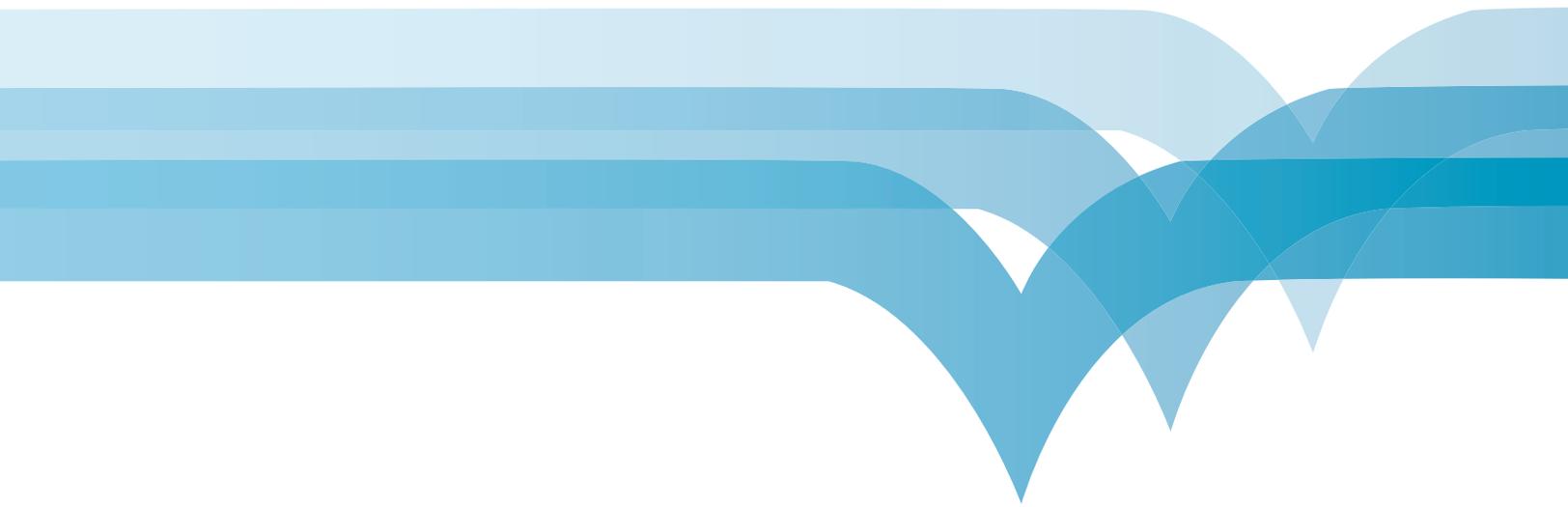


# **Drain Tiles and Groundwater Resources: Understanding the Relations**

MINNESOTA GROUND WATER ASSOCIATION  
WHITE PAPER 03

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# Acknowledgments

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# Drain Tiles and Groundwater Resources: Understanding the relations

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## Glossary of Terms and Acronyms

**aquifer:** an underground layer of water-bearing permeable rock or unconsolidated materials (sandstone, sand, and gravel) from which groundwater can be extracted using a water well.

**anthropogenic:** relating to or resulting from the influence of humans on nature.

**aquitard (or confining layer):** a layer made of materials with low permeability, such as clay and shale, which prevent any rapid movement of water.

**bedrock:** the consolidated rock at surface or underlying unconsolidated surface materials such as soil or glacial sediment.

**blowouts:** a collapse caused by a failing tile or clogged tile where a sinkhole can be created as the soil is drawn into the tile and transported downstream. Can also become a direct conduit for sediment and pollutants, also can cause the catastrophic failure of a tile drainage system.

**buried aquifer (or confined aquifer):** a body of porous and permeable sediment or bedrock which is buried beneath the ground surface by a low permeability layer.

**carbonates:** class of sedimentary rocks composed primarily of carbonate minerals.

**Clean Water Act:** primary federal law in the United States governing water pollution, enacted in its modern form in 1972.

**Cretaceous:** an era of geologic time from about 145 to 65 million years ago.

**denitrification:** a process by which oxidized forms of nitrogen such as nitrate (NO<sub>3</sub><sup>-</sup>) are reduced to form nitrites, nitrogen oxides, ammonia, or free nitrogen; commonly brought about by the action of denitrifying bacteria and usually resulting in the escape of nitrogen to the air.

**drainage coefficient:** a key drain system design parameter. It is the rate (in e.g. cm/24-hr or in/24-hr) the drain pipe and outlet can remove water from the site. It is dependent on the size, slope, and roughness of the pipe and pumping capacity in cases where the outlet is pumped.

**drain tile (or tile drain):** a pipe with either joint gaps or perforations used to control groundwater levels.

**evapotranspiration:** the process by which water is transferred from the land to the atmosphere by evaporation from the soil and other surfaces and by transpiration from plants.

**glacial:** relating to or derived from a glacier or depositional processes associated with a glacier.

**groundwater:** water that collects or flows beneath the surface of the earth, filling the porous spaces below the water table in soil, sediment, and rocks.

**hydrogeology:** the study of subsurface water, including its physical and chemical properties, geologic environment, role in geologic processes, natural movement, recovery, contamination, and use.

**hypoxia zone (or dead zone):** a level of oxygen inadequate to support most marine life in bottom or near-bottom water, leading to the use of the phrase “dead zones”; one of the world’s largest hypoxia zones is the Gulf of Mexico hypoxia zone, located beyond the mouth of the Mississippi River drainage.

**infiltration:** the movement of water from the land surface into the subsurface under unsaturated conditions.

**nitrate** (nitrate-N, NO<sub>3</sub><sup>-</sup>): a salt of nitric acid, commonly used as a plant nutrient.

**Paleozoic:** an era of geologic time from about 542 to 251 million years ago.

**peatlands:** a special type of wetland, consisting largely of peat or peat bogs.

**perched aquifer:** an unconfined groundwater separated from an underlying main body of groundwater by an unsaturated zone.

**potentiometric surface:** a surface representing the total head of groundwater in an aquifer and defined by the levels to which water will rise in tightly cased wells.

**prairie potholes:** shallow wetlands resulting from glaciation (e.g. Wisconsin Glaciation age); the Prairie Pothole Region is an area of the northern Great Plains extending from Alberta to Iowa, that contains thousands of prairie potholes.

**Precambrian:** an era of geologic time from about 3.8 billion to 542 million years ago, prior to the Paleozoic.

**Quaternary:** an era of geologic time that began 2.588 million years ago and continues to today. The Quaternary Period comprises the Pleistocene and Holocene epochs.

**recharge:** processes by which water enters the groundwater system; also referred to as deep drainage or deep percolation.

**riparian:** relating to or situated on the banks of a river.

**runoff (surface):** water, from rain, snowmelt, or other sources, that flows over the land surface; runoff that occurs on surfaces before reaching a channel is also called overland flow.

**sandstone:** a sedimentary rock made mostly of sand-sized grains. Water is stored primarily in joints, fractures, and bedding planes.

**soil moisture:** the quantity of water in the soil pore spaces. It is a key variable in controlling water and heat exchange between the land surface and the atmosphere through evaporation and plant transpiration (a process often termed evapotranspiration).

**STATSGO:** U.S. Department of Agriculture Natural Resources Conservation Service soils database, short for State Soil Geographic Data Base.

**stratigraphy:** a branch of geology that studies rock layers and layering (stratification). It is primarily used in the study of sedimentary and layered volcanic rocks. Also used to refer to the sequence of rock layers in a region.

**subsurface drainage:** the practice of using pipes made of various materials (i.e., clay, plastic, cement) to control groundwater levels; in the case of this white paper, all subsurface drainage referred to in this paper is agricultural-based.

**till:** unsorted glacial sediment deposited directly by ice. It is derived from the erosion and entrainment of rock and sediment over which the glacier has passed; an unstratified mixture of clay, silt, sand, gravel, and boulders.

**unconfined:** an aquifer that has direct contact with the atmosphere through an unsaturated layer.

**watershed (or drainage basin):** the area of land drained by a single stream or river.

**water table:** the top water surface of an unconfined aquifer at atmospheric pressure.

**wetland:** an ecosystem whose soil is saturated for long periods seasonally or continuously; consisting of marshes, swamps, and ephemeral ponds.

## Executive Summary

Drainage for agricultural production over the past 150 years has been an integral component of human-driven change to Minnesota's rural landscapes.

### Benefits of drainage

Historically, poorly drained soils across much of the State would often remain saturated or flooded after spring snowmelt, preventing timely farm operations such as tilling and planting crops (Arneman, 1963). Installation of agricultural drainage, both surface ditches and subsurface drainage, accelerated transport of water off farm fields and imparted producers higher crop yields (Beauchamp, 1987; Stoner and others, 1993). Agricultural drainage offered many other benefits such as preventing crop drown out, aerating the soil profile for improved plant growth, limiting surface runoff and soil erosion, and allowing farmers better access to croplands (Fausey and others, 1987). Without agricultural drainage on much of Minnesota's croplands, it would have been difficult to realize high enough crop yields to remain economically viable.

### Environmental concerns

While drainage of Minnesota croplands provided the benefits mentioned above, several environmental concerns result. These include wetland loss, degradation of downstream water quality, and reduced [potential for] recharge.

Early agricultural drainage efforts (pre-20th century) led to the disappearance of much of Minnesota's natural wetlands. Increased focus on preventing or mitigating wetland loss over the last 50 years has helped curtail further losses, even as agricultural drainage proceeds. Prior to establishment of Minnesota statehood, wetlands accounted for more than 10 million acres in Minnesota, including prairie wetlands, peatlands, and forest wetlands that comprised approximately 19 percent of the total land area (Palmer, 1915; King, 1980). In 2018, only half of Minnesota's pre-settlement wetlands remain, mostly in parts of the State that have not experienced widespread drainage, such as northern Minnesota.

Water-quality monitoring has shown that agricultural drainage, in particular the practice of subsurface drainage, provides a direct flow path for nutrient (nitrogen and soluble phosphorus) losses to surface water resources. The negative consequences of agricultural drainage on surface water quality are well documented (for example, Dinnes and others, 2002; Klavivko and others,

2004; Richards and others, 2008; Rozemeijer and others, 2010; Schottler and others, 2013). Agricultural basins with a high percentage of agricultural drainage have been implicated as part of the cause of the Gulf of Mexico hypoxia zone due to excessive nitrogen export (Goolsby and Battaglin, 2001; Randall and Mulla, 2001).

The connection of hydrological effects of agricultural subsurface drainage on groundwater recharge and aquifers, on the other hand, has not been well-established. Agricultural subsurface drainage intercepts infiltrating water below croplands and directly discharges the water to nearby surface waters. However, the size of the water balance shift from drained water that would have evapotranspired or run off the land to drained water that would recharge underlying aquifers has been poorly characterized (Schuh, 2008).

### Drain Tiles and Groundwater

Given the poor accounting of subsurface drainage effects on groundwater resources, the Minnesota Ground Water Association (MGWA) deemed it imperative that we document these effects so that groundwater resources in agricultural regions with substantial drainage can be effectively managed. This white paper documents the relations of drain tiles and groundwater resources and discusses the historical significance of agricultural drainage practices, the recognized positive benefits and potential negative consequences of agricultural drainage practices, and the gaps in understanding of the connections between agricultural drainage and groundwater resources.

The major messages emerged from the findings of this white paper are:

- ◆ **Complex history.** Minnesota has a long history of agricultural drainage, spanning over 150 years. Agricultural drainage, and the eventual widespread usage of subsurface drainage, can be separated into at least four distinct periods of time: (a) early drainage to get water off the land, pre-20th century; (b) the boom and bust era (1900-1945); (c) postwar resurgence of subsurface drainage and early conservation efforts (1945-1960); and, (d) emergence of the environmental movement (1960 to present). The State's regulatory framework that both allowed for drainage and controlled its usage during these periods is complicated and has been governed by a patchwork of both State and Federal statutes.
- ◆ **Drainage Provinces.** This white paper advances the concept of tile drainage provinces to aid in the dis-

cussion of regional differences in subsurface drainage and its overall effect on groundwater resources. Built upon the concept of groundwater provinces (Minnesota Department of Natural Resources, 2001), three distinct tile drainage provinces were conceptualized: (1) the Southeastern Province; (2) the South-Central Province; and, (3) the Western Province. The distinct geology and the soils that developed in these regions have implications for each region's subsurface drainage density and the potential implications for groundwater.

◆ **Knowledge gaps.**

Several critical knowledge gaps are identified in this paper, creating opportunities for further research to improve our understanding for better managed water resources:

- 1. Extent of drainage is unknown.** Direct estimates of the extent of subsurface drainage do not exist in Minnesota. However, several indirect methods have been utilized to estimate subsurface drainage, from the field-scale to county-level through the use of geographic information system (GIS) analysis and aerial photography. Based on a 2012 U.S. Geological Survey estimate of subsurface drainage extent (Nakagaki and Wieczorek, 2016), about 21% of the land area in Minnesota has some density of subsurface drainage.
- 2. Effect of drainage on underlying aquifers is unknown.** A basic understanding of unconfined and confined aquifers and their recharge is necessary to connect any hydrological effects from agricultural drainage to groundwater. The basic goal of subsurface drainage to efficiently drain saturated soils clearly alters the water balance in croplands. However, its overall effect on groundwater resources has been poorly characterized, and is in large part determined by the geology below drained areas and the arrangement of underlying aquifers.
- 3. Water balance shifts.** An improved understanding of historical water balance shifts from pre- to post-drainage periods is necessary to understand long-term implications on net groundwater recharge. Also, more direct field-scale studies and indirect modeling studies are needed to characterize water budgets for fields with subsurface drainage.

# 1. Problem Statement and Definition

In May 2016, the White Paper Committee (WPC) of the Minnesota Ground Water Association (MGWA) circulated a request for participation to its members and others who had interest and expertise in developing a white paper with the project name: *Drain Tiles and Groundwater Resources: Understanding the Relations*. The workgroup was organized into three subgroups: Experts, History, and Science. The Experts subgroup was tasked with finding subject experts related to subsurface drainage (also known as drain tiling) and groundwater resources. During information gathering, experts were consulted on subjects ranging from subsurface drainage design and drainage policy to hydrogeology. The History subgroup focused on documenting the history of agricultural drainage both across the United States and Minnesota, as well as the history of Minnesota drainage management. The Science subgroup was tasked with looking for and assessing research that investigated the interaction of subsurface drainage with the groundwater resources in the State.

Overall, the goals of this white paper were to document the current state of the science for describing, understanding, and quantifying the relation of subsurface drainage (drain tiling) to groundwater resources. The white paper brings together the following information to:

- ◆ Summarize concisely the history and current trends of tiling in Minnesota;
- ◆ Highlight the regulatory environment for subsurface drainage;
- ◆ Review the scientific literature related to quantifying or otherwise describing the effect of subsurface drainage on groundwater resources;
- ◆ Detail the state of understanding related to tiling and groundwater resources, including the potential changes to recharge of surficial and confined aquifers; and,
- ◆ Identify knowledge gaps and opportunities for research related to understanding subsurface tiling effects on groundwater resources.

While it is known that there are instances of other types of subsurface drainage influencing groundwater resources, the scope of this white paper is limited to the relation of agricultural subsurface drainage and groundwater.

The primary audience for this white paper are agricultural producers, decision makers who affect agricultural drainage and groundwater policies, academic and government agency researchers, and the general public.

## 2. Agricultural subsurface drainage: Goals, materials, and design

Agricultural drainage engineers and soil scientists often debate the definitions, goals, and objectives of agricultural drainage systems (for example, Wright and Sands, 2001; Panuska and others, 2009; Hofstrand, 2010). However, the singular outcome of a functioning subsurface drainage system is clear: subsurface drainage allows growers to manage soil moisture by moving water from shallow soils to surface water features (Evans and others, 1992; Skaggs and others, 1994). Subsurface drainage systems can be used to lower the water table and thus allow more robust root systems to develop beneath crops (Kanwar and others, 1988). By facilitating partial saturation of the soil pores beneath farm fields, drain tiling improves soil health by permitting biological processes that require the presence of oxygen (Moebius-Clune and others, 2017). Subsurface drainage systems also facilitate improved access and use of fields by eliminating wet surface or near surface areas (Fausey and others, 1987). From increasing root zone soil temperature to reducing surface runoff from overflowing surface depressions, drain tiling is known to provide numerous improvements to crop production.

A simple summary of subsurface drainage systems is difficult because the design of any one system is usually customized to maximize its effectiveness to the field in which it is to be used. A typical system that includes a series of parallel subsurface drainage pipes, located at a depth approximately three to four feet below land surface, is shown in Figure 1 (Busman and Sands, 2002). In this example, the horizontal drainage pipes lower the

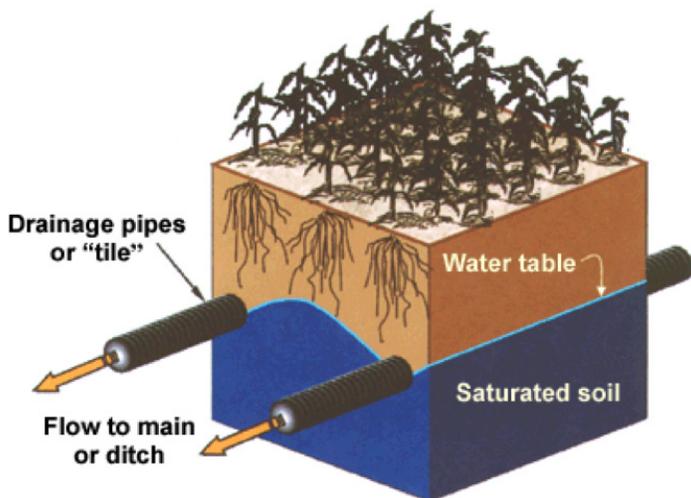


Figure 2. Open pipe leading to an underground network of sub-horizontal pipe, from west-central Minnesota (photo by B. Hoppie).

water level to the depth of the submerged drainage pipes. Several methods exist to connect the horizontal drainage pipes to land surface. For example, some systems start simply with an open vertical pipe (Fig. 2), known as an open intake (also known as an open inlet). The open intake is installed flush with the level of the wet area and is connected below ground to a network of sub-horizontal pipes. In other cases, the inlet to these underground pipes can be blind (also known as a French drain). A French drain (Fig. 2) includes a column of coarse sedimentary fill brought to the site and installed above the pipe to enhance the vertical drainage into the subterranean pipes. In yet another variation of design, some subterranean piping networks have no direct vertical connection. These pipes are jointed or perforated and water levels in soils are lowered by the slow, continuous leakage of pore water through the joints between tiles or perforations incorporated directly into the pipe.

The principal component of an agricultural tile system is the tile itself, which is most commonly no longer even clay tile. Originally, the sub-horizontal subterranean pipes were relatively short sections of clay tile laid end-to-end in a narrow, subsequently back-filled trench (Fig. 3). Concrete pipes of similar size were used in mineral soils. Most recent applications now utilize perforated polyethylene plastic (Fig. 3). Regardless of the vintage and materials, most systems exist in a configuration of smaller (three- to six-inch diameter) laterals that drain to

Figure 1. Subsurface drainage pipes draw down the water table to the depth of the semi-horizontally submerged drainage pipes or "tiles". Drainage tiles are typically placed at depths of three to four feet below land surface. Image courtesy of the Agricultural Drainage home page, University of Minnesota Extension (Busman and Sands, 2002).

larger (24- to 48-inch diameter) pipes that are known as mains.

Drain tiling is plumbed to use gravity to move water below cropped fields to off-field receiving points such as agricultural drainage ditches or neighboring wetlands, ponds, or some other low point in the landscape that can hold the water drained by the tile. The highest point of the tile is at a depth below the frost line, which can vary in Minnesota from (average minimums of) three to five feet. Tile is generally not installed deeper than necessary as greater depths add cost and logistical challenges (for example, wheel trencher size, soil strength, and increased glacial erratic obstructions). The desire to use gravity drainage is another factor that limits the depth of installation. Pumps (also known as lift stations) are sometimes used to lift the water out of the tile; however, pumping requires additional capital and operational costs.

The distribution of the underground pipes may exist within any one or combination of several typical designs (Panuska, 2012) (Fig. 4):

- ◆ **Targeted** or Custom fit: Some tile systems are installed to specifically target the lowest areas of natural depressions and provide an interconnected, subterranean drainage to the pour point. This design works especially well in small, wet areas within fields where the remaining soils drain adequately.
- ◆ **Herringbone** systems increase the coverage area through a combination of offset laterals that drain to

a larger main that drains to a point off the field. More pipe and junctions make this design more expensive; however, the increased density of the laterals allows improved drainage in soils that contain more clays that limit the horizontal movement of water.

- ◆ **Gridiron**, commonly referred to as parallel or pattern tiling, uses numerous arms that are regularly spaced, at nearly uniform depth, all sloping at an equal gradient into a main, or sometimes a sub-main that joins into the single, larger pipe that carries the water away from the field. These designs involve a substantial amount of pipe and are the most expensive option available to the producer. However, in clay-rich, perennially wet soils, this option provides the means to significantly improve crop yields while reducing overland flow and the loss of top soil.

Additional, subtle design parameters include the orientation and grade of the laterals and mains. Laterals are aligned parallel to equal elevations of the existing water table to facilitate an equal intake of water along the entire length of pipe, and thus preventing vertically different soil-pore-saturation values within the field and maximizing the effectiveness of the pipe. Similarly, consideration must be given to finding the optimal grade of the laterals and mains. Grades of 0.2 percent are generally held as a minimum; steep grades, however, are generally avoided because of costs associated with additional excavations, finding a receiving reservoir that is sufficiently lower than the pour point, and other soil manage-



Figure 3. The image on the left illustrates an older clay tile (photo courtesy of Johnson Farm House historical site, <http://townoffayetteny.org/history-drainage-tiles.php>). On the right, modern polyethylene perforated pipe (<https://collingwoodbluemountain.com/our-wet-basement-and-lessons-learned-part-1/>).

ment issues related to moving water too rapidly in the subsurface (for example, soil sink holes and blowouts).

The preceding discussion of subsurface drainage system design paints a picture of a complex system that must be considered thoroughly and planned properly prior to installation and operation. The science and engineering of sizes, depths, gradients, and patterns of agricultural subsurface drainage systems is beyond the scope of this paper (for example, van Schilfgaarde, 1957, Skaggs, 1986); if further information regarding the determination of “drainage coefficients” or pattern spacing are required, the reader is referred to any of the available university agricultural extension offices (for example, <http://www.igrowdrainage.org/#/calculators/drainage-coefficient>) or vendors (<http://www.ads-pipe.com/en/documentlisting.asp?documenttypeID=682>) that provide such services.

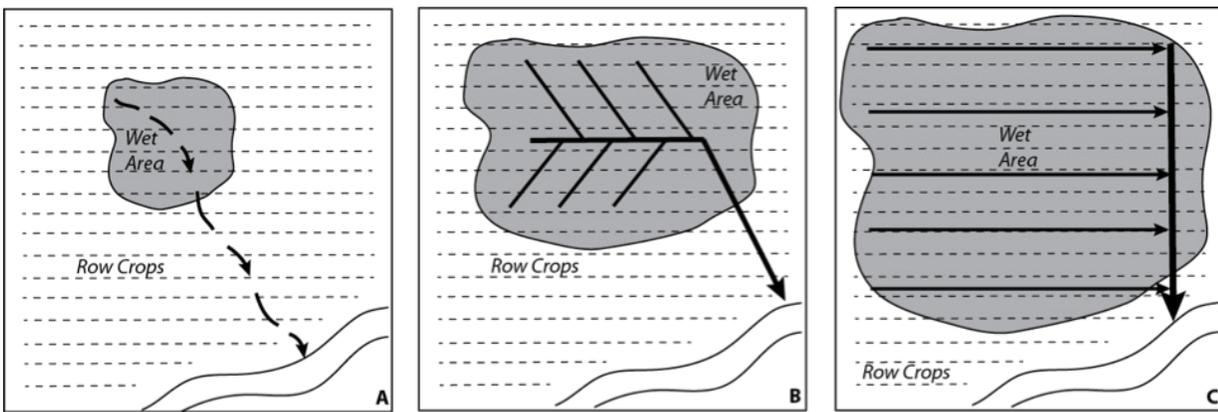


Figure 4. Examples of drain tile patterns. A) Targeted or custom fit tile drawing water away from a small, isolated wet area within the field of row crops. B) Facilitating drainage from a larger area, the herringbone design collects water through a series of laterals that drain to sub-main and main drainage pipes. C) Grid iron or parallel patterns use regular spacing to affect a uniform lowering of soil moisture from large areas.

### 3. Agricultural subsurface drainage: History

#### Getting Water off the Land – Early Statehood

Agricultural drainage is integral to Minnesota’s evolution as a state. It is estimated that at the time of statehood in 1858, the Minnesota territory contained over 10 million acres of wetlands, including prairie wetlands, peatlands, and forest wetlands that comprised approximately 19 percent of the total land area (Palmer, 1915; King, 1980). These lands were viewed as breeding grounds for disease and impediments to transportation, agriculture, and development (Wilson, 2016).

As codified in 1887, the goals of Minnesota’s wetland drainage policy were two-fold: first, they were to improve land productivity; secondly, they were to “remove... causes of malaria”. Subsequently, a series of legislative acts formed the basis for drainage law as it exists today, under which the costs of drainage improvements are assessed to the “benefited” parties. The focus of drainage law was on enabling joint drainage systems across ownership, township, and county boundaries, and minimizing conflict. These acts included the following:

- ◆ In the Swamp and Overflowed Lands Act of 1860, the federal government granted title to over four million acres of these “swamplands” to the state (Swamp and Overflowed Lands Act of 1860, 1860). The proceeds from these lands were intended to pay for their drainage, although most of the lands were ultimately

granted to railroads and to educational, charitable, and state institutions.

- ◆ Authority to oversee drainage was vested in a variety of government entities: registrar of deeds, justice of peace and jury (1866), township supervisors (1877), county commissioners (1879), state drainage commission (1897), and district courts (1902) (Wilson, 2016).
- ◆ The basis for modern drainage law is an 1887 act that enabled a single landowner to petition for construction of a ditch (Laws of Minnesota, 1887). If the county commissioners determined that the ditch was of public benefit, they accepted the petition and appointed three “viewers” to survey and locate the ditch and to define benefits and damages (Laws of Minnesota, 1887). Benefits were assessed to the lands that benefitted from the construction.

Minnesota drainage law (i.e., the drainage code) is currently contained in Minnesota Statutes, Chapter 103E Drainage. As the drainage law has evolved, only county, joint county, or watershed district boards can act as drainage authorities. Many other original features of drainage law remain unchanged, however, including the use of viewers and the drainage assessment costs for drainage improvements to benefited landowners.



Figure 5. Installation of clay tile on the Johnston farm, circa 1938 (photo from [http://www.nejohnston.org/wej/120 Years of Johnston Farming/120 years of Johnston Farming.html](http://www.nejohnston.org/wej/120%20Years%20of%20Johnston%20Farming/120%20years%20of%20Johnston%20Farming.html)).

Although the multiple statutes mentioned above formed the foundation for drainage law, little organized drainage took place until settlement had advanced to the Red River Valley of western Minnesota in the 1890's. The flat topography of the Red River Valley hindered drainage of fertile soils, which were otherwise well-suited to wheat cultivation. The Red River Drainage Commission was formed in 1893 to initiate large-scale drainage systems. Work was then begun on nineteen State ditches, each fed by local and county ditches (Palmer, 1915; Hanson, 1987).

From surface ditches, drainage practices evolved to incorporate tiling: the practice of installing short, cylindrical sections of concrete or clay, called tile, at depths of three up to six feet, placed to remove water from isolated wet areas or installed in a pattern to drain an entire field (Wilson, 2016). The tile lines feed water drained from the field into surface ditches or natural watercourses.

Tiling is an ancient agricultural practice. Tiling by Roman farmers was extensively documented by the author Cato in 160 B.C. in his treatise titled *De Agri Cultura* (translated as "On Farming"). Tile drainage was first introduced to the United States in 1838 when John Johnston brought the practice from his native Scotland to his farm in Seneca County, New York (Fig. 5). Johnston laid 72 miles worth of clay tile on his 320-acre farm, increasing his wheat yield from 20 bushels per acre to 60 bushels per acre (Biebighauser, 2007). Upstate New York became a center for tile manufacture (Weaver, 1964). Most tile drainage in Minnesota was installed by hand-digging as late as the 1920s, but was gradually replaced by mechanical equipment (Wilson, 2016). Much clay and concrete tile was manufactured in Iowa, particularly Mason City, and Ohio.

#### Boom and Bust Era — 1900-1945

Drainage proceeded together with the growth of railroad networks and trade centers, to directly benefit agriculture. Transportation in agricultural areas was further expanded as roads were constructed on the fill material excavated from ditches. Activity peaked between 1900 and 1915 when it is estimated that approximately nine million acres were drained, fully 17% of Minnesota's total land surface (Hanson, 1987).

Flooding during the years 1916 to 1919 led to some tile failures and a decline in drainage activity. Below-normal rainfall in the 1920s and extreme drought in the 1930s, combined with low commodity prices and other effects of the Great Depression halted most drainage activities, while soil conservation emerged as a priority (Hanson, 1987).

Research on drainage methods at the University of Minnesota led to improvements in ditching and trenching, as ditching machines replaced hand tools. Tiling materials were also investigated. Concrete tile had become widespread but was subject to sudden failure. In 1925, the Minnesota Legislature appropriated funds to the University to study causes of these failures. Over the following 30 years, researchers compared thousands of samples of concrete tile and its constituent materials. It was determined that concrete tile tended to degrade when exposed to sulfates of magnesium and sodium in subsurface water, and improvements were made to the mixture of chemicals in the cement to prevent such failure (Wilson, 2016).

Driven in part by fishing and hunting interest groups, concerns for protecting meandered water bodies and defining public waters arose during the 1920s and 1930s. Statutes enacted during this period prohibited draining a meandered lake without state approval (Laws of Minnesota, 1925). Statutes were also expanded during this period in the definitions of navigable and public waters (Laws of Minnesota, 1937).

#### Postwar Resurgence and Conservation Concerns — 1945-1960

The return of "normal" rainfall patterns between 1938 and 1945 and an increase in commodity prices gave rise to an increased interest in drainage. Systems that had deteriorated through disuse during the Dust Bowl years were repaired and the use of drain tile became more widespread. Changes in drainage law eliminated state and township drainage authorities, leaving only district courts and county boards with the ability to establish drainage systems (Laws of Minnesota, 1947). Expansion of drainage continued throughout the 1950s. For example, the Division of Waters of the Department of Conservation (today's Minnesota Department of Natural Resources) reported that about 15,000 miles of drain tile were installed from 1954 to 1956, while almost 500 miles of open ditch were constructed or improved (Hanson, 1987).

In 1955, drainage law was amended relating to natural resources: conservation of soil, water, forests, animal habitat, and related resources were to be given consideration. State lands used for conservation purposes and public waters were not to be damaged by drainage projects without compensation (Laws of Minnesota, 1955a). The concept of watershed districts was also enabled by the Legislature, creating new types of drainage authorities (Laws of Minnesota, 1955b). In 1959, drainage authorities were granted the authority to require spread-

ing of spoil banks and planting of a one-rod grass buffer strip, presumably to improve ditch bank stability (Laws of Minnesota, 1959).

#### Environmental Movement — 1960s-1990s

In the late 1960s and early 1970s, while land values increased, conservationists began to question more-and-more whether drainage was always in the public interest. A host of new state and federal environmental regulations were enacted, ranging from the federal Clean Water Act (1972) to the Minnesota Environmental Protection Act (1973). Thereafter, drainage was scrutinized more closely. Several examples of how statutory regulations were adjusted during this period are provided below.

Judicial authority to establish drainage systems was eliminated and potential ecological impacts were to be considered in the review of projects or improvements (Laws of Minnesota, 1973). In 1976, the Legislature directed the Department of Natural Resources (DNR) commissioner to inventory public water basins and watercourses, and required the DNR and drainage authorities to examine specific environmental and conservation criteria before establishing drainage projects (Laws of Minnesota, 1976). Public wetlands that were to be preserved were inventoried, and a state water bank program was established to pay landowners for not draining private wetlands.

At the federal level, the 1985 “Swampbuster Act” (Food Security Act of 1985, 1985) removed eligibility for certain federal farm programs for farmers who converted wetlands to cropland. These requirements have continued in subsequent farm bills. In Minnesota, the Wetland Conservation Act (WCA) (Laws of Minnesota, 1991) regulates activities that may result in the draining, filling, or excavating of wetlands in Minnesota, including those on agricultural land. The WCA is implemented by local government units, typically counties, soil and water conservation districts, and cities. Generally, WCA applies to non-public waters wetlands. Public waters wetlands protections are administered by the DNR.

Notwithstanding the many environmental considerations in today’s drainage law, no regulations specific to the practice of drain tiling have been enacted. In fact, as the environmental requirements for surface drainage increase, the incentives for drain tiling may increase as well. Drain tiling, unlike construction, maintenance, and improvements to surface drainage systems, is largely a private activity conducted by individual landowners, not drainage authorities. Drain tile outlets into public or private surface water bodies are not considered point

sources of pollution under the Clean Water Act.

Advances in conservation drainage practices show some promise in reducing the high volumes of nitrate and other pollutants frequently discharged from drainage systems to nearby waterways (for example, Dinnes and others, 2002). Conservation drainage practices include but are not limited to controlled drainage via retention structures, shallow drainage, woodchip bioreactors, saturated buffers, gravel inlets, two-stage ditch design, and various kinds of storage basins (for example, Brandel, 2016; Lagzdins and others, 2016; Liu and others, 2016; Reinhart and others, 2016). Controlled drainage is a practice that has become more common in Minnesota (NRCS, 2013). Typically, a vertical control structure that intercepts the buried tile drain, such as a water control structure (Fig. 6), is installed at various locations around the tile drain system. Inside the control structure, adjustable sets of weirs control the flow of water through the tile drain. During periods of high flow, such as the spring, the weir is lowered to allow for efficient flow of water out of the field; during dry periods, the weir is raised to hold back water to raise water levels in the field for plant root development. Controlled drainage structures also can assist in limiting the flow of nitrate export (Dinnes and others, 2002), although this benefit can be limited by high nitrate export during high spring flows when the weirs are lowered (Fang and others, 2012).



Figure 6. Example of a control structure, an AgriDrain, being installed in a southeast Minnesota field (photo by E. Smith).

## 4. Agricultural subsurface drainage: Trends

Currently (2018), agricultural subsurface drainage exists throughout large parts of southern and western Minnesota, but the exact extent and configuration of subsurface drainage systems across the state has not been fully characterized. Generally, tile drainage is installed on private lands and the reporting of the installation configuration or extent of acreage is not required by state law. Instead, several different methods have been used for estimating subsurface drainage tile extent.

### Tile drainage reporting

In a paper entitled *Tile Drainage Rules: A Review of Minnesota Watershed District Rules* (Scott SWCD, 2017), it was reported that there were eleven watershed districts that require permits for the installation of private or public drainage systems and another eleven watershed districts that require permits for the installation of drain tile under certain circumstances.

Although other watershed or soil and water conservation districts might compile the extent of tile installation within their boundaries, only the Bois de Sioux Watershed District has records of permits required for private drain tiles in their district. The Bois de Sioux Watershed District, at the headwaters of the Red River, has documented the areal extent of tile drains since about 1999. In Figure 7, the proliferation of subsurface drain tiles is shown for the Bois de Sioux watershed (Engels, 2017). Figure 7 shows the increasing trend in drainage tile permitted since 2000, as measured in miles of tile line.

Figure 7 also indicates that the peak years for subsurface tiling for the Bois de Sioux were 2012 and 2013, with approximately 3,000 miles of drain tile installed each year.

### Estimation of tile drainage extent – World Resources Institute and U.S. Geological Survey

Subsurface drainage is often considered the “most extensive soil and water management activity in agriculture” (Fausey and others, 1987). However, at this time (2018), only indirect estimates of subsurface drainage exist in Minnesota or at the national level. Sugg (2007), from the World Resources Institute, used a geographic information system (GIS) analysis based on soil and land cover maps to estimate tile drainage on a county-by-county basis across the United States. Sugg (2007) also pointed out that a lack of data in recent years (2007) “makes it difficult to assess just how much tile has been sold and installed over the last twenty plus years”. Despite the lack of information, it is well known that farmers have continued to invest in tile drainage and that the extent of tile-drained land has increased, both spatially and through increasing density on previously tiled agricultural fields.

Newer estimates, similar to Sugg (2007), have been established by the U.S. Geological Survey; Nakagaki and others (2016) have estimated the subsurface tile drainage extent for the upper Midwestern United States through the early 1990s. Their methodology included the Sugg (2007) estimates, in addition to the construction of a

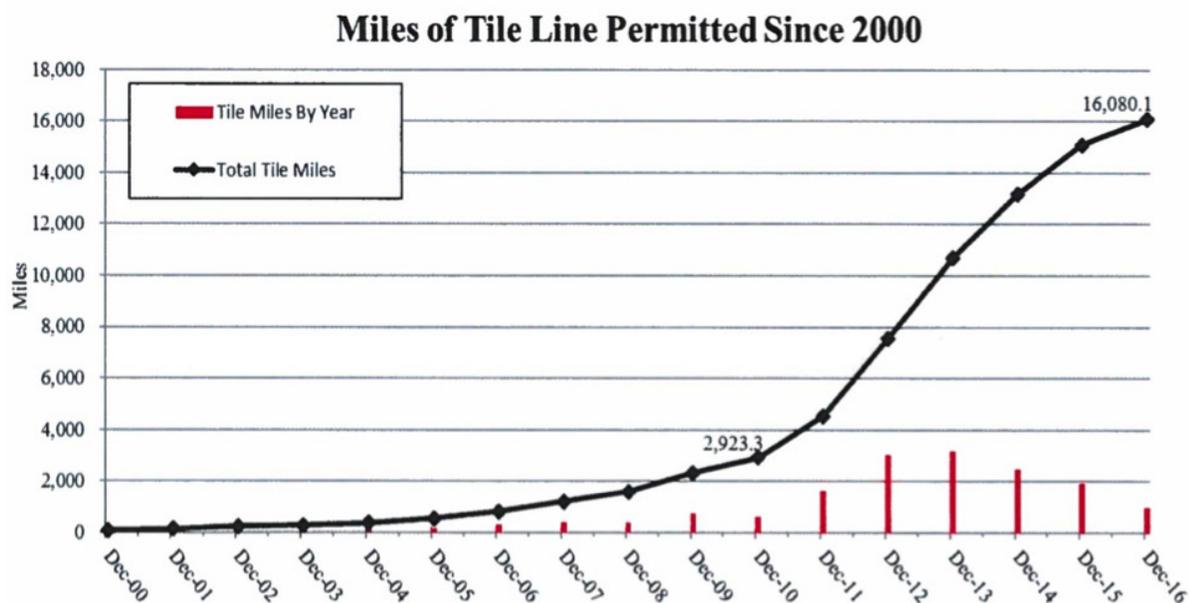


Figure 7. Miles of tile line permitted for the Bois de Sioux watershed, from 2000 to 2016 (Engels, 2017).

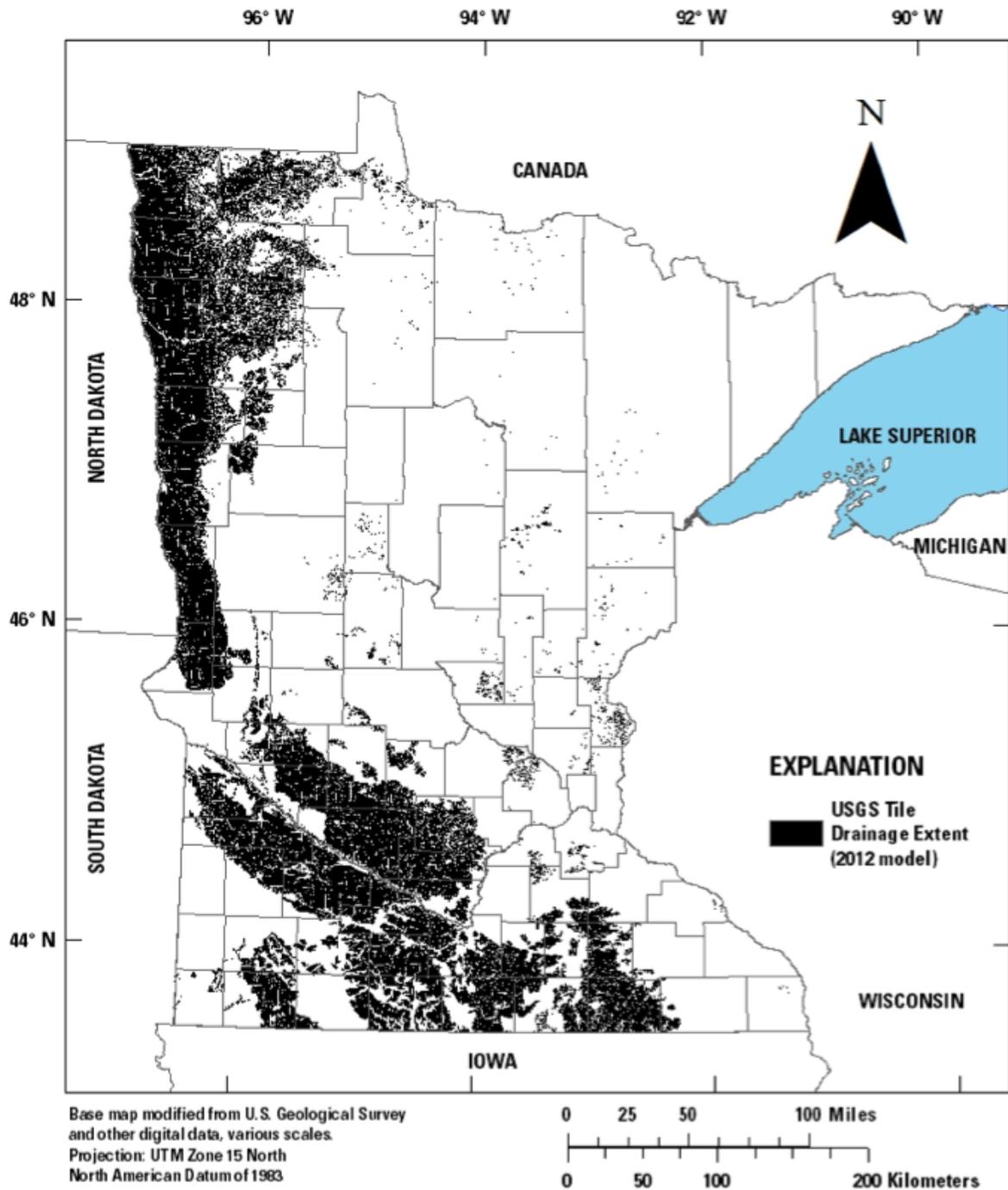


Figure 8. U.S. Geological Survey (USGS) tile drainage extent in Minnesota shown by a 30-meter raster, based on the Nakagaki and Wieczorek (2016) model of 12 Midwestern states.

model based on the extent of cultivated land and the extent of poorly drained soils from the State Soil Geographic Data Base (STATSGO). Rather than a county-by-county estimate, this new estimate was summarized from a 30-meter raster dataset illustrating the density of tile drainage in each cell in square meters. Additionally, Nak-

agaki and Wieczorek (2016) applied the same techniques for a 2012 tile drainage estimate (Figure 8). For Figure 8, the drainage density by cell has been eliminated and only shows if drainage existed in each cell.

## Estimation of tile drainage extent — Minnesota state agency estimates

Two Minnesota state agencies, the Minnesota DNR and MPCA, created a new approach to estimating tile drainage densities (D. Wall, written communication, November 1, 2017). The Minnesota state agency approach determined the existing tile drainage information for eight areas of Minnesota using three different sources. The sources included tile installation permitting, aerial photographic interpretation, and land owner interviews combined with aerial photography. The eight different areas represented a combination of different size areas, different geographic areas, and different methods of determining existing tile drainage. An example of aerial photographic interpretation of tile line locations is shown in Figure 9 (Giglierno and others, 2015).

After finding areas with mapped tile drainage, the Minnesota methodology estimated the amount of land within 50 feet of tile lines. The fifty-foot interval was chosen as a typical effective drainage distance for tile lines, recognizing that this distance varies by soil and hydrologic conditions. Next, nine different models that used combinations

of soil (Natural Resources Conservation Service, 2005), slope (Minnesota Geospatial Information Office, 2017), and crop information (based on the 2011 U.S. Department of Agriculture (USDA) Cropland Data Layer (CDL); U.S. Department of Agriculture, 2013) were constructed and compared to the available mapped tile drainage densities. Because there was a physical check on the modeled estimates, the best combination of soil, slope, and crop parameters was determined and then utilized for areas without any independent tile drainage density estimate.

Out of the nine different models, five were determined to be a significant (P value less than 0.05) predictor of tile drainage density with a coefficient of determination ( $R^2$ ) above 0.60. Table 1 summarizes the five different models. The hydric class for prediction had to be greater than 80 percent of the soil map unit, and the hydrologic soil group was one of four different classes: A/D, B/D, C/D, or D. Of the five models presented in table 1, the best hydrologic soil group predictor had less than a 3 percent slope (of land surface), and the best hydric class predictor also had a slope of less than 3 percent.

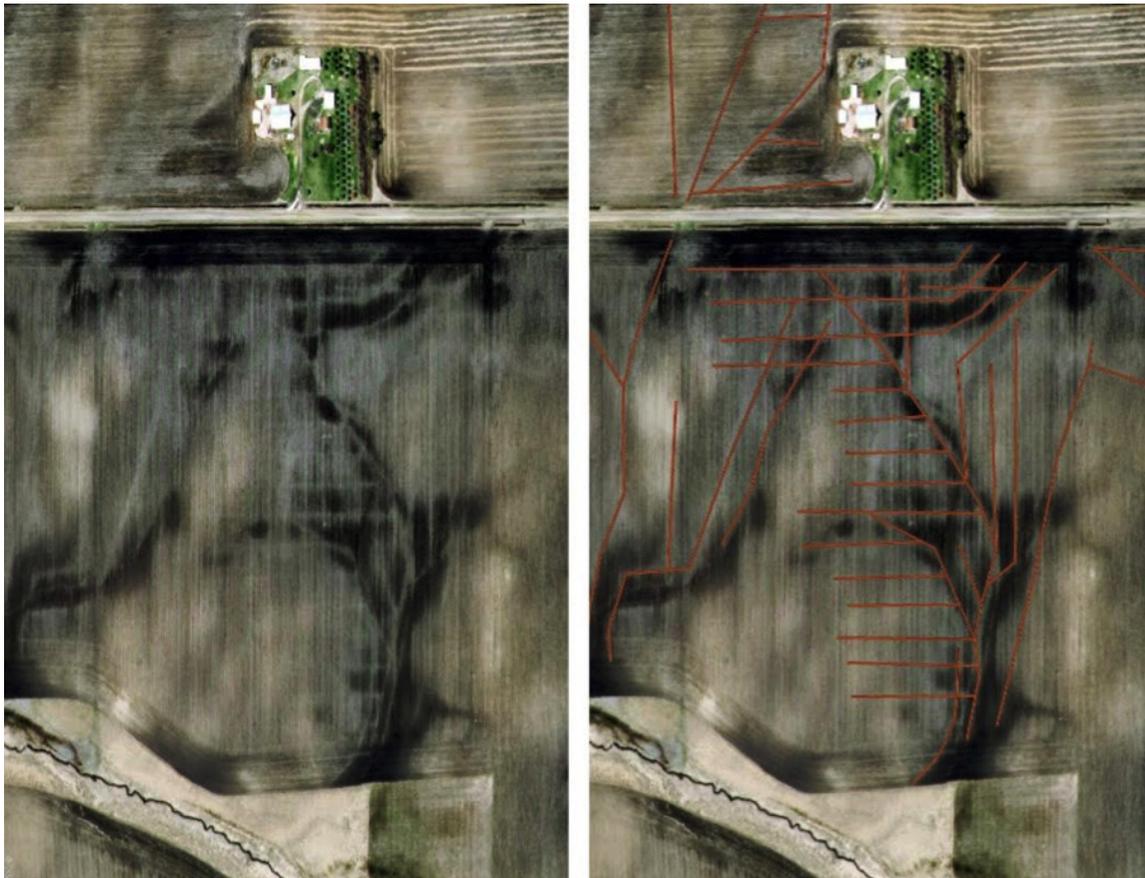


Figure 9. An example of aerial photographic interpretation of tile drainage locations, from Giglierno and others (2015), shown for a tile-drained field in the prairie pothole region of Iowa.

Tile drainage estimate	Intercept of line	Slope of line	P value (test if slope is zero)	R <sup>2</sup>
Hydric class, less than 3% slope	4.21	0.669	0.0223	0.6089
Hydrologic soil group, less than 3% slope	-7.63	0.726	0.0143	0.6597
Hydric class, less than 4% slope	4.08	0.656	0.0260	0.6051
Hydrologic soil group, less than 4% slope	-8.76	0.725	0.0115	0.6826
Hydric class, less than 5% slope	4.02	0.649	0.0232	0.6043
Hydrologic soil group, less than 5% slope	-9.26	0.724	0.0102	0.6943

Table 1. Five different tile prediction models built by Minnesota Department of Natural Resources and Minnesota Pollution Control Agency personnel (D. Wall, written communication, November 1, 2017), as compared to the independent tile drain estimate, including the line slope, intercept, P value, and coefficient of determination (R<sup>2</sup>).

Appendix 1 includes three different examples of the predicted tile-drained field maps: (1) Des Moines River – Headwaters watershed, MN; (2) Le Sueur River watershed, MN; and, (3) Root River watershed, MN. Of the three different watersheds, the Le Sueur River watershed (appendix 1-2) had the highest density of tile drains. This is also corroborated by the USGS coverage (Nakagaki and Wieczorek, 2016) that is shown in Figure 8. The Des Moines River – Headwaters watershed (appendix 1-1) shows more tile drained land for the Minnesota state agency estimate versus the USGS estimate. Finally, the Root River watershed shows less estimated tile drainage under either estimate as one moves farther east towards the border with Wisconsin. This part of the state has a more undulating landscape and the farmland is directly underlain by karst geology, both perhaps explaining the historically low densities of installed tiling in this area.

#### Recent trends in drain tiling

At a statewide level, increasing row crop cultivation has replaced small grains and livestock in many areas, in tandem with the conversion of Conservation Reserve Program lands back to row crops (Gonzalez-Ramirez and Ji, 2015). Over the last 20 years extreme rainfall events have become more common (Minnesota Environmental Quality Board, 2015). Across Minnesota, it is difficult to ignore ongoing tiling efforts in agricultural fields from the Red River Valley to southeastern Minnesota in Fillmore County. Particularly before and after harvest, large spools of perforated tile, with tiling machines and disturbed trenches can be observed. Despite the recently observed low commodity prices for both corn and soybeans in 2017, tiling activities continue. In addition to statewide patterns, several forces are driving the increase in tiling at the regional level:

- In northwestern Minnesota, newer corn and soybean varieties are better suited for short growing seasons and these row crops are being more widely cultivated. Therefore, the same trends of subsurface drainage expansion, in pursuit of higher yields, continues in this part of the State. The extensive surface drainage system of the Red River Valley, with ditches placed next to roads at roughly one-mile intervals, aids in drain tiling expansion.
- In southwestern Minnesota, the first era of subsurface drainage was driven by interest in draining prairie potholes. While not very effectively depicted in tile drainage estimates (due to the models used in estimating), many fields are being pattern-tiled (earlier referred to as gridiron) to assure dry conditions for farming operations.
- In southeastern Minnesota, the topography, soil types, and underlying bedrock suggests that tile drainage would not bring added value to the agricultural fields. However, local estimates based on interviews with several local environmental professionals indicate an increase in tiling although no corroborating documentation of drain tiling magnitude has been found for this report.

In central and northern Minnesota (Fig. 8), only scattered tiling exists; these areas do not show the same densities as western and southern Minnesota largely due to the presence of well-drained soils. However, surficial geology in some areas still warrants tile drainage. Northern Minnesota, particularly north-central and northeastern Minnesota, remains untilled due to minimal row crop agriculture, the climate, and the high concentrations of lakes and wetlands.

## 5. Groundwater resources

The following section gives a brief introduction to aquifers, groundwater, and recharge. This section is not meant to be comprehensive, only to give context to the reader in relation to the concepts extrapolated in this white paper on the relation of agricultural subsurface drainage and groundwater resources.

### Aquifers

Aquifers are underground reservoirs made up of permeable rock (such as sandstones and carbonate rocks) or sediment (such as sand and gravel) that yield enough water when pumped from a water supply well. Water is stored in the spaces between the grains or in fractured spaces in rock (Fig. 10).

Although all media below the saturated zone hold water, not all media release water easily. For a saturated medium or buried hydrogeological layer to be considered an aquifer, it must be permeable, porous, and release enough water from storage to be usable from a water well. In fine-grained material like clay, very low saturated hydraulic conductivities due to the small diameter and tortuous pore spaces limit pumping volumes. Therefore, layers made up of material such as clay and shale are not generally considered to be aquifers. Instead, these layers are confining layers (Fig. 10), and although water can and does flow through them, it flows at a much slower rate than in an aquifer. Confining layers prevent water below

from rising above them or water above from flowing to aquifers below them. The two general types of aquifers, confined and unconfined, differ primarily in how water in each type is stored and released.

Unconfined aquifers are also referred to as water table aquifers or occasionally shallow aquifers. However, the term “shallow” can be misleading as these aquifers can extend for several hundred feet below the land surface. The top of the aquifer is defined by the level of water or water table. The bottom is a confining layer that does not transmit water easily. The water level in these aquifers rises and falls as the aquifers are recharged and drained, because the water drains from and fills the pore space with changes in water volume. These aquifers are often in contact with surface water bodies which can replenish or remove water from them, and therefore wetlands, streams, and lakes are often a visual expression of the water level in the aquifer. Perched aquifers are a special type of unconfined aquifer. Water accumulates on top of a low permeability layer above the regional water table and the soil below is unsaturated.

Confined layers have a layer of less permeable material above and below. The confining layers slow down the flow of water vertically so that the flow of water into the aquifer horizontally exceeds the flow upwards or downwards. These are sometimes referred to as deep aquifers,

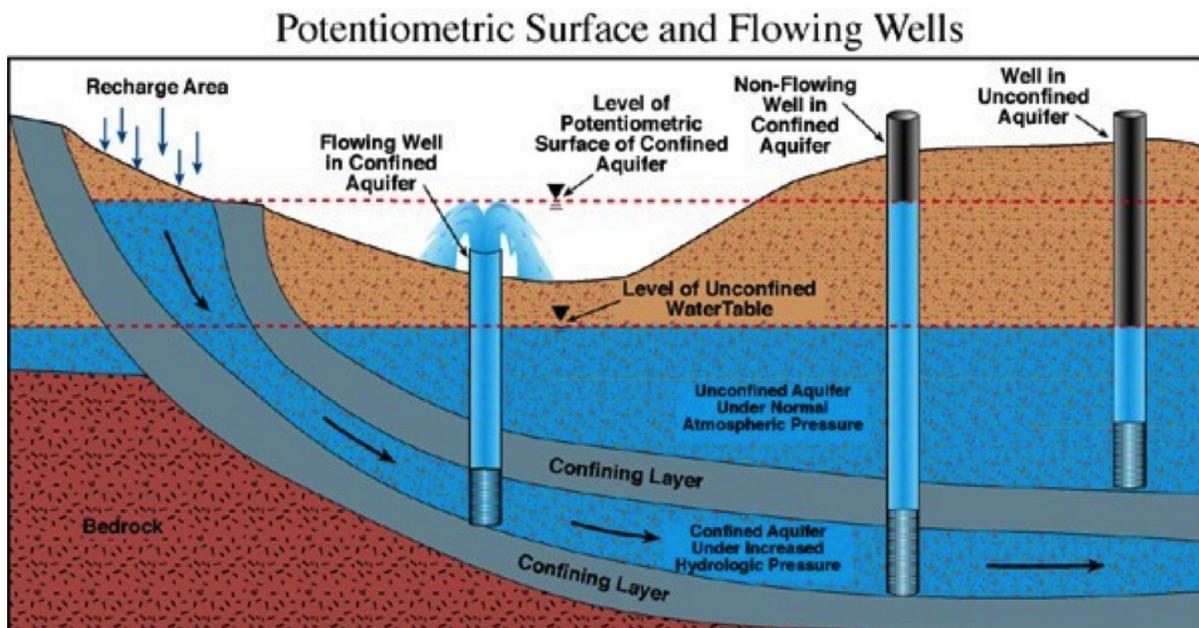


Figure 10. Water entering an aquifer moves towards lower gradients and eventually is discharged from the aquifer from springs, seeps into streams, or is withdrawn from the ground by wells. Groundwater in aquifers between layers of poorly permeable rock (i.e., confining layer) may be confined under pressure. Also shown are the potentiometric surface differences between unconfined water table aquifer and a confined aquifer. Figure courtesy of Ohio Department of Natural Resources ([http://water.ohiodnr.gov/portals/soilwater/Images/maps/PSurface\\_Flow\\_Well\\_sml.jpg](http://water.ohiodnr.gov/portals/soilwater/Images/maps/PSurface_Flow_Well_sml.jpg)).

although these aquifers could be at any depth below the ground surface. Confined aquifer water is pressurized between the confining beds. Water in these aquifers does not rise and fall; however, the water pressure does increase and decrease with recharge and extraction. Pressure change permits water to be released from these aquifers, even though the pore space remains filled. Water is not drained from the pore; a significant difference from an unconfined aquifer.

Pressure in confined aquifers causes the water inside a well to rise to a level above the confining layer, equal to the pressure the water is under (Fig. 10). Water level rise in the well represents the potentiometric surface, which is the elevation of an imaginary surface of the water in the aquifer or above the aquifer if the confining layer were removed. The potentiometric surface rises and falls with pressure changes as water is extracted and replenished, just as a water table aquifer fluctuates vertically with water volume changes (Fig. 10).

When a well is used to withdraw water from an aquifer, a cone of depression is formed around the well as water flows out of the pore spaces towards the well (Fig. 11). In an unconfined aquifer, the pore spaces are drained and the water table drops in the shape of an inverted cone. In a confined aquifer, the potentiometric surface drops. If the potentiometric surface drops below the confining bed, the aquifer converts to an unconfined aquifer and will begin draining water from its pores. For confined

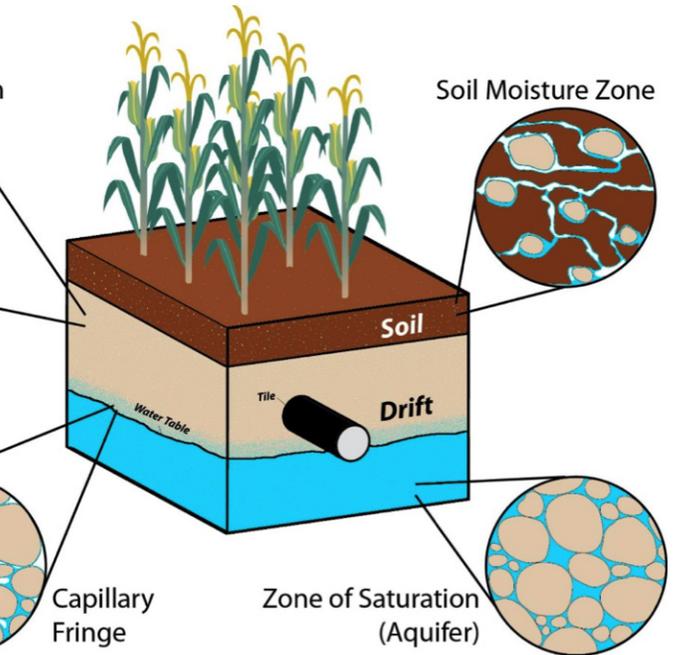
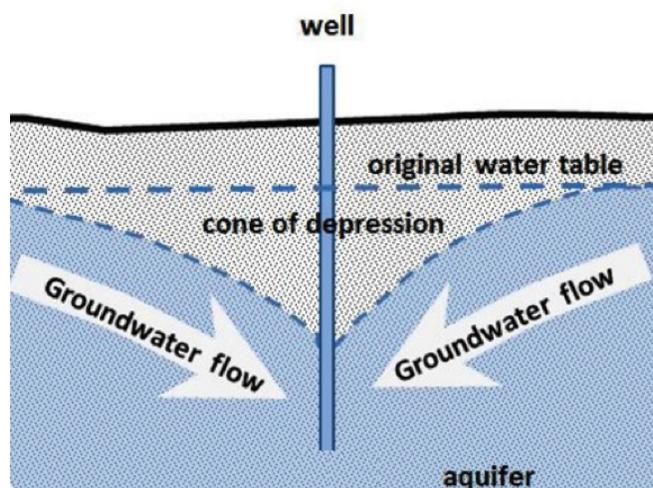


Figure 12. Idealized groundwater distribution in agricultural areas subject to tile drainage. The varying degrees of saturation are also shown, with the water table depth influenced by the tile drain depth (figure by B. Hoppie).

aquifers, less water is released from the same amount of pumping and the effects of the pumping reach further distances because more area is needed to get the same volume of water.

Groundwater distribution within agricultural areas subject to tile drainage presents a special case. The shallow perched water in these areas represents a water table, but is often not connected to the regional surficial aquifer. Instead, soil horizons can extend greater than five feet into the subsurface (Fig. 12). Consequently, the soil moisture horizon contains the tile drains, and this is the water that is generally being drained. In Figure 12, the glacial till (labelled as drift) consists of sand, silt, and clay sediment that was deposited during times of glaciation, with the soil horizons forming on top. Figure 12 also illustrates the increasing degrees of saturation, with only small amounts of water clinging to grains in the zone of aeration, to partial saturation among particles in the capillary fringe, to complete saturation of all pores within the saturation zone. The water table, marking the top of the saturated zone, is generally reflective of the surface topography but can possess irregularities, both large and small, depending on textural attributes of the glacial

Figure 11. Cone of depression developing around a shallow water table well. Figure courtesy of Nebraska Extension (<http://extensionpublications.unl.edu/assets/html/g2150/build/g2150.htm>).

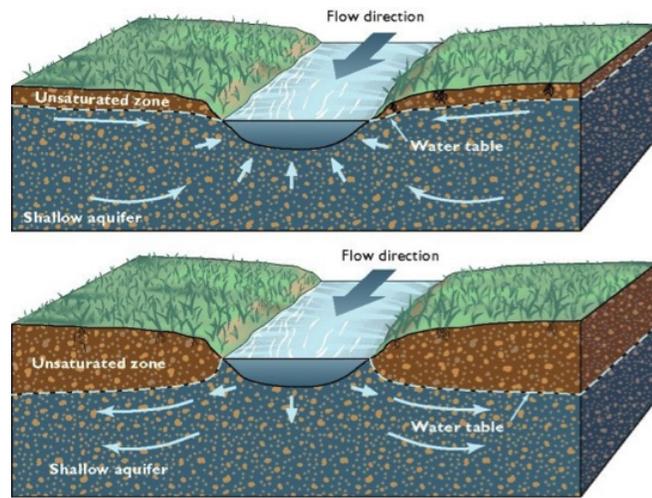
till, biological activity, and the design and operational aspects of the tile drain.

### Recharge

Groundwater, like surface water, is the result of precipitation flowing to the lowest pressure point of a defined area, such as a drainage basin, where it then discharges. Conceptually, recharge is simple. The precipitation that falls on any specific area either runs off to surface water (Fig. 13), evaporates or transpires back into the atmosphere through evapotranspiration, infiltrates below the unsaturated zone to recharge ground water (Fig. 14), or is stored in surface water bodies such as lakes. Recharge can occur either through natural means via diffuse recharge, such as infiltration of precipitation, or artificially through injection wells, pipes, or irrigation (not shown).

Recharge can also occur via lakes, wetlands, or rivers, which are often the sites of more focused recharge to aquifers. When the elevation of the surface water is higher than the groundwater table, water will flow into the aquifer (Fig. 14). The opposite of recharge is discharge. When the water table is higher than the surface water elevation, water flows from the aquifer into the surface water body (Fig. 14). Aquifers are generally recharged at higher elevations and discharge at lower elevations. If a confined aquifer finds a path to release its pressure it will discharge. Springs and flowing wells are examples of isolated pressure releases from confined aquifers.

Aquifers are recharged directly through precipitation and snowmelt, excess irrigation, surface water discharge, or through a confining layer. Water table aquifers are recharged when enough water infiltrates through the



From Winter and others, 1999

Figure 14. The water level in an aquifer influences whether the surface water body, such as a stream, will recharge the aquifer or the aquifer will discharge into the surface water body. Figure from Winter and others (1998), available at <https://pubs.usgs.gov/circ/circ1139/pdf/circ1139.pdf>.

soil profile to reach the aquifer. The water table rises with aquifer recharge. The water table rise can increase the rate at which water flows through a confining bed to recharge a confined aquifer. Also, some portions of a confined aquifer are unconfined aquifers in their recharge areas (Fig. 10). Water infiltrates into the unconfined portion of the aquifer during recharge events and flows to where the aquifers are confined.

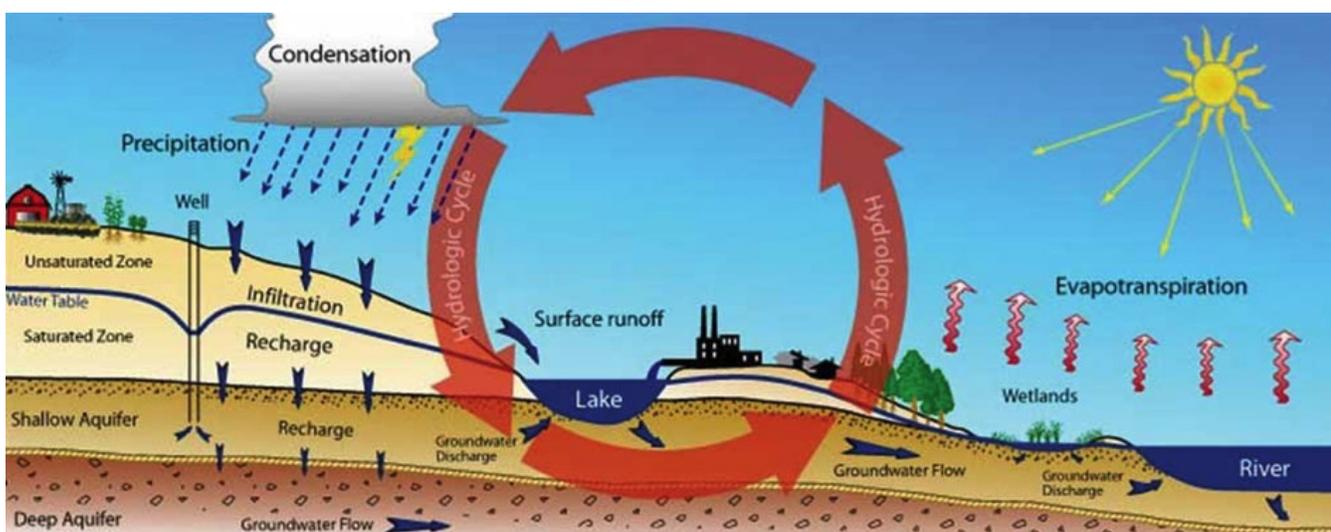


Figure 13. The water cycle, with emphasis on evapotranspiration, infiltration, groundwater discharge, and surface runoff. Figure available at <http://www.esri.com/news/arcuser/0408/groundwater.html>.

Water in unconfined aquifers can rise above the root zones of plants or above the land surface at lower elevations. Because the water table rises and falls, subsurface drains may be placed in these types of aquifers to prevent damage caused by a high water table. Subsurface drainage lowers the water table to the specified depth of the drain. Agricultural subsurface drainage is designed to transfer surface and shallow soil water to nearby surface waters. At the local level, subsurface drainage affects the water balance of the drained areas.

Some water also enters the confined aquifer vertically through the low permeability layers. The rate that water flows through a confining layer is dependent on the pressure head of water in the aquifer above. If a confined aquifer is overlain by an unconfined aquifer, the elevation of the water table directly affects the direction and rate of flow through the confining bed. In figure 15, on the left-hand side, the potentiometric surface is less than the water table surface, so the water will flow down from the water table aquifer to the confined aquifer; in this case, the water table aquifer is recharging the confined aquifer (i.e., downward leakage). On the right-hand side, the water table is lower than the potentiometric surface, so the water will flow up into the unconfined aquifer; in this case, the confined aquifer is recharging the unconfined aquifer (i.e., upward leakage). In relation to agricultural drainage, if the water table is artificially lowered, it could potentially change the direction of flow, or at least change the rate of flow leading to less

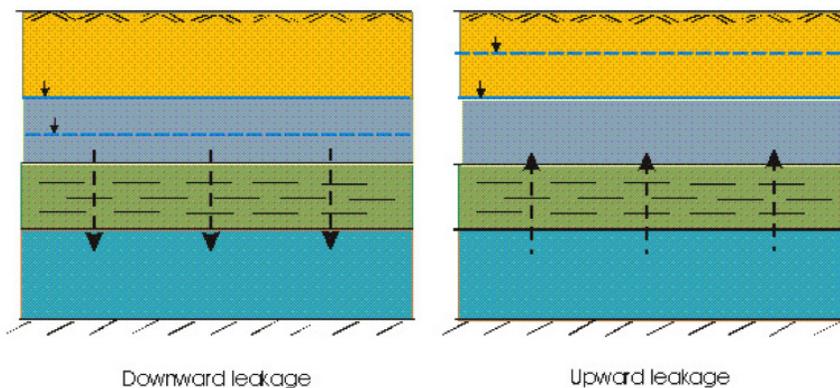


Figure 15. Possible positions of the potentiometric surface (light-blue dashed line) in relation to the water table (upper blue section). The example on the left-hand side illustrates downward leakage to the confined aquifer (lower blue section) through the green confining layer, the right-hand side illustrates upward leakage. Figure courtesy of the Virtual Campus in Hydrology and Water Resources ([http://echo2.epfl.ch/VICAIRE/mod\\_3/chapt\\_9/main.htm](http://echo2.epfl.ch/VICAIRE/mod_3/chapt_9/main.htm)).

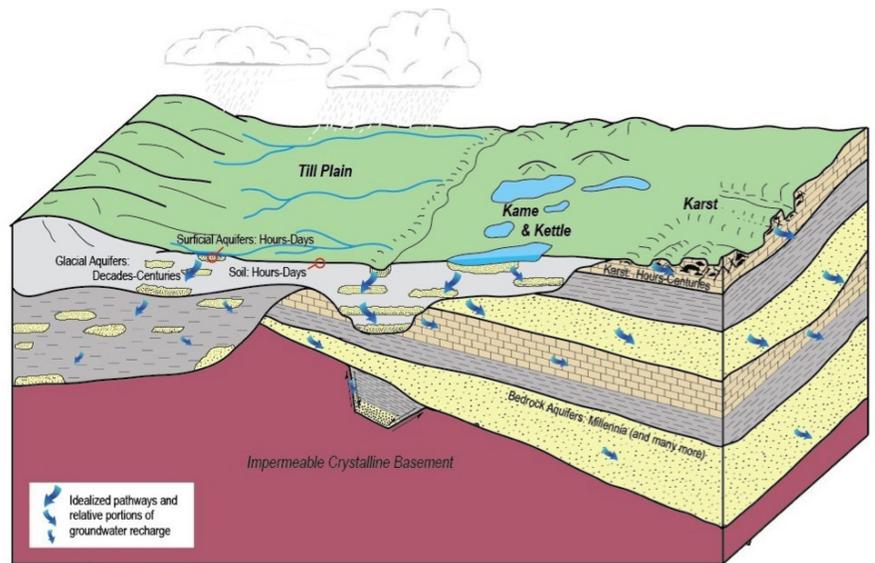


Figure 16. Theoretical groundwater recharge within areas prior to the influence of agricultural tile drainage (figure by B. Hoppie). Time scales for recharge can range over several orders of magnitude, from hours and days to several thousand years. In the upper portions of the figure, the light and dark gray areas denote different glacial till layers, with interbedded sand and gravel aquifers shown in yellow. On the right side of the figure, in the karst terrain, dark gray areas with horizontal hashes denote confining layers, with interbedded sandstone (light yellow) and carbonate (dark yellow with box pattern) aquifers.

recharge into the confined aquifer. However, this change in volume may be negligible compared to the volume recharged at its unconfined source.

In areas subject to agricultural drainage, surficial aquifer recharge may be diverted to surface water. Figure 16 illustrates the theoretical groundwater recharge distribution within areas prior to the influence of agricultural drainage on the landscape. While soils and some surficial (water table) aquifers receive rapid, direct recharge from atmospheric and surface hydrological sources, buried glacial sands and bedrock aquifers are recharged by smaller volumes of water that are delivered slowly,

periods of time of more than 1,000 to 10,000 years (Berg and Pearson, 2012a). Although less commonly drained, shallow aquifers within karst terrain, shown on the right side in figure 16, have highly variable recharge rates. Some fractures support rapid recharge while unweathered and unbroken sections of carbonate rock within the overall karst region might contain water that has been virtually locked in place for tens of thousands of years.

## 6. Agricultural subsurface drainage provinces

Agricultural subsurface drainage exists throughout the State of Minnesota, with the bulk of tile drainage being found in southern and western Minnesota. The geological history of these regions is dominated by a series of glaciations that occurred over the past 2 million years (Wright, 1972; Johnson and others, 2016). These regions consist of thick deposits of unconsolidated sediments rich in silt and clays. Thus, the soils that form on these parent materials are often poorly drained and do not allow for the easy transmission of water through the subsurface.

### Groundwater provinces

The Minnesota DNR developed the concept of groundwater provinces to broadly characterize the differences between aquifers in Minnesota (Fig. 17), dividing the state into six groundwater provinces (Minnesota Department of Natural Resources, 2001). Although the defined boundaries of these provinces do not necessarily exactly coincide with the province characteristics as described

in Figure 17, the provinces do assist in characterizing the general properties of the state's groundwater aquifers. For example, the western province, region 5 in Figure 17, covers the western margins of Minnesota and all of southwestern Minnesota. It is characterized by clayey glacial till overlying Cretaceous and Precambrian bedrock. By contrast, region 3 in southeast Minnesota is characterized by thin glacial till (less than 100 feet, often close to 0 feet) overlying Paleozoic sandstone and carbonate aquifers.

### Tile drainage provinces

For the purpose of this paper the white paper group developed the concept of Minnesota tile drainage provinces to help the discussion of key differences in tile drainage across specific regions and its overall effect on the underlying groundwater aquifers. Built upon the concept of groundwater provinces, the tile drainage provinces started with three of the six groundwater provinces (southeastern, central, and western) to help define these

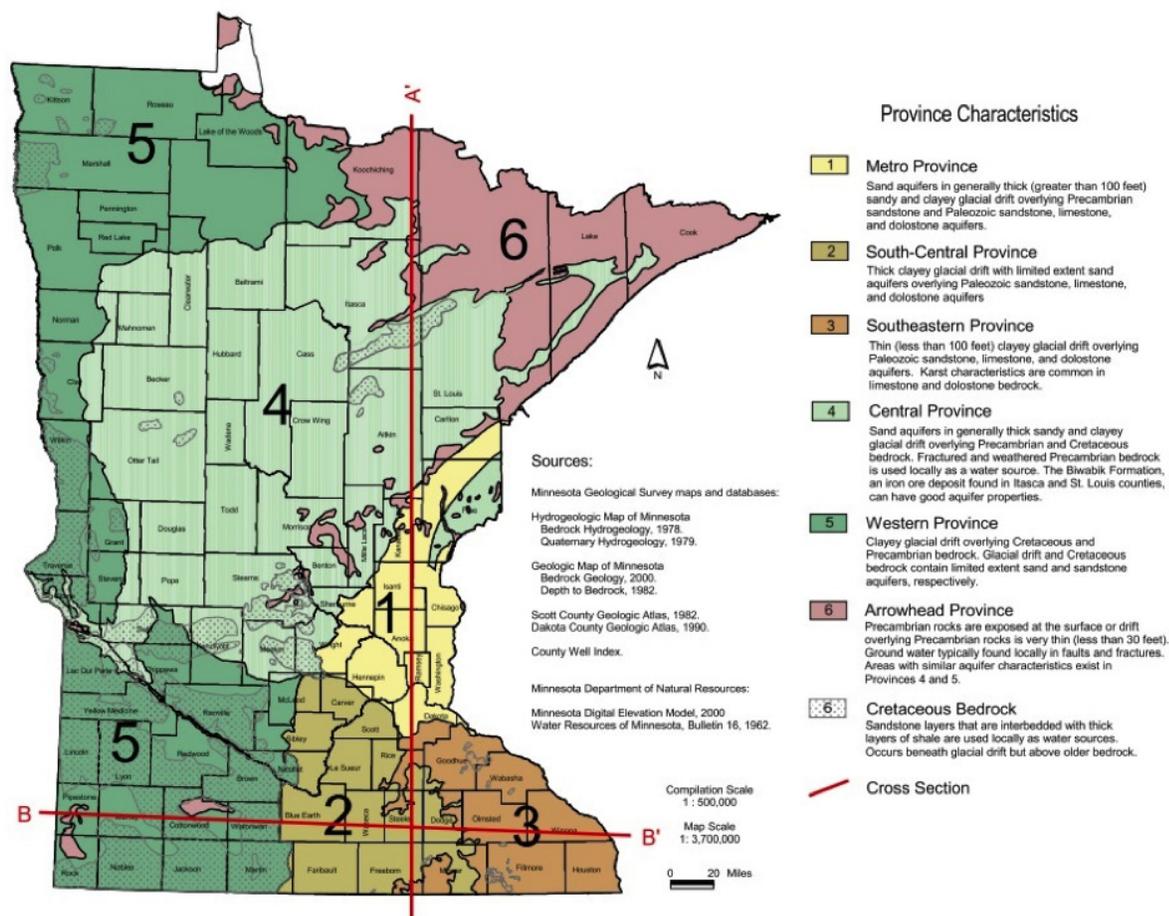


Figure 17. Six Minnesota groundwater provinces, as defined by the Minnesota Department of Natural Resources (Minnesota Department of Natural Resources, 2001). The cross-section lines, A-A' and B-B', are retained from the original source and the cross sections are not presented in this white paper.

different tile drainage areas. As defined by the white paper group, the three distinct tile drainage provinces are (Fig. 18):

1. **Southeastern Province:** characterized by thin loess deposits and pre-Wisconsin tills overlying Paleozoic-age sedimentary bedrock, which include the major aquifers of the area. Unlike most other portions of Minnesota, the lack of Wisconsin-age surficial glacial deposits has a large effect on the drainage characteristics, the landscape, and the topography. Up to the present (2018), subsurface drainage extent has been limited by this region's higher slopes, proximity to the deeply eroded stream and river valleys, and the inability to effectively pattern tile because of the undulating landscape.
2. **South-Central Province:** characterized by thick Wisconsin-age glacial deposits overlying Paleozoic-age sedimentary bedrock sandstone, limestone, and dolostone aquifers, the major aquifers of the area. The silty clay loams, common to this region, have extensive subsurface drainage to increase agricultural yields. This province includes Mt. Simon aquifer recharge areas, a bedrock aquifer that underlies both the South-Central and Southeastern Provinces (Berg and Pearson, 2012a).
3. **Western Province:** characterized by clayey glacial till and lacustrine deposits overlying Cretaceous and Precambrian bedrock. The Western Province lacks extensive bedrock aquifers generally with only limited-extent sand and sandstone aquifers in the glacial till and Cretaceous bedrock, respectively. According to Figure 18, the southwestern portion of the Western Province has limited subsurface drainage due to increasing slopes and generally lower precipitation

amounts compared to the other drainage provinces.

Several GIS operations were done to create Figure 18 beyond the initial delineation of the three groundwater provinces. The Southeastern tile drainage province was defined by clipping out several geological groups from the statewide Quaternary geology map (Hobbs and Goebel, 1982), including alluvium, terraces, colluvium, and weathering residuum over bedrock. Only the areas within the Southeastern groundwater province were retained from the Quaternary geology map; the resultant Southeastern tile drainage province extent (Fig. 18) is close to that of the Southeastern groundwater province (Fig. 17) but subtly different.

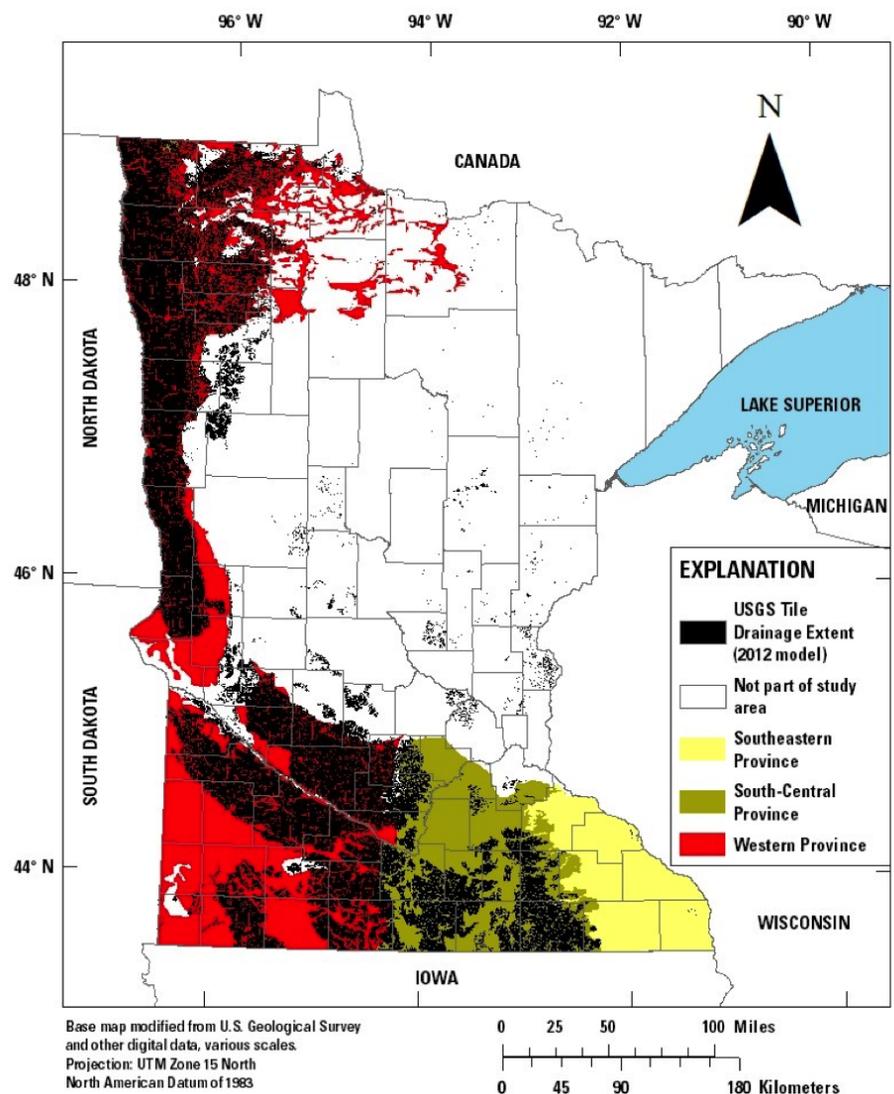


Figure 18. The three tile drainage provinces defined by the white paper group, in addition to the U.S. Geological Survey (USGS) 30-meter resolution estimate tile drainage extent raster (in 2012), based on the Nakagaki and Wiczorek (2016) model of 12 Midwestern states.

For the other two large provinces, in addition to the groundwater province map, the Minnesota bedrock geology map (Jirsa and others, 2011) was used to differentiate the South-Central Province and the Western Province. The South-Central tile drainage province is mainly defined by the Paleozoic geologic deposits in the bedrock geology map. For the Western tile drainage province, the comparable Western groundwater province was used with peatlands from the Quaternary geology map clipped out in addition to Upper and Lower Red Lake.

Two groundwater provinces that covered most of the non-metropolitan (Twin Cities Metropolitan Area) central, northern, and northeastern portions of Minnesota are from the groundwater province map (Fig. 17). The Central groundwater province contains significant amounts of surficial sand and gravel deposits that do not require extensive drainage. While tile drainage does exist in portions of the Central groundwater province, further discussion is limited in this paper's discussion. The Arrowhead groundwater province, mostly in northeastern Minnesota, is defined by Precambrian bedrock close to land surface with minimal glacial till, minimal row crop agriculture, and very limited subsurface tile drainage.

#### Key differences between the tile drainage provinces

The impetus of this MGWA white paper is to explore the relations between agricultural subsurface drainage and groundwater resources. Given the prevalence of subsurface drainage networks in both southern and western Minnesota, it is important to discuss the implications of these subsurface drainage networks on groundwater resources, the aquifers that are the storehouses of groundwater, and groundwater recharge.

The installation of subsurface drainage networks over the past 150 years has influenced water storage. The subsurface drainage networks have moved excess water towards the newly constructed open ditches, draining previously unconnected depressions and wetlands to nearby streams, rivers, and lakes (Blann and others, 2009). Also, the waters from these unconnected depressions and isolated wetlands, landscape features that were previously dominated by high evapotranspiration (ET) rates, were now interconnected throughout the watershed. Therefore, drainage networks moved the water towards surface waters on shorter timescales, thus decreasing ET.

A potential unintended consequence of agricultural drainage, particularly in glacial terrain underlain by

deposits having low permeability, is that the drainage of former wetlands and the ongoing drainage of poorly drained soils can change the areal distribution of potential groundwater recharge and discharge (Winter and others, 1998). Decreased groundwater recharge, if sustained over a long enough period or a wide spatial extent, can reduce the amount of groundwater available for long-term withdrawals in the underlying aquifers (Winter and others, 1998).

Currently (2018), decades of research exist on the potential effects of agricultural drainage on surface water quality (e.g. Gentry and others, 2009), runoff rates (for example, Nangia and others, 2005), and the contributions of subsurface tile drainage to downstream flooding (i.e., surface water effects) (Morton and others, 2015). However, potential decreases in groundwater recharge underlying areas with substantial subsurface drainage are poorly understood. Little research currently exists on the potential consequences to groundwater, in particular groundwater quantity. The potential effects of subsurface drainage on groundwater are mentioned in USDA Natural Resources Conservation Service (NRCS) practice standards. According to the 2003 National Handbook of Conservation Practices (NHCP), for the code 606 (subsurface drainage), one of the considerations for designing subsurface drainage systems is the potential effect on groundwater recharge (NRCS, 2003).

To date, the best summary of the potential mechanisms and effects of subsurface tile drainage on groundwater recharge is from the work of William Schuh, hydrologist with the North Dakota State Water Commission. In a North Dakota State Water Commission paper, titled the *Potential Effects of Subsurface Drainage on Water Appropriation and the Beneficial Use of Water in North Dakota*. Schuh extensively discussed the various mechanisms and effects that subsurface drainage would have on groundwater recharge (Schuh, 2008). In the paper's introduction, Schuh noted that limited data exist about the effects of subsurface drainage on groundwater, but he does attempt to provide at least some answers. Although Schuh refers to North Dakota throughout the 2008 paper, many of the same types of drained landscapes exist in the drained provinces of Minnesota (especially western Minnesota); therefore, the same conclusions can be drawn for much of Minnesota. The following two excerpts from Schuh (2008) summarize concisely the general hydrologic cycle for a typical tile-drained landscape:

*“While the estimated total annual drainage seems large, tile-drained waters are removed from an upper zone of “active” storage which is not sustainable for long-term*

storage. Almost all tile-drained waters would be removed through natural discharge within a year or two at most, if not drained, by seepage to surface waters or through evapotranspiration. In the hydrologic cycle common to North Dakota's glacial aquifers, recharge occurs through precipitation and runoff (and sometimes losing streams), and discharge occurs through evaporation, transpiration, runoff, and seepage to rivers and streams. Sustainable withdrawal of water for human purposes (drainage or pumpage) must be recovered from existing natural discharge."

"The simplest and most direct answer to the question of drainage effects on hydrologic balance . . . is that in the absence of pumping, subsurface drainage will be captured from waters previously discharged through runoff, seepage to streams, evaporation and transpiration. Tile drainage is practiced where there are high water tables. High water tables cause enhanced evaporation and runoff. Drainage, by lowering the water table, decreases evaporation and runoff. For conditions of most glacial aquifers in eastern North Dakota, tile-drain waters will be captured primarily from combined evaporation and runoff."

However, there are variations to the above statement, which are important to explore in the context of the three different Minnesota tile drainage provinces. A series of four cross-sections were constructed to explore the key differences across the three tile drainage prov-

inces. Each example shows the location within Minnesota, the line of cross section from west to east, and the underlying geology that defines the hydrostratigraphic framework. An individual cross section is meant as an illustrative example to define the general geology of the region, not as a definitive source to summarize the entire region.

The first cross section (Fig. 19) is from Wabasha County, located in the Southeastern tile drainage province. From west to northeast, several different layers of bedrock aquifers and aquitards are below the land surface with a thin layer of till and isolated glacial and recent aquifers. The bedrock aquifers are made up of Paleozoic sandstone and carbonate aquifers, interstratified by low permeability carbonates and shales. The thin till layers are the general location of subsurface drainage in the Southeastern tile drainage province, although steeper slopes limit the widespread usage of tile drains. The residence time data shown in Peterson (2005) demonstrate that the top regional water table aquifer, which can be up to 150 feet below the surface along this cross section (Fig. 19), is dominated by recent recharge with clear evidence of nitrate contamination, proving its connection to modern recharge. This is an important consideration in this part of the State; if any subsurface drainage potentially limits downward percolation of recharging waters, it could present a vulnerability to the overall water balance and

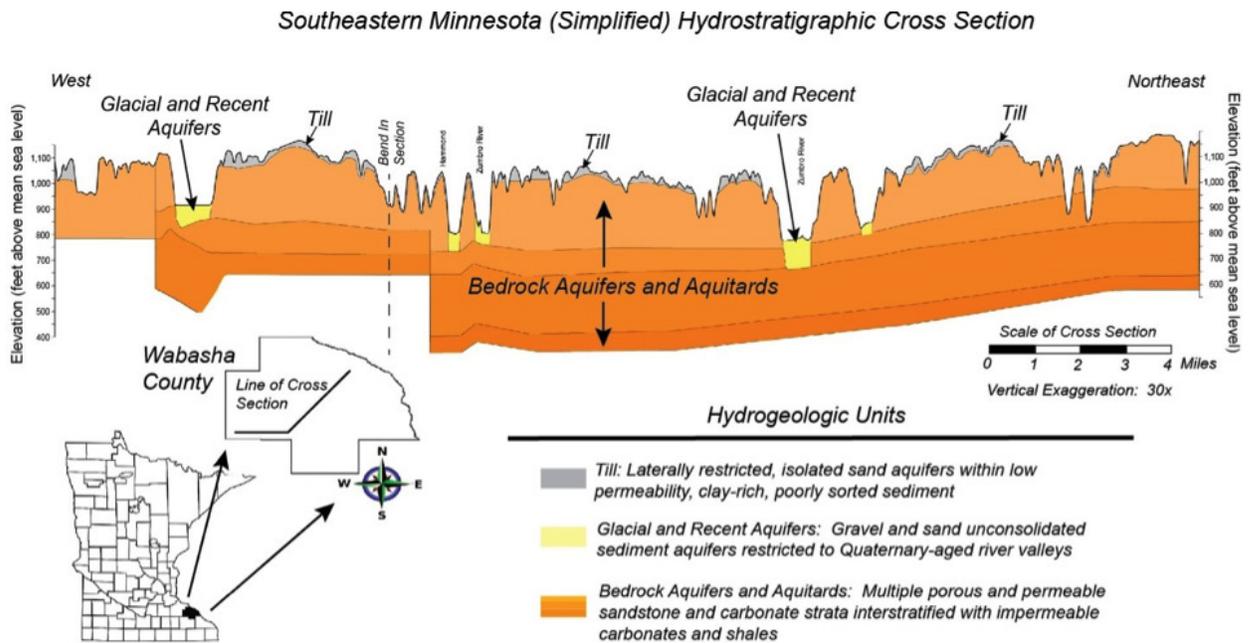


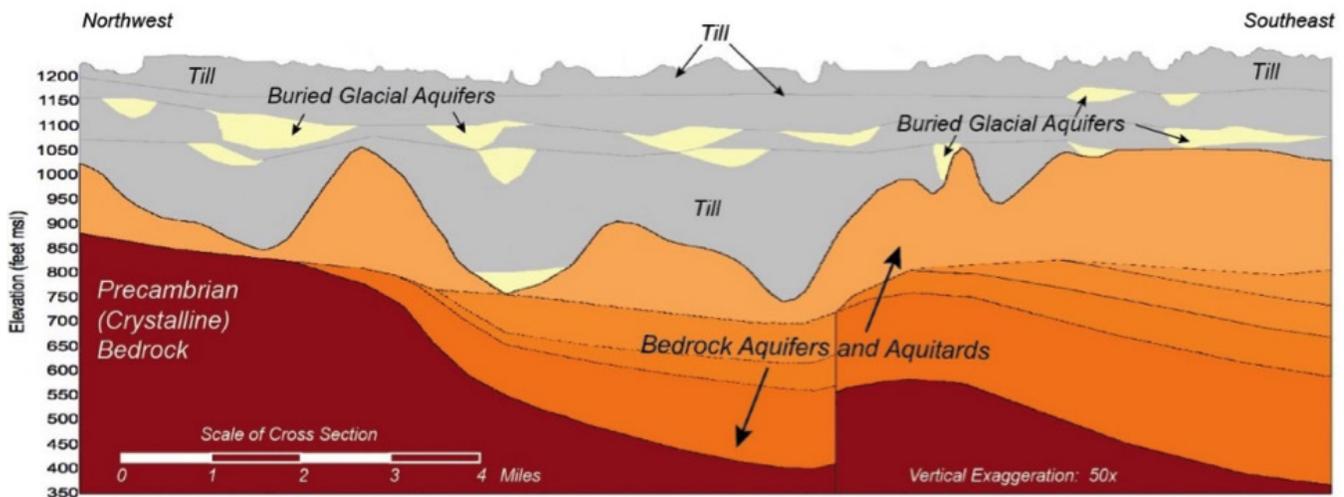
Figure 19. Southeastern Minnesota (simplified) hydrostratigraphic cross section in Wabasha County, Minnesota, from west to northeast with depth shown in elevation in feet above mean sea level. Three generalized hydrogeologic units are illustrated: till, glacial and recent aquifers, and bedrock aquifers and aquitards. Modified from section G'-G' in Peterson (2005).

potentially limit the downward percolation of recent recharging waters to the deeper series of bedrock aquifers.

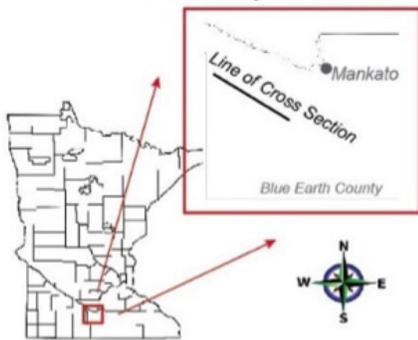
The second cross section (Fig. 20) is from Blue Earth County, in the South-Central tile drainage province. From northwest to southeast, several of the same bedrock aquifers and aquitards from Figure 18 exist in this tile drainage province. However, several hundred feet of glacial till overlies the deeper bedrock aquifers with interspersed buried glacial aquifers scattered throughout the glacial till. Due to the thick sequence of glacial tills with high concentrations of silt and clay, the South-

Central tile drainage province is heavily drained. As briefly noted in the trends section (Section 4), tiling continues today and new pattern tiling is being installed. As compared to the more significant concerns for groundwater recharge effects to the bedrock aquifers for the Southeastern tile drainage province, the potential effect seems more limited in the South-Central province. As with the previous work in North Dakota (Schuh, 2008), only the limited infiltration over time could affect groundwater recharge in cases where the depth to bedrock is several hundred feet.

### South-Central Minnesota (Simplified) Hydrostratigraphic Cross Section



#### Blue Earth County Minnesota



#### Hydrogeologic Units

- Till:** Pervasively low permeability, clay-rich, poorly sorted sediment acting as a regional aquitard
- Buried Glacial Aquifers:** Gravel and sand unconsolidated sediment aquifers associated with fore and sub-glacial depositional processes
- Bedrock Aquifers and Aquitards:** Multiple porous and permeable sandstone and carbonate strata interstratified with impermeable carbonates and shales
- Precambrian Bedrock (Basement):** Nonporous, impermeable crystalline igneous and metamorphic rock

Figure 20. South-Central Minnesota (simplified) hydrostratigraphic cross section in Blue Earth County, Minnesota, from northwest to southeast with depth shown in elevation in feet above mean sea level. Four generalized hydrogeologic units are illustrated: multiple layers of till, buried glacial aquifers, bedrock aquifers and aquitards, and Precambrian bedrock. Modified from Berg and Pearson (2012b).

The next two cross sections are from the Western tile drainage province: Redwood County in southwestern Minnesota (Fig. 21) and Clay County in northwestern Minnesota (Fig. 22). The southwestern Minnesota portion, covered by Figure 21, does not have as much tile drain coverage as the northwestern section. Several hundred feet of till divide the bedrock aquifers and buried

glacial aquifers from land surface. Like the South-Central province, the effect of tile drainage is likely limited for these aquifers. Vulnerable conditions exist where the aquitard water table is near land surface, as expected in a drained area, and the confined aquifer potentiometric head is also near land surface and very close to that of the aquitard (Schuh, 2008). In these cases, tile drainage

could have a significant effect on local recharge – this effect will be greatest when the aquitard is thinner, and these drainage effects would more likely be limited to local effects rather than the entire surficial aquifer (Schuh, 2008). For the northwestern cross section (Fig. 22), effects would likewise be local in nature. The largest difference between these two sections is the presence of the flat sections of glacial lake clays that make up the bulk of

the Red River Valley.

Overall, the cross-sections illustrate that the interaction between subsurface drainage and the underlying geology varies across Minnesota. The regional framework can help the discussion of potential groundwater effects, both in terms of groundwater quality and quantity.

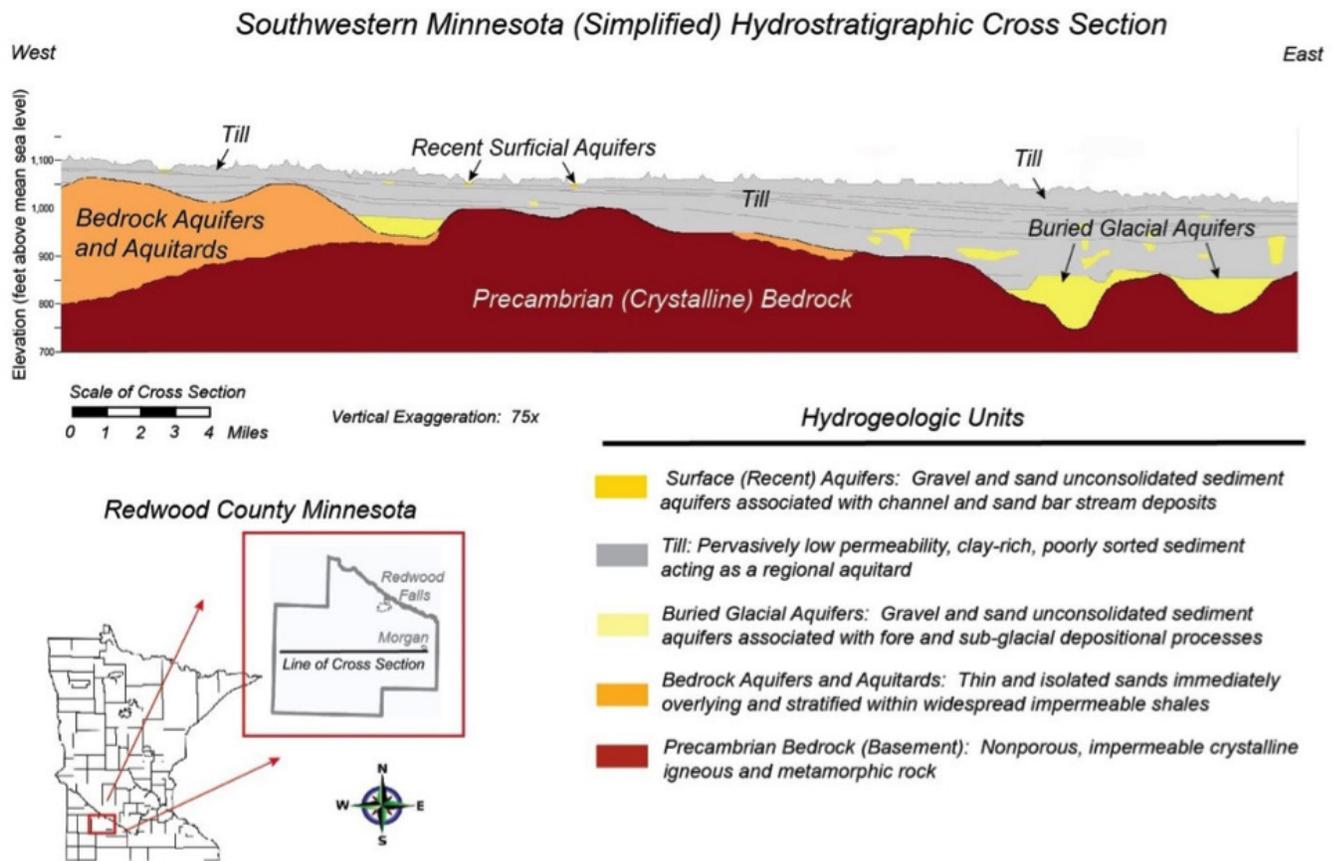
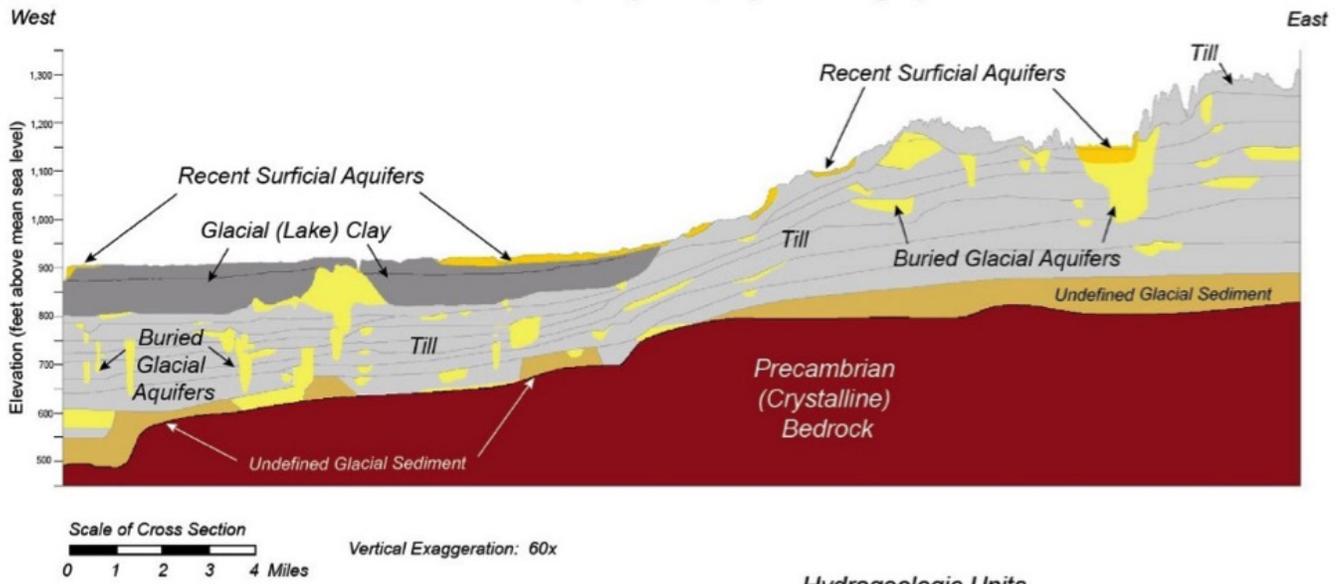


Figure 21. Southwestern Minnesota (simplified) hydrostratigraphic cross section in Redwood County, Minnesota, from west to east with depth shown in elevation in feet above mean sea level. Five generalized hydrogeologic units are illustrated: recent surficial aquifers, till, buried glacial aquifers, bedrock aquifers and aquitards, and Precambrian bedrock. Modified from Gowan (2016).

## Northwestern Minnesota (Simplified) Hydrostratigraphic Cross Section



### Hydrogeologic Units

- Surface (Recent) Aquifers:** Gravel and sand unconsolidated sediment aquifers associated with channel and sand bar stream deposits
- Till:** Pervasively low permeability, clay-rich, poorly sorted sediment acting as a regional aquitard
- Buried Glacial Aquifers:** Gravel and sand unconsolidated sediment aquifers associated with fore and sub-glacial depositional processes
- Undefined Glacial Sediment:** Investigators have not defined the the compositional or textural attributes of these deposits
- Precambrian Bedrock (Basement):** Nonporous, impermeable crystalline igneous and metamorphic rock

### Clay County Minnesota

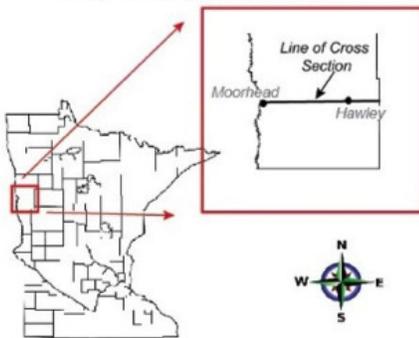


Figure 22. Northwestern Minnesota (simplified) hydrostratigraphic cross section in Clay County, Minnesota, from west to east with depth shown in elevation in feet above mean sea level. Five generalized hydrogeologic units are illustrated: recent surficial aquifers, till, buried glacial aquifers, undefined glacial sediment, and Precambrian bedrock. Modified from Gowan (2014).

## 7. Agricultural subsurface drainage: Effects

Agricultural Drainage for agricultural production, transportation, and other land development is a major component of anthropogenic change to both rural and urban landscapes in Minnesota. Much of Minnesota's wetter agricultural lands have been, or can be, made much more productive by drainage, including subsurface drainage. The specific effects of drain tile discharge on surface water quantity and quality have long been the subject of research and debate. However, groundwater has been largely absent from the debate and rarely the focus of research. Therefore, to discuss the tile drainage and groundwater quality, it is necessary to look at the research on tile drainage and surface water to understand the effect on groundwater.

### Effects on water quantity

The magnitude and direction of subsurface drainage effects on peak flows and total runoff are extensively studied, but are complex and variable depending on many different hydrogeological factors. In dominantly agricultural land use areas with extensive subsurface tile drainage, it is clear that by lowering the water table over a large area, a corresponding volume of water is being delivered by the drains to another location, usually a downstream surface water body. In a study of ponds in prairie pothole country, Amado and others (2016) found "that intermittent ponding was observed in pothole depressions but hydrologic connectivity among three pothole depressions via surface water ponding was rarely established".

Qualitative information on groundwater changes due to tile drainage can be determined from a review of surface water drainage studies. Subsurface drainage effects on peak flows have been found to be variable, depending on factors such as the timing and amount of precipitation, current soil moisture, soil type, depth to water table, topography, and the configuration of the catchment drainage network (Skaggs and others, 1994; Robinson and Rycroft, 1999; Wiskow and van der Ploeg, 2003). Also, management factors play a role, such as tillage practices as well as the depth and spacing of the drainage system design. Compared to cropland drained by surface drainage alone, subsurface drainage can increase temporary storage capacity in the upper layer of soil, allowing water to infiltrate and spread through the soil over a longer period (Fraser and Fleming, 2001). Skaggs and others (1994) cited more than 17 studies where systems with improved subsurface drainage had less runoff and lower

peak outflow rates than systems that depend primarily on surface drainage.

Alternatively, other research has shown that tile drainage can alter the total water yield from a field or small watershed (Basin Technical and Scientific Advisory Committee, 2011). The total runoff increase tends to be significant, and occurs since subsurface drainage (on average) increases the precipitation proportion that is discharged to surface waters via subsurface flow relative to the amount that is stored semi-permanently, evaporated, or transpired (Magner and others, 2004). While part of the increased discharge to surface water probably came from water that would otherwise have been evapotranspired from the closed basins, part of the increased discharge potentially came from shallow groundwater and decreased net groundwater recharge to deeper aquifers.

Some of the best sources of work to understand groundwater effects on quantity include water budgets in drained systems. Roth and Capel (2012), in a north-central Iowa study, studied the water balance of a topographic depression (i.e., prairie pothole) and found the perched water table was the groundwater source to the pothole when soils were saturated, while the water in the pothole infiltrated to the subsurface drain when soils were drier. Jin and others (2004) used DRAINMOD to model water budgets for different soil types in the Red River Basin (northwest Minnesota) and found that, in general, deep infiltration to groundwater accounts for a very small percentage of the overall water budget in most years (less than 1 to 3 percent). Although this represents a small proportion of the overall water budget, the fate of this water for long-term recharge is important to understand.

Prior to tile drainage, most of the water that is now removed by tile drains was removed through evapotranspiration or natural discharge to surface waters through lateral movement of shallow groundwater. For example, Schuh (2008) suggested that almost all tile-drained waters in eastern North Dakota underlain by glacial aquifers will eventually be captured from evaporation or transpiration in the hydrologically active zone, or from intercepted runoff, that is not contributing significantly to long-term storage. While the methods for quantitative determinations of long-term recharge effects were limited in Schuh (2008), the conceptual considerations indicate the possible limited effects on long-term recharge in eastern North Dakota, and by extension sig-

nificant portions of the Western tile drainage province in Minnesota. The effects in other parts of the State are also poorly understood, and are among the knowledge gaps highlighted in the next section.

#### Effects on water quality

Agricultural subsurface drainage is a major pathway for nitrate loss to surface waters in the agricultural Midwest. According to the MPCA, subsurface drainage in Minnesota contributes 37 percent of nitrogen contamination of surface waters (MPCA, 2013). Furthermore, tile-drained waters often bypass saturated riparian buffers next to streams (Dinnes and others, 2002) and nitrate losses can be further exacerbated because the natural denitrification potential of these zones is lost where water bypasses buffers. An important part of the reduced denitrification potential is the shortened travel time of groundwater to surface water. For example, for a 7,400-hectare drainage basin in Iowa, Schilling and others (2015) found that mean shallow groundwater travel times were reduced with increasing intensity of tile drainage intensity, decreasing from 5.6 to 1.1 years, with drainage densities ranging from 0.005 per meter to 0.04 per meter, respectively.

The effect on phosphorus delivery to surface waters has been assumed to be less of a concern since subsurface drainage reduces overland runoff. Therefore, runoff-derived phosphorus loads from phosphorus sorbed onto soil particles are reduced in a tile-drained field. However, some newer literature has shown that phosphorus leaching from tile drainage can be large. King and others (2014) showed that tile drainage accounted for 47 percent of discharge and 48 percent of the dissolved phosphorus in the Upper Big Walnut Creek watershed in central Ohio. Similar losses via subsurface drainage were shown from the St. Joseph River watershed in northeastern Indiana (Smith and others, 2014).

## 8. Knowledge Gaps and Opportunities to Improve Understanding

Our purpose was to synthesize the state of the science on the effect of tile drainage on quantity and quality of infiltration to aquifers. The challenge in limiting the scope of this paper is that the entire hydrologic cycle is connected. Therefore, it is not possible to completely and cleanly separate a discussion of groundwater in source water aquifers from shallow subsurface flow. Additionally, the issue of effects on surface water is also important, hence the review in the “Effects” section, although the primary focus for this paper is groundwater.

### Knowledge gaps and uncertainties

- ◆ Agricultural drainage is extensive across Minnesota, particularly the southern and western portions where agriculture is the dominant land use. However, detailed, up-to-date information on the extent of tile drainage does not exist.
- ◆ Drainage and land use change had already extensively transformed the water budget across much of Minnesota by the time baseline information on streamflow and groundwater levels began to be collected. Therefore, the baseline data are being collected at a time when the system has already been greatly altered.
- ◆ There are many different groundwater pathways. During the white paper discussions, some members referred to “shallow groundwater” as that surrounding the tile while a hydrogeologist refers to shallow groundwater as the surficial aquifer. Almost all perched water is considered shallow groundwater although it is often separate from a true regional aquifer.
- ◆ Water budgets can be difficult to accurately quantify, largely due to substantial variations in evapotranspiration rates, infiltration rates, and the general flow of groundwater. Although groundwater flow can be well constrained and approximated using groundwater models, these models are time consuming, expensive, and may not capture critical details of recharge such as the exact locations of high infiltration zones. In the absence of accurate flow models, there is a lack of knowledge regarding the effect of artificial drainage on deep infiltration rates that lead to recharge of aquifers.
- ◆ Related to water budgets, there is uncertainty on how much of the additional runoff to streams is from a decrease in overall evapotranspiration in agricul-

tural watersheds versus reduced infiltration below the tile drains. For example, under pre-settlement conditions, the landscape included abundant native vegetation and generally there was more standing water. Although a row crop such as corn has a much higher evapotranspiration rate during the growing season, the change brought about by agricultural drainage that enables corn and other crop production has decreased evapotranspiration during fallow periods. The relative magnitude of these two effects on the total water budget is unknown.

- ◆ Most current relevant research focuses on monitoring the accessible parts of the water balance on already tiled areas. This research focuses on whether subsurface drainage increases or decreases evapotranspiration, increases or decreases the total runoff (both the surface and subsurface runoff), changes water storage, or affects the recharge to underlying aquifers. These components are dynamically interacting with each other. The recharge to groundwater is generally the smallest of these and is not continuous in time or space, is difficult to monitor, and likely is less than the margin of uncertainty in the measurement of the larger components. Therefore, the question of whether groundwater recharge is affected is difficult to answer, remarkably complicated, site specific, and rarely researched.

### Research opportunities to improve understanding

The following activities would help fill important knowledge gaps:

- ◆ Some mode of systematically mapping the current extent of agricultural subsurface drainage and the recording of new tile drainage installation.
- ◆ Baseline modeling to reconstruct the historical baseline: what have been the cumulative effects of historical changes from the land use shift from prairie to agricultural production, including agricultural drainage?
- ◆ Studies to understand the effect of agricultural drainage on groundwater recharge, both quantity and quality. Research should focus on how much water is moving past the tile drain depths, particularly at the field-scale research farms that currently exist in Minnesota. Most current drain tile research efforts do not monitor the near-surface water table aquifer.

- ◆ A long-term study to understand the groundwater recharge before a study site is tilled, and then monitored again after the tiling is installed. Such data, to this committee's knowledge, does not currently exist. Such data can, in principle, be obtained in areas as yet undrained but would require years to obtain and cannot be obtained in areas already tilled.
- ◆ Further exploration of near-field effects of agricultural drainage on water budgets under different soil and climate conditions. Potential models that could be used include DRAINMOD, GSSHA (Downer and others, 2014), PRMS, and MODFLOW (Mirlas, 2009). However, these existing models will need to include the effects of preferential flow in the soil zone and in the underlying aquifers.
- ◆ Innovative techniques to refine our ability to measure groundwater recharge at the field and regional scales, building upon past recharge estimate methodologies such as Dripps and others (2006) and as synthesized by Scanlon and others (2002).

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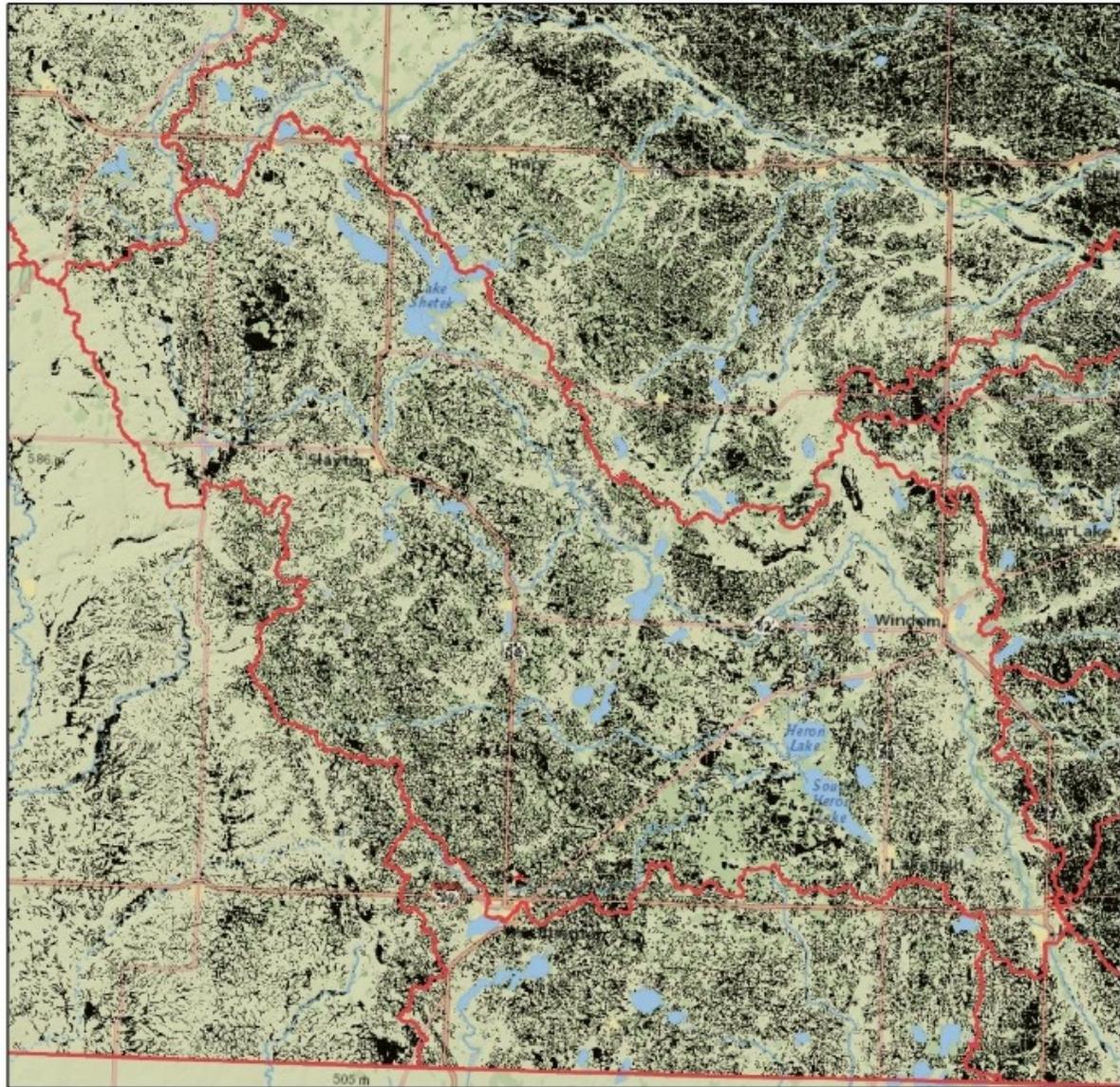
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## Appendix 1-1. Des Moines River – Headwaters, Minnesota

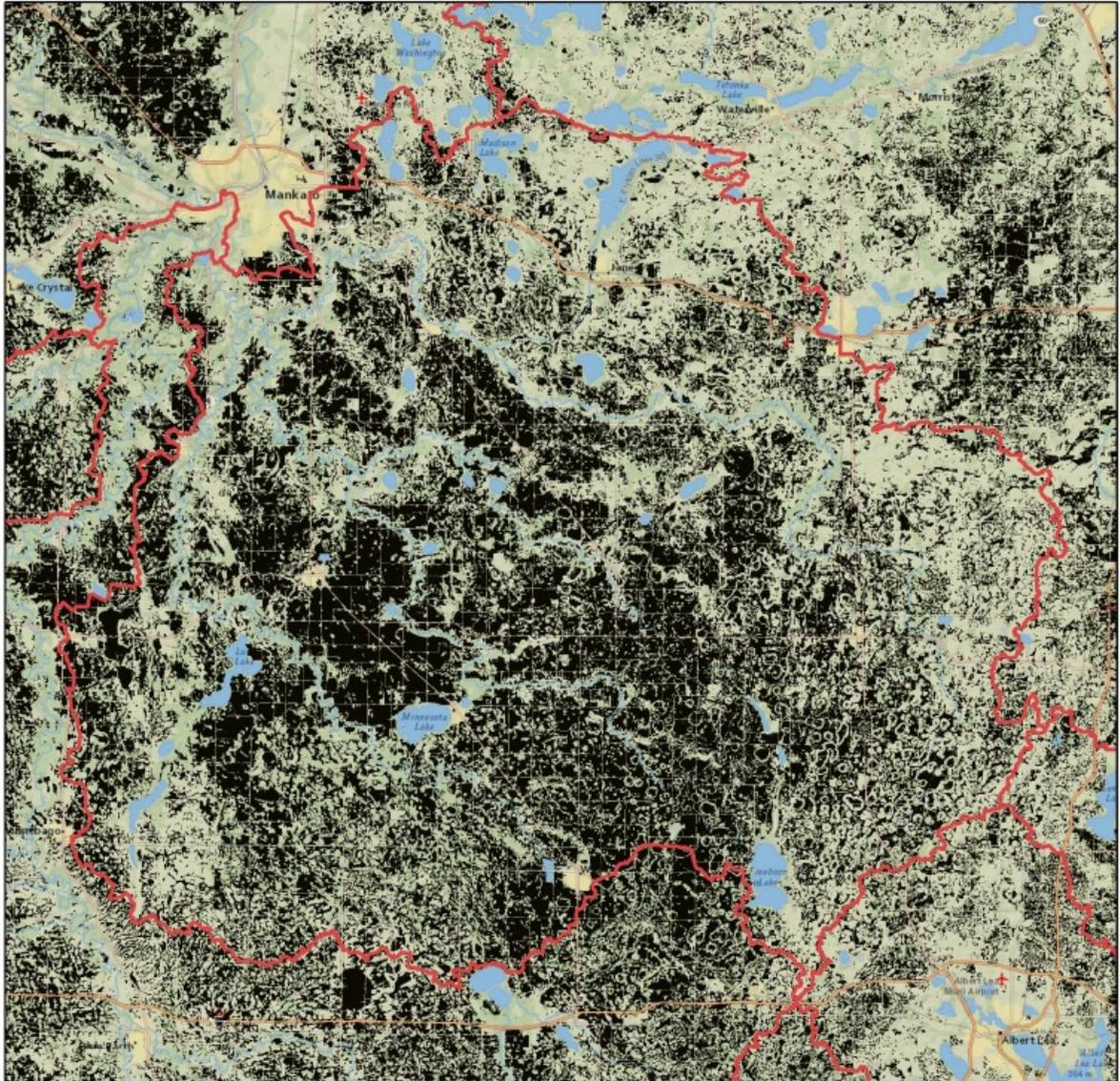


Predicted tile drained areas are based on the intersection of row crops (CDL 2011), slope < 3% (LiDAR derived DEM), and soils with hydric class presence > 80% of the soil mapping unit (SSURGO).

 Major Watershed Boundaries  
 Tile-drained Fields

**Appendix Figure 1:** Predicted tile drained fields for the Des Moines River – Headwaters watershed, Minnesota. The model used to predict the tile drained fields included the following criteria: (1) row cropped fields, based on the 2011 U.S. Department of Agriculture Crop Data Layer (CDL; U.S. Department of Agriculture, 2011); (2) slope of less than 3 percent, based on a LiDAR-derived digital elevation model (DEM) (Minnesota Geospatial Information Office, 2017); and, (3) greater than 80 percent of hydric class soils from the U.S. Department of Agriculture SSURGO data set (Natural Resources Conservation Service, 2005).

## Appendix 1-2. Le Sueur River, Minnesota

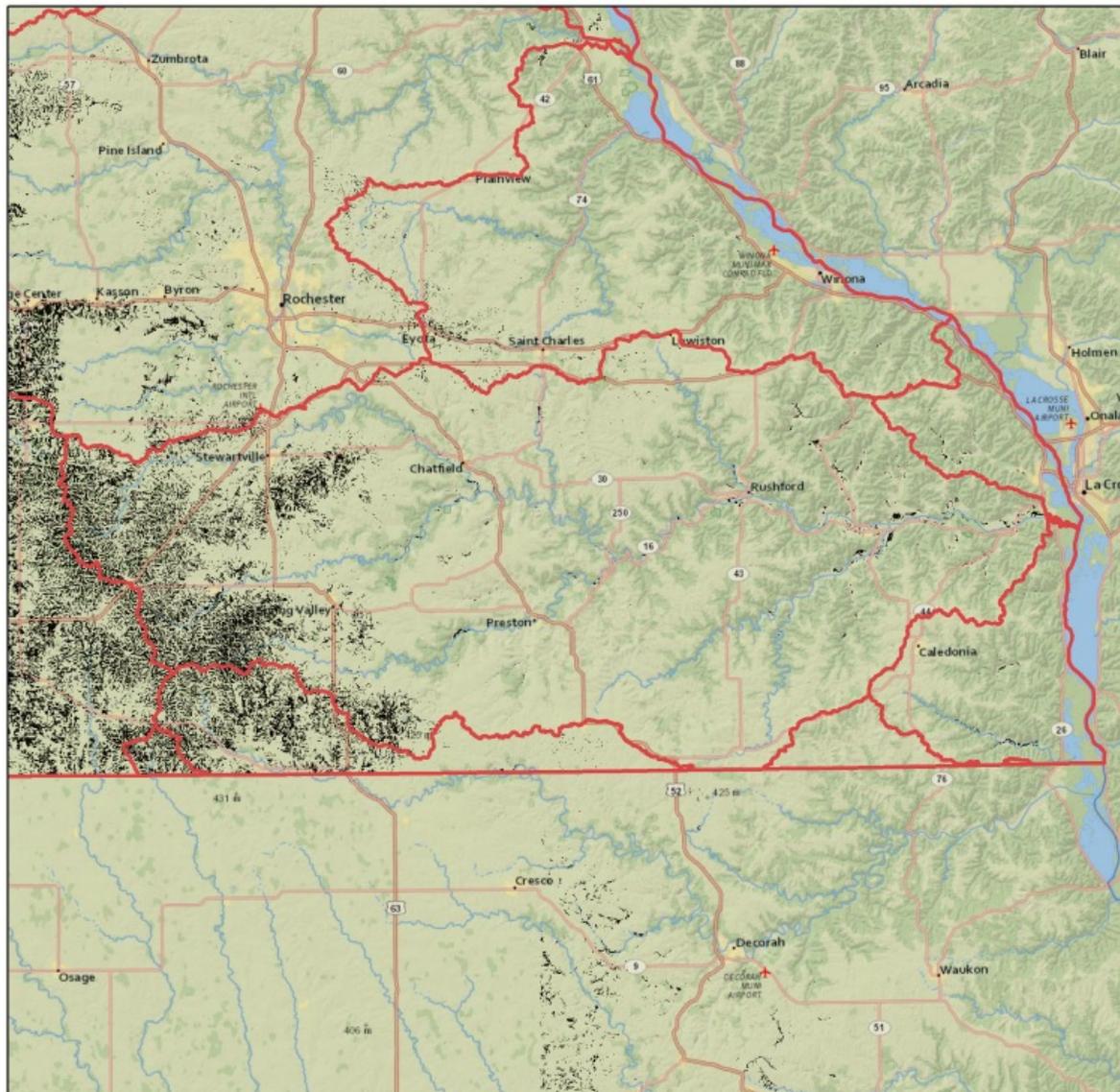


Predicted tile drained areas are based on the intersection of row crops (CDL 2011), slope < 3% (LiDAR derived DEM), and soils with hydric class presence > 80% of the soil mapping unit (SSURGO).

 Major Watershed Boundaries  
 Tile-drained Fields

**Appendix Figure 2:** Predicted tile drained fields for the Le Sueur River watershed, Minnesota. The model used to predict the tile drained fields included the following criteria: (1) row cropped fields, based on the 2011 U.S. Department of Agriculture Crop Data Layer (CDL; U.S. Department of Agriculture, 2011); (2) slope of less than 3 percent, based on a LiDAR-derived digital elevation model (DEM) (Minnesota Geospatial Information Office, 2017); and, (3) greater than 80 percent of hydric class soils from the U.S. Department of Agriculture SSURGO data set (Natural Resources Conservation Service, 2005).

## Appendix 1-3. Root River, Minnesota



Predicted tile drained areas are based on the intersection of row crops (CDL 2011), slope < 3% (LiDAR derived DEM), and soils with hydric class presence > 80% of the soil mapping unit (SSURGO).

 Major Watershed Boundaries  
 Tile-drained Fields

**Appendix Figure 3:** Predicted tile drained fields for the Root River watershed, Minnesota. The model used to predict the tile drained fields included the following criteria: (1) row cropped fields, based on the 2011 U.S. Department of Agriculture Crop Data Layer (CDL; U.S. Department of Agriculture, 2011); (2) slope of less than 3 percent, based on a LiDAR-derived digital elevation model (DEM) (Minnesota Geospatial Information Office, 2017); and, (3) greater than 80 percent of hydric class soils from the U.S. Department of Agriculture SSURGO data set (Natural Resources Conservation Service, 2005).



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