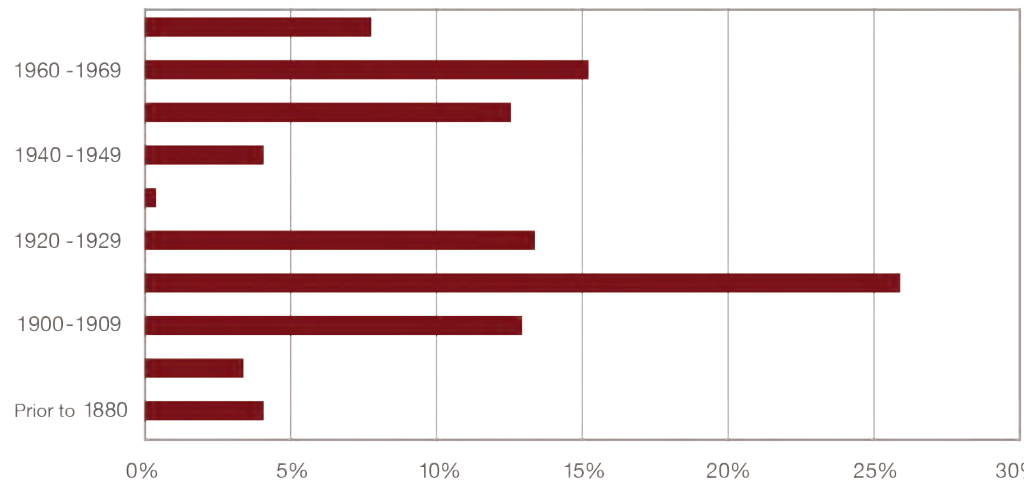
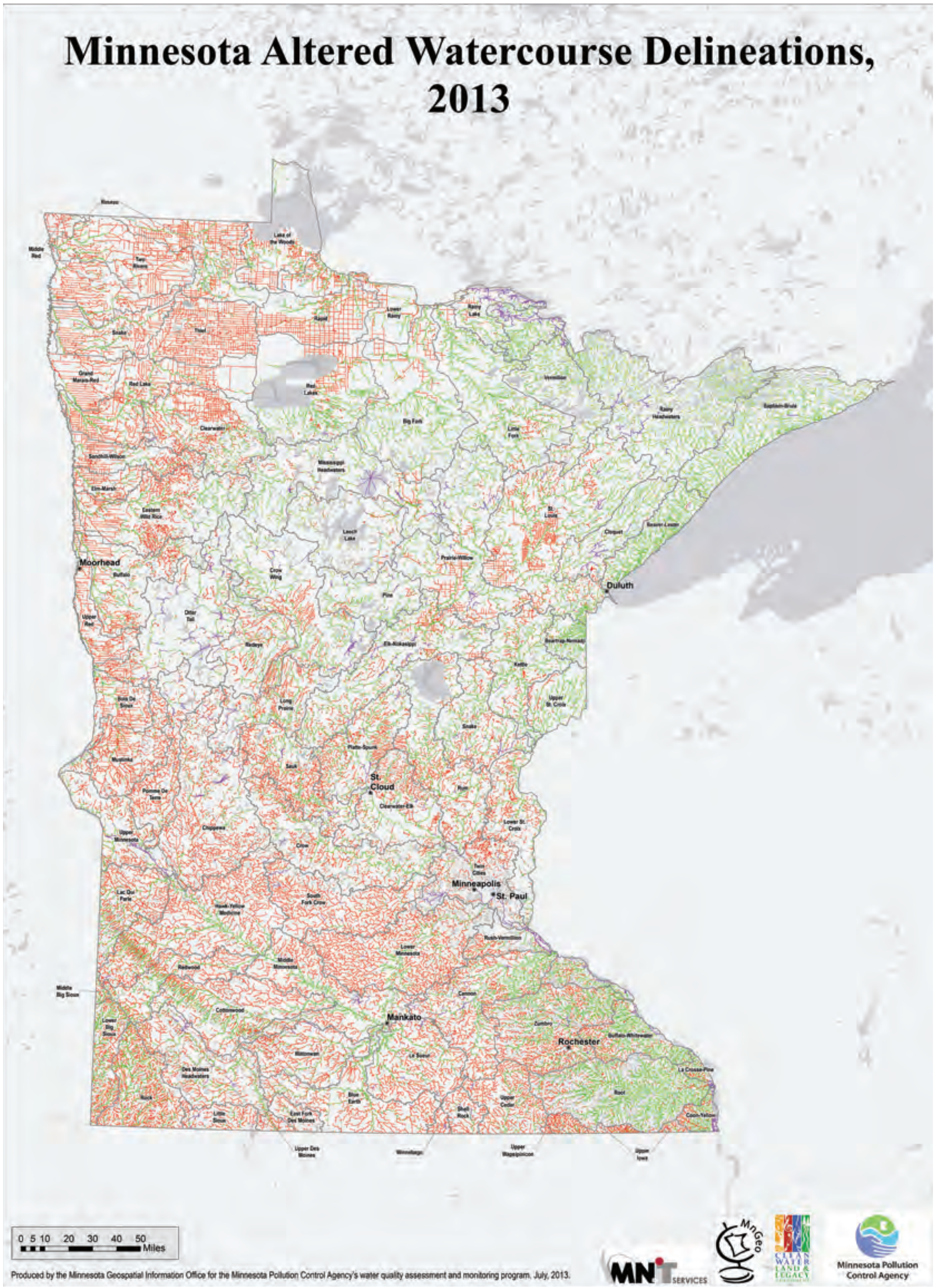


Figure 41: Percent of drainage ditch system constructed each decade through 1980 for Blue Earth, Brown, Le Sueur, and Nicollet Counties, Minnesota.

Source: Bruce Wilson, UM from data in Quade et al, 1980

The most active ditch construction occurred in the period from 1900 to 1929, with the decade of greatest drainage being 1910 to 1919. There was little new drainage installed during the dry years and economic depression of the 1930s. Drainage activity reemerged after World War II, driven by economic factors and periods of above-average precipitation.

Figure 42 shows the extent of altered surface drainage, including both ditches and altered streams. The concentration of red lines (ditches and altered streams) is greatest in the areas of fine textured soils of glacial origin.



USGS Subbasins — Altered (41,204 miles - 49.6%) — Natural (38,861 miles - 46.8%)

Impounded (2,968 miles - 3.6%) — No Definable Channel (83,033 total stream miles)

Figure 42: Altered watercourses

Source: Minnesota Geospatial Office, 2013. Developed from the National Hydrography Dataset and modified by inspection of aerial imagery and LiDAR elevation data "Minnesota Statewide Altered Watercourse Project" http://www.mngeo.state.mn.us/ProjectServices/awat/index.

A representative small watershed, Seven Mile Creek in Nicollet County, Minnesota, has been mapped for extent of wetlands, ditches, and county "mains" (collector tile) over time since European settlement (Figure 43).

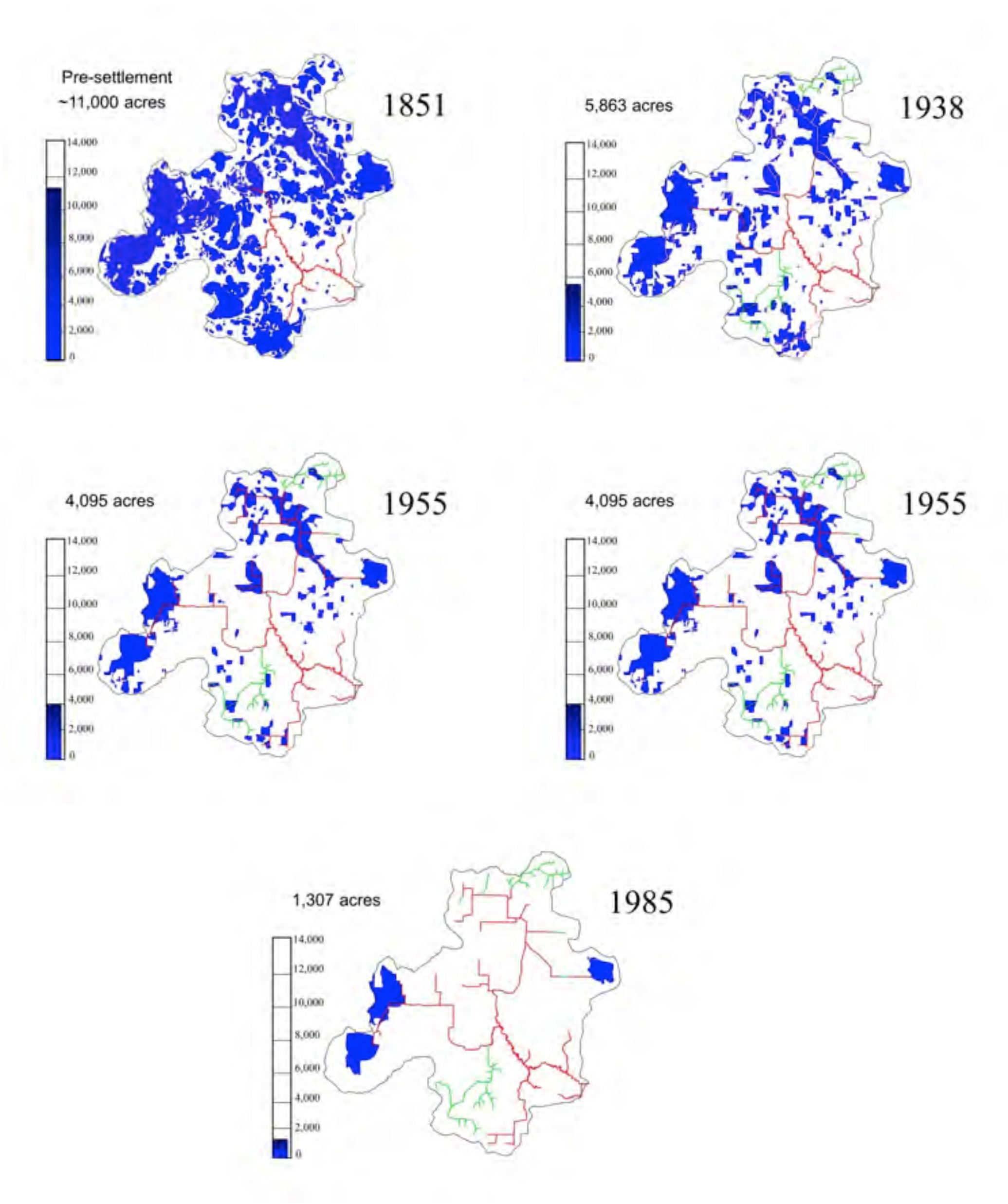


Figure 43: Extent of wetlands (blue), ditches (red), and subsurface county collector tile (green) over years in Seven Mile Creek Watershed, Nicollet County, MN

Source: Kuehner 2004

8.2 SUBSURFACE DRAINAGE

The network of ditches for surface drainage was augmented by installation of subsurface drainage tiles primarily fabricated from clay or concrete. More recently, perforated plastic pipe is being used instead of clay or concrete, but the term "tile" persists for both tile and plastic pipe systems. Initially the tile lines were installed to drain individual wet areas that were not intersected by the ditches. With the development of the less expensive plastic drainage pipe and efficient installation equipment, the systems have been and are being expanded by pattern installation of pipe to systematically remove water from entire fields.

As with the ditch system, there is no statewide record of subsurface field tile installation over time. Unlike the public ditch systems however, there has not been a county-maintained record of subsurface field drainage because those systems are installed by individual landowners. Subsurface tile has been mapped in a few small watersheds, for example Seven Mile Creek Watershed (Figure 45).

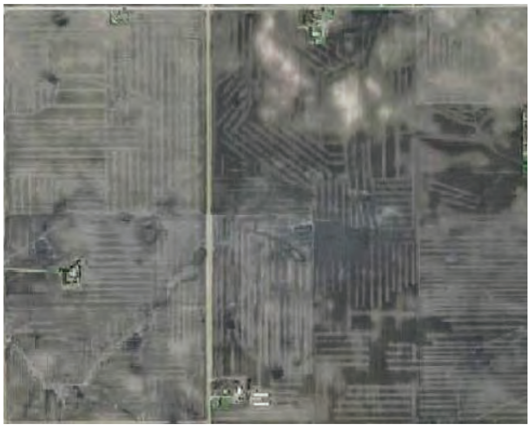


Figure 44: Pattern tile in fields of Blue Earth County, MN

Source: Aerial Photo, MPCA

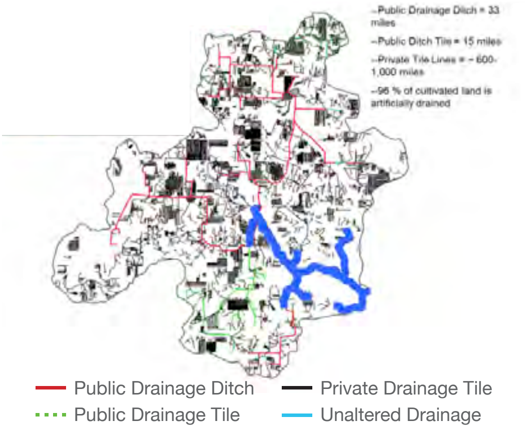


Figure 45: Public ditches and public and private subsurface tile, Seven Mile Creek Watershed, Nicollet County, MN

Source: Kuehner 2004

Subsurface field tile installation in southern Minnesota advanced throughout the 1900s and continues today. Systematic field drainage in the Red River valley was largely limited to surface drainage by ditches until about 2005, when subsurface system installation began at a rapid rate (Figure 46).

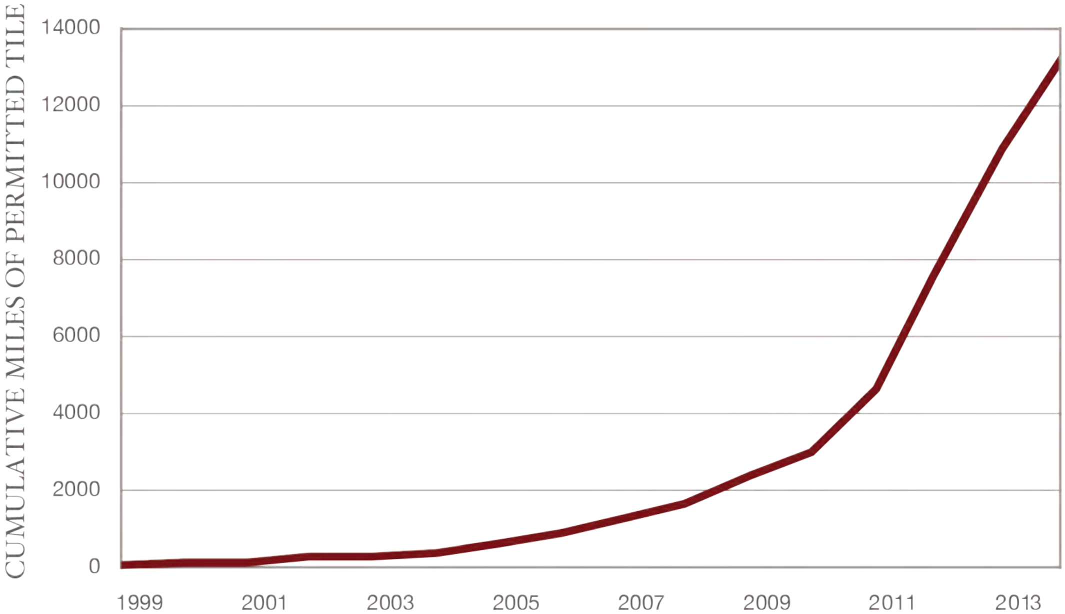


Figure 46: Cumulative miles of permitted drainage tile by year in the Bois de Sioux Watershed, Red River Basin, Minnesota

Source: Data - Bois de Sioux Watershed District, Red River Basin

Anderson and Craig (1984) estimated that the total acres of wetlands in Minnesota at the time of European settlement was 18.6 million acres, 8.8 million acres remained in 1984, and losses were much greater in the agricultural and urban areas than in the forested regions of the state.

For more on the politics, economics, precipitation patterns, research, and attitudes that shaped the history of Minnesota drainage, see ISG (2015), Prince (1997), and Wilson (no date).

REFERENCES

Anderson JP, Craig WJ. 1984. Growing energy crops on Minnesota's wetlands: the land use perspective. CURA 84-3. University of Minnesota. http://www.cura.umn.edu/publications/catalog/e1037

ISG. 2015. Final Report prepared for Minnesota Legislative-Citizens Commission on Minnesota Resources. Mapleton Area Agricultural + Urban Runoff Analysis. Pg 9.

Kuehner KJ. 2004. An historical perspective of hydrologic changes in Seven Mile Creek Watershed. In Proc. ASAE Conference on self-sustaining solutions for streams, wetlands, and watersheds. St. Paul, MN. ASAE, St. Joseph, MI. 401 pp. and also found as report of the Brown Nicollet Cottonwood Water Quality Board, Minnesota. http://mrbdc.mnsu.edu/sites/mrbdc.mnsu.edu/files/public/org/bnc/sevenmile.html

Prince H. 1997. Wetlands of the American Midwest: A Historical Geography of Changing Attitudes. University of Chicago Press. Book, 400 pages.

Quade HW, Boyum KW, Braaten DO, Gordon D, Pierce CL, Silis AZ, Smith DR, Thompson BC. 1980. Nature and Effects of County Drainage Ditches in South Central Minnesota. Water Resources Research Center. Retrieved from the University of Minnesota Digital Conservancy, http://purl.umn.edu/91392.

Wilson, Bruce. No date. "History of Drainage Research at the University of Minnesota". A presentation including a timeline of drainage policy changes. http://www.extension.umn.edu/agriculture/water/history.html.

Chapter Nine

Agricultural Drainage and the Water Cycle

HIGHLIGHTS

In some areas, most stream water is first routed through ditches, straightened channels, drainage tile, or storm sewer systems.These structures are a significant aspect of the water cycle.

Agricultural drainage systems are designed to modify hydrology. The specific impact of a particular system depends on local conditions, system design, and weather.

In general (but with site-specific variations), compared to unmodified conditions, agricultural drainage systems increase the total annual flow volume to streams.

In general (but with site-specific variations), subsurface tile increases the amount of water flowing through soil rather than over the surface. Thus rain may reach a stream slower than through an untiled landscape.

Throughout history, people have worked to change how water flows – building dams and dikes, straightening and dredging channels, armoring streambanks, digging ditches, installing subsurface tile, and constructing complex storm sewer systems. The most extreme hydrologic alteration is the construction of impervious surfaces such as roads and buildings. The most widespread alteration of Minnesota hydrology was the conversion of native prairie to farmland and the construction of the network of drainage ditches and subsurface tile that was essential for intensive crop production and transportation infrastructure (See Chapter 8).

The subject of this chapter is hydrologic alterations in rural landscapes, recognizing that alterations in urban landscapes are locally more extreme.

9.1 HOW AGRICULTURAL DRAINAGE ALTERS THE WATER CYCLE

The hydrologic purpose of installing agricultural drainage is to reduce or eliminate storage of excess water in soil, allowing enough air in the root zone to grow crops, and for trafficability.

TYPES OF IMPACTS

Potential impacts of agricultural drainage systems on the water cycle are to:

- **Reduce time that water is being stored in the soil.**
  Only drainable water is removed by tile and ditches. The amount of plant available water (i.e., water held by soil particles against the pull of gravity) is not affected by artificial drainage systems.
- **Change the pathway of water over land.**
  Some ditches and tile link streams to depressions (potholes) that were previously not connected.
- **Reduce overland flow** (and soil erosion) if water instead moves through soil and subsurface tile. Overland flow still occurs on tiled land if surface soil structure is poor, blocking infiltration, or if the soil is saturated.
- **Decrease evaporation** by removing areas of standing water.
- **Increase annual transpiration** if rooting depth and productivity increase.
- **Increase the total amount of water that reaches streams** (annual yield). Models show that tiling increases the annual amount of water leaving the field.
- **Reduce, delay, and extend the peak flow in a stream** after a precipitation or snowmelt event (if water is moving through tile systems instead of overland). Water takes longer to travel through soil to a tile system than to move overland or through ditches. This means rainfall will reach a stream later than if it only flowed overland. Soil continues to drain long after an event, so elevated stream flow lasts longer than if the rain all reached the stream overland.

WHAT DETERMINES THE IMPACT?

Whether an agricultural drainage system has any of these impacts depends on:

- **Type of drainage.** For example, drainage ditches may increase the rate of overland flow, while subsurface tile may reduce the amount of overland flow in favor of subsurface flow.
- **Scale of impacts.** The hydrologic impact at the edge of a field may not add up to the same effect in a stream. Watershed-wide impacts on a stream are much more complex than field-edge impacts and vary with different runoff events.
- **Precipitation patterns.** The amount of water in the soil before a snowmelt or rain event will determine the downstream impact of a drainage system – the more water in the soil before an event, the more surface runoff and tile flow. The size of the event also matters. Even with drainage tile, a short, heavy rainfall will generate more runoff than the same amount of precipitation in several lighter events.
- **Field conditions.** The soil management practices in a tiled field will affect flow to the tile.
- **The rest of the watershed.** The impact of ditches and tile may be large or small relative to other influences on hydrology in the watershed including the amount of lakes, wetlands, and other water storage (Section 3.4 “Natural Water Storage”); the amount of impervious surfaces; channelization of streams (Section 10.2 “Streams are Dynamic”); the presence of dams and culverts; and climatic patterns.
- **System design and landscape details.** The type of soil and the capacity of the system – determined by tile size, spacing, depth, and outlet characteristics – have known hydrologic effects. Sands and Canelon (2013) modeled significant variation in ET, water yield, and surface runoff depending on the type of soil, precipitation, and drain spacing and depth.

HOW BIG ARE THE IMPACTS?

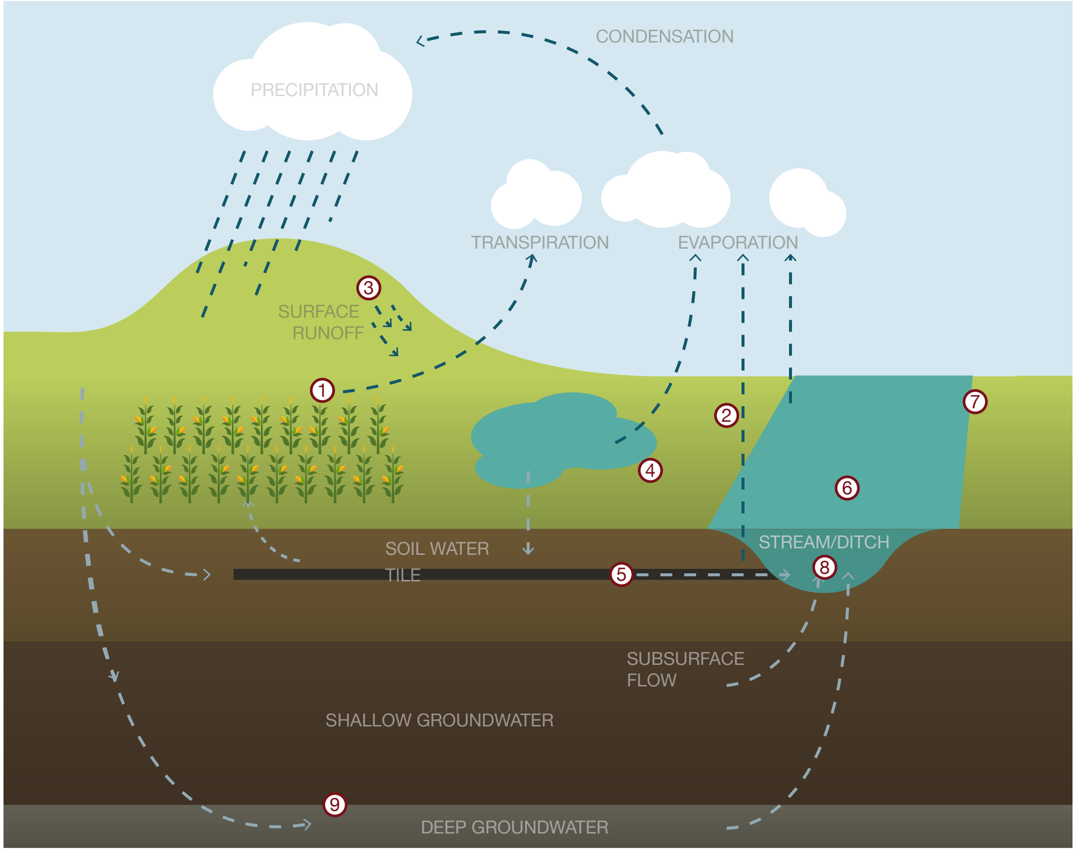
The actual impact of adding to an existing subsurface drainage system is complex and varies widely.

In summarizing regional data, Zucker and Brown (1998) concluded that subsurface drainage reduces surface runoff by 29 to 65 percent, reduces peak flows from watersheds by 15 to 30 percent, and has little impact on the total annual flow from watersheds (though, the authors do not explain the size of watersheds, nor provide citations). A literature review by Blann et al. (2009) described the increase in total water yield as “about 10%”. Sands (2010) said “studies indicate potential for overall increases in water yield from 5 to 10%”. For more on water yield from drainage, see Skaggs et al. 1994; and Busman and Sands, 2002.

At the large watershed scale, Schottler (2013) attributes more than half of the increase in stream flow to changes in evapotranspiration brought about by increased agricultural drainage over past half century.

Figure 47: How agricultural drainage systems alter the water cycle

Source: ISG



1 - Higher **transpiration** in the summer due to greater crop growth

2 - Less opportunity for **evaporation** due to less water in the soil and less standing water

3 - Less **overland flow** and erosion, but only if water can infiltrate the soil

4 - New **flow paths** where ditches connect depressions to streams will increase peak flows

5 - Greater **subsurface flow**, either directly through tile outlets, or because ditches create lower water tables

6 - Lower and longer **elevated flows** after a storm where more water moves through soil and pattern tile instead of overland before reaching the stream. Higher and earlier **peak flows** where a ditch creates a straighter, shorter path to a stream

7 - Tiling may have little impact on **severe floods** that are dominated by overland flow. Tile may impact **local flooding**, depending on the design and capacity of the outlet

8 - Greater **baseflow** (stream flow between events) if tiling increases annual water yield by reducing evapotranspiration losses

9 - There has been little research on the impact of tile on **groundwater** aquifers

9.2 COMMON QUESTIONS ABOUT AGRICULTURAL DRAINAGE

WHAT IS THE SPONGE EFFECT?

Soil can be thought of like a sponge with air spaces that hold water. When the spaces (pores) are filled with water, the soil cannot take on more water. The soil pores in a tile-drained field are open more often than the pores in a poorly drained field. When the pores are open, water can infiltrate into and move down through the pores, preventing rapid overland flow. In other words, tile-drained soils can have higher infiltration rates. This process is thought to be most common in the middle to late part of the growing season (July, August) when vigorously growing crops are drawing water out of the soil sponge. The process is less common in the early season (May, June) when soil pores are more likely to be saturated. (See Sands 2001 for more about soil and water.)

DOES AGRICULTURAL DRAINAGE INCREASE OR REDUCE FLOODING?

There is no general answer to this question. Flooding is a combined result of the topography, soil types, characteristics of the storm or snowmelt event, moisture conditions before the event, and the hydrology of the watershed, including agricultural drainage systems. It is important to distinguish between flooding of a large stream, which reflects the complex interaction of factors across the watershed, from flooding of a neighboring property, which could reflect the design of a local drainage system. The influence of tile drainage on streamflow and flooding at larger watershed scales is not well understood.

The following are some general scenarios of the contribution of agricultural drainage to flooding:

- In a small or moderate event, a tile system may allow water to flow through soil and then tile instead of overland. In this case, tile would reduce the downstream peak flows that are often a concern for flooding (Sands et al. 2012).
- In a large rainfall or snowmelt event, water doesn't infiltrate into the soil quickly enough or the capacity of tile is overwhelmed by the amount of water. In either case, the subsurface tile has little impact on flooding because large floods are dominated by surface runoff (Sands et al. 2012).
- Ditches and tile can increase flow if they reduce or eliminate closed basins that otherwise would store water during a high precipitation or snowmelt event.
- Drainage capacity is the rate of water removal per unit of time, frequently expressed as a drainage coefficient with units of inches per day. It is usually increased by increasing the density and size of drainage tile or expanding open ditches. If the drainage capacity is increased in the upper part of a drainage system without increasing storage or conveyance in the lower part of the system, flooding may occur on neighboring properties.

DOES AGRICULTURAL DRAINAGE INCREASE STREAM FLOW?

Separate from the question of flooding is the question of whether tile and ditches increase the total amount of water in a stream.

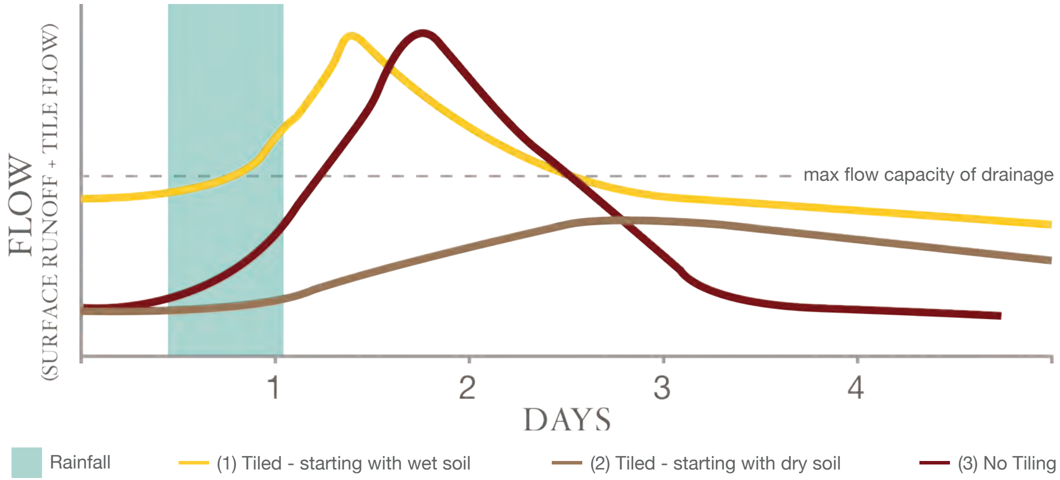
While there is wide variation, modeling shows that agricultural tile tends to increase the amount of water leaving a field. Increased flow occurs to the extent that a drainage system reduces evaporation from standing water and saturated soil.

DOES AGRICULTURAL DRAINAGE MAKE RIVERS FLASHIER?

At a watershed scale, subsurface drainage systems generally do not increase the height of peak flows, but do increase the duration of elevated flows.

Figure 48 - Idealized hydrograph showing flow after storm

The graph compares the flow after a rainstorm in three scenarios: (1) A tiled field that was saturated before the rain started; (2) a tiled field that was dry before the rain started; (3) a field with no tile regardless of whether the soil was wet or dry before the storm. The total volumes of water loss in the three scenarios are similar, but the untiled field (3) has a peak flow rate twice as high as the tiled field (2). Notice that flow from the tiled field continues longer as the soil gradually drains. If the soil was saturated before the storm, the tiled field will generate high surface runoff as would the untiled field (1).



REFERENCES

Blann K., Anderson JL, Sands GB, Vondracek B. 2009. Effects of agricultural drainage on aquatic ecosystems: A Review. Critical Reviews in Environmental Science and Technology 39(11):909-1001

Busman L, Sands G. 2002. Agricultural Drainage: Issues and Answers. University of Minnesota Extension. BU-07740-S, http://www.extension.umn.edu/agriculture/water/publications/pdfs/issues__answers.pdf

Sands G. 2001. “Agricultural drainage: Soil water concepts.” University of Minnesota Extension. http://www.extension.umn.edu/agriculture/water/agricultural-drainage/soil-water-concepts/

Sands G. 2010. “Drainage Fact Sheet”. University of Minnesota Extension M1292. http://www.extension.umn.edu/agriculture/water/publications/pdfs/u_of_m_drainage_fact_sheet_m1292_sands_2010.pdf

Sands GR, Canelon DJ. 2013. Developing Optimum Drainage Design Guidelines for the Red River Basin. http://www.rrbdin.org/wp-content/uploads/2013/09/final_report__developing_drainage_guidelines_for_rrb_sands1.pdf

Sands GR, Kandel H, Hay C, Scherer T. 2012. Frequently Asked Questions about Subsurface (Tile) Drainage in the Red River Valley. University of Minnesota Extension. http://www.extension.umn.edu/agriculture/water/publications/pdfs/faqs_of_tile_drainageprint_61313.pdf

Schottler SP, Ulrich J, Belmont P, Moore R, Lauer JW, Engstrom DR, Almendinger JE. 2013. Twentieth century agricultural drainage creates more erosive rivers. Hydrol. Process. DOI: 10.1002/hyp

Skaggs RW, Breve MA, Gilliam, JW 1994. Hydrologic and water quality impacts of agricultural drainage. Crit. Rev. Environ. Sci. Tech., 24, 1–32.

Zucker LA, Brown LC (eds.). 1998. Agricultural Drainage: Water Quality Impacts and Subsurface Drainage Studies in the Midwest. Ohio State Univ. Extension Bulletin 871. http://ohioline.osu.edu/b871/

Chapter Ten

How Water Shapes the Land

HIGHLIGHTS

Stream channels are always changing.

The ability of water to erode a channel and transport or deposit sediment depends on its slope, water depth, and total flow.

Sediment loads result from gully and ravine formation, channel widening, channel migration, and bluff collapse.

Previous chapters described **hydrology** or how precipitation is distributed in and generates flow from a watershed. This chapter addresses **hydraulics and geomorphology,** or how water moves through and shapes a stream channel and other landforms over time.

10.1 SEDIMENT AND ENERGY

Watersheds gather and concentrate water, forming channels wherever the volume of water and the slope combine to exceed the threshold of the soils to resist erosion. Channels migrate and diverge upslope into the watershed forming a stream network. The rate of channel formation and enlargement is related to the shear force (or shear stress) of the water. The stream power determines the rate of transport or deposition of the sediment.

Figure 49: Elevation map of a small stream network in Southeast Minnesota with outlet to the north

Shear force (shear stress) is the force of flowing water to erode and shape stream channels. If the water's shear force exceeds the soil's shear strength (resistance) then erosion will occur. The shear force depends on the depth of water and the slope of the stream. Thus, shear is greatest at the toe or bottom of a channel where the water is deepest (Figure 50).

Shear Force = Water Depth x Weight of Water x Stream Slope

Shear force depends on water depth and stream slope

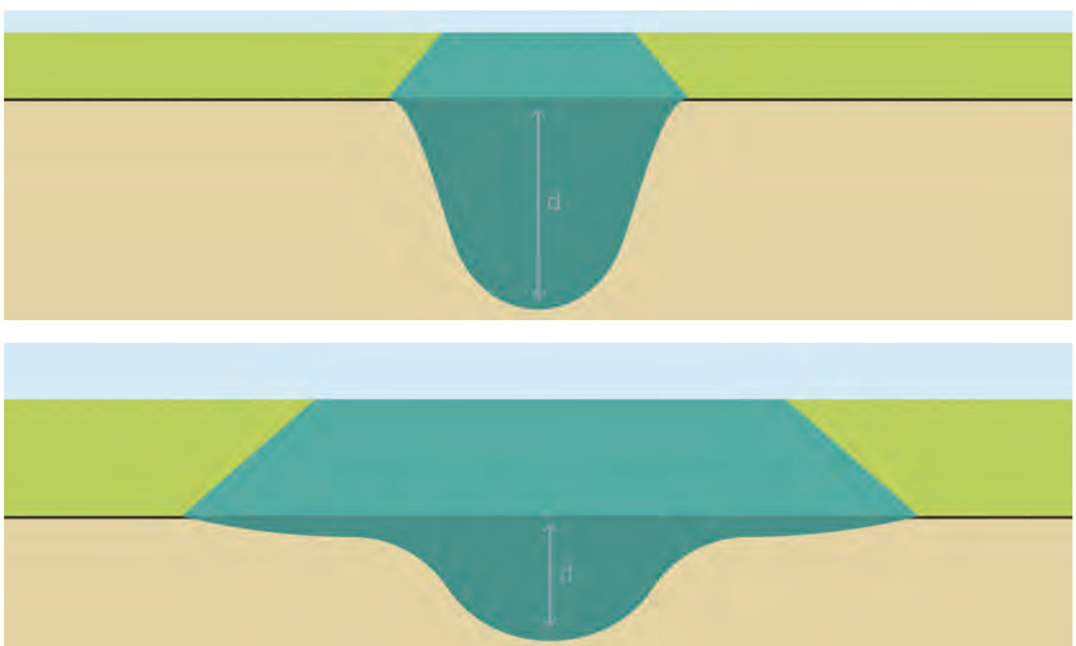


Figure 50: Shear force in a deep vs. a shallow channel

The water depth (d) and therefore shear force on the bottom and lower sides of the channel in the entrenched stream (top diagram) are much greater than in a stream that can spread the same amount of water over its flood plain at high flow (bottom diagram).

Source: Adapted from a diagram by Scott Bohlingh, Minnesota DNR

Greater stream flow increases the sediment transport capacity

Stream power is the capacity of water to transport sediment downstream. Stream power depends on the stream flow and stream slope (related to velocity). Greater stream flow or velocity increases the sediment transport capacity, leading to greater sediment load transported downstream over time. When stream power declines, such as on the inside of a bend or where flow slows, sediment drops out of the water and is deposited. Over decades, the most sediment is transported by the more frequently occurring high flow events, for example two to three inch rain events.

Stream Power = Stream Flow x Weight of Water x Stream Slope

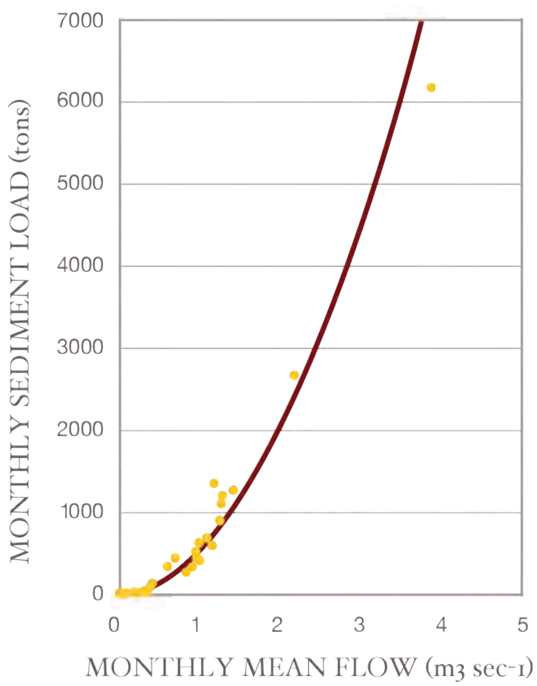


Figure 51: Relationship between monthly average flow and sediment delivery to the outlet of Seven Mile Creek, Nicollet County, Minnesota

Source: Dalzell et al, 2012

STREAM FLOW DRIVES SEDIMENT EROSION AND TRANSPORT.

Increases in flow depth and volume therefore have the dual effects of increased channel erosion through increased shear force, and increased sediment transport through increased stream power. (Compare Stage 1 with Stage 2 photos in the channel evolution model later in this chapter.) For example, there is a strong relationship between flow volume and sediment delivery to the outlet of Seven Mile Creek at the Minnesota River in Nicollet County (Figure 51). The relationship between flow and sediment is stronger close to the sediment source and for coarse more than fine sediment, since fine sediment is maintained in suspension over longer distances and flow conditions (Wang et al., 2015). In this case, the Seven Mile Creek outlet is close to the main sediment source, the nick zone where the creek drops rapidly from the glacial till plain to the Minnesota River Valley.

10.2 STREAMS ARE DYNAMIC

STREAMBANK EROSION AND CHANNEL MEANDER

There is a balance between erosion and deposition in natural rivers and streams. Streams migrate laterally across their valleys over time, eroding and depositing sediment. In a stable stream, bank erosion is approximately balanced by deposition over many years or decades (Figures 52 and 53). Streams may also develop a longer, more sinuous (meandering) channel over time, resulting in a decreased channel slope and therefore decreased erosive power and transport capacity (Figure 54).

Figure 52: Cannon River, southeast Minnesota, cutting the outside bend (left) and depositing on the inside bend (right)

Source: B. DeZiel, MN Pollution Control Agency

Figure 53: Minnesota River channel migration, near Redwood Falls

Note sediment deposition on the inside of the bends.

Source: Google Earth

Figure 54: Channel meanders of the Red Lake River in Northwest Minnesota near Grand Forks

Source: MN Topo

In many river systems with undisturbed riparian vegetation (vegetation along a river or stream), bank erosion rates are typically low, less than a few inches per year in lateral movement in Minnesota. However there is great variability in rates of bank erosion. Some streams in the Midwest experience up to 10 feet per year erosion on outer bends (Odgaard, 1987). Large, powerful rivers located within easily erodible soils like sandy alluvium migrate rapidly. In contrast, streams that are set in dense clay such as the Red River Valley or hard glacial till migrate slowly. Vegetation in the riparian zone may retard migration rates through increased soil cohesion and direct resistance to erosion. Streams with poor riparian vegetative cover or with species that have shallow root depth, such as brome grass or Kentucky bluegrass, will erode faster than similar channels with dense and deep roots from perennial plants such as prairie or forest.

STREAM STRAIGHTENING CHANGES STREAM ENERGY

When streams are straightened they are also made shorter, increasing channel slope and stream power and accelerating erosion in those reaches. Many rivers have been straightened over the past century as part of channelization for drainage, aligning streams with field borders, or relocation to accommodate infrastructure such as road crossings (Figure 55).

Stream straightening can also occur by channel cutoffs during large floods, and are more common as stream flow increases (Figure 56). For example, Elm Creek, a stream in southern Minnesota lost 15% of its main channel length between 1938 and 2003 (Lenhart et al. 2012). High-flow cutoffs, combined with the more frequent occurrence of intentional straightening, have led to the straightening and shortening of many streams and rivers in the United States (Verry et al. 2000).

Figure 55: Stream straightening

A formerly meandering stream (blue line) was straightened and deepened in the 1950s to improve drainage and increase tillable acres on this Iowa farm. Increased shear force is enlarging and creating new meanders in the straight ditch.

Source: Historic air photo collection, Iowa DNR

Figure 56: Channel cutoffs in aerial view of Elm Creek, Minnesota

The previous, longer channel is visible below the current river. Channel cutoff is a natural process, however streams may respond to increased flow with more channel cutoffs which occur primarily during large floods.

Source: J. Magner, UM

10.3 STREAM EVOLUTION AND SEDIMENT SOURCES

GULLIES AND RAVINES: WHERE CHANNELS BEGIN

Gullies are often the starting point for channel evolution in farm fields and other areas of concentrated flow not protected by deep rooted plants or erosion resistant material. Small channels such as gullies may erode very rapidly through down-cutting and upstream migration (Harvey et al. 1985), with greater erosion usually occurring during large storm events (Figure 57). Gullies contribute a disproportionate amount of sediment relative to their size in farm fields and may contribute large volumes of sediment to Midwestern rivers (Gordon et al. 2008, Cox et al. 2011). Field gullies that become too large for filling by tillage may be abandoned and grow into wooded ravines over time. Actively eroding ravines, with field runoff or tile outlets at the head, can also be a major source of sediment (Figure 58).

Figure 57: Field Gully

Source: USDA NRCS

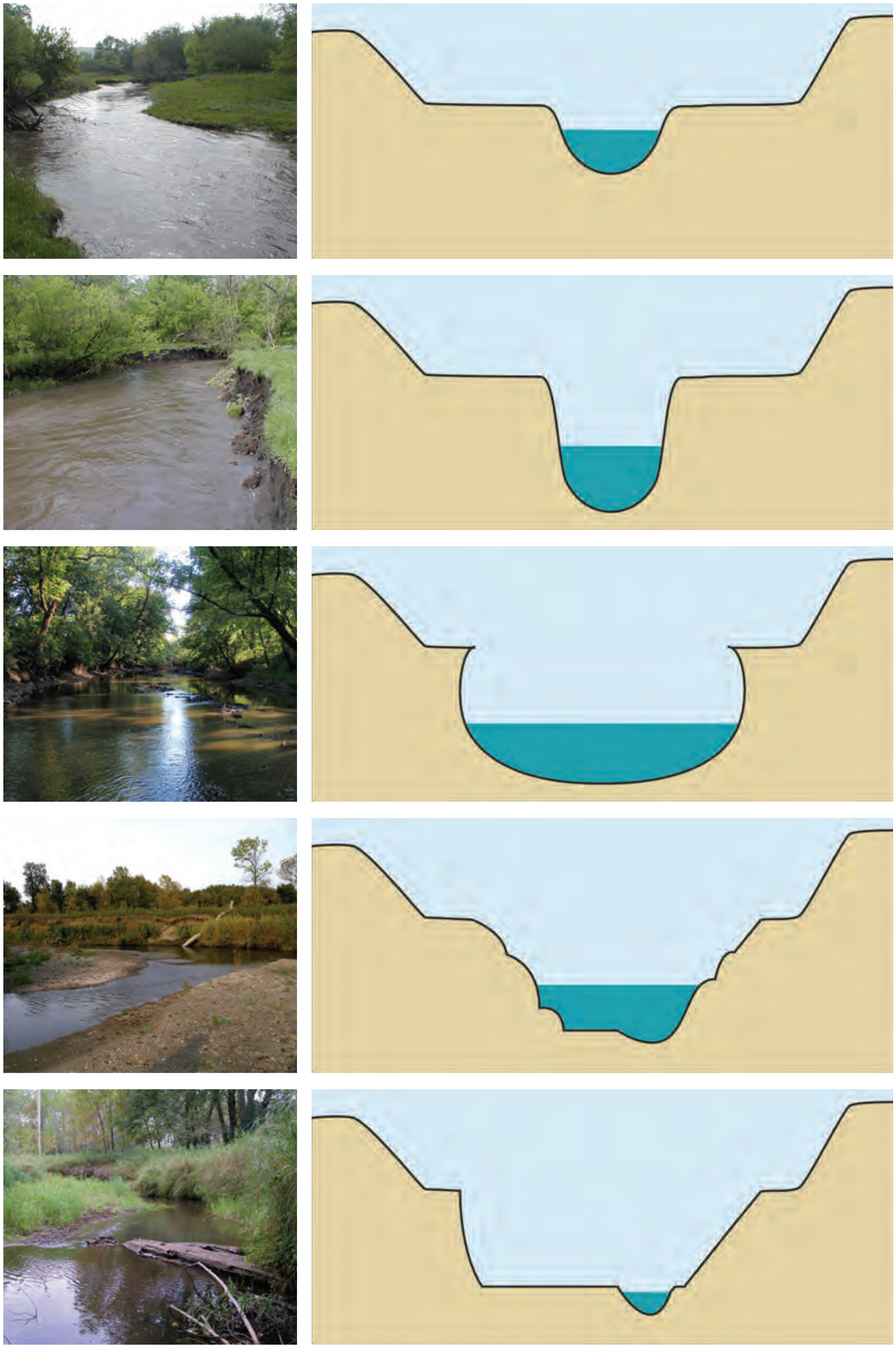
Figure 58: Actively eroding ravine with tile outlet at the head in the Seven Mile Creek watershed, Nicollet County, Minnesota

Source: K. Kuehner. Brown, Nicollet, Cottonwood Water Quality Joint Powers Board. CWP Report to MPCA.

HOW CHANNELS EVOLVE

Stream channels may evolve by eroding downward (down-cutting) or laterally (widening). They may also accumulate sediment by deposition. The channel evolution model in Figure 59 describes changes that typically occur when a channel disturbance or change in flows is introduced into a stable stream. However, not all stream and river segments progress through the stages described in this channel evolution model. For example, river segments in the nick zone of Minnesota River tributaries continue cutting down (Incision, Stage 2) as the nick zone advances into the till plain, and progress through other stages only where the stream slope has decreased downstream of the nick zone.

Figure 59: Channel Evolution Model



Stage 1

Pre-adjustment, stable equilibrium

- Bank erosion and deposition are in balance
- Active floodplain - allows out of bank flows

Stage 2

Incision/Down-cutting

- An increase in stream power or decrease in sediment supply causes down-cutting (incision)
- The channel disconnects from the floodplain
- Channel widening dominates if coarse material or bedrock is armoring the channel bottom

Stage 3

Over-Widening and Deposition

- Banks steepen, destabilize and collapse
- Cutting along one or both banks
- Channel cross-section is over-widened
- Reduced stream power leads to excess deposition

Stage 4

Low-Flow Channel Redevelopment

- Redevelopment of a low-flow channel on the outside bend and a depositional bar on the inside bend
- Some cutting and bank collapse may occur as flow is directed along the outside bend by the developing depositional bar (Thorne 1999)

Stage 5

New Dynamic Equilibrum

- Low-flow channel re-formed, banks stable, and sand bars re-vegetated
- Smaller floodplain within active channel
- Old terraces may be visible
- Due to lower base level and channel confinement, stream is sensitive to high flows

Source: Asmus et al. 2009, modified from Schumm et al. (1984) and Thorne (1999). Diagram adapted from Schultz et al. (2009). Photos by B. DeZiel, MN Pollution Control Agency.

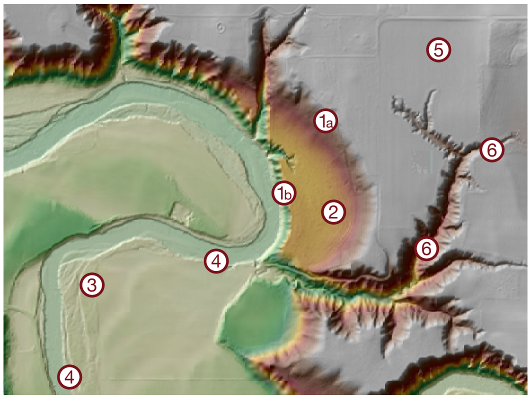


Figure 60: Elevation map showing river-related elements in the Le Sueur River watershed

1 - Bluffs
 1a - 40m tall paleobluff
 1b - 27m tall, connected to river

2 - Terrace

3 - Active Floodplain

4 - Streambank

5 - Upland

6 - Ravine

Source: Adapted from P. Belmont

The resulting three dimensional landscape in an actively incising region includes the active channel, streambanks and floodplains; former floodplains (terraces) and abandoned channels; and ravines, bluffs, and uplands.

RIVER WIDENING

In southern Minnesota many streams and rivers have undergone widening in recent decades. Widening is common where the stream slope or gradient is not very steep but flows have increased. Often a channel may cut down a small amount in response to increased flows and then the banks will collapse as described in the channel evolution model above. The width of the lower Minnesota River and some its tributaries has increased by 20-50% since 1938 (Lenhart et al. 2013, Gran et al. 2011). Schottler et al., 2013, found that rivers in Minnesota that had significant increases in annual flow volume experienced channel widening of 10–40%, whereas rivers with no flow increase had no change in channel width. The net effect of channel widening is an increase of sediment delivered to the outlet.

Figure 61: Channel Widening - Le Sueur River, 1939-2010

Source: R. Moore, Minnesota Information Technology

BLUFF COLLAPSE

High bluffs often develop along rivers with a large elevation drop between the upper part of the watershed and the outlet. They develop below the nick zone, this area of rapid down-cutting in the region of high channel slope. Gravity causes a bluff to collapse when the river erodes the toe of the bluff to the point that the bluff angle exceeds a threshold determined by the cohesive force of the bluff materials and the amount of saturation of those materials. When the river removes the collapsed material and advances the bluff toe to again exceed the critical angle, the collapse cycle can continue, supplying a great amount of sediment over time. The Le Sueur River in the Minnesota River Basin is an example, contributing high levels of sediment from bluffs (Figure 62). Bluff collapse resulting in sediment transport can also occur when a river meander reaches a valley wall, like the Minnesota River Valley, and erodes the toe past the critical angle. Bluffs can also fail higher up when saturated soils weaken and collapse. Whether the sediment source is the top or bottom of a bluff, the stream power determines how fast the sediment is transported or deposited. For more information on bluff collapse and landslides see Nelson (2012).

Figure 62: Collapsed bluff on the Le Sueur River

Source: L. Everett, UM

REFERENCES

Asmus B, Magner JA, Vondracek B, Perry J. 2009. Physical integrity: the missing link in biological monitoring and TMDLs. Environmental monitoring and assessment 159: 443-463.

Cox C, Hug A, Bruzelius N. 2011. Losing ground. Environmental Working Group, Washington, DC. Available online at http://www.ewg.org/losingground. (Verified 20 Sept. 2011).

Dalzell BJ, Pennington D, Polasky S, Mulla D, Taff S, Nelson E. 2012. Lake Pepin Watershed Full Cost Accounting Project. Final Report prepared for the Minnesota Pollution Control Agency 177 p.

Gran K, Belmont P, Day S, Jennings C, Lauer JW, Viparelli E, Wilcock P, Parker G. 2011. An integrated sediment budget for the Le Sueur River Basin. Final report to the Minnesota Pollution Control Agency. http://www.pca.state.mn.us/index.php/view-document.html?gid=16202

Gordon LM, Bennett SJ, Alonso CV, Bingner RL. 2008. Modeling long-term soil losses on agricultural fields due to ephemeral gully erosion. Journal of Soil and Water Conservation 63: 173-181.

Harvey M D, Watson C C, Schumm SA. 1985. Gully erosion. Water Engineering and Technology, Incorporated. BLM Technical Note 366.

Lenhart CF, Titov ML, Ulrich JS, Nieber L, Suppes B J. 2013. The role of hydrologic alteration and riparian vegetation dynamics in channel evolution along the lower Minnesota River. Transactions of the American Society Agricultural Biological Engineers 56: 549-561.

Lenhart CF, Verry ES, Brooks KN, Magner JA. 2012. Adjustment of prairie pothole streams to land-use, drainage, and climate changes and consequences for turbidity impairment. River Research and Applications 28: 1609–1619.

Nelson, S.A. 2012. Mass Movements. Web page for EENS 1110 at Tulane University. http://www.tulane.edu/~sanelson/eens1110/massmovements.htm

Odgaard AJ. 1987. Streambank erosion along two rivers in Iowa. Water Resources Research, 23: 1225-1236.

Schottler SP, Ulrich J, Belmont P, Moore R, Lauer JW, Engstrom DR, Almendinger JE. 2013. Twentieth century agricultural drainage creates more erosive rivers. Hydrol. Process. DOI: 10.1002/hyp

Schultz RC,.Isenhart TM, Colletti JP, Simpkins WW, Udawatta RP, Schultz PL. 2009. Riparian and upland buffer practices. p. 163–218. In Garrett HE. (ed.) North American agroforestry: An integrated science and practice. ASA, Madison, WI.

Schumm SA, Harvey MD, Watson CC. 1984. Incised channels: morphology, dynamics, and control. Water Resources Publications. Littleton, Colorado. 200 pp.

Thorne CR. 1999. Bank processes and channel evolution in the incised rivers of north-central Mississippi. pgs. 97 – 122 In Darby SE, Simon AS. Incised river channels: processes, forms, engineering and management. John Wiley & Sons. Chichester, England.

Verry ES, Hornbeck JW, Dolloff CA (eds.). 2000. Riparian management in forests of the continental eastern United States. CRC Press.

Wang Zhao-Yin, Lee JHW, Melching CS. 2015 River Dynamics and Integrated River Management. Springer, 847 pages.

ADDITIONAL READING

Knighton D. 2014. Fluvial forms and processes: a new perspective. Routledge.

Knox JC. 1983. Responses of river systems to Holocene climates. pgs. 26-41 In Porter SC, Wright HE. Late quaternary environments of the United States University of Minnesota Press

Chapter Eleven

How is the Landscape Changing? Trends in Stream Flow, Sediment, and Channels

HIGHLIGHTS

The amount of water in streams has increased, especially in southern Minnesota.

While the amount of sediment in the Minnesota River is naturally high, the rate of sediment transport has increased substantially in recent decades.

Stream channels across southern Minnesota have become wider over recent decades.

All of these changes result from an interaction of factors.

A stream is the summary of the watershed. Changes in precipitation, vegetative cover, and land management in a watershed are reflected in the amount of water, amount of sediment, and shape of a stream. The nature of these impacts depends on the local geology, soils, and landscapes. The preceding chapters summarized each of these factors and their effects. This chapter describes trends in streamflow, sediment transport, and stream channels in the light of geology, soils, climate trends, and land use trends. Part Two of this publication addresses land and water management practices that can moderate some of these effects.

11.1 STREAM FLOW TRENDS

In general, the amount of water flowing in Minnesota streams has been increasing in recent decades. This trend has several components:

Region – Flow volumes have especially risen in southern and western Minnesota, predominantly agricultural regions of the state (Figure 63 and Figure 64).

Time of year – In watersheds with increased flow, spring and early summer flows have increased the most, and late summer-to-fall flows have increased the least (Figure 63, Figure 64, and Figure 65).

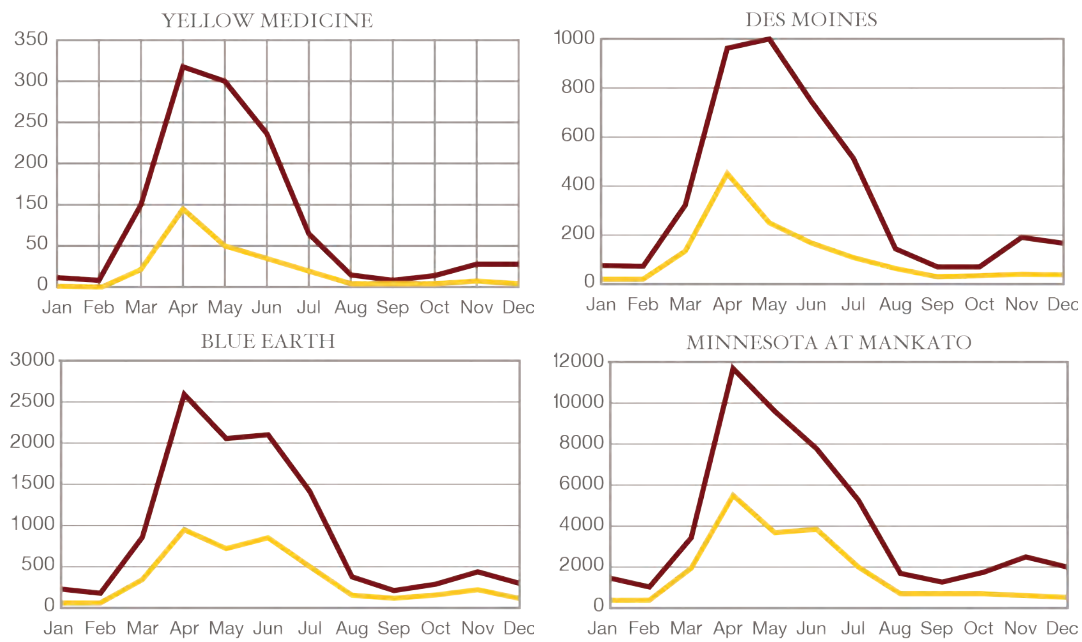


Figure 63: Change in streamflow in southern Minnesota rivers

Average monthly flow (cfs) in 1940-1979 (gold) and in 1980-2009 (maroon)

Source: Lenhart et al. 2011a,b.

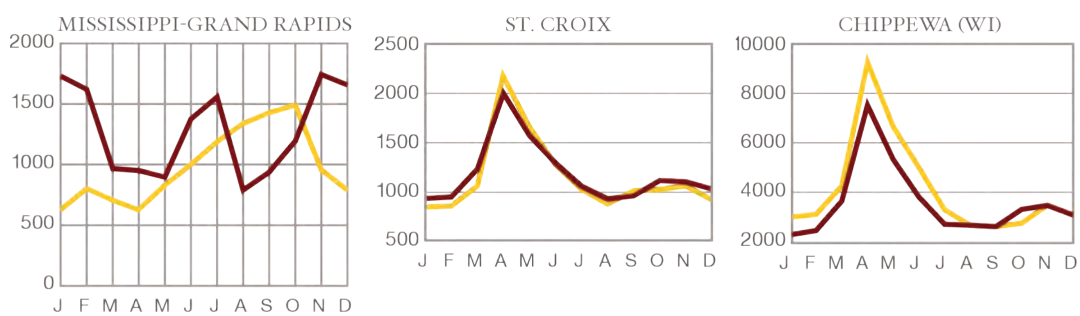


Figure 64: Change in streamflow in northern Minnesota and Wisconsin rivers

Average monthly flow (cfs) in 1940-1979 (gold) and in 1980-2009 (maroon)

Source: Lenhart et al. 2011a,b.

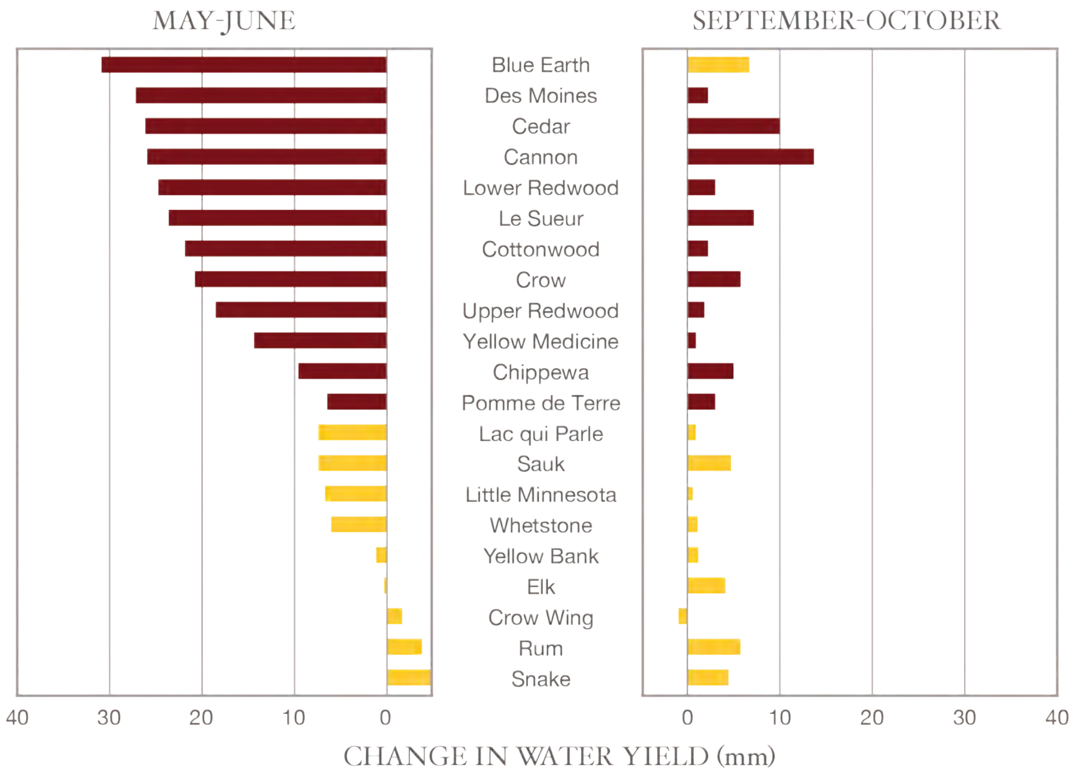


Figure 65: Seasonal Increase in flow for selected watersheds of Minnesota

Change in median water yield (flow volume/watershed area) from 1940-1974 compared to 1975-2009 (Schottler 2013). The watersheds in the top half of each graph are more intensely row-cropped and drained. Change in May-June precipitation between the two periods was not significant, however the change in water yield was significant for the watersheds with maroon bars.

Source: Schottler 2013

Flow volume and duration – Proportionally, the biggest increases have been seen in base flow (amount of low flow between storms), median flow (the average across a month or year), and the duration of elevated flows. Peak flows (the height of the biggest flow each year) have not increased as much. (Figure 66 and Figure 67). Greater duration of elevated flow – even if peak flows are not higher – means more days each year when a stream has the power to significantly erode and transport streambank sediment.

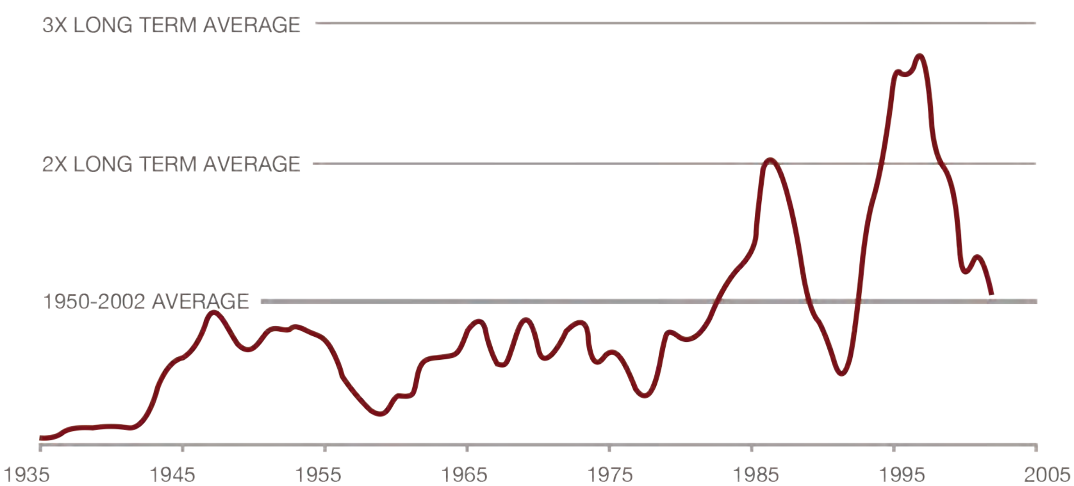


Figure 66: Relative number of high flow days across the Minnesota River Basin

Number of days each year that flow at a station was greater than one standard deviation above the mean flow. Five-year running average from twelve stations across the basin.

Source: Novotny and Stefan, 2007

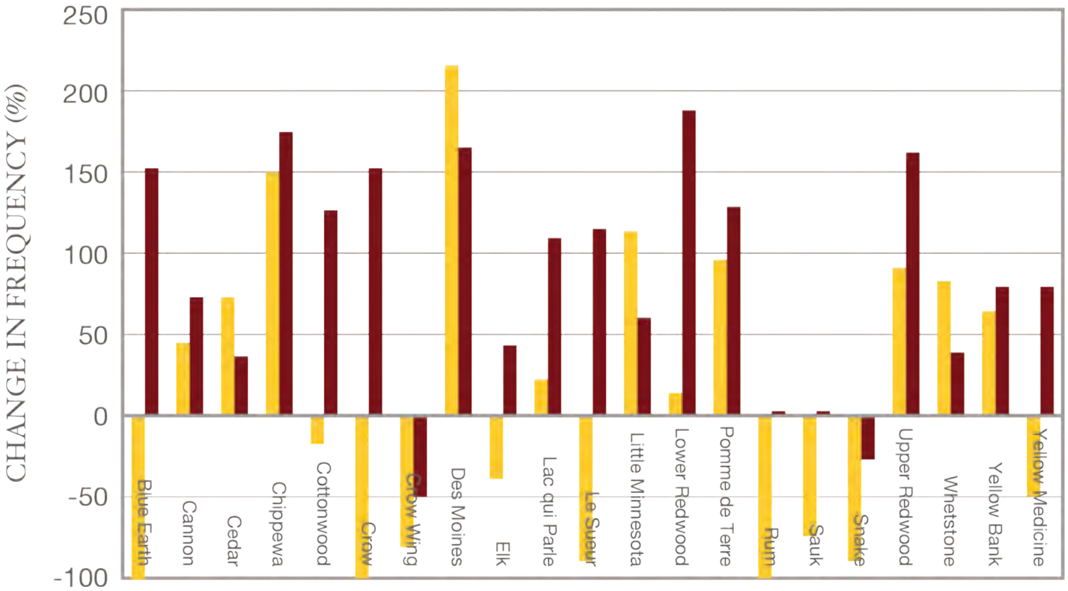


Figure 67: Trends in 2-year and 10-year flows for several watersheds

Percentage change in the annual number of days of 2-year return flows and 10-year return flows in 1975-2009 compared to 1940-1974. The frequency of channel-forming flows (2-year return) increased in almost all watersheds, often doubling, while the frequency of high flows both increased and decreased.

10 Year Frequency Change

2 Year Frequency Change

Source: Schottler 2012, Figure 33

11.2 SEDIMENT LOADS AND SOURCE TRENDS

As explained in Chapter 10: How Water Shapes the Land, increased stream flows are related to increased soil loss and transport from streambanks, bluffs, and ravines because of increased shear force and stream power. Impacts of the increasing sediment load can be seen in streams across the region, but has been measured most intensely in Lake Pepin, formed by a natural dam on the Mississippi River downstream of where the Minnesota River joins the Mississippi River. In order to measure long term trends in sediment loads, researchers analyzed sediment layers in cores of bottom sediment from Lake Pepin and other reference lakes. Figure 68 and Figure 69 show results of these analyses. Several pieces of information can be gathered from these figures and related publications:

- Sedimentation rates were about 80,000 metric tons/year before European settlement and are about 800,000 metric tons/year now (Blumentritt et al 2013; Engstrom et al, 2009).
- Sedimentation rates increased rapidly from the early 1900s to about 1960 and continue a high rate of deposition.
- Radioisotope tracers (radioactive forms of lead and beryllium) were deposited on soil surfaces from natural atmospheric sources and during nuclear testing. They are found at much high levels in sediment from field surfaces than from stream banks and bluffs. Samples from lake sediment deposits and river water indicate that a large proportion of the sediment deposited prior to 1990 was from field surfaces. (Belmont et al. 2011)
- A rapid drop in concentration of radioisotope tracers in lake core sediment starting in the 1990's indicates a decrease in proportion of sediment from field surfaces and an increase in proportion of sediment originating from near-stream sources such as bluffs, ravines, and streambanks (Belmont et al, 2011; Schottler et al, 2010). These sources of sediments are associated with higher flows.
- Compared to the Minnesota River, sediment loads from the Mississippi and St. Croix Rivers also increased since European settlement, but considerably less (Kelley et al, 2000).
- The average width of the lower Minnesota River downstream of Mankato has increased by approximately 50% since 1938 (Lenhart et al. 2013). Other rivers in southern Minnesota, including the Blue Earth and Le Sueur Rivers are also increasing in width (Gran et al, 2011).

Figure 68: Analysis of sediment cores from Lake Pepin

Rates of sedimentation in Lake Pepin (bottom axis) reflect sediment contributed from the Minnesota, Upper Mississippi, and St. Croix rivers. The top axes show concentrations of two markers that indicate the amount of sediment from surface sources.

Minnesota River

Mississippi + St. Croix Rivers

Decay Corrected ^{110}Pb Activity

^{10}Be Concentration

Source: Belmont et al. 2011

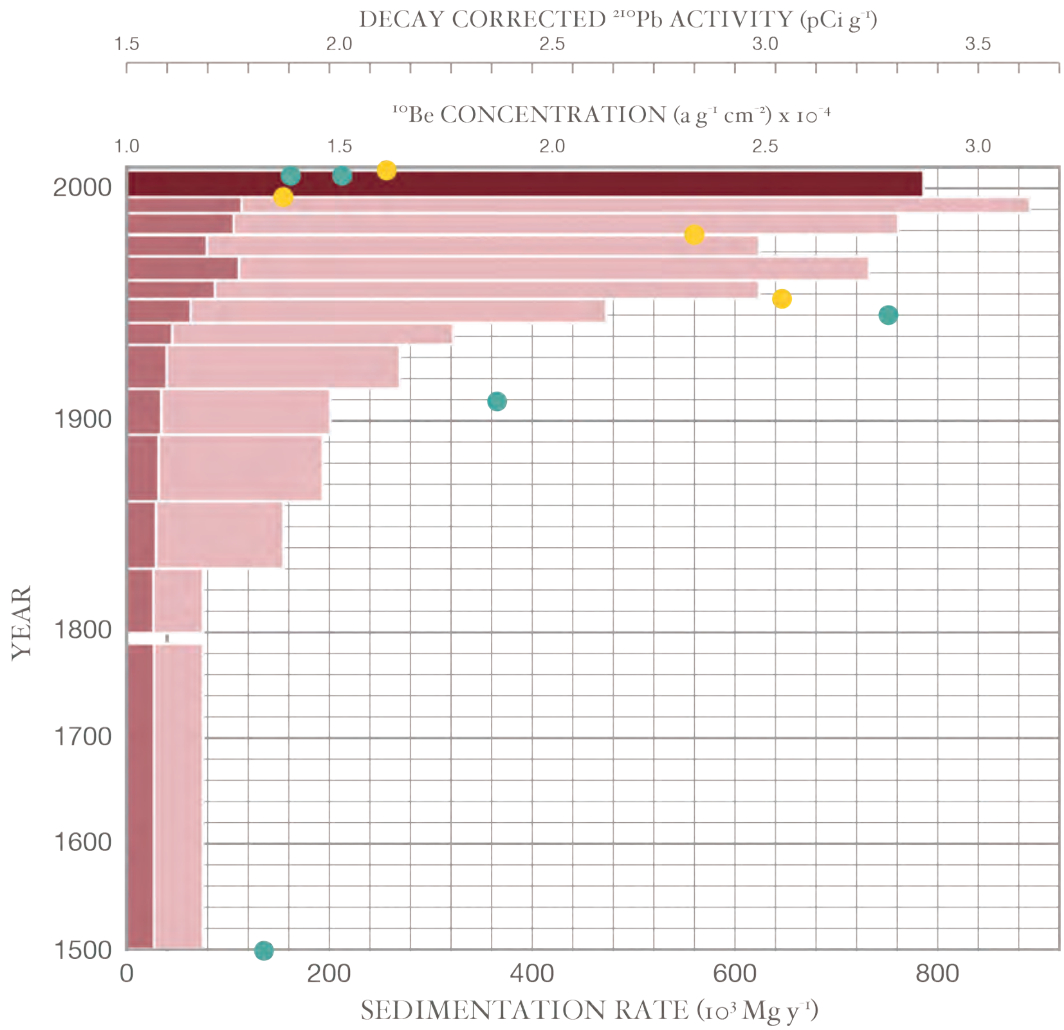
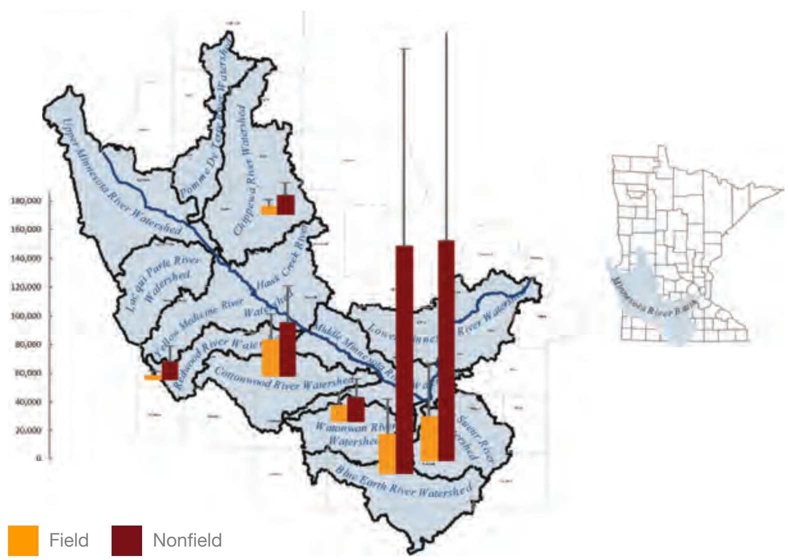


Figure 69: Loads of sediment coming from field and non-field sources for selected watersheds.

The majority of stream sediment derives from non-field sources including ravines, streambanks, and bluffs. Data is based on radioisotope analysis of suspended sediment collected during rain events and sediment deposited in backwater areas.

Source: Schottler et al. 2010



Factors that have changed in recent decades, and that impact stream flow at some scales and locations:

- Greater precipitation
- More large rain events
- Lower spring evaporation and transpiration rates
- Less water storage in depressions
- Greater annual flow via constructed drainage systems (ditches, subsurface tile, and storm sewers)
- Straightened stream channels

11.3 WHAT'S DRIVING THE CHANGES?

Increasing precipitation, larger rain events, lower spring evaporation and transpiration, less water storage in depressions, greater flow through drainage infrastructure, and straightened stream channels are all potential contributors to trends in stream flow and sediment transport.

Teasing apart these factors is challenging and requires looking at evidence from multiple perspectives. Scale and location are important to interpreting the evidence. A process or relationship that is meaningful at the edge of a farm field may be different from an explanation of a change in a small watershed or large river basin. The explanation in one location will differ from the explanation in another place.

Asking how we got where we are today is different than asking how to effectively manage under current conditions. Part 2 describes approaches to managing water in a world where precipitation and stream flow patterns are changing and agriculture is becoming increasingly intensive.

REFERENCES

Belmont P, Gran KB, Schottler SP, Wilcock PR, Day SS, Jennings C, Lauer JW, Viparelli E, Engstrom DR, Parker E. 2011. Large shift in source of fine sediment in the Upper Mississippi River, Environmental Science & Technology 45: 8804-8810.

Gran K, Belmont P, Day S, Jennings C, Lauer JW, Viparelli E, Wilcock P, Parker G. 2011. An integrated sediment budget for the Le Sueur River Basin. Final report to the Minnesota Pollution Control Agency. http://www.pca.state.mn.us/index.php/view-document.html?gid=16202

Lenhart CF, Titov ML, Ulrich JS, Nieber JL, Suppes BJ. 2013. The role of hydrologic alteration and riparian vegetation dynamics in channel evolution along the lower Minnesota River. Transactions of the ASABE 56(2): 549-561.

Lenhart CF, Peterson H, Nieber J. 2011a. Increased streamflow in agricultural watersheds of the Midwest: Implications for management. Watershed Science Bulletin. Spring 2011: 25-31

Lenhart C, Nieber J, Peterson H, Titov M. 2011b. Quantifying differential streamflow response of Minnesota ecoregions to climate change and implications for management. University of Minnesota Water Resources Center research report to the National Institutes for Water Resources.

Novotny EV, Stefan HG. 2007. Stream flow in Minnesota: Indicator of climate change. Journal of Hydrology 334:319-333. doi:10.1016/j.jhydrol.2006.10.011 http://static.msi.umn.edu/rreports/2007/346.pdf

Schottler SP, Engstrom DR, Bluementritt D. 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 SP. 2012. Intensified Tile Drainage Evaluation: Final Report to the LCCMR. http://www.lccmr.leg.mn/projects/2009/finals/2009_05d.pdf

Schottler SP, Ulrich J, Belmont P, Moore R, Lauer JW, Engstrom DR, Almendinger JE. 2013. Twentieth century agricultural drainage creates more erosive rivers. Hydrol. Process. DOI: 10.1002/hyp

Appendix A

Common Pollutants and Their Pathways

In agricultural regions the principal pollutants that most frequently exceed water quality standards are suspended sediment, phosphorus, nitrate, and bacteria. Mercury can also exceed standards, however conversion to the bioactive methyl mercury form has been more of a problem in the northern forested lakes region of Minnesota.

A.1 COMMON POLLUTANTS

Suspended sediment is the result of erosion of soil from field surfaces, gullies, ravines, and streambanks, as well as collapse of near-channel bluffs from toe-slope erosion and other mechanisms. While some sediment movement and erosion is natural and necessary to maintain stream stability, excessive suspended sediment diminishes light penetration and suppresses aquatic plant growth. It can also reduce habitat for fish and invertebrates in streams by burying gravel and cobbles that provide structure. Sediment also fills lakes and reservoirs where it settles out.

Phosphorus in agricultural areas originates from fertilizers and livestock manure applied to the soil as an essential crop nutrient, and from mineralization of soil organic matter. Our young Minnesota soils also contain some native phosphorus minerals. Phosphorus promotes growth of algae (eutrophication) particularly in freshwater bodies. Dissolved phosphorus is more quickly available to algae than sediment-bound phosphorus, however both are available over time in water. Excess phosphorus can be a pollutant concern for decades because it can be bound to soil particles and later mobilized and converted to biologically available forms.

Nitrate in agricultural fields results from direct application of nitrate-containing fertilizers, nitrification of ammonium containing fertilizers and manure, and mineralization of organic nitrogen in manure and soil organic matter. The drinking water standard (upper limit based on health effects) for nitrate is 10 parts per million. Nitrate can impact aquatic life and contributes to hypoxia (low oxygen) in salt water systems, including the Gulf of Mexico. It increases growth of algae that grow, die, and sink to the bottom, where oxygen is consumed in the decomposition process.

Pathogenic bacteria in water originate from wildlife and livestock manure, and malfunctioning human waste treatment systems. While not all bacteria are pathogenic, contamination of drinking water sources by pathogens is a health hazard.

A.2 POLLUTANT PATHWAYS

When precipitation arrives at the soil surface, the route it takes determines what pollutants, if any, it will transport:

Infiltration: If the soil is permeable, water will move into the soil profile, and if it reaches “field capacity”, it can move further down, out of the root zone and into tile or groundwater. Nitrate is soluble in water and not tightly bound to soil particles. As water moves through the soil profile, the nitrate goes into solution and can move out of the root zone to groundwater or drainage tile. Groundwater contamination with nitrate is most susceptible in areas of the state with coarse textured soils or shallow soils over porous bedrock. In Minnesota as in much of the Midwestern cornbelt, most nitrate in surface water is delivered by subsurface tile drainage. Because phosphorus readily attaches to soil particles other than sand, it is less likely than nitrate to be transported through the soil profile. However, sufficient levels of soluble phosphorus for algae growth are being found in tile drainage water in some agricultural areas where soil test P values are maintained at very high levels.

Saturation and ponding: If water containing nitrate is retained in or just above the soil surface sufficiently long for oxygen to be depleted, the nitrate can be converted to gaseous forms of nitrogen [nitrogen gas (N_2) and nitrous oxide (N_2O)] by the process of denitrification. Conditions required for denitrification are low oxygen, the presence of denitrifying bacteria that use nitrate as an oxygen source, and organic matter that the bacteria use as an energy source. In agricultural soils, this results in a loss of nitrogen as a nutrient for the crop. Nitrate in water that will enter streams or groundwater is a pollutant, so denitrification to reduce nitrate in that water is preferable. Intentional denitrification is enhanced by routing the water through shallow ponds and wetlands as well as saturated riparian buffers and woodchip bioreactors.

Surface runoff: If the soil is compacted or saturated, water will move across the surface, eroding and carrying soil particles (sediment) and organic material, including bacteria. The amount of runoff and soil erosion is related to the slope, slope length, and crop or residue cover for a given soil type and precipitation. Since most phosphorus is attached to soil particles, it moves with sediment in suspension. However, water can also interact with the soil surface, dissolving soluble phosphorus and carrying it in solution. The risk for soluble phosphorus transport in runoff is higher when soluble sources of phosphorus, like fertilizers and manure, are concentrated at the soil surface rather than injected or incorporated. Similarly, when manure is surface applied without incorporation, pathogens can be transported in surface runoff to streams and lakes when precipitation falls soon after application.

Streambank, bluff, and ravine erosion: These are the largest sources of sediment that reach the Mississippi River from the Minnesota River. The phosphorus content of these sediments varies, depending on the source. Streambank alluvium derived from upland soils can be high in phosphorus, while parent material in bluffs is often much lower.

Appendix B

The Glacial Origin of Minnesota Agricultural Landscapes

By Carrie Jennings, Geologist, Minnesota Department of Natural Resources

This chapter describes how glaciers created the major landscapes of northern Minnesota, eastern North and South Dakota, and northern Iowa. The different landforms left by these glacial events have and are responding differently to the erosion processes that continue to shape the landscape and deliver sediment to and through streams.

B.1 GLACIATION

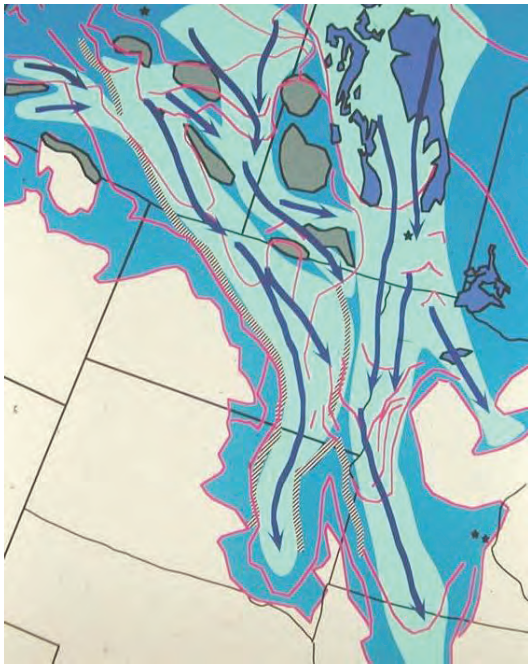
The soils of Minnesota are developed in glacial sediment that was deposited during many glacial periods between 2.5 million and 13,000 years ago. Glaciers imported exotic materials, ground up what lay beneath them, and spread it across every part of Minnesota. Erosion exposed bedrock in northeastern Minnesota, in patches along the Minnesota River valley and along the steep slopes of the Paleozoic plateau in southeastern Minnesota. But even there we have the glaciers to thank for creating these landscapes because they stripped some areas clean and created mighty rivers that cut into the landscape elsewhere.

Glaciers tended to level the land where they last flowed because they plastered it with till, a stony mixture of clay, silt, and sand that is deposited directly by ice. The exact texture of the till matrix and rock types varied depending on the glacier's path into Minnesota. The margins of the ice are places where till accumulated in curved bands of irregular hills, commonly with lakes and wetlands in the depressions. As the ice melted it deposited sand and gravel in broad, braided meltwater streams or silt and clay in cold, glacial lakes. Lakes sometimes grew very large and drained catastrophically, creating deep spillway valleys like the Minnesota and St. Croix valleys. Strong winds associated with glacial climate picked up silt and sand from the unvegetated landscape and blanketed the region beyond the ice in silty dust or loess. The southeastern and southwestern corners of Minnesota lay beyond the margin of the ice during the last glacial event (but didn't escape earlier glaciations) so are the loess-draped areas today.

The official Minnesota state soil, the Lester, is developed in the till of the most recent glacial advance. The Des Moines lobe spread the till from northwestern Minnesota to Des Moines, Iowa (see map below). It ground up shale and limestone from Manitoba and Saskatchewan to create a gray, loamy clay that is more yellow-brown near the surface. The Des Moines lobe was almost as wide as the state and stretched from a narrow moraine that lies on the Prairie Coteau known as Buffalo Ridge on its western margin (the moraine runs from Hendricks to Lake Benton to Holland to Edgerton to Adrian) to the Bemis moraine on the eastern margin, which is almost aligned with I-35 south of the Twin Cities (Northfield to Faribault to Owatonna to Albert Lea). The Prairie Coteau is a thick stack of older glacial sediment that was bypassed during the last glaciation (elevation map below).

The ice had a series of advances followed by stagnation and retreat. Subtle hummocky ice margins loop across the central part of the state, interrupting the flat till plains and even flatter lake plains of southern Minnesota. Even in a drought year, when corn may be wilting and withering in other places, it stands tall and green in the Blue Earth watershed where clayey and silty sediment from glacial Lake Minnesota holds enough moisture to sustain it. The lake only lasted a few decades before the retreat of the ice allowed it to drain but that was enough time to add 6 to 20 feet of stone-free silt and clay to the top of the stack of glacial till. Lake Benson was a similar-sized lake that covered much of the Chippewa River watershed. Although a boon in drought years, fine-grained, flat-lying lake sediment has its challenges in being poorly drained. Ditches and natural drainages that cut through it can also be problematic because they may have high sediment loads.

Toward the end of the last glacial period, Lake Agassiz fronted the retreating ice sheet and it grew to be larger than all of the Great Lakes combined, covering western Minnesota, eastern North Dakota, Manitoba, and northwestern Ontario (map below).



Advance of the Des Moines lobe of the Wisconsin glaciation.

Source: C. Jennings, MN DNR

Locations of glacial lakes Agassiz (blue area at top of map), Benson, and Minnesota at their maximum extents. These lakes were present at different times.

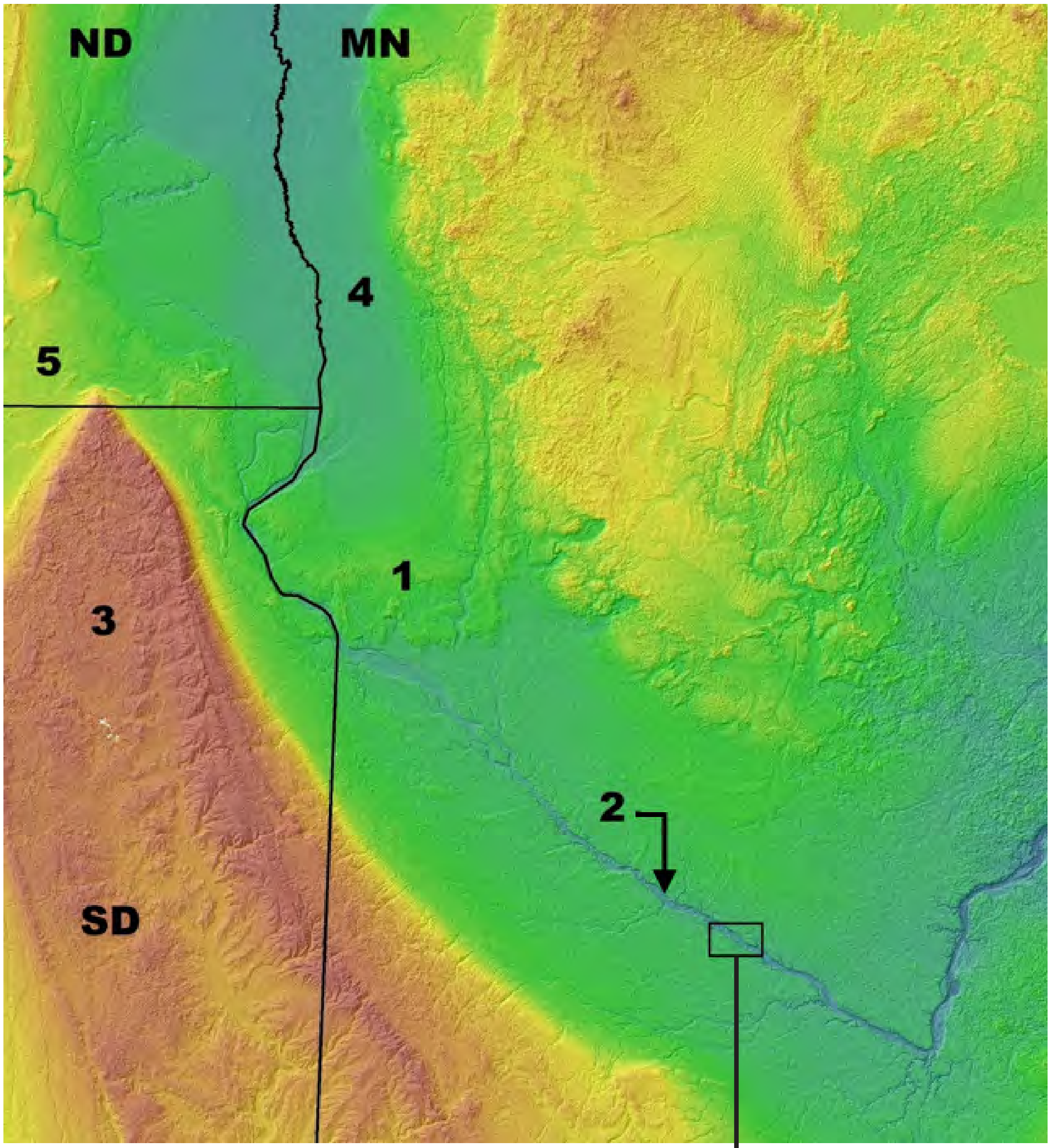
Source: MN DNR 2007, Teller et al. 1983, Hobbs and Goebel 1982

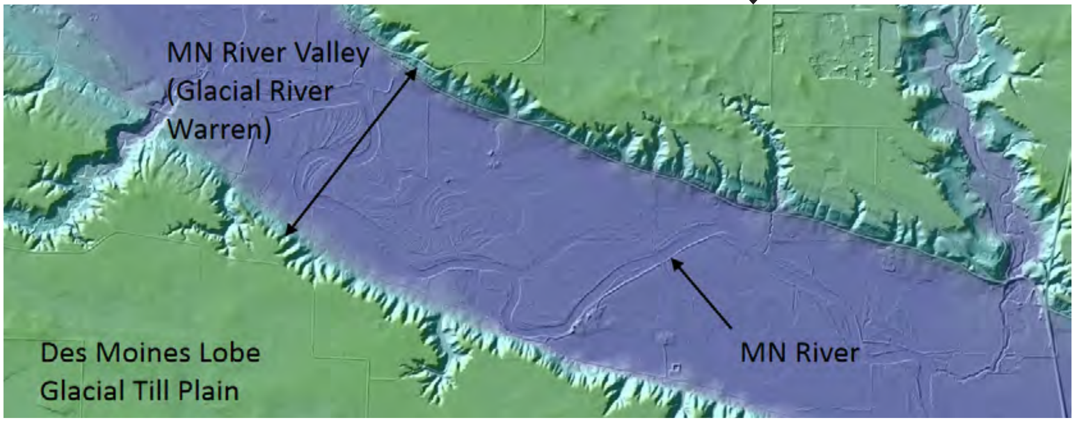
B.2 MINNESOTA RIVER BASIN

Glacial Lake Agassiz covered the Red River watershed in Minnesota. The lake was impounded by the Big Stone Moraine, the broad curved hummocky area that separates the Minnesota watershed from the Red River watershed. North of that moraine, the lake floor is a nearly level surface that appears flatter than the other lowlands (elevation map below). About 13,400 years ago the lake began to drain across the moraine. It formed the valley now occupied by Lake Traverse and Big Stone Lake. Glacial River Warren, as it is known to distinguish it from the modern Minnesota River, flowed episodically during the next 2000 years, creating the deep, mile wide valley as it cut through up to 200 feet of glacial sediment and in places, exposed the bedrock. This had a profound effect on the Minnesota River watershed because the newly deepened valley meant that all of the tributaries to the river had to adjust their gradients to match. They are still adjusting to this event today and are not very far along in the process. Every drop of water they get helps them erode more in their effort to adjust to an event that seems like ancient history.

Topography of Minnesota and the eastern Dakotas

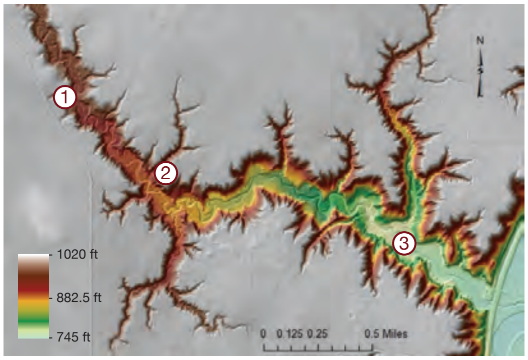
Glacial Lake Agassiz was impounded by the Big Stone moraine (1) that separates the Red River watershed from the Minnesota River watershed. Glacial River Warren, an outlet channel created by the draining of glacial Lake Agassiz (2), follows the centerline of the glacial trough south of the Big Stone moraine. The Minnesota River now only partially occupies the valley created by Glacial River Warren (enlargement). The Prairie Coteau (3) with the narrow Buffalo Ridge separates the troughs of the Des Moines glacial lobe (4) and the James lobe (5) in the Dakotas.





The tributaries would have instantaneously become waterfalls or very steep steps in the river profile (known as nick points). Nick points work their way upstream by the turbulence at the base of a falls undercutting the ledge causing it to break off. At least, that's how it works when bedrock is present. In sediment or till, waterfalls are not supported and instead, steep reaches with rapids and boulder beds stretch over the actively eroding zone. Reaches of the river with steep bluffs along the valley walls have already adjusted or at least begun adjusting. Lazy streams that seem to be level with the land around them don't even know what is in store yet. As the nick point or zone moves up the tributary stream, its tributaries experience a sudden drop at their mouths and they become overly steep ravines. In this way, tributaries, ravines and newly formed bluffs increase the supply of sediment to the river at a rate related to flows.

The nick points will continue to move up the tributaries until the entire watershed of the Minnesota River has adjusted to the level of the river itself. Nick points divide tributaries of the Minnesota River Basin into an upper segment receiving sediment primarily from field, ditch, and stream erosion and a lower, incised segment, which receives additional sediment from high bluffs and ravines (elevation map below). While incision is a natural part of stream network development, increases in precipitation, decreases in spring transpiration with the shift from perennial vegetation to annual row-crops, and removal of water storage in wetlands, shallow lakes, and other surface depressions has resulted in increased flows to the streams. This has accelerated incision in this vulnerable landscape. Streambanks, bluffs, and ravines are now the source of the majority of sediment reaching the Mississippi River from the Minnesota River.

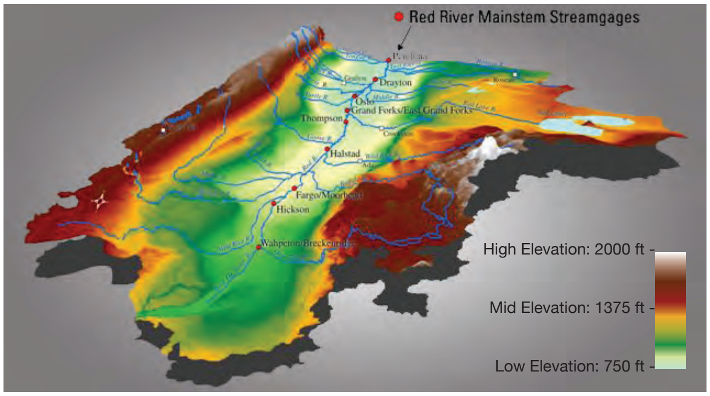


Seven Mile Creek Incision from the Minnesota River with elevation change of >200 ft. from uplands to valley floor.

B.3 RED RIVER BASIN

Over the life of Lake Agassiz, fine-grained sediment consisting of silt and clay settled to the lake bed. This became the parent material for the heavy soils of today's agriculturally productive Red River Valley. The modern Red River slopes very gently to the north at less than one foot per mile and has not incised because it had no valley incision event like the Minnesota River watershed did. It also loses a tiny bit of gradient every year as the land to the north, that was covered by thicker ice, continues to rebound. Floods of the Red River spread over wide distances with no deep valleys to confine them. Floods are also exacerbated because in a north-flowing river, spring flooding comes to the southern part of the watershed first and may encounter still frozen parts of the river to the north.

Although the flat lake plain portion of the valley is large, it is not the whole of the Red River watershed, which extends beyond the beach ridges of the former glacial lake and is drained by tributaries originating in higher elevation glacial deposits (elevation map to the right).



Elevation of the Red River of the North watershed in the U.S.

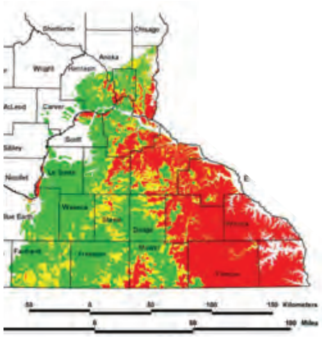
The Red River watershed is larger than the flat lake plain portion of the valley.

Source: USGS

B.4 SOUTHEASTERN MINNESOTA KARST LANDSCAPE

Southeastern Minnesota was bypassed by the last glaciation but all of Minnesota has been glaciated at some point in time. The long history of glacial meltwater draining through the Mississippi River has allowed the tributary rivers in southeastern Minnesota to become deeply incised, highly evolved rivers that control the relief. They expose gently sloping layers of limestone, shale, and sandstone bedrock that were originally deposited in shallow seas two to five hundred million years ago. Away from the valleys, these layers may be shallowly buried by older glacial till and windblown loess. Sediment cover generally thickens westward.

These rock layers dissolve in slightly acidic rainwater over time, and cracks have enlarged to form caves and sinkholes. These conduits allow surface water to quickly enter the groundwater system. This water may resurface lower in the landscape in the incised valleys as springs and streams. This karst topography, where it is overlain with relatively thin sediment on the eastern side of the region, is very susceptible to groundwater contamination. Natural drainage is usually good in this region. The dissected and steeply sloping landscape created by incision of tributaries from the much lower Mississippi River valley makes the eastern side susceptible to high rates of erosion when exposed by tillage.



Covered Karst

Transition Karst

Active Karst

Minnesota karst lands

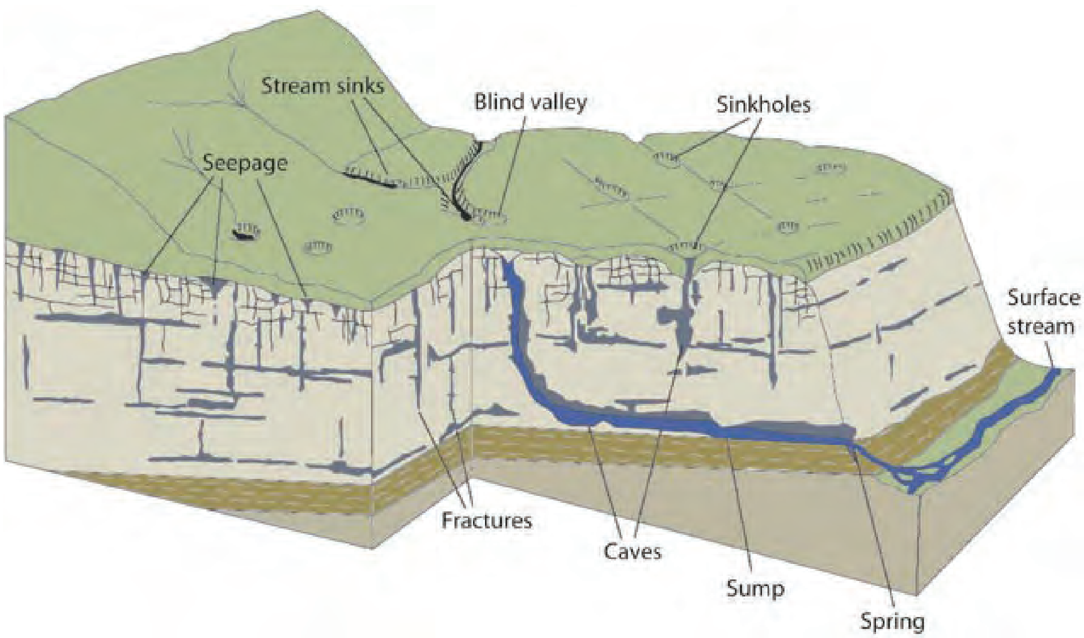
Limestone bedrock runs as far west as Faribault County, but is overlain by an increasingly thick layer of glacial till. The active exposed karst areas and the transition areas with only a thin layer of till are susceptible to groundwater contamination.

Covered Karst - Areas underlain by carbonate bedrock but with more than 100 ft. of sediment cover.

Transition Karst - Areas underlain by carbonate bedrock with 50-100 ft. of sediment cover.

Active Karst - Areas underlain by carbonate bedrock with less than 50 ft. of sediment cover.

Source: E. Calvin Alexander



Karst topography

Source: Wisconsin Geological Survey

The area glaciated by older events where the evidence of glaciation is less pronounced is two counties wide along the Mississippi River in southeast Minnesota, however the limestone bedrock continues west, and is overlain by an increasingly thick layer of glacial till. Consequently the transition area with a thinner layer of till is still somewhat susceptible to groundwater contamination (see karst map).

REFERENCES

Clayton L, Moran SR. 1982. Chronology of late-Wisconsinan glaciation in middle North America: Quaternary Science Reviews. v. 1: 55 – 82.

Dalzell B J, Pennington D, Polasky S, Mulla D, Taff S, Nelson E. 2012. Lake Pepin Watershed Full Cost Accounting Project. Final Report prepared for the Minnesota Pollution Control Agency 177 p.

Green JA, Barry JD, Alexander EC Jr. 2014. Springshed assessment methods for Paleozoic bedrock springs of Southeastern Minnesota. http://www.dnr.state.mn.us/waters/groundwater_section/pilot/springshed.html

Hobbs HC, Goebel JE. 1982. Geologic map of Minnesota, Quaternary geology [map]. 1:500,000. Map S-1. St. Paul: Minnesota Geological Survey, University of Minnesota.

Matsch CL. 1983. River Warren, the southern outlet of Lake Agassiz. In Teller JT, Clayton L. eds., Glacial Lake Agassiz: Geological Association of Canada Special Paper 26:232–244.

Minnesota Department of Natural Resources. 2007. Native plant communities and rare species of The Minnesota River Valley counties. Biological Report No. 89 http://files.dnr.state.mn.us/eco/mcbs/mn_river_report.pdf

Teller JT, Thorleifson LH, Dredge LA, Hobbs HC, Schreiner BT. 1983. Maximum extent and major features of Lake Agassiz. In Glacial Lake Agassiz, ed. Teller JT, Clayton L. p. 43–45. Special Paper 26. St. John' s, Newfoundland: Geological Association of Canada.

UNIVERSITY OF MINNESOTA
EXTENSION