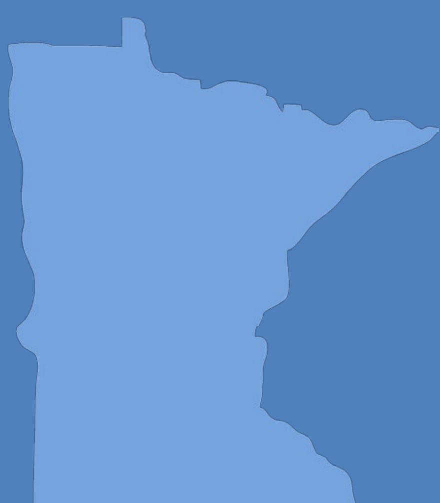
Groundwater Report
Lake Superior North Watershed



Minnesota Pollution Control Agency

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I. Introduction

Groundwater reviews are detailed reports on the condition of groundwater within the boundaries of one of the 81 major surface watersheds in Minnesota. This approach follows the Minnesota Pollution Control Agency (MPCA) focus on watersheds as the starting point for water quality assessment, planning, implementation and measurement of the watershed's condition. Though groundwater and surface watersheds do not always coincide, this method of investigating the condition of the hydrologic resource as a watershed unit can be usefully applied to groundwater because groundwater and surface water are dynamically linked. This linkage will be explored and explained in this report through the use of the water cycle, tracing the movement of water through the watershed from precipitation to runoff, recharge to withdrawal, and to conclude with evapotranspiration (Figure 1).

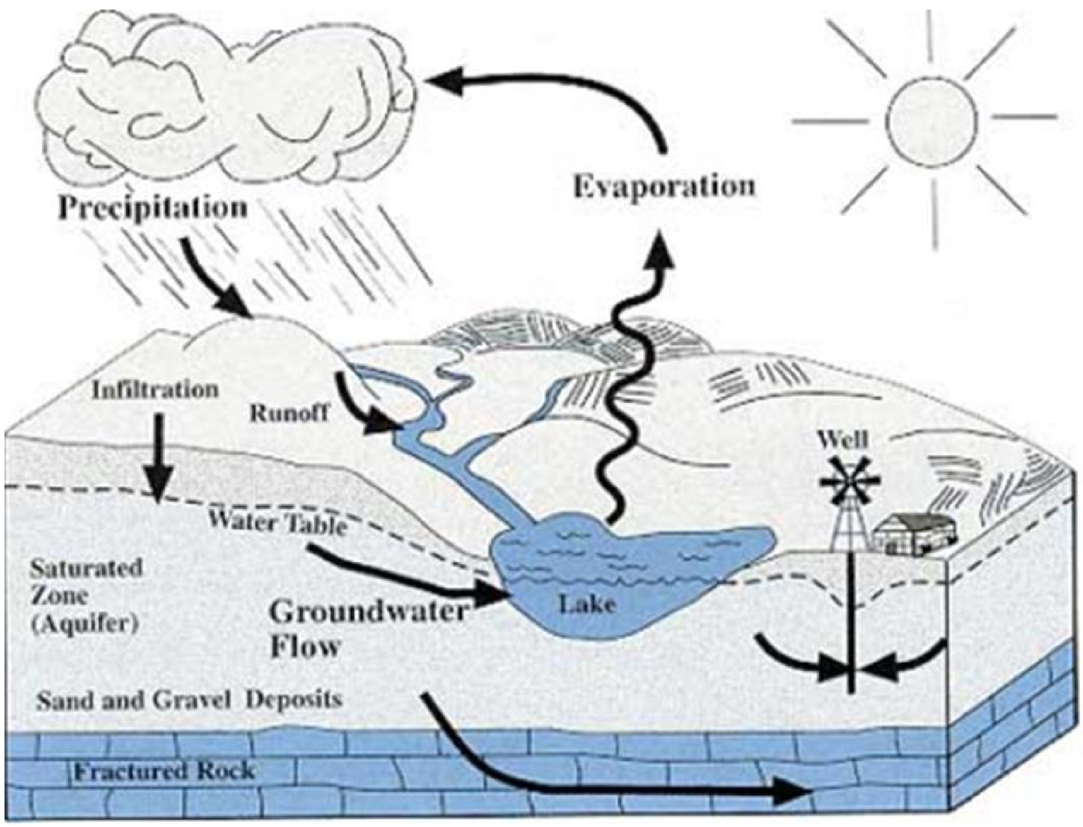

Figure 1: Simplified hydrologic cycle demonstrating the changing states of water above and below the earth's surface

The groundwater reports rely on the analysis of a wide spectrum of hydrologic datasets to provide context for the understanding of groundwater within the hydrologic cycle. The datasets analyzed include precipitation, streamflow, permitted high volume pumping, lake and groundwater elevations, evapotranspiration estimates, water quality samples, contaminant releases, and estimates of recharge to surficial aquifers, and hydrogeological maps from local Geological Atlases.

The watershed monitoring approach

The watershed monitoring approach was adopted by the MPCA as a means to intensively monitor and assess the condition of Minnesota's lakes and streams at a watershed level. This was in compliance with the responsibility of the agency to the Clean Water Legacy Act to "protect, restore and preserve the quality of Minnesota's surface waters" (MPCA, 2009). The approach focused efforts on 8-digit hydrologic unit code (HUC) watersheds during a 10-year cycle for all 81 major watersheds in Minnesota.

The Minnesota Department of Natural Resources (MNDNR, 2015a) defines surface water and groundwater watersheds as follows:

Surface water watersheds are generally delineated from topographic maps based on land elevations ("height-of-land" method). The MNDNR completed a standard delineation of minor watershed boundaries for Minnesota in 1979. Using U.S. Geological Survey quadrangle maps, the MNDNR defined minor watershed outlets and delineated height-of-land minor watershed boundaries for all watersheds greater than five square miles. However, actual boundaries may be different due to map interpretation assumptions or human-induced changes that have occurred since the map was made. Field inspection of areas in question is required to be certain of actual boundaries.

Groundwater watersheds are conceptually similar to surface water watersheds because groundwater flows from high points (divides) to low points (outlets, discharge areas). However, the boundaries of surface water and groundwater watersheds do not always coincide. Groundwater movement occurs in below ground aquifer systems and is subject to 1) hydraulic properties of the aquifer, 2) input to (recharge) and outflow from (discharge) the aquifer system, and 3) geological factors such as formations that block the flow of water and tilted formations that create a flow gradient. Surficial aquifers (the water table) generally mimic surface water watersheds, and their flow usually does not cross surface boundaries. Deeper (confined) aquifers, on the other hand, are less likely to conform to surface features and exhibit watersheds (or basins) determined by geologic factors. As described in the MNDNR website: http://www.dnr.state.mn.us/watersheds/surface_ground.html. For the purposes of this report, groundwater watersheds will be treated as contiguous with surface water watersheds.

Watershed overview

The Lake Superior North Watershed (HUC 04010101) is located in the far northeastern corner of Minnesota. It is a part of the Great Lakes Basin within the Northern Lakes and Forest ecoregion and its eastern border lies directly adjacent to Lake Superior (Figure 2). It covers 1,019,923 acres (1,594 square miles) and its reach stretches over most of Cook County (80.7%) and part of Lake County (19.3%). Open waters make up 6.0%, including 2,751 stream miles, of the land cover and wetlands encompass another 3.0% (USDA, NRCS). The watershed's elevation ranges from 2,301 feet above mean sea level at Eagle Mountain to 307 feet above mean seal level at Lake Superior, with steep elevation changes occurring near the shore of Lake Superior (Figure 3) (USDA, NRCS).

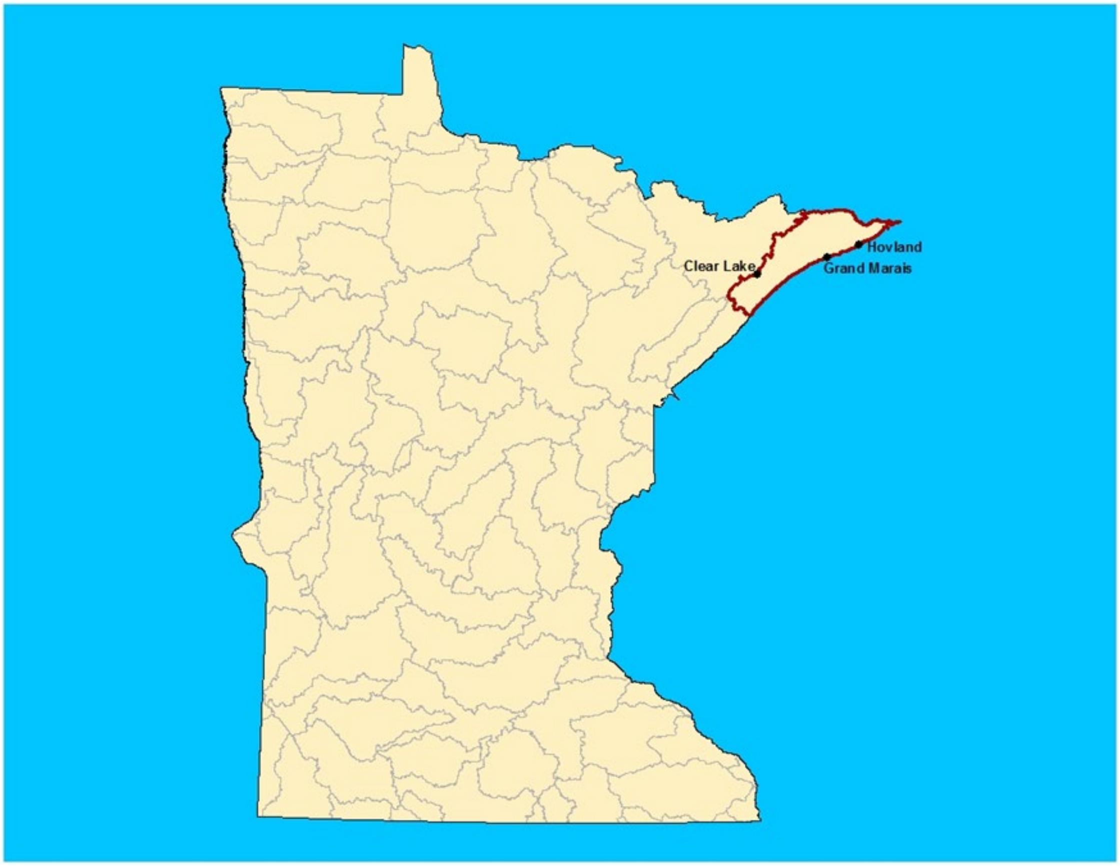

Figure 3: The location of the Lake Superior North Watershed

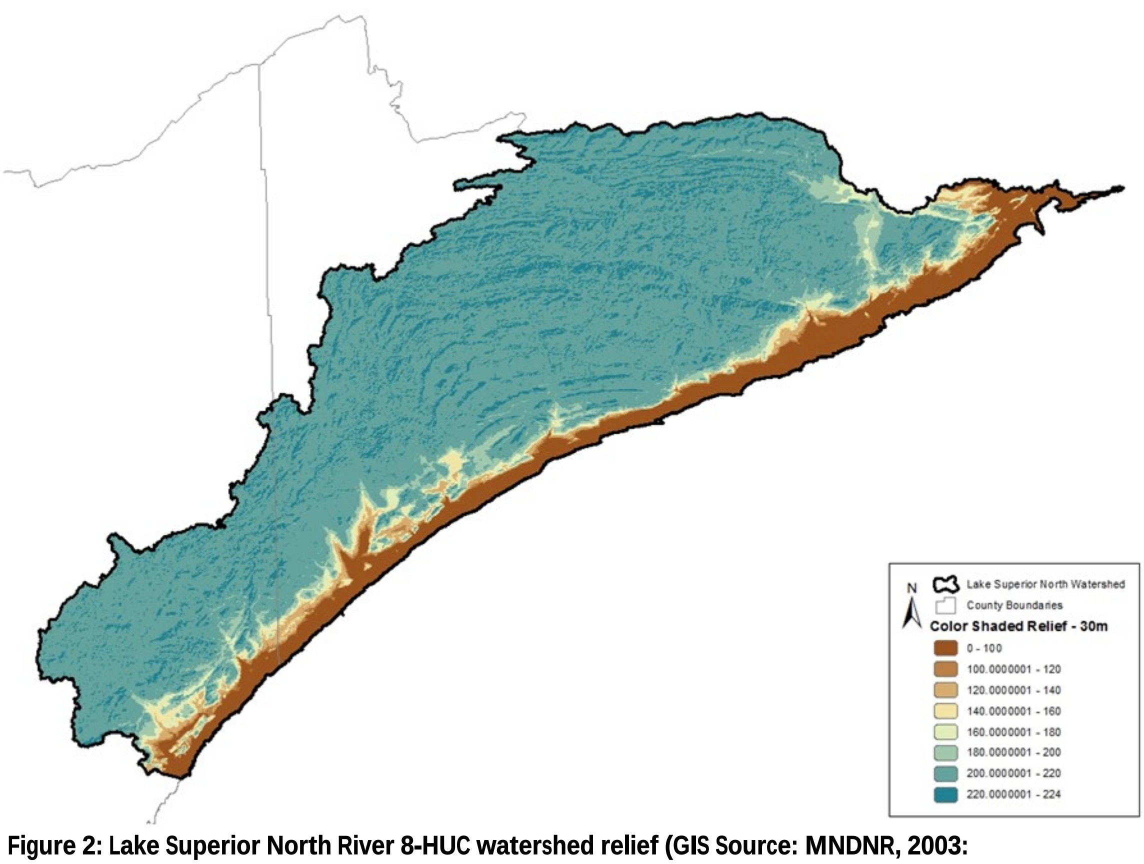

Figure 2: Lake Superior North River 8-HUC watershed relief (GIS Source: MNDNR, 2003:

Land use

The land use in the Lake Superior North Watershed consists of small towns, commercial and resort business, and rural residential. A significant amount of development is located along Lake Superior's shoreline on the eastern border of the watershed boundary. Land use activity is largely made up of forest products and tourism. Certain commercial and industrial uses including marinas, shipping ports, and processing rely heavily on water resources (MPCA, 2015a). Land use categories are forested (70.9%), wetlands (17.2%), open water (6.0%), developed (1.9%) and cropland (0.02%) (Figure 4) (NLCD, 2011). Very little land is utilized for agriculture, primarily due to the poorly erodible soils, with approximately 22 farms located within the watershed (USDA, NRCS). The majority of the land is owned by federal (57.1%), state (21.8%), tribal (4.3%), conservancy (0.2%), or county (0.1%), while 14.4% is privately owned (USDA, NRCS).

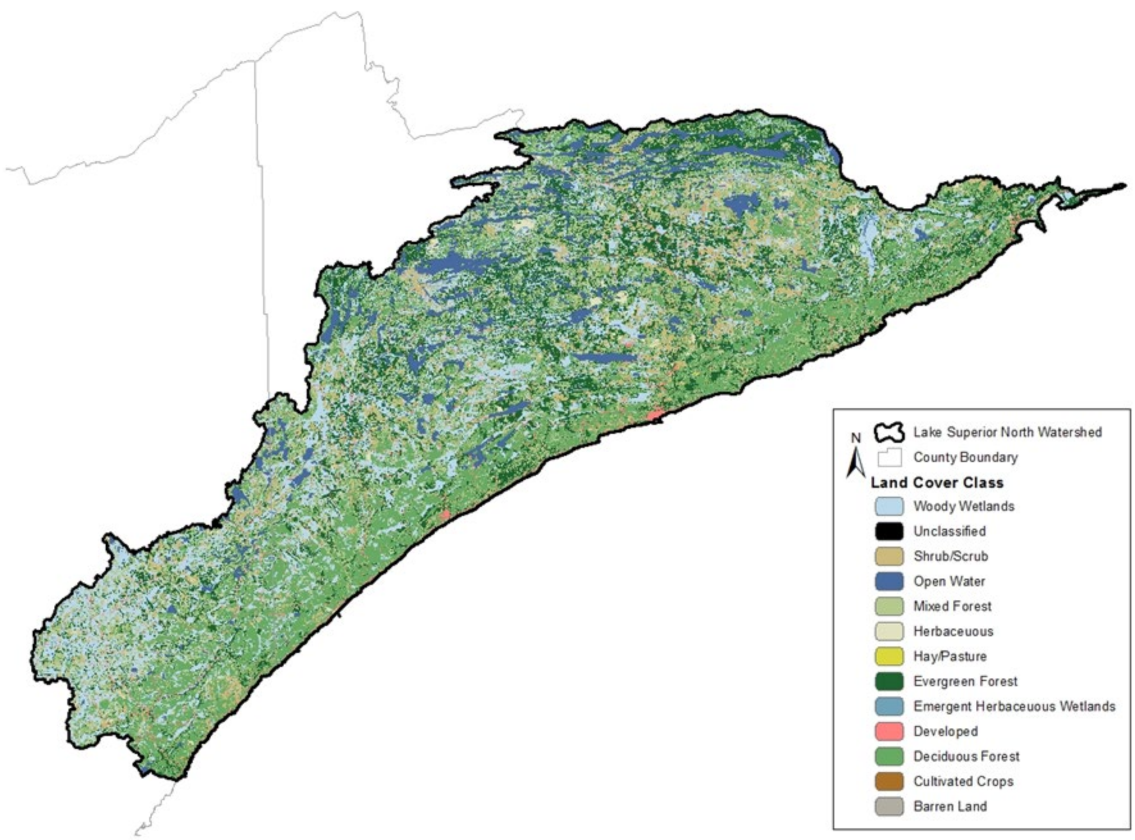

Figure 4: Land cover in the Lake Superior North Watershed (GIS Source: NLCD, 2011)

Ecoregion and soils

The agroecoregion of the watershed is made up of drift and bedrock complex, forested moraine and Northshore moraine. The watershed is located within the Northern Lakes and Forest Ecoregion of Minnesota. According to the Ecological Classification System (ECS), the Lake Superior North Watershed is located within the Laurentian Mixed Forest Province and the Northern Superior Uplands Section. The watershed also lays within the ECS subsections Border Lakes (north), the Laurentian Uplands (west central) and the North Shore Highlands (south and eastern border) Subsections (Figure 5).

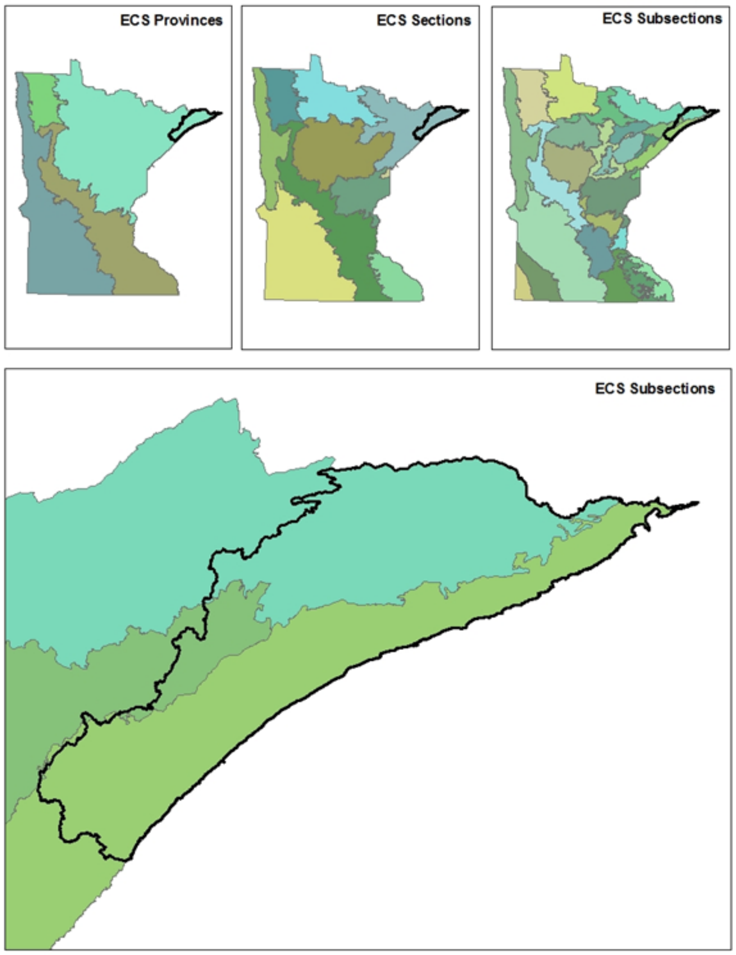

Figure 5: Three levels of Ecological Classification System for the Lake Superior North Watershed

The watershed is primarily comprised of non-calcareous glacial deposits of sand and gravel outwash from the Superior and Rainy Lobes. These unconsolidated glacial sediments consist of red to brown sandy and stony till, outwash and ice-contact deposits of sand and gravel, and red silty to clayey glacial lake deposits (USDA, NRCS). Subsurface geology is dominated by bedrock, glacial till complexes and unconsolidated glacial lake deposits of sand, gravels, clay and silt (MPCA, 2015a). The glacial deposits can be grouped into three categories: 1) loamy soils with coarse fragments (gravels, cobbles, stones and boulders), 2) heavy clayey soils with few coarse fragments, and 3) shallow soils on top of bedrock (Walczynski & Risley, 2016). A more detailed list of the soil types can be found in Figure 6 (below).

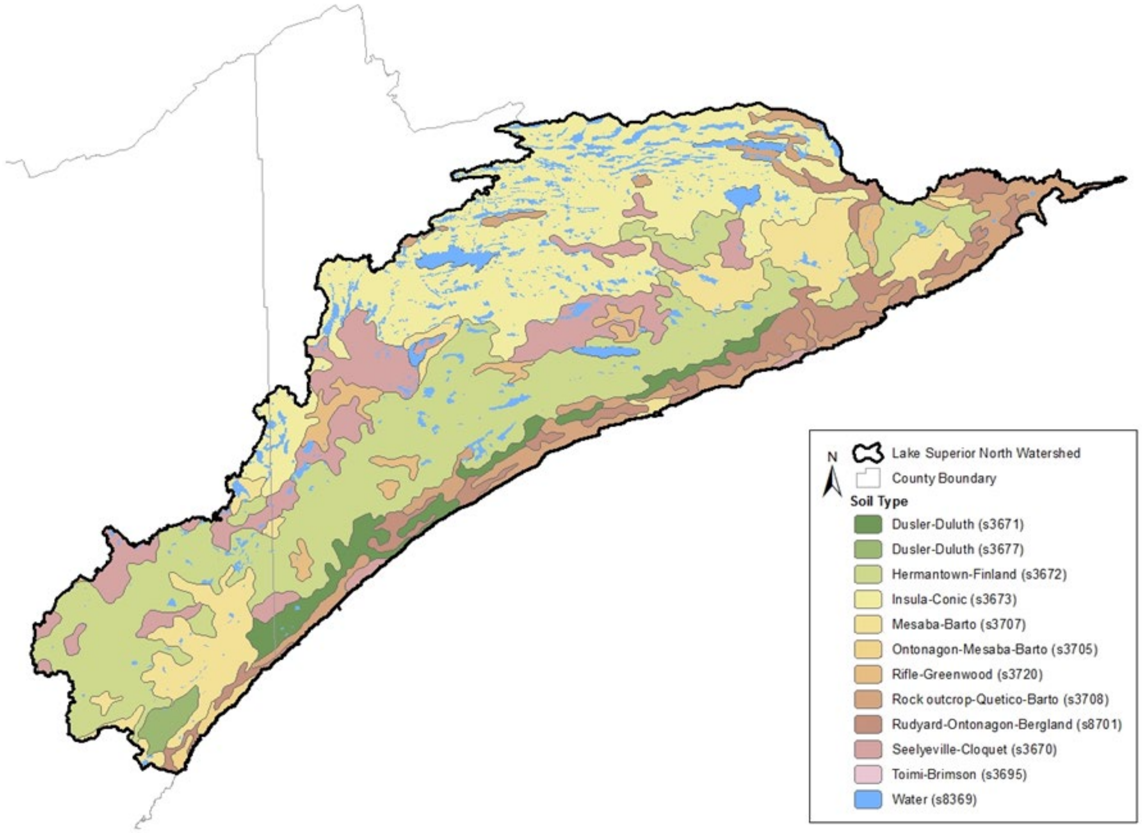

Figure 6: Soil classification for the Lake Superior North Watershed (GIS Source: USDA NRCS, 2006)

II. Climate and precipitation

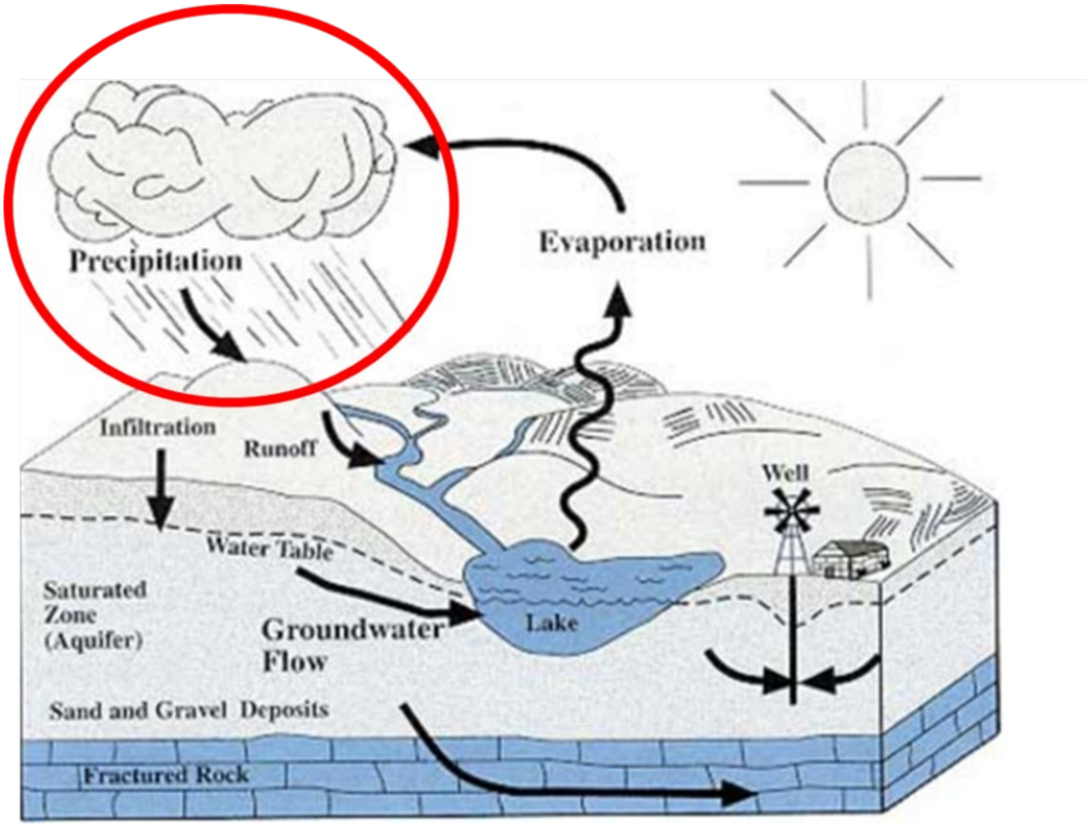

Figure 7: Precipitation within the hydrologic cycle

Minnesota has a continental climate, marked by warm summers and cold winters. The mean annual temperature for the state is 4.6˚C (NOAA, 2016); the mean summer temperature for the Lake Superior North Watershed is 15.0˚C and the mean winter temperature is -11.7˚ C (MNDNR: Minnesota State Climatology Office, 2003).

Precipitation is an important source of water input to a watershed. Figure 8 shows two representations of precipitation for calendar year 2014. On the left is total precipitation, showing the typical pattern of increasing precipitation toward the eastern portion of the state. According to this figure, the Lake Superior North Watershed area received 28 to 32 inches of precipitation in 2014. The display on the right shows the amount those precipitation levels departed from normal. For the Lake Superior North Watershed, the map shows that precipitation ranged from 4 inches below normal to 2 inches above normal.

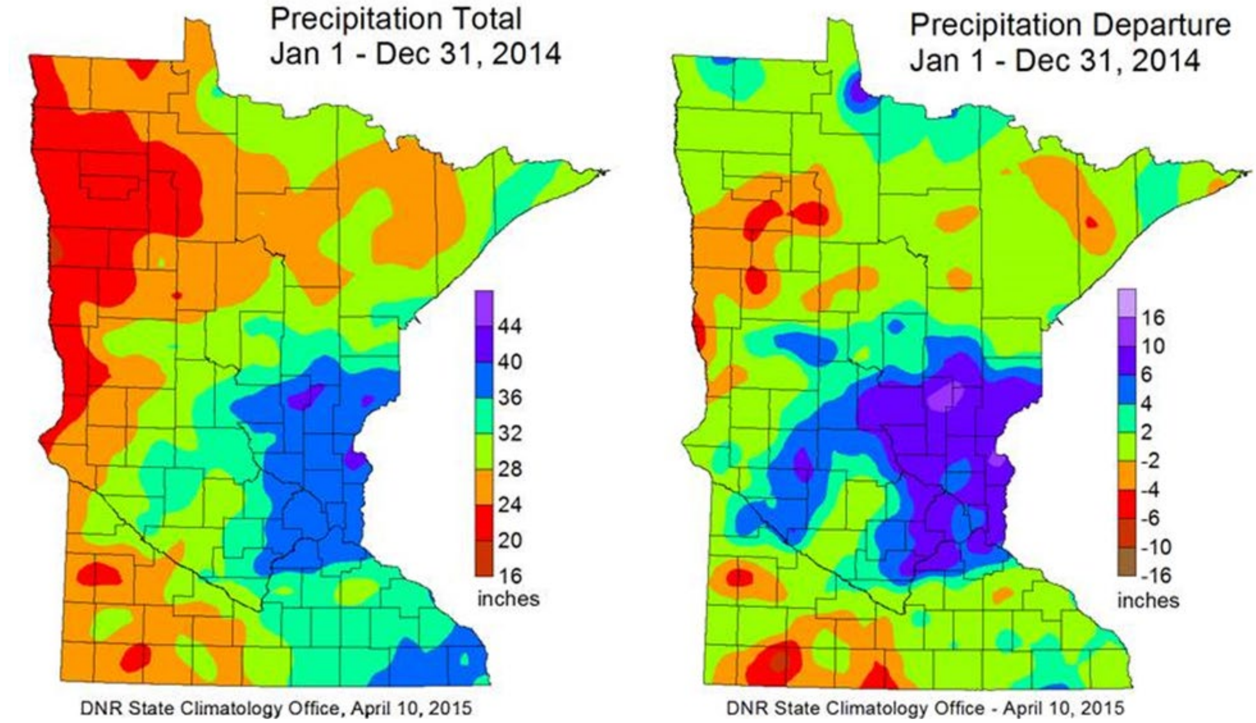

Figure 8: Statewide precipitation levels during 2014 (Source: MNDNR State Climatology Office, 2015)

The Lake Superior North Watershed is located in the Northeast precipitation region. Figure 9 and 10 (below) display the areal average representation of precipitation in Northeast Minnesota for 20 and 100 years, respectively. An areal average is a spatial average of all the precipitation data collected within a certain area presented as a single dataset. Though rainfall can vary in intensity and time of year, rainfall totals in the Northeast region display no significant trend over the last 20 years. However, precipitation in Northeast Minnesota exhibits a significant rising trend over the past 100 years (p=0.001). This is a strong trend and matches similar trends throughout Minnesota.

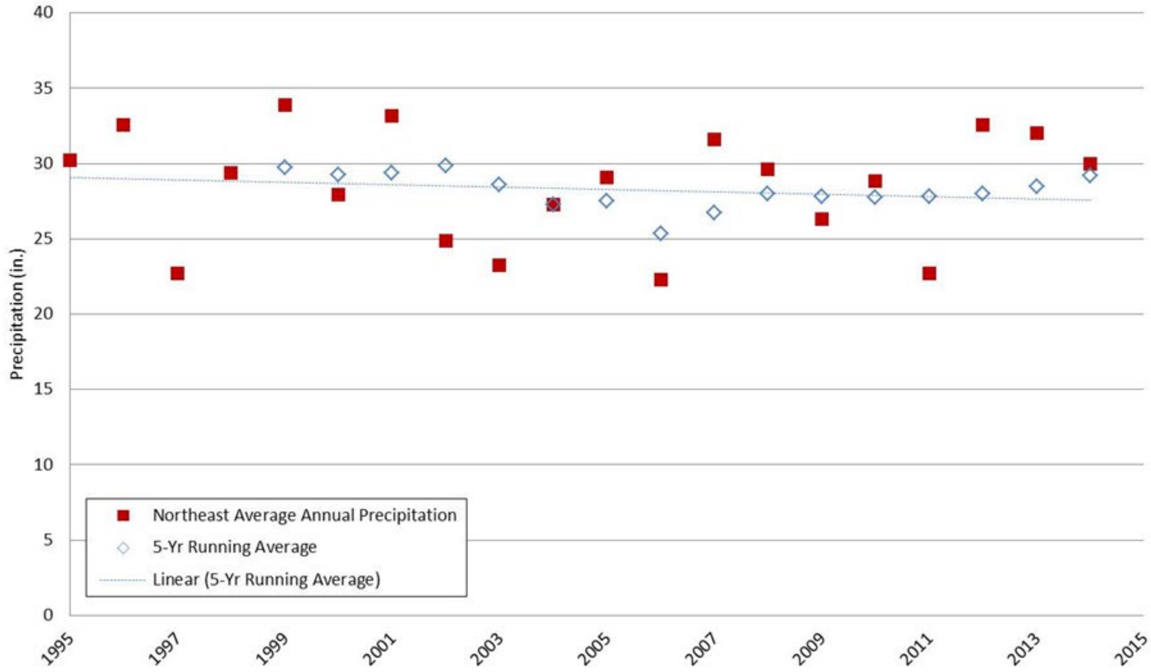

Figure 9: Precipitation trends in Northeast Minnesota (1955-2014) with five-year running average

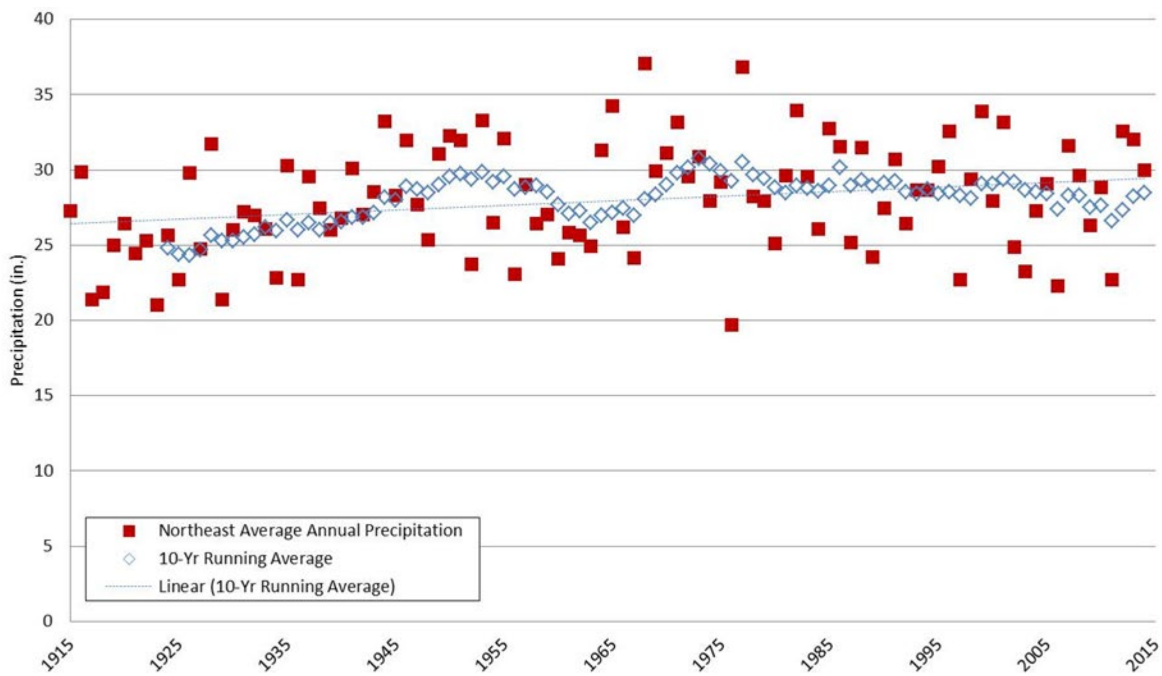

Figure 10: Precipitation trends in Northeast Minnesota (1915-2014) with 10-year running average

III. Surface water hydrology

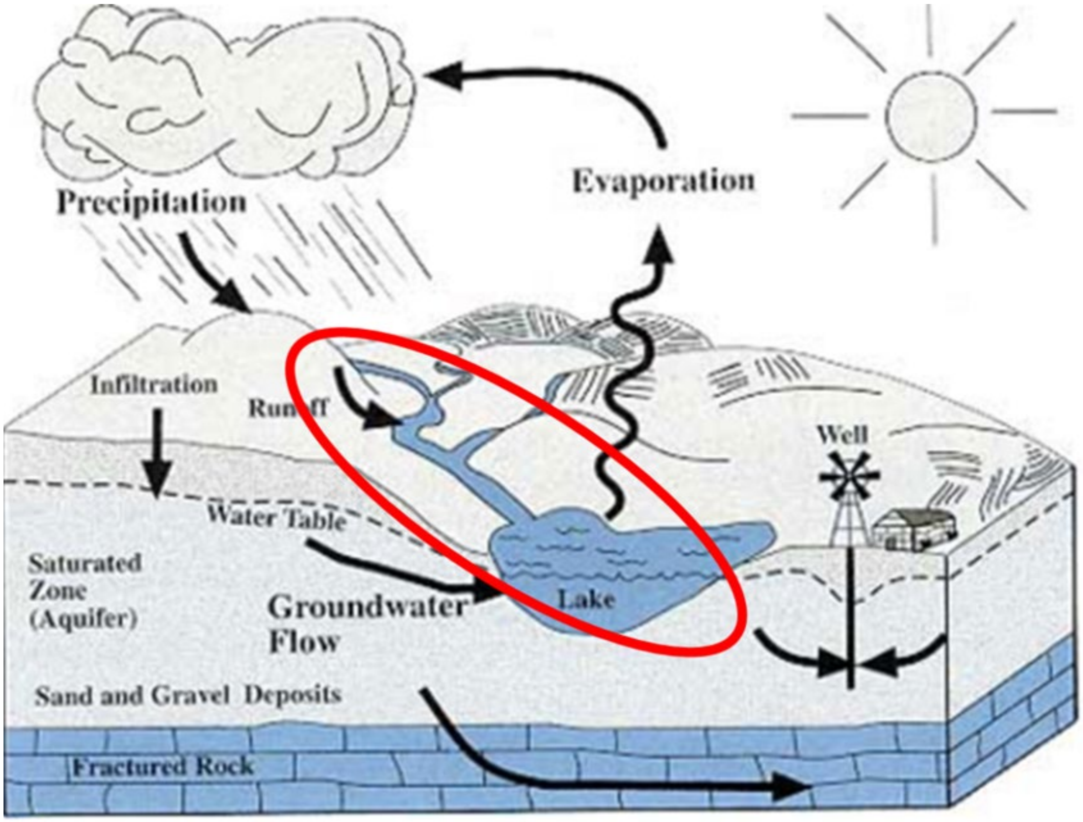

Figure 11: Surface water within the hydrologic cycle

The Lake Superior North Watershed's surface hydrology is a water-rich area, with 2,751 stream miles, 633 lakes, and 174,808 acres of wetlands (Figure 12) (USDA, NRCS; NLCD, 2011; MNDNR, 2015b). Many rivers and streams are located throughout the watershed; some notable rivers include Baptism, Manitou, Caribou, Temperance, Poplar, Devil Track, Brule, and Pigeon River, among others. Major lakes in this watershed include Devil Track, Caribou, Tait, Trout, Tom, Hungry Jack Lake, Poplar, Bearskin, West Bearskin, and Clearwater Lake. Most areas in the Lake Superior North watershed are recognized as having exceptional water quality, aside from some lakes and streams that do not meet turbidity standards.

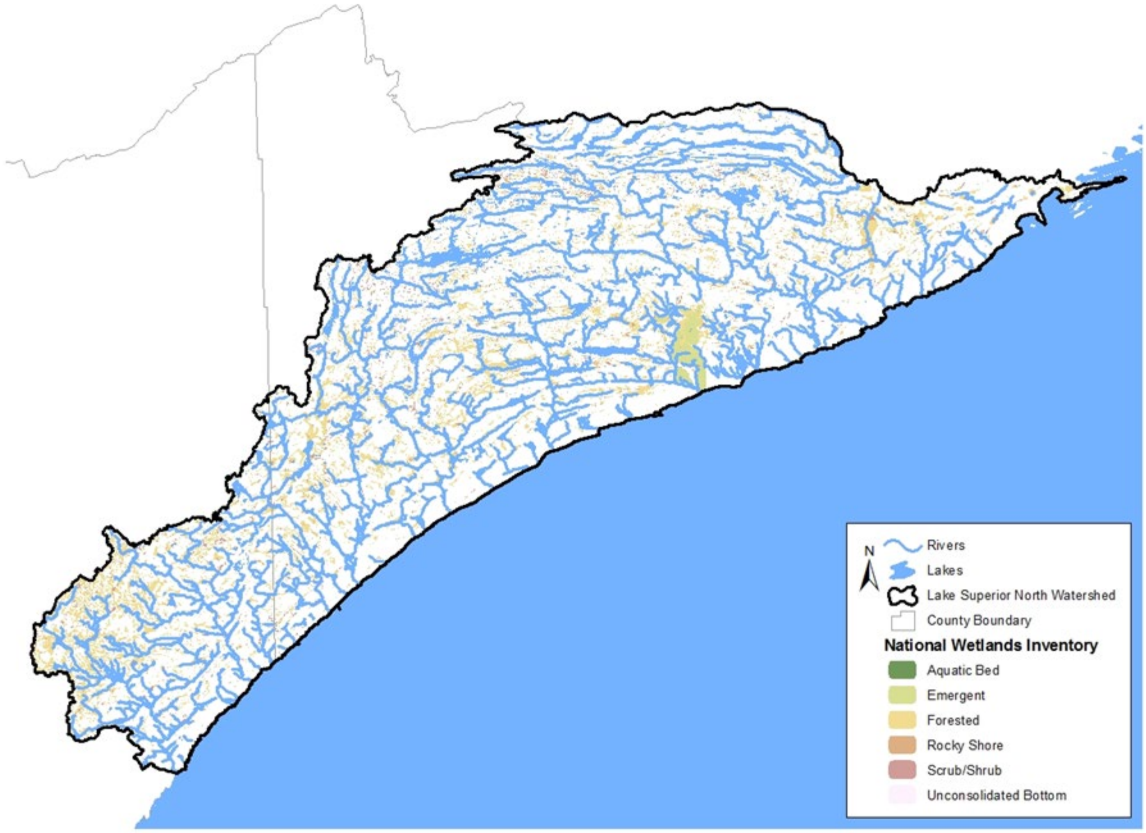

Figure 12: Lakes, wetlands and waterbodies in the Lake Superior North Watershed

Streamflow

Streamflow data from the United States Geological Survey's real-time streamflow gaging stations for one river in the Lake Superior North Watershed was analyzed for annual mean discharge and summer monthly mean discharge (July and August). Figure 13 is a display of the annual mean discharge for the Pigeon River at Middle Falls near Grand Portage from water years 1996 to 2015. The data shows that although streamflow appears to be slightly decreasing, there is no statistically significant trend. Figure 14 displays July and August mean flows for water years 1996 to 2015 for the same water body. The data appear to be increasing in July and August, but not at a statistically significant rate. By way of comparison at a state level, summer month flows in Minnesota have declined at a statistically significant rate at a majority of streams selected randomly for a study of statewide trends (Streitz, 2011). For additional streamflow data throughout Minnesota, please visit the USGS website: http://waterdata.usgs.gov/mn/nwis/rt.

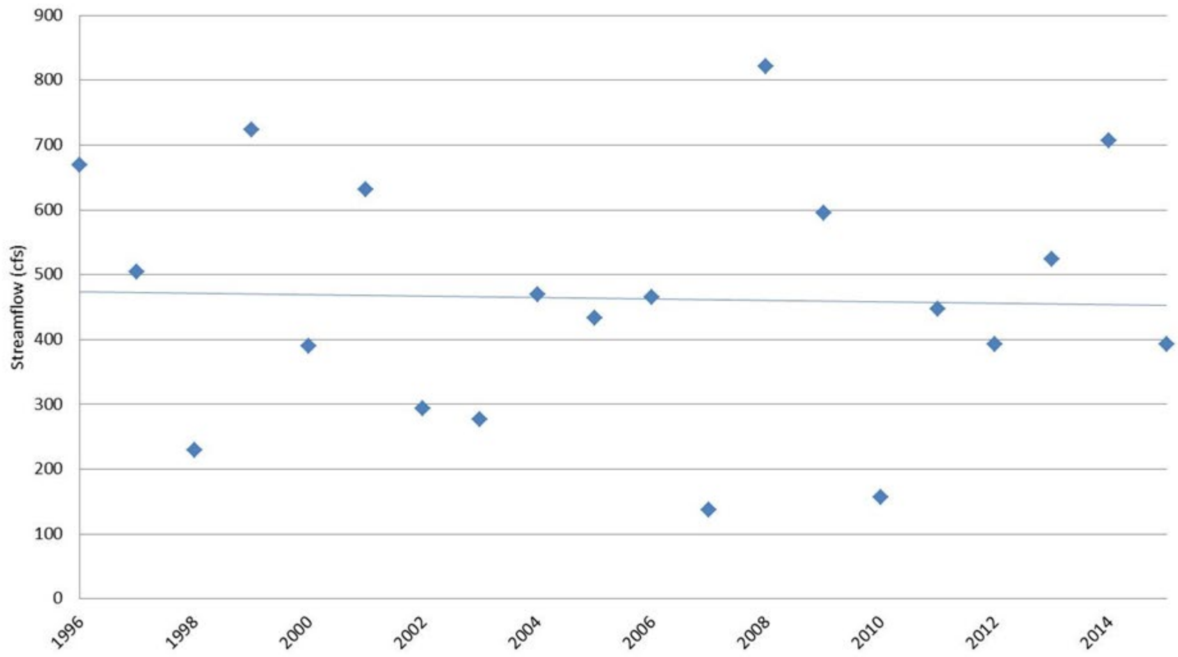

Figure 13: Annual mean discharge for Pigeon River at Middle Falls near Grand Portage, Minnesota (1996-5015)

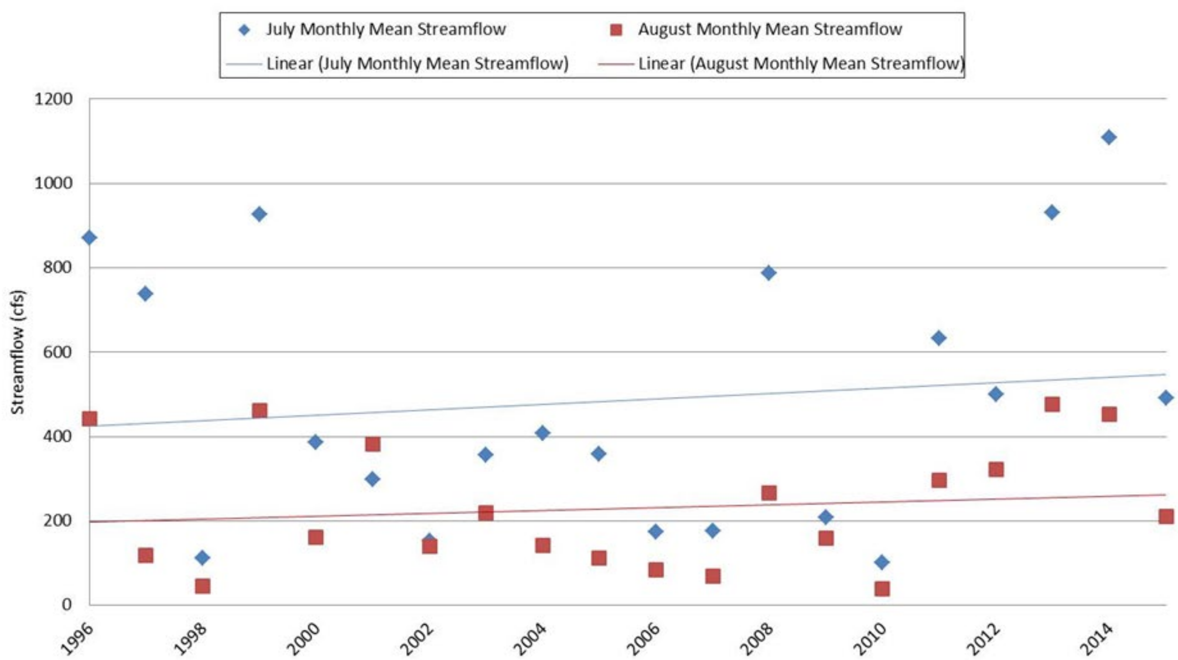

Figure 14: Mean monthly discharge for Pigeon River at Middle Falls near Grand Portage, Minnesota (1996-2015)

Lake levels

Poplar Lake (Identification Number 16023900) is located in Cook County, 20 miles northwest of Grand Marais in the northern area of the watershed (Figure 15). The lake surface area is 758 acres with a maximum depth of 73 feet and an average lake water level elevation of 1853.7 (MPCA, 2015b). The lake's use classification is 1C, 2Bd, 3C, which is defined as drinking water use after advanced treatment; a healthy warm water aquatic community; industrial cooling and materials transport use without a high level of treatment (MPCA, 2015b). The overall condition is described as "suitable for swimming and wading with good clarity and low algae levels throughout the open water season. Concentrations of mercury in fish tissue exceed the water quality standard" (MPCA, 2015b).

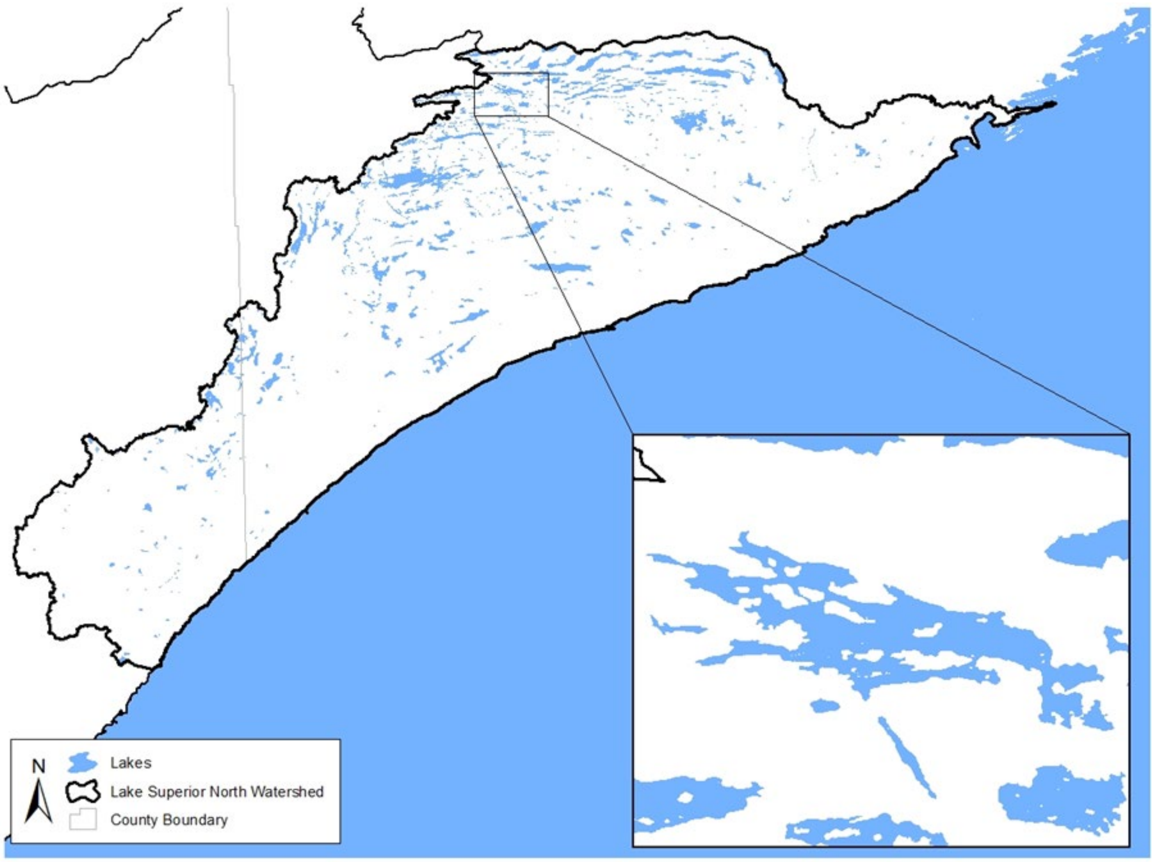

Figure 15: Poplar Lake within Lake Superior North Watershed

A 2012 survey by the Minnesota Department of Natural Resources (MNDNR) determined the average water clarity to be 10.4 feet, which is considered good water clarity, and the littoral area to be 290 acres (MNDNR, 2015c). The lakeshore is considered one of the more heavily developed lakes in Cook County and walleye management has proven to be difficult over the years, with low catch and growth rates for a lake of this size that is heavily stocked (MNDNR, 2015c). In 2007, the MPCA determined the lake to be impaired for aquatic consumption from elevated mercury levels in fish tissue (MPCA, 2015b). Mercury, a neurotoxin, is considered a concern due to the damage it can cause from bioaccumulation to the central nervous system (MPCA, 2007). Over the last 20 years, lake level elevation has remained constant, altering for seasonal fluctuations (Figure 16). Lake elevation data can be found from the MNDNR Lake Finder website: http://www.dnr.state.mn.us/lakefind/index.html.

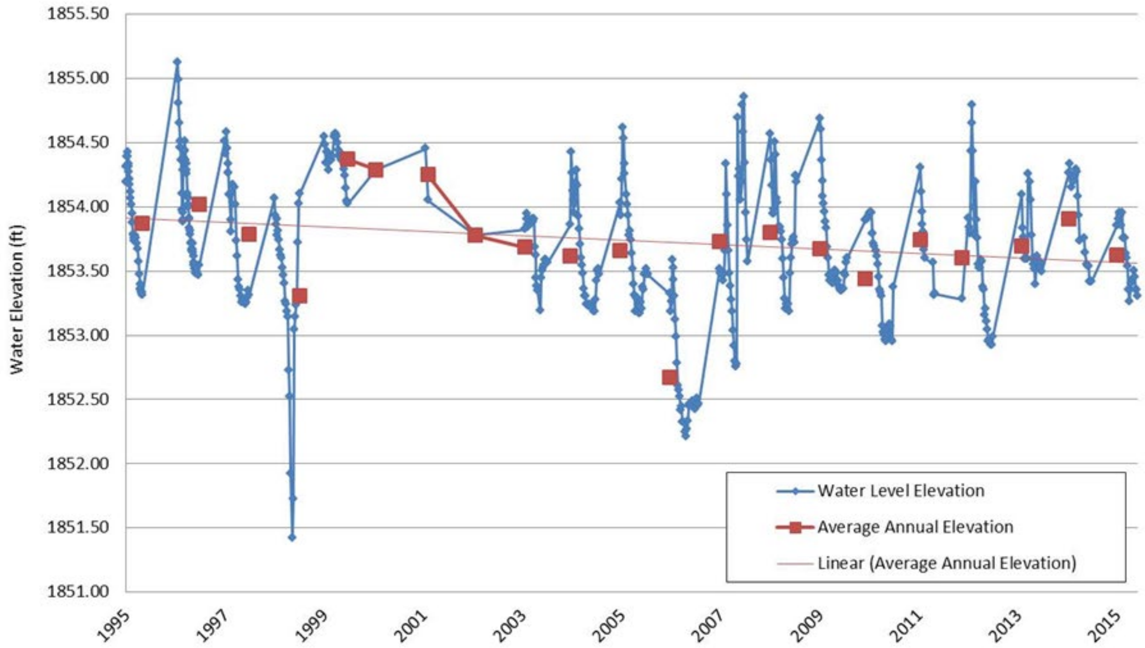

Figure 16: Poplar Lake water level elevations (1996-2015)

Wilson Lake (Identification Number 38004700) in Lake County is located 13 miles east of Isabella in the south-central area of the watershed (Figure 17). The area of the lake is 652 acres with a maximum depth of 53 feet and an average lake water level elevation of 1,687.9 feet (MPCA, 2015c). The lake's use classification is 2B, 3C, identified as a healthy warm water aquatic community; industrial cooling and material transport use without a high level of treatment class. The overall condition is described as "suitable for swimming and wading with good clarity and low algae levels throughout the open water season. Concentrations of mercury in fish tissue exceed the water quality standard" (MPCA, 2015c).

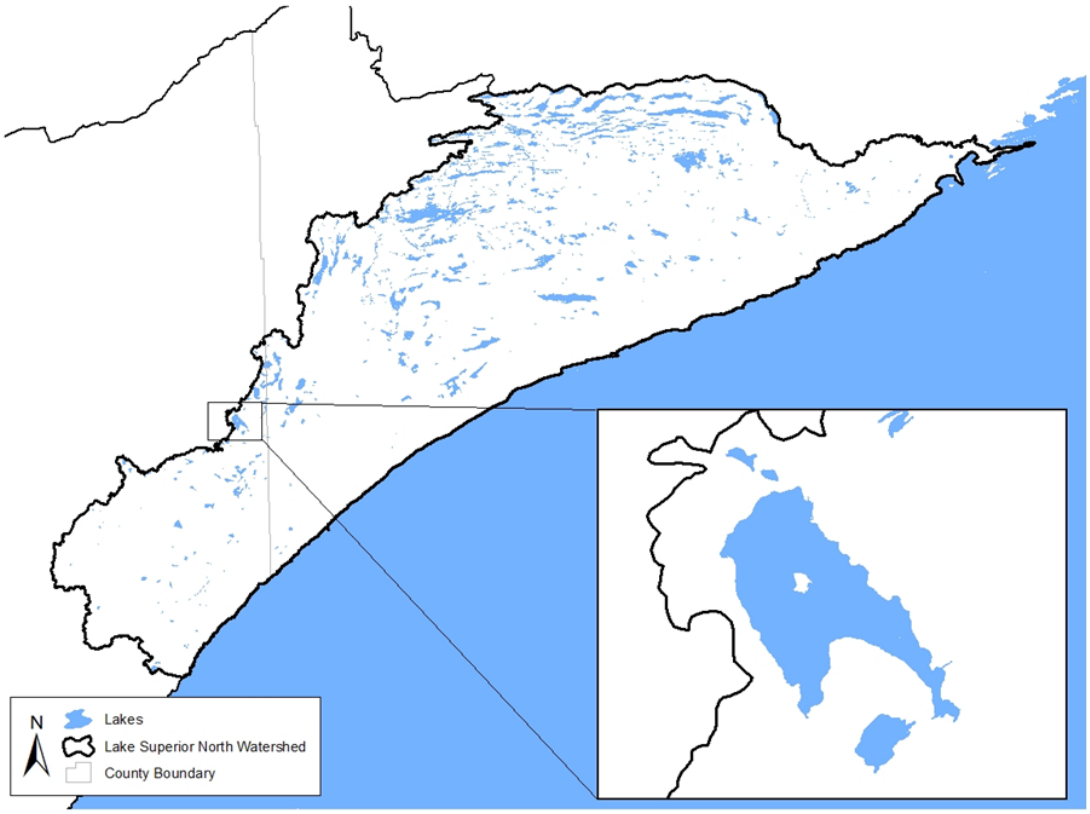

Figure 17: Wilson Lake within the Lake Superior North Watershed

A 2011 survey by the MNDNR determined the average water clarity to be 18 feet, which is considered good water clarity, and the littoral area to be 239.9 acres (MNDNR, 2015d). The surrounding area is primarily forested, with one public access at the south entrance of the lake and a small campground maintained by the U.S. Forest Service (MNDNR, 2015d). During the fisheries survey in 2011, walleye, yellow perch and large white suckers numbers were above average for this lake class, while the northern pike numbers were below average (MNDNR, 2015d). In 2007, the MPCA determined the lake to be impaired for aquatic consumption from elevated mercury levels in fish tissue (MPCA, 2015c). Over the last 20 years, lake level elevation has remained constant, altering for seasonal fluctuations (Figure 18).

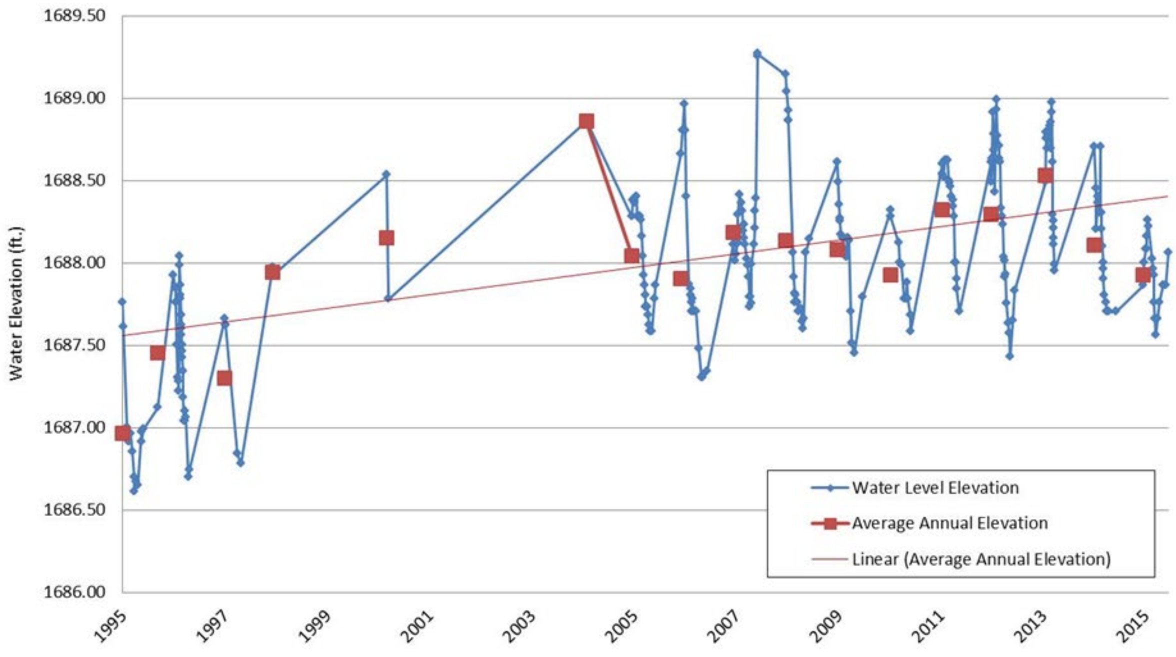

Figure 18: Wilson Lake water level elevations (1996-2015)

III. Hydrogeology

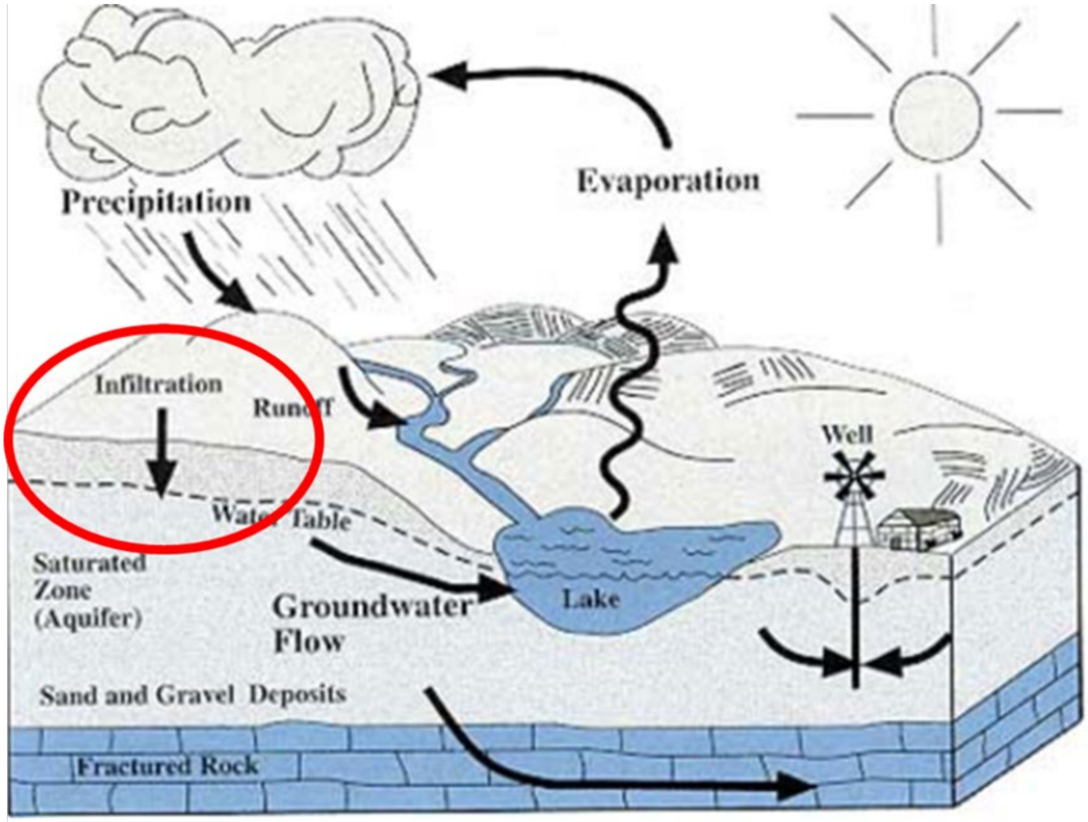

Figure 19: Groundwater within the hydrologic cycle

Surficial and bedrock geology

The MNDNR and Minnesota Geological Survey (MGS) have collaborated to develop the County Geologic Atlas Program, with the purpose of eventually developing maps and reports of the geology and hydrogeology for all the counties in Minnesota. Each completed county atlas consists of a Part A (geology by MGS) and Part B (hydrogeology by MNDNR). For Lake Superior North Watershed, Part A is in progress for Lake County, but is incomplete for Cook County and Part B is incomplete for both counties. For more information on the County Geologic Atlases available, please visit: http://www.dnr.state.mn.us/waters/groundwater_section/mapping/index.html.

Surficial geology is identified as the earth material located below the topsoil and overlying the bedrock. Glacial sediment is at the surface in the Lake Superior North Watershed, and is thin and discontinuous, with deposits of coarse loamy till and numerous lakes (MNDNR, 2016). Although deposits throughout the watershed are primarily thin, the depth to bedrock ranges from exposure at the surface to over 600 feet. The bedrock is buried by deposits of the various ice lobes that reached this watershed during the last glacial period, as well as during previous glaciations in the last 2.58 million years. The majority of glacial sediment at the surface is associated with the Superior and Rainy Lobes. Both of these lobes originated from the northeast and have red to brown till color containing fragments of basalts, gabbro, granite, iron formation, red sandstone, slate and greenstone (MNDNR, 1995). The Superior Lobe till tends to contain more red clay while the Rainy Lobe till is more sandy and coarse. The glacial deposits can be grouped into three categories: 1) loamy soils with coarse fragments (gravels, cobbles, stones and boulders), 2) heavy clayey soils with few coarse fragments, and 3) shallow soils on top of bedrock and lithology grouped by material texture: 1) non-calcareous till, 2) clay and silt, and 3) peat till (Figure 20) (Walczynski & Risley, 2016; MGS, 1982).

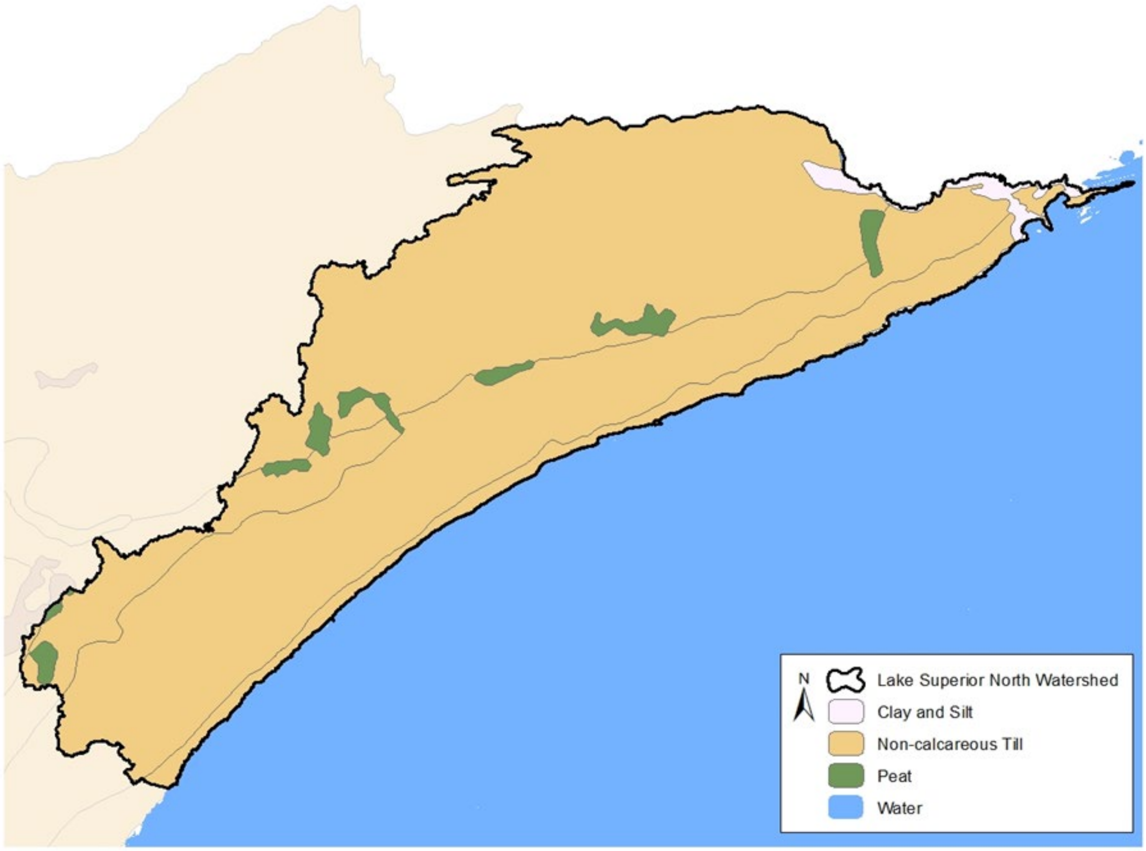

Figure 20: Quaternary geology, glacial sediments within the Lake Superior North Watershed (GIS Source: MGS, 1982)

Bedrock is the main mass of rocks that form the earth, located underneath the surficial geology and can only be seen where weathering has exposed the bedrock. The bedrock geology of the Lake Superior North Watershed consists of Precambrian crystalline rocks and the Keweenawan Rift under Lake Superior (Figure 21).

The Keweenawan Rift, also referred to as the Midcontinent Rift System, occurred approximately 1.1 billion years ago, when rifting from a mantle plume pulled apart the area from Lake Superior to Kansas, while filling the graben with volcanic and sedimentary rocks (Cannon et al., 1989). These rocks are currently exposed at the lake bottom of Lake Superior. This failed rift initially carved out a basin that was later formed by glaciers into Lake Superior. The Keweenawan rocks are underlain by Archean rocks of the Batchawana Greenstone Belt that consists of mafic to intermediate metavolcanic and minor felsic metavolcanic rocks, as well as the Algoman-type iron formation (Hart & Pace, 2006). The Keweenawan Supergroup includes the terrane groups Northshore Volcanic Group: upper (basalt, basaltic andesite) and lower (basaltic lava flows), the Duluth Complex: Anorthositic series (anorthositic intrusion and inclusions, undifferentiated), as well as miscellaneous intrusions of diabase, gabbro, ferromonzodiorite sills and dikes (MGS, 2011).

The Precambrian bedrock covers the extent of the watershed, and is comprised of two basement terranes of Archean age: gneiss terrane and greenstone-granite terrane (Morey & Van Schmus, 1988). The Subdivisions include the Penokean, Midcontinent Rift Intrusive Supersuite and the Keweenawan Supergroup, displaying great evidence of volcanic activity. The main terrane groups include Animikie Group: Rove Formation (Virginia, Thompson, mudstone and graywacke), the Beaver Bay Complex (diabase, ferrodiorite, gabbro, gabbronorite), the Duluth Complex: Anorthositic Series, Early Gabbro Series (gabbroic cumulates), Felsic Series (granophyre, ferromonzodiorite, leucogabbro), and the Layered Series (gabbro), the North Shore Volcanic Group: lower (Nopeming and Puckwunge Sandstones, basaltic lava flows) and upper sequences (basalt, basaltic andesite, rhyolite, icelandite, interflow sandstone, siltstone, conglomerate; undifferentiated mafic to felsic lava flows; Schroeder-Lutsen basalts) (MGS, 2011). In addition, reversed magnetic polarity and miscellaneous intrusions including diabase, gabbro, ferromonzodiorite sills, dikes, felsic intrusions and gabbroic intrusions are prevalent throughout the watershed.

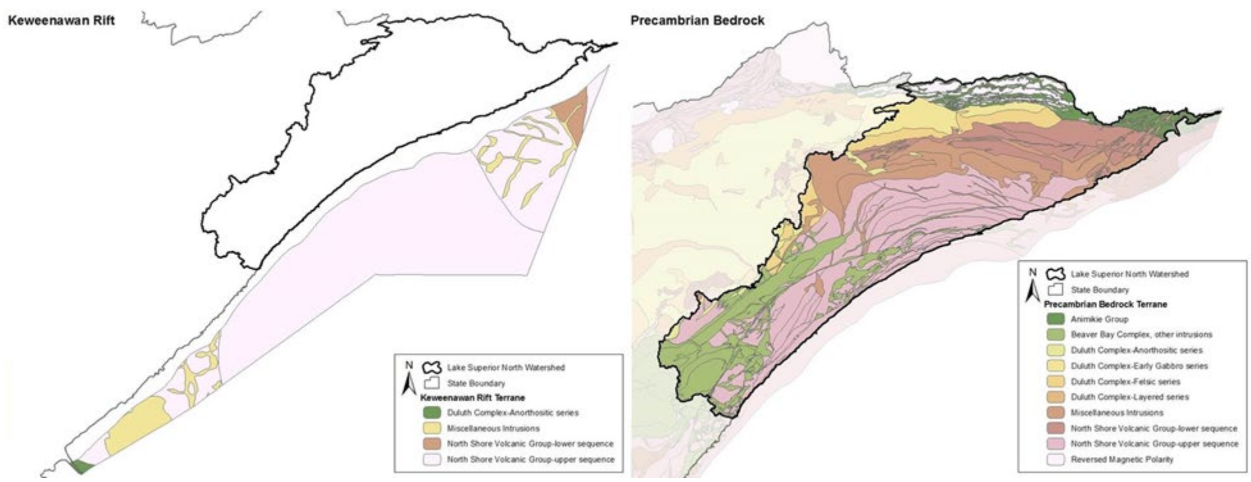

Figure 21: Bedrock geology of the Lake Superior North Watershed: Keweenawan Rift and Precambrian Bedrock (GIS Source: MGS, 2011)

Groundwater provinces

The Lake Superior North Watershed falls within two of Minnesota's six groundwater provinces: the Arrowhead and Central Provinces (Figure 22). The majority of the watershed lies within the Arrowhead Province, which is characterized as "Precambrian rocks are exposed at the surface or drift overlying is very thin (less than 30 feet). Groundwater typically found locally in faults and fractures" (MNDNR, 2001). The Central Province is located as a strip within the southwest region and is characterized by "sand aquifers in generally thick sandy and clayey glacial drift overlying Precambrian and Cretaceous bedrock" (MNDNR, 2001). There is no Cretaceous bedrock within this watershed.

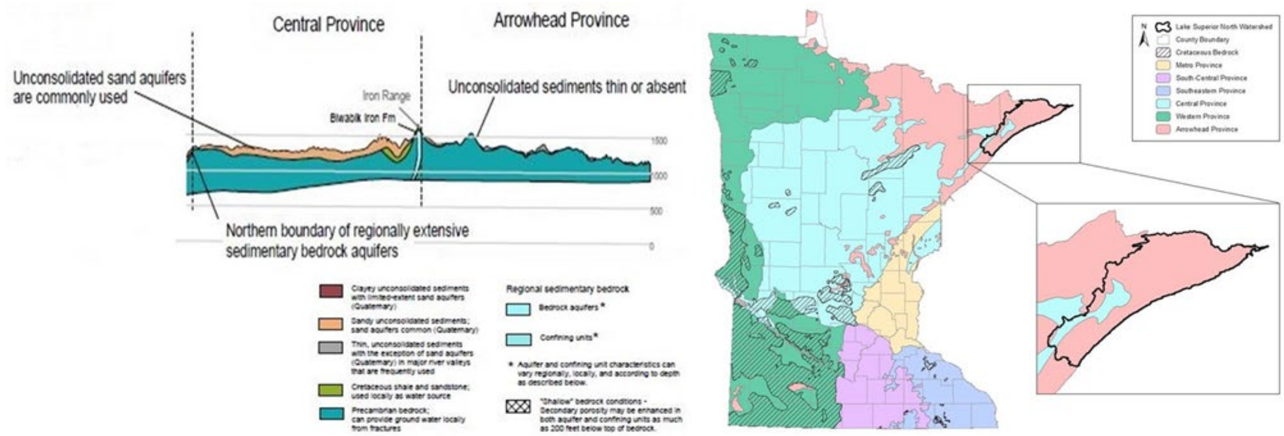

Figure 22: Central and Arrowhead Province generalized cross section (Source: MNDNR, 2011)

Aquifers

Groundwater aquifers are layers of water-bearing rocks that readily transmit water to wells and springs (USGS, 2015a). As precipitation hits the surface, it infiltrates through the soil zone and into the void spaces within the geologic materials underneath the surface, saturating the material and becoming groundwater (Zhang, 1998). The water table is the uppermost portion of the saturated zone, where the pore-water pressure is equal to local atmospheric pressure. The geologic material determines the permeability and availability of water within the aquifer. Sand and gravel materials are considered highly permeable and are utilized as aquifers, while till layers are less permeable and are considered confining units.

Minnesota's groundwater system is comprised of three types of aquifers: 1) igneous and metamorphic bedrock aquifers, 2) sedimentary rock aquifers, and 3) glacial sand and gravel aquifers (Figure 23). The first group, igneous and metamorphic rock aquifers, is restricted to water available within the fractures of the rock and typically holds limited quantities of water (MPCA, 2005). These aquifers are utilized only when the other two groups are not available, such as in northeastern Minnesota. The second group, sedimentary rock aquifers, consists of sandstone, limestone and shale, which occur primarily in southern and extreme western Minnesota (MPCA, 2005). This type of aquifer contains large quantities of groundwater due to fractures, higher porosity and weathering capabilities of the rocks. The third group is the glacial sand and gravel aquifers. These are shallow aquifers that occur as a result of glacial influences and are found in outwash plains, along river and in old lake beds throughout the state (MPCA, 2005). Also included in this group are deeper, buried glacial aquifers that cover the entire state, except the Arrowhead region and some areas in central and Southwest Minnesota (MPCA, 2005). These aquifers are highly utilized since they contain large and useable quantities of groundwater due to high porosity and permeability and are also less expensive to drill.

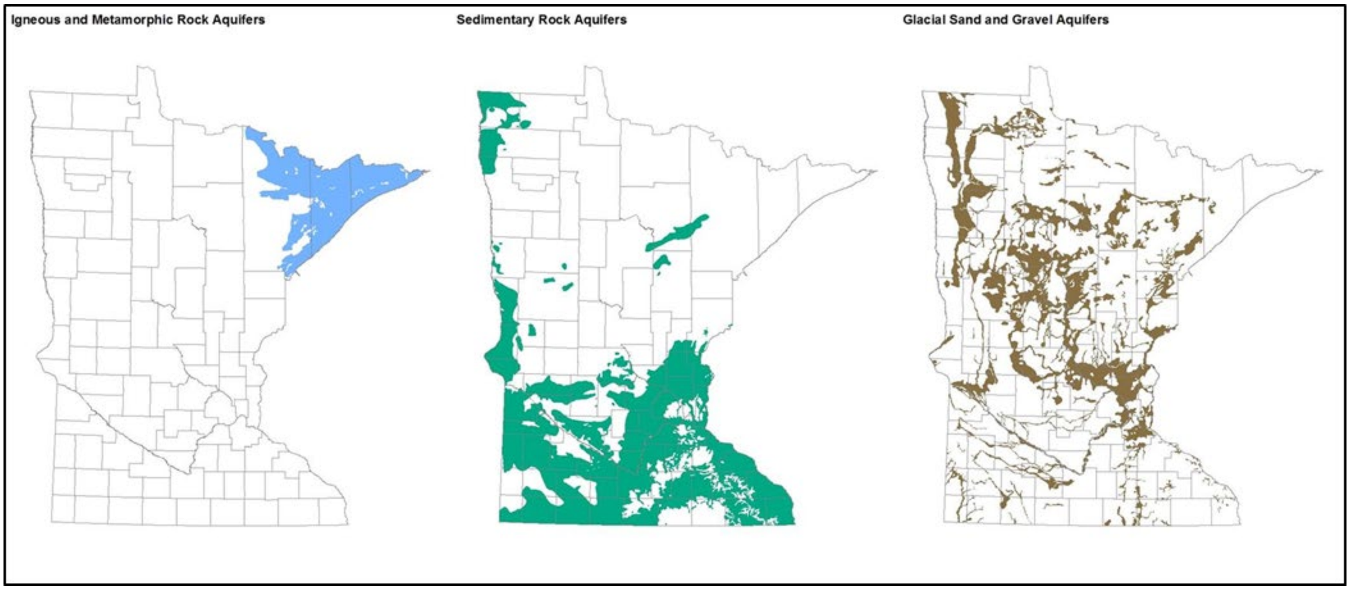

Figure 23: Minnesota's three basic types of aquifers: Igneous and Metamorphic Rock, Sedimentary Rock, and Glacial Sand and Gravel Aquifers (MPCA, 2005)

The Arrowhead Province contains two types of aquifers: glacial drift and Precambrian bedrock. The Metro Province contains four types of aquifers: surficial and buried aquifers, Cretaceous bedrock, Precambrian Bedrock and Biwabik Iron Formation. However, Lake Superior North Watershed does not contain any Cretaceous bedrock or Biwabik Iron Formation. The buried sand and gravel aquifers include the Quaternary Buried Artesian Aquifer (QBAA), the Quaternary Buried Unconfined Aquifer (QBUA), and the Quaternary Buried Undifferentiated Aquifer (QBUU). It is from these aquifers that the majority of wells in this region of Minnesota yield the greatest amount of groundwater (MPCA, 1999). Other important sources of groundwater are the surficial sand and gravel aquifers, which consist of well-sorted outwash deposits left behind from the Des Moines Lobe. Two main aquifers included in this category are the Quaternary Water Table Aquifer (QWTA) and the Quaternary Undifferentiated Unconfined Aquifer (QUUU). For the Lake Superior North Watershed, the Precambrian aquifers (PCUU) are the dominant source for groundwater withdrawal while QBAA and QWTA aquifers are the primary Quaternary sources.

Groundwater pollution sensitivity

When defining and discussing groundwater pollution sensitivity, refer to the MNDNR website: http://www.dnr.state.mn.us/waters/groundwater_section/mapping/sensitivity.html.

> "The MDNR defines an area as sensitive if natural geologic factors create a significant risk of groundwater degradation through the migration of waterborne contaminants. Migration of contaminants dissolved in water through unsaturated and saturated sediments is affected by many things, including biological degradation, oxidizing or reducing condition and contaminant density. General assumptions include: contaminants move conservatively with water; flow paths are vertical; and permeability of the sediment is the controlling factor.
>
> The pollution sensitivity of buried sand and gravel aquifers and of the first buried bedrock surface represents the approximate time it takes for water to move from land surface to the target (residence time). Groundwater chemistry is used to support hypotheses relating geologic factors to travel time. Dye traces, naturally occurring chemicals, and other human-introduced chemicals are used to date groundwater and better understand flow paths and residence times" (MNDNR, 2015e).

Since bedrock aquifers are typically covered with thick till, they are normally better protected from contaminant releases at the land surface. It is also less likely that withdrawals from these wells would have a direct and significant impact on local surface water bodies. In contrast, surficial aquifers are typically more likely to 1) be vulnerable to contamination, 2) have direct hydrologic connections to local surface water, and 3) influence the quality and quantity of local surface water. The MNDNR is currently working on a hydrogeological atlas focused on the pollution sensitivity of the bedrock surface. It is being produced county-by-county and is not completed for the Lake Superior North Watershed at this time. Until the hydrogeological atlas is finished, a 1989 statewide evaluation of groundwater contamination susceptibility completed by the MPCA is utilized to determine aquifer pollution vulnerability. This display is not intended to be used on a local scale, but as a regional-scale screening tool. According to this data, the Lake Superior North Watershed is estimated to have primarily low level contamination susceptibility, most likely due to the Precambrian bedrock aquifers, which tend to have relatively impermeable surface deposits (Figure 24) (Porcher, 1989).

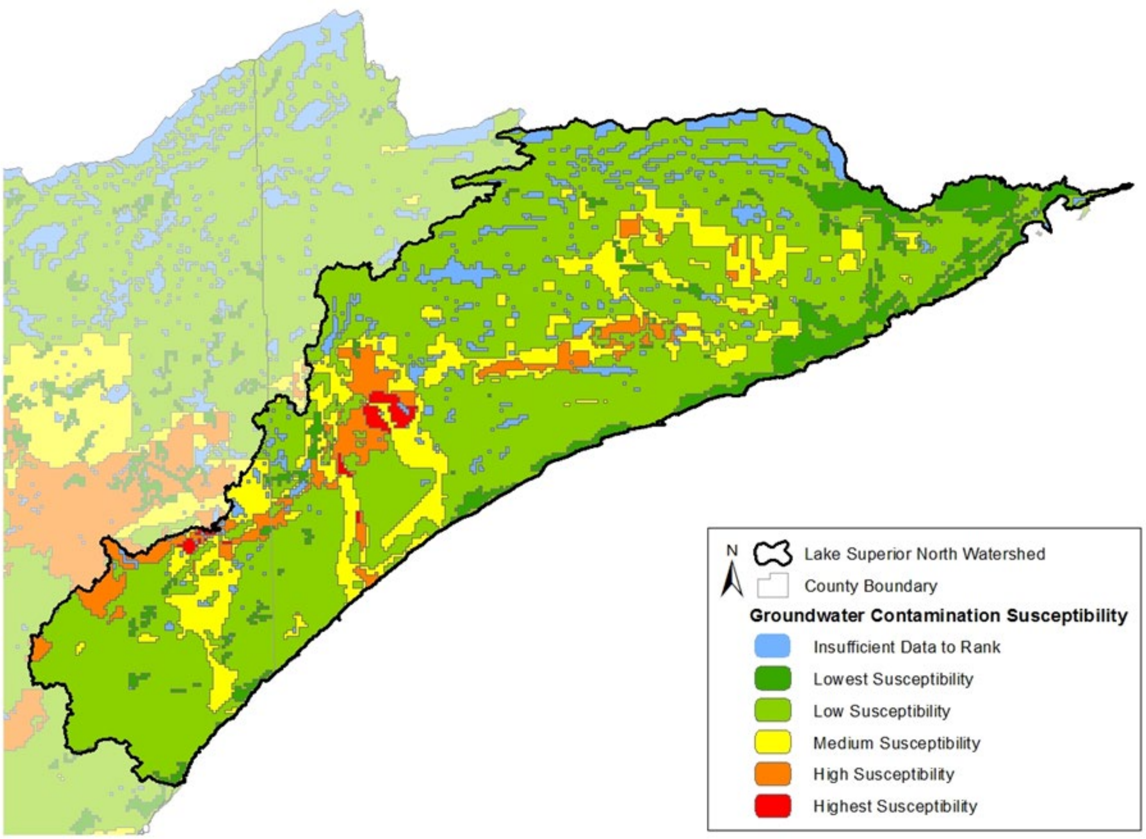

Figure 24: Groundwater contamination susceptibility for the Lake Superior North Watershed (GIS Source: MPCA, 1989)

Groundwater potential recharge

Groundwater recharge is one of the most important parameters in the calculation of water budgets, which are used in general hydrologic assessments, aquifer recharge studies, groundwater models, and water quality protection. Recharge is a highly variable parameter, both spatially and temporally, making accurate estimates at a regional scale difficult to produce. The MPCA contracted the US Geological Survey to develop a statewide estimate of recharge using the SWB (Soil-Water-Balance Code). The result is a gridded data structure of spatially distributed recharge estimates that can be easily integrated into regional groundwater studies. The full report of the project as well as the gridded data files are available at: https://gisdata.mn.gov/dataset/geos-gw-recharge-1996-2010-mean.

Recharge of these aquifers is important and limited to areas located at topographic highs, those with surficial sand and gravel deposits, and those along the bedrock-surficial deposit interface (Figure 25). Typically, recharge rates in unconfined aquifers are estimated at 20 to 25% of precipitation received, but can be less than 10% of precipitation where glacial clays or till are present (USGS, 2007). For Lake Superior North Watershed, the average annual potential recharge rate to surficial materials ranges from 3.7 to 17.8 inches per year, with an average of 10.5 inches per year (Figure 26). The statewide average potential recharge is estimated to be four inches per year with 85% of all recharge ranging from three to eight inches per year (Figure 27). When compared to the statewide average potential recharge, the Lake Superior North Watershed receives a higher average and range of potential recharge, mostly likely attributed to the variability of the thin surficial sediment distribution of the area.

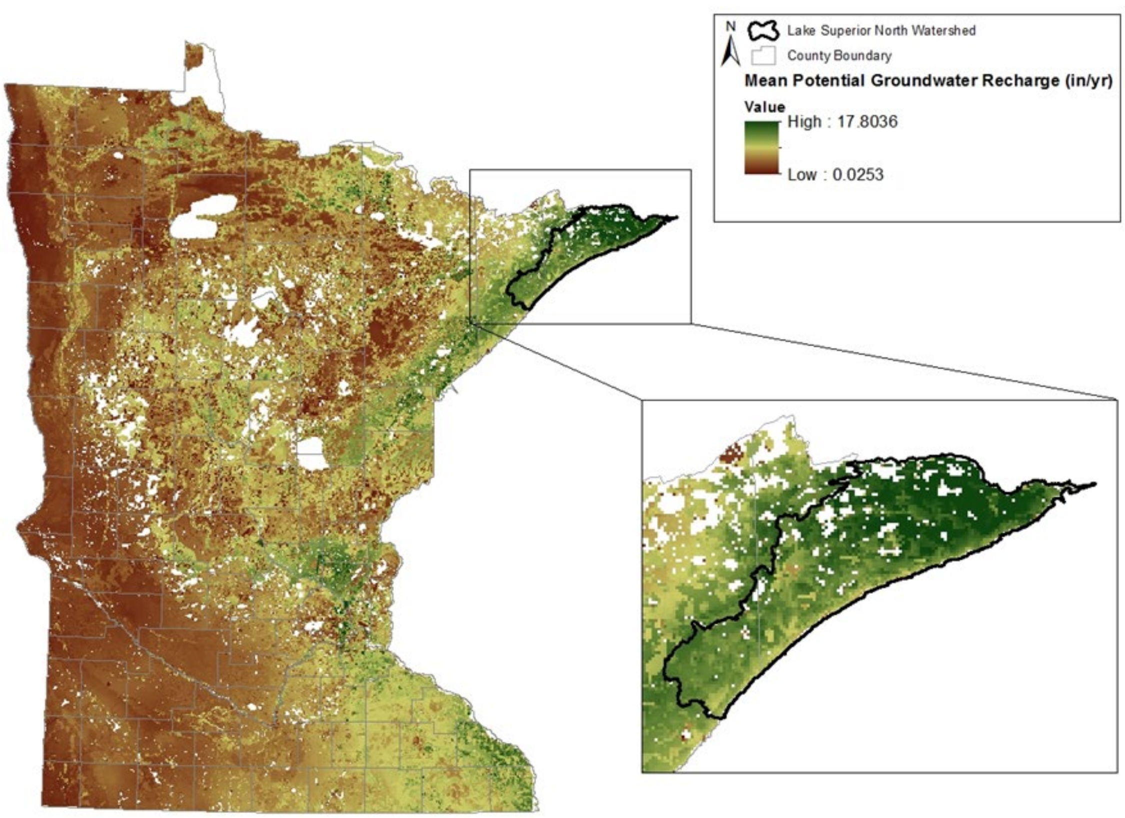

Figure 25: Average annual potential recharge rate to surficial materials in Lake Superior North Watershed (1996-2010)

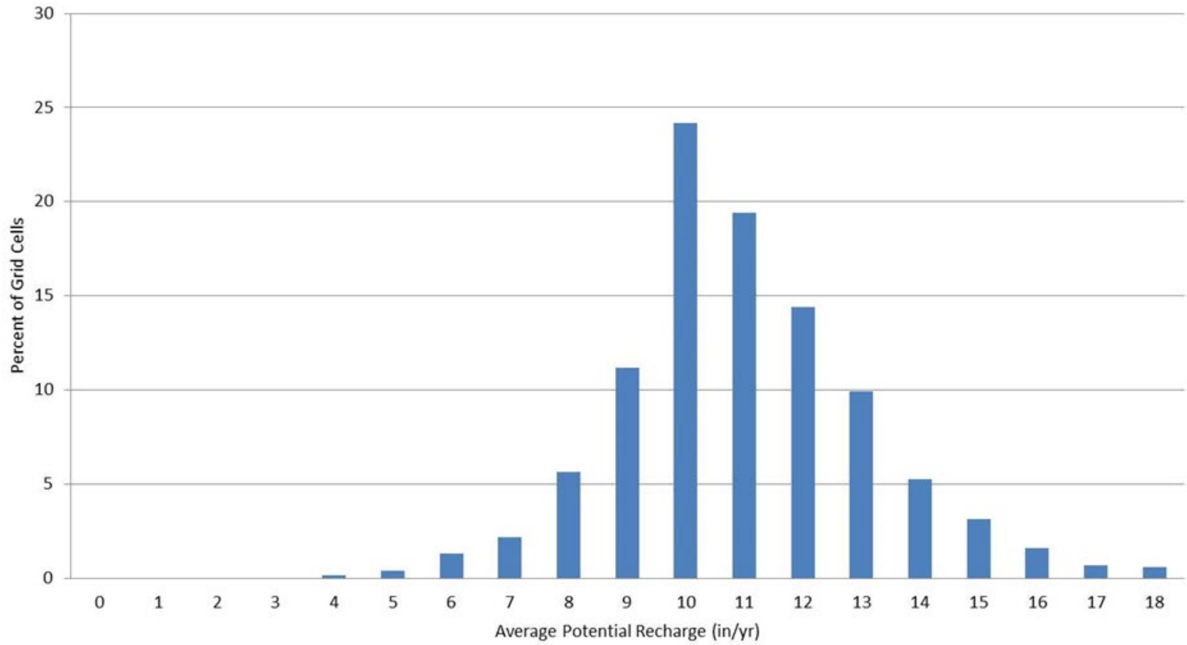

Figure 26: Average potential recharge rate percent of grid cells in the Lake Superior North Watershed (1996-2010)

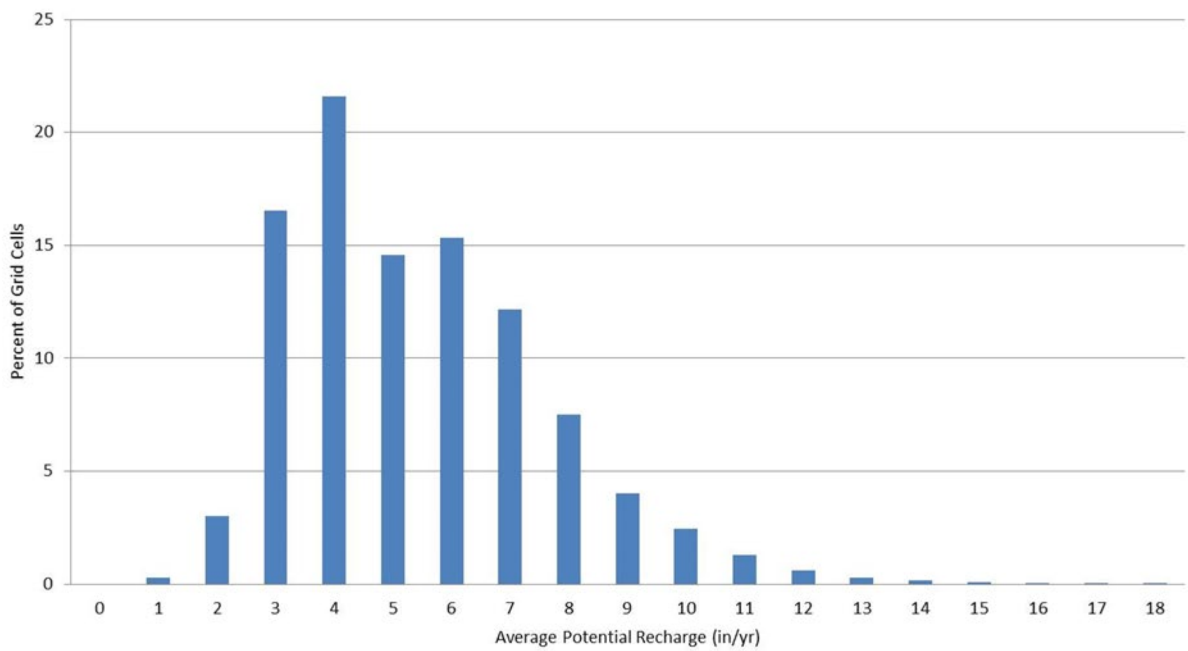

Figure 27: Average annual potential recharge rate percent of grid cells statewide (1996-2010)

IV. Groundwater quality

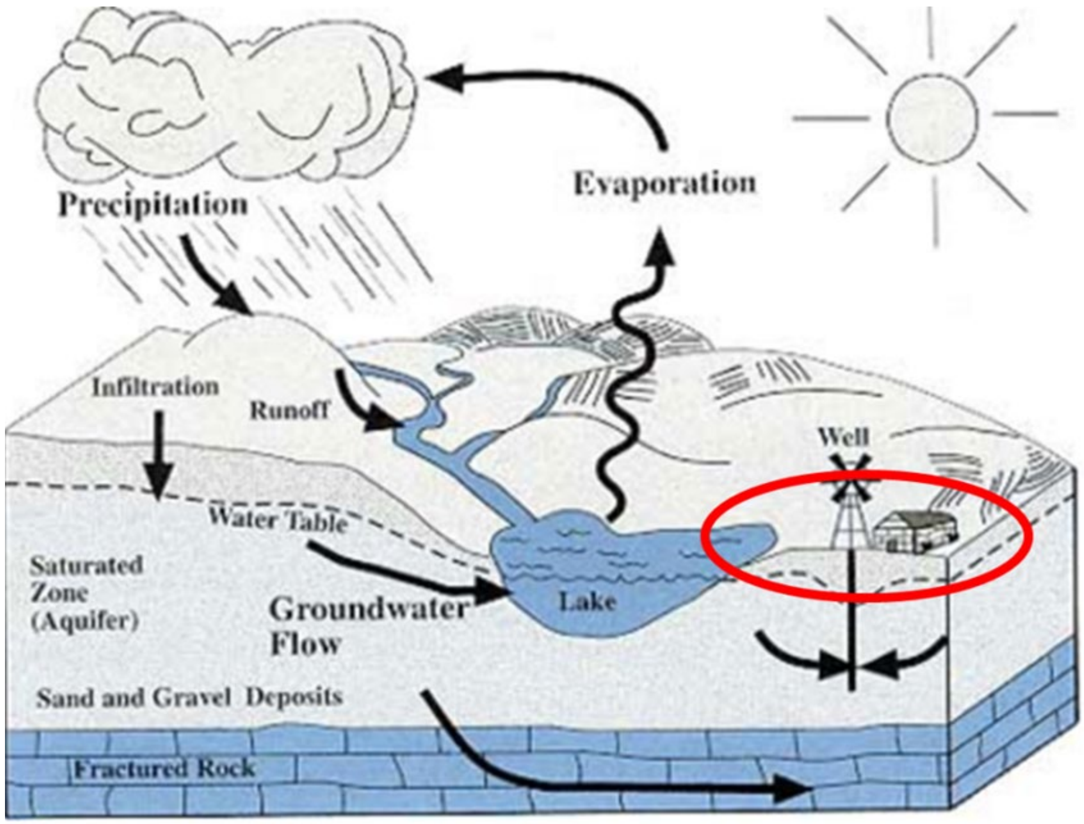

Figure 28: Groundwater quality within the hydrologic cycle

Ambient groundwater network

Approximately 75% of Minnesota's population receives their drinking water from groundwater, undoubtedly indicating that clean groundwater is essential to the health of its residents. The Minnesota Pollution Control Agency's Ambient Groundwater Monitoring Program monitors trends in statewide groundwater quality by sampling for a comprehensive suite of chemicals including nutrients, metals, and volatile organic compounds. These Ambient wells represent a mix of deeper domestic wells and shallow monitoring wells. The shallow wells interact with surface waters and exhibit impacts from human activities more rapidly. Available data from federal, state and local partners are used to supplement reviews of groundwater quality in the region.

Currently, there are no MPCA Ambient Groundwater Monitoring wells within the Lake Superior North Watershed. Figure 29 displays the locations of ambient groundwater wells near the specified watershed.

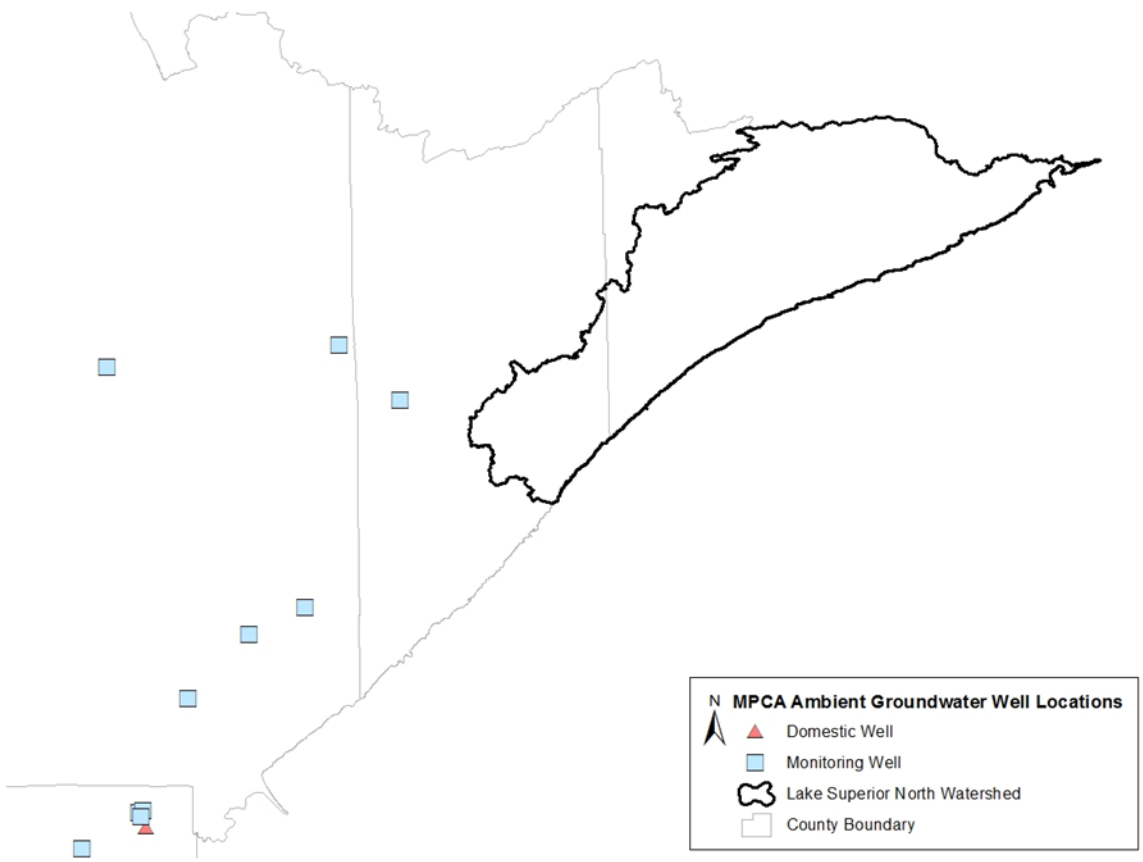

Figure 29: MPCA ambient groundwater monitoring well locations near the Lake Superior North Watershed

Regional groundwater quality

From 1992 to 1996, the MPCA conducted baseline water quality sampling and analysis of Minnesota's principal aquifers based on dividing Minnesota into six hydrogeologic regions: Northwest, Northeast, Southwest, Southeast, North Central and Twin Cities Metropolitan Regions. The Lake Superior North Watershed lies within the Northeast Region (Figure 30).

The baseline study determined that the groundwater quality in the Northeast Region is considered good when compared to other areas with similar aquifers, but with exceedances of drinking water criteria in arsenic, beryllium, boron, manganese and selenium (MPCA, 1999). Concentrations of chemicals within the Precambrian aquifers were comparable to similar aquifers throughout the state and concentrations of major cations and anions were lower in the surficial and buried drift aquifers when compared to similar aquifers statewide (MPCA, 1999). Many of the exceedances identified were contributed to geology, but some trace inorganic chemicals may be of concern locally. Volatile organic compounds were also detected in this region, with the most commonly detected compounds associated with well disinfection, atmospheric deposition and fuel oils (MPCA, 1999).

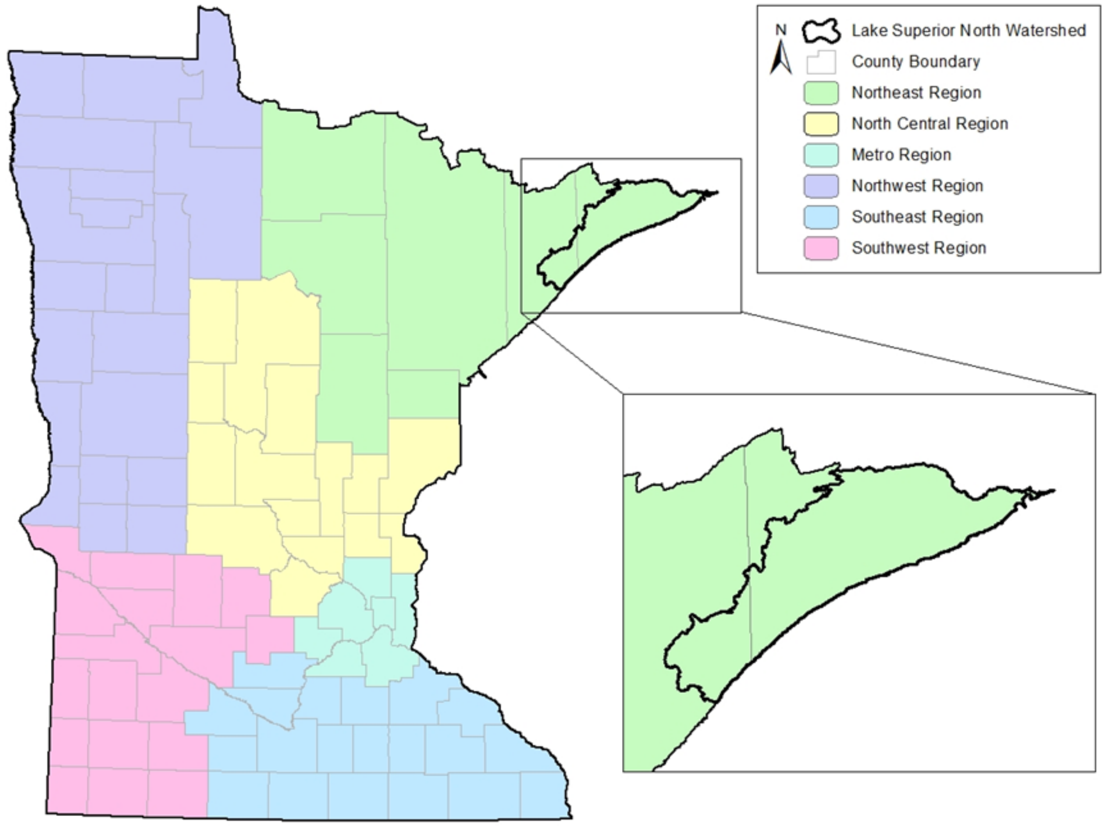

Figure 30: Lake Superior North Watershed within the MPCA hydrogeologic regions

The Minnesota Department of Agriculture (MDA) monitors pesticides and nitrate on an annual basis in groundwater across agricultural areas in the state. The MDA also separates the state into regions, which consist of ten regional water quality monitoring networks that are referred to as Pesticide Monitoring Regions (PMRs). The Lake Superior North Watershed lies within the regional water quality monitoring networks for Region 3 (PMR 3), which is referred to as the Northeast Region.

The Monitoring and Assessment Unit (MAU) of the MDA sampled 166 sites throughout Minnesota for pesticides in groundwater in 2015. However, due to the limited agricultural use and heavily forested areas, there is no groundwater monitoring currently done by the MDA for this region. Statewide, some wells detected up to five common detection pesticides or degradants, which include acetochlor, alachlor, atrazine, metolachlor and metribuzin, but no detections exceeded drinking water standards for human consumption (Figure 31) (MDA, 2015).

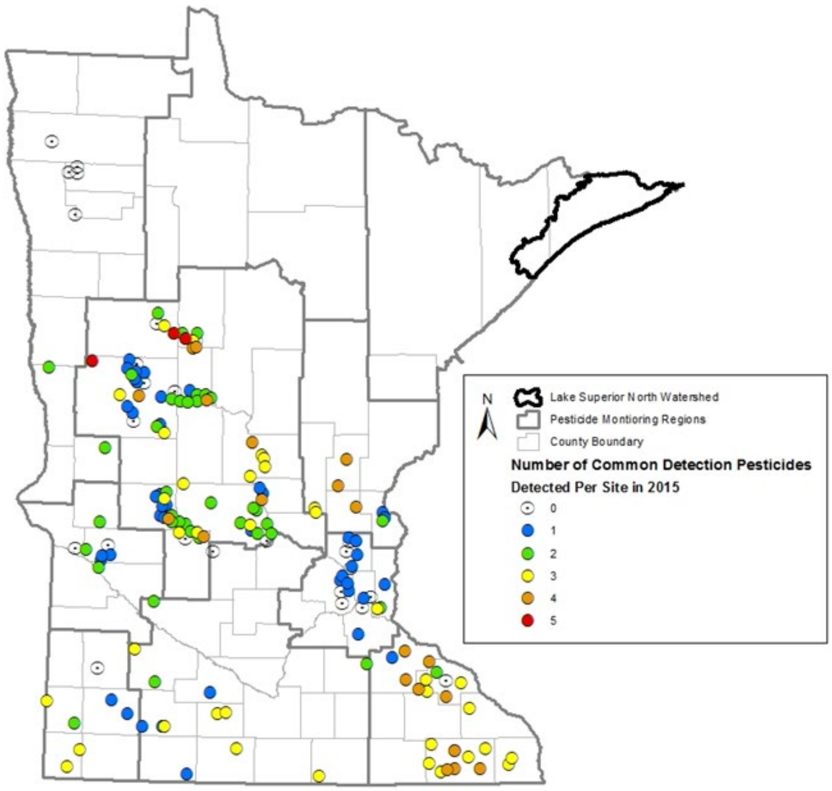

Figure 31: Statewide Pesticide detections (Source: MDA, 2015)

Another source of information on groundwater quality comes from the Minnesota Department of Health (MDH). Mandatory testing for arsenic, a naturally occurring but potentially harmful contaminant for humans, for all newly constructed wells has found that 10.7% of all wells installed from 2008 to 2015 have arsenic levels above the maximum contaminant level (MCL) for drinking water of 10 micrograms per liter (MDH, 2015). In the Lake Superior North Watershed, the majority of new wells are within the water quality standards for arsenic levels, but there are some exceedances to the MCL. When observing concentrations of arsenic by percentage of wells that exceed the MCL of 10 micrograms/liter per county, the watershed lays within counties that range from less than 5 to 15%. By county, the percentages of wells identified with concentrations exceeding the MCL are as follows: Cook (11.6%) and Lake (2.1%) Counties (Figure 32) (MDH, 2015). For more information on arsenic in private wells, please refer to the Minnesota Department of Health's website:
http://www.health.state.mn.us/divs/eh/wells/waterquality/arsenic.html.

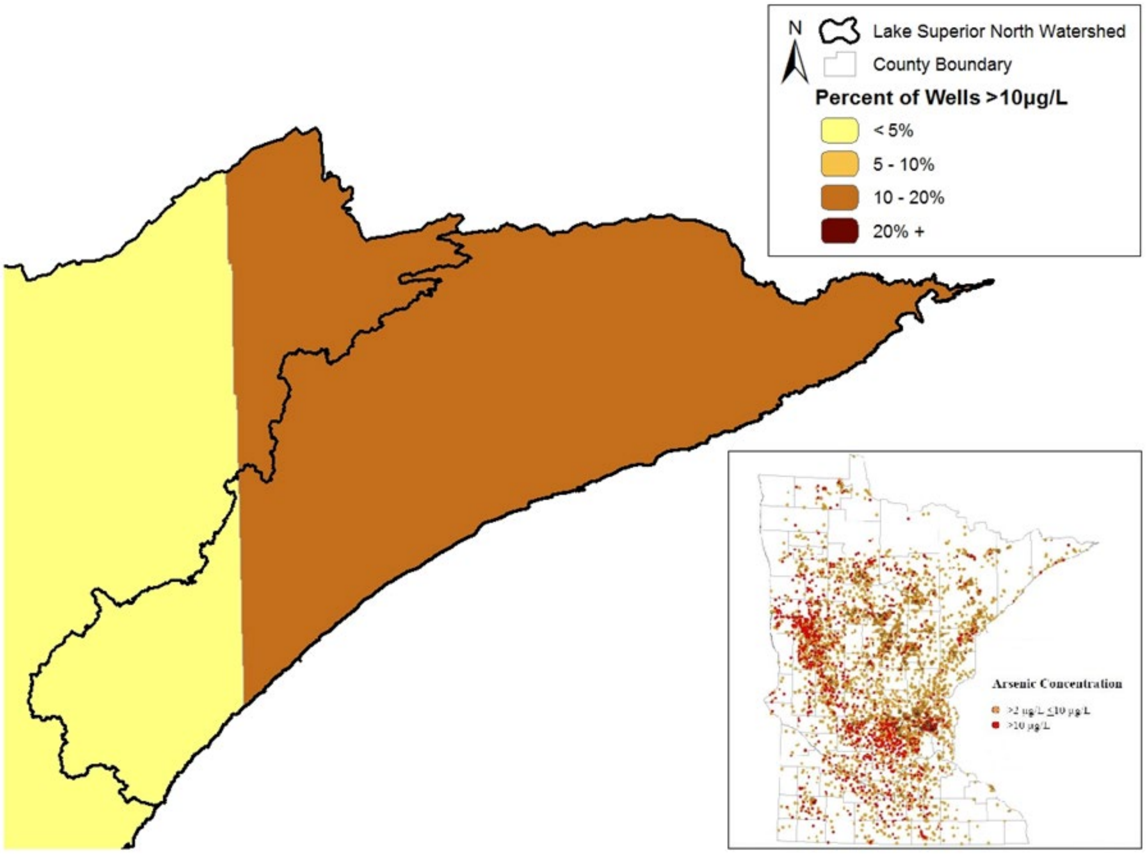

Figure 32: Percent wells with arsenic occurrence greater than the maximum contaminant level by county for the Lake Superior North Watershed (2008-2015) (Source: MDH, 2015)

A statewide dataset of potentially contaminated sites and facilities with environmental permits and registrations is available at the MPCA's website, through a web-based application called, "What's In My Neighborhood" (WIMN). This MPCA resource provides the public with a method to access a wide variety of environmental information about communities across the state. The data is divided into two groups. The first is potentially contaminated sites, and includes contaminated properties, formerly contaminated sites, and those that are being investigated for suspicion of being contaminated. The second category is made up of businesses that have applied for and received different types of environmental permits and registrations from the MPCA. An example of an environmental permit would be for a business acquiring a permit for a storm water or wastewater discharge, requiring it to operate within limits established by the MPCA. In the Lake Superior North Watershed, there are currently 510 sites identified by WIMN: 226 tanks and leaks, 166 water quality sites, 73 hazardous waste sites, 26 investigation and cleanup sites, 11 solid waste sites, 7 air quality sites and 1 feedlot site (Figure 33). For more information regarding "What's in My Neighborhood", refer to the MPCA webpage at https://www.pca.state.mn.us/data/whats-my-neighborhood.

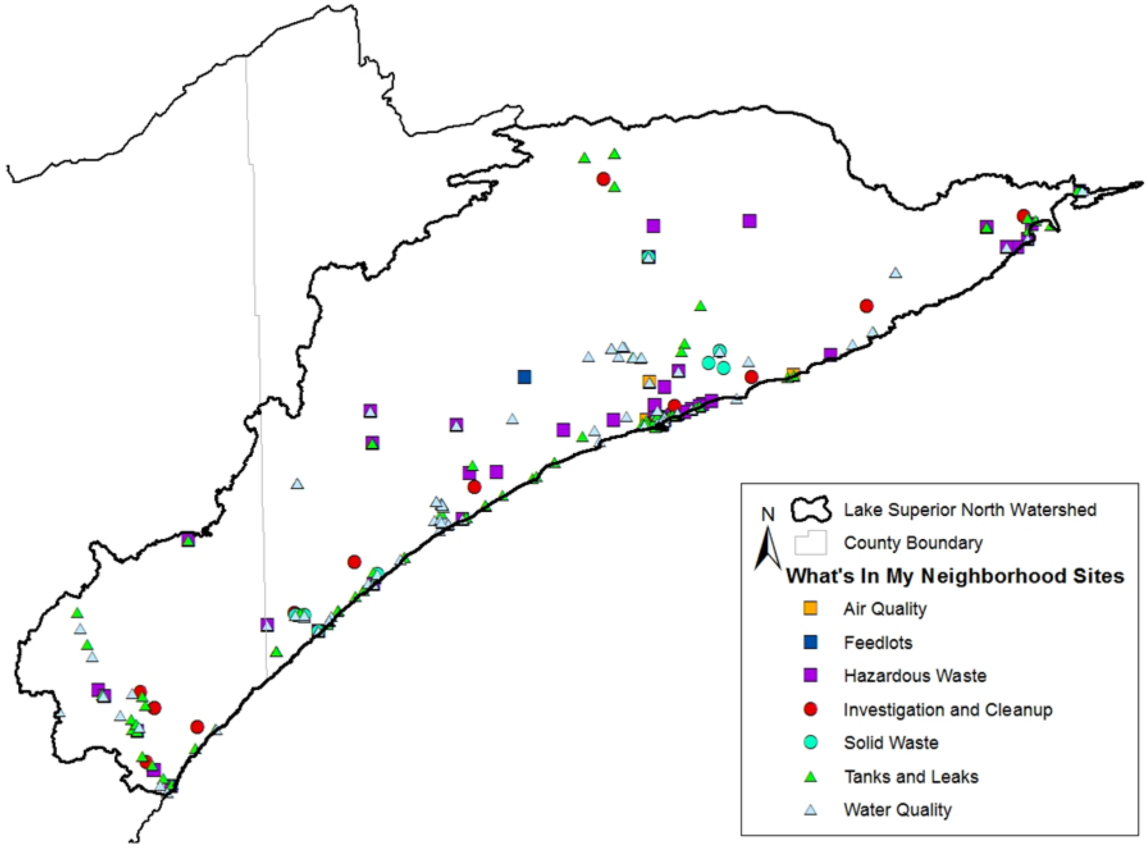

Figure 33: "What's in My Neighborhood" site programs and locations within the Lake Superior North Watershed

V. Groundwater quantity

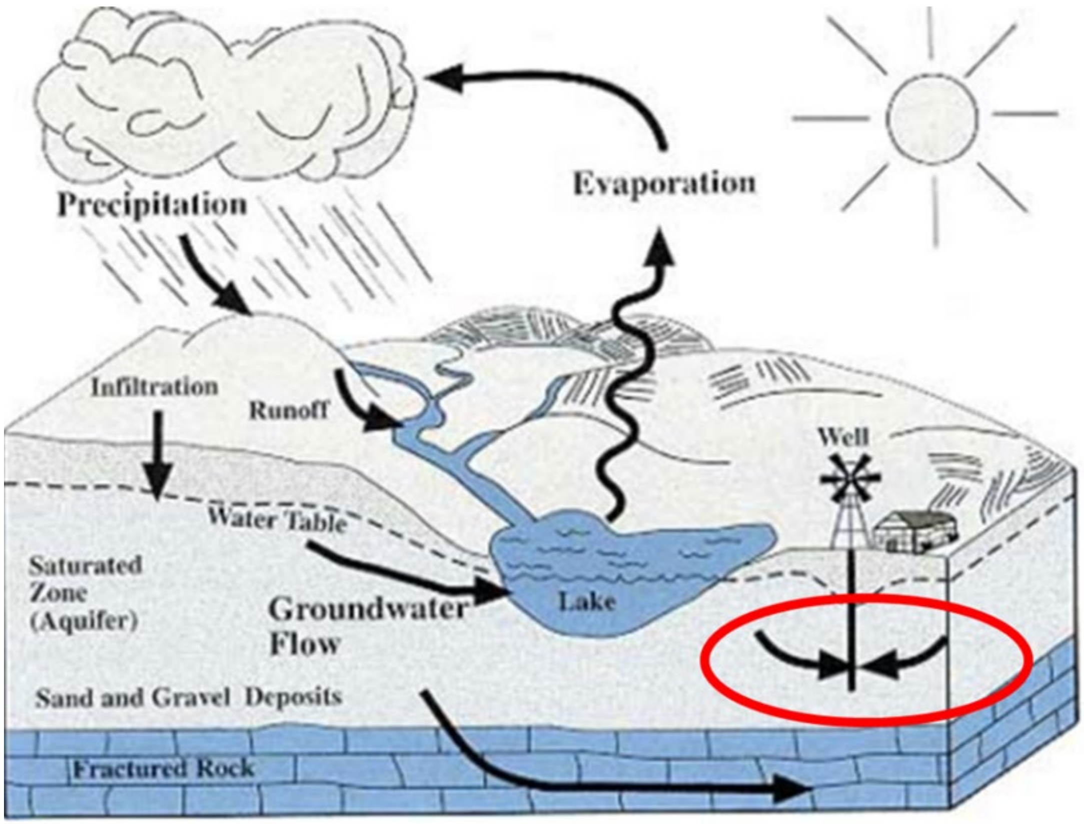

Figure 34: Groundwater quantity within the hydrologic cycle

Groundwater and surface water withdrawals

The MDNR permits all high capacity water withdrawals where the pumped volume exceeds 10,000 gallons per day or 1 million gallons per year. Permit holders are required to track water use and report back to the MNDNR yearly. The changes in withdrawal volume detailed in this groundwater report are a representation of water use and demand in the watershed and are taken into consideration when the MNDNR issues permits for water withdrawals. Other factors not discussed in this report but considered when issuing permits include: interactions between individual withdrawal locations, cumulative effects of withdrawals from individual aquifers, and potential interactions between aquifers. This holistic approach to water allocations is necessary to ensure the sustainability of Minnesota's groundwater resources.

The three largest permitted consumers of water in the state (in order) are power generation, public water supply (municipals), and irrigation (MNDNR, 2015f). According to the most recent USGS site-specific water-use data system (SWUDS), in 2013, the withdrawals within the Lake Superior North Watershed are primarily utilized for special categories (46.7%), such as snow/ice making and dust control. The remaining withdrawals include: water supply (predominantly private) (41.3%), non-crop irrigation (golf courses) (11.2%), and industrial processing (0.79%) (Figure 35). From 1994 to 2013, withdrawals associated with irrigation and special categories have increased significantly (p=0.001). Industrial Processing and water supply have remained relatively constant over this time period.

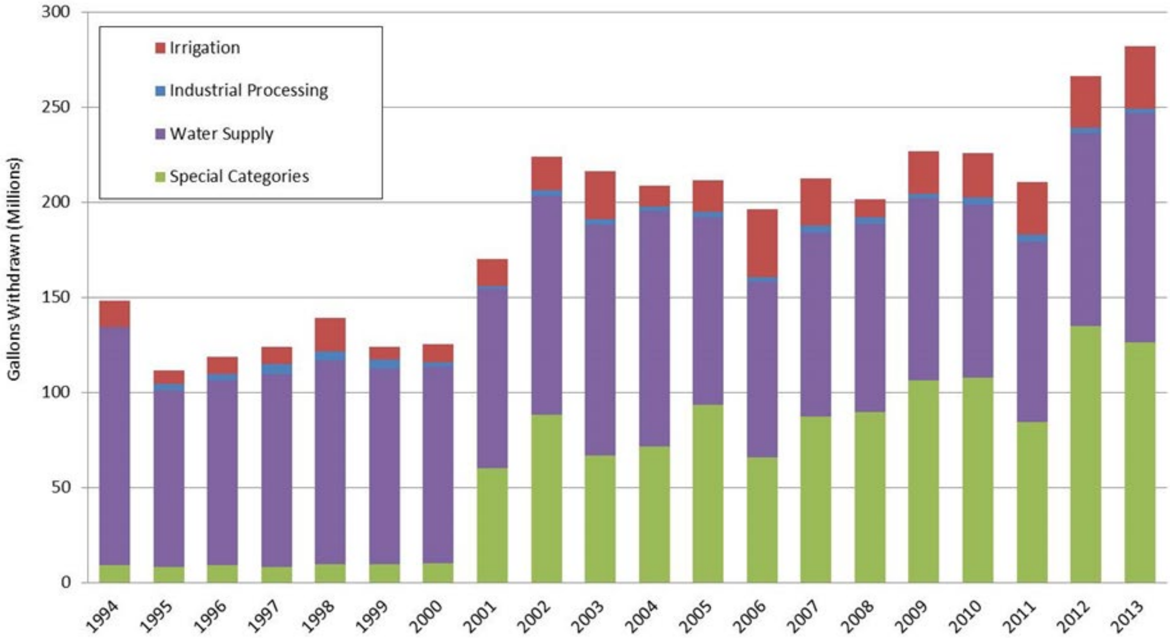

Figure 35: Groundwater and surface water permitted withdrawals by category - Lake Superior North Watershed (1994-2013)

Figure 36 displays total high capacity withdrawal locations within the watershed with active permit status in 2013. During 1994 to 2013, groundwater withdrawals within the Lake Superior North Watershed do not exhibit a statistically significant trend (Figure 37), while surface water withdrawals are increasing with a significant trend (p=0.001) (Figure 38).

The increase in groundwater withdrawals can be quantified further by the SWUDS data. In 1994, the number of active permits within the watershed for groundwater sources that reported withdrawal quantities was six, pumping a reported amount of approximately 7.8 million gallons of water. In 2013, the number of active permits for groundwater that reported withdrawal quantities doubled to 12, withdrawing 10.1 million gallons of water. For surface water withdrawals in 1994, the number of active permit holders was seven and withdrew 140.4 million gallons, while in 2013, the number of active permit holders increased to eight, but the amount withdrawn increased to 271.7 million gallons.

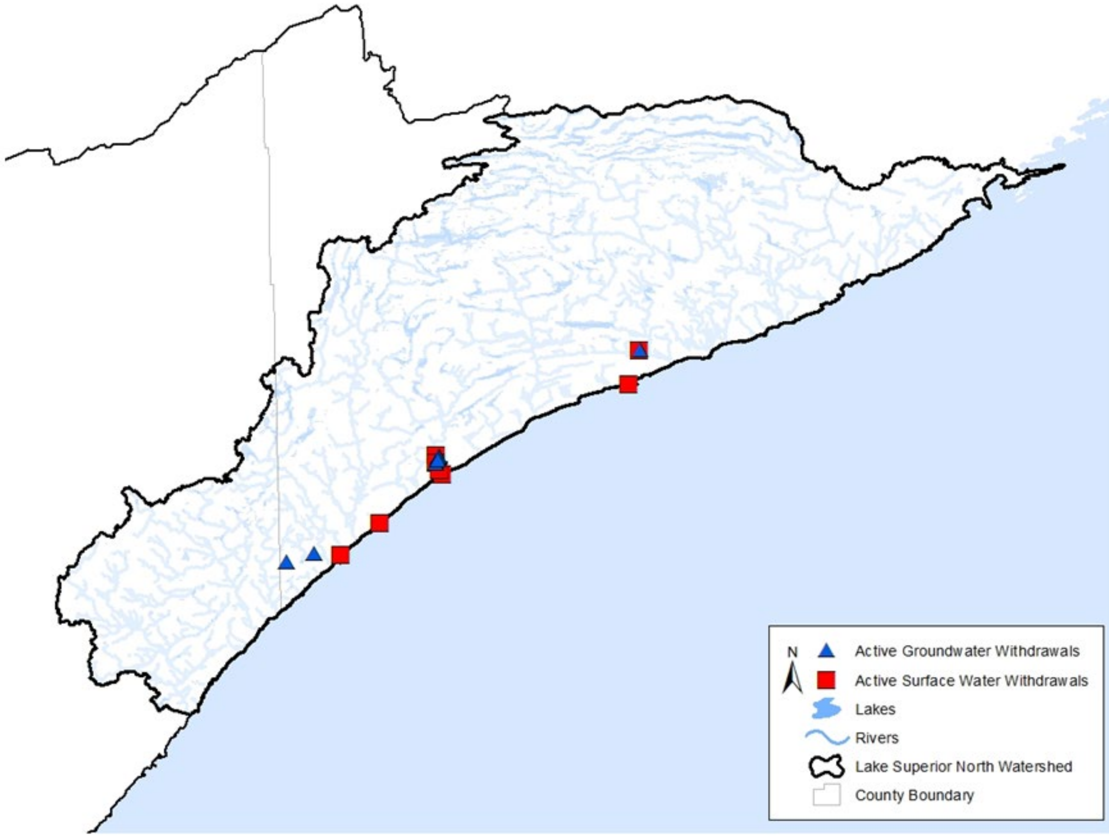

Figure 36: Locations of active status permitted high capacity withdrawals in 2013 within the Lake Superior North Watershed

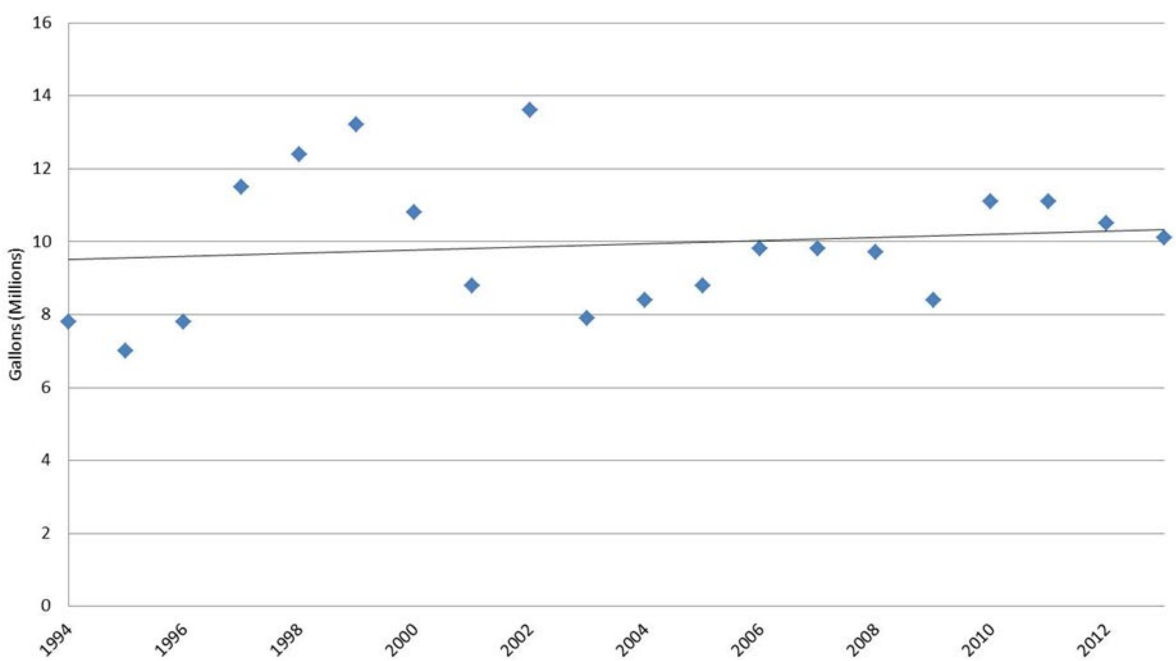

Figure 37: Total annual groundwater withdrawals in the Lake Superior North Watershed (1994-2013)

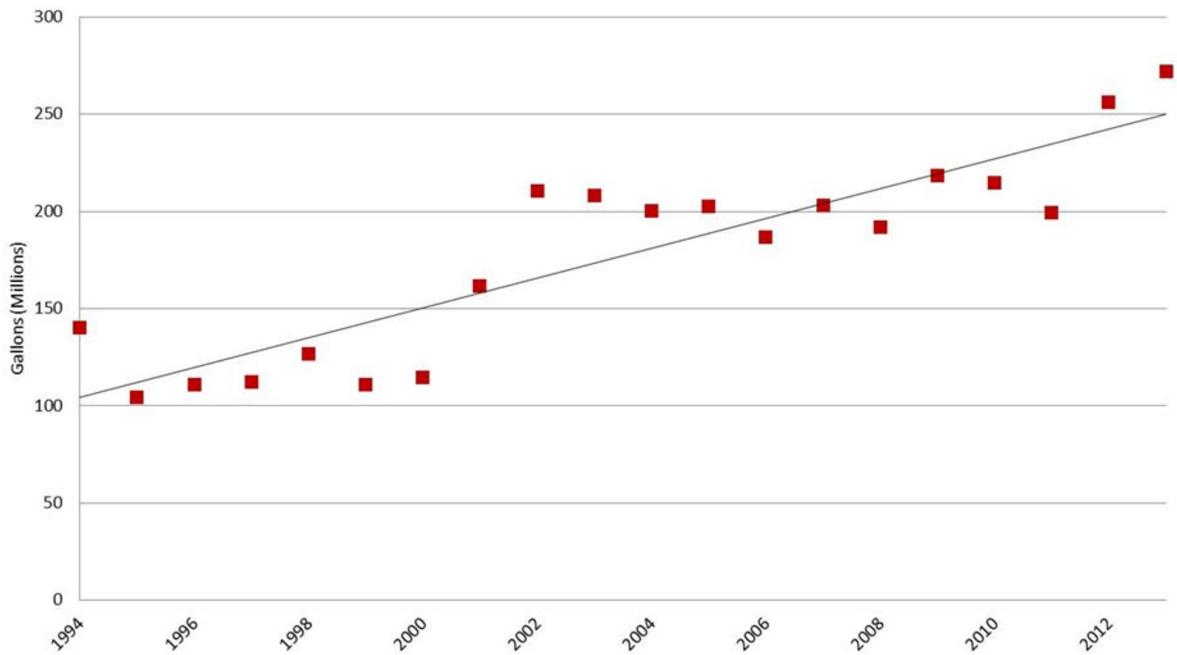

Figure 38: Total annual surface water withdrawals in the Lake Superior North Watershed (1994-2013)

MNDNR Observation Wells

Monitoring wells from the MNDNR Observation Well Network track the elevation of groundwater across the state. The elevation of groundwater is measured as depth to water in feet and reflects the fluctuation of the water table as it rises and falls with seasonal variations and anthropogenic influences. To access the MNDNR Observation Well Network, please visit http://www.dnr.state.mn.us/waters/cgm/index.html.

Currently, there are no MNDNR Observation Wells within or near the Lake Superior North Watershed(Figure 39).

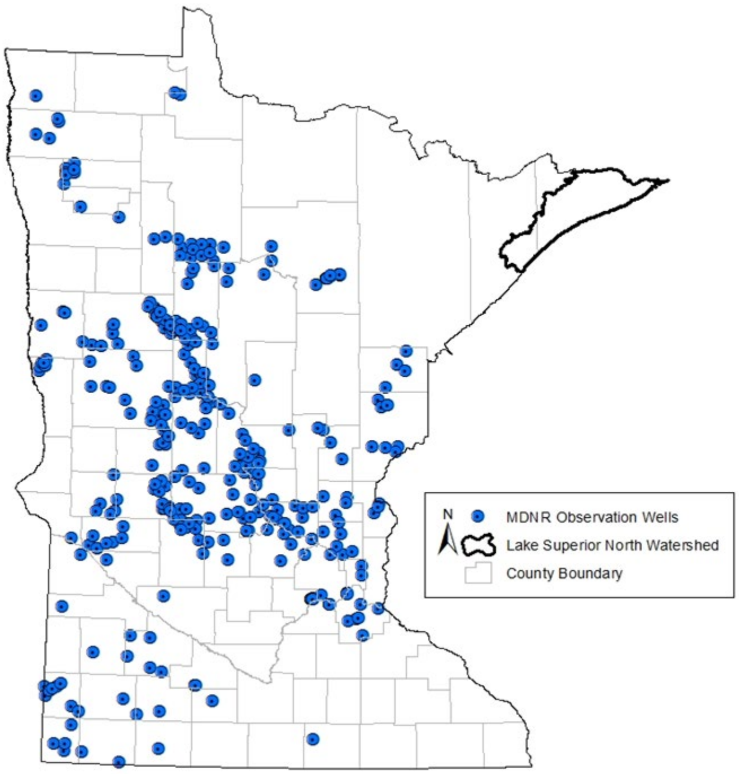

Figure 39: MNDR water table observation well locations statewide

VI. Evapotranspiration

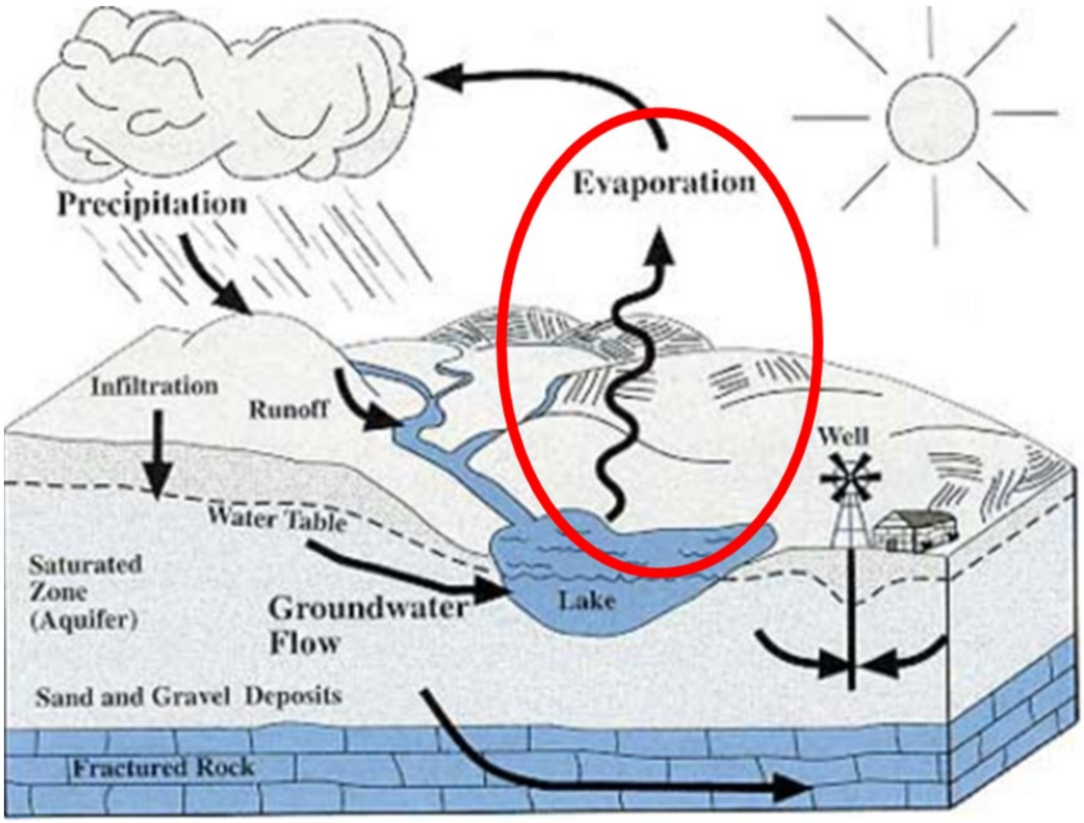

Figure 40: Evapotranspiration within the hydrologic cycle

Evapotranspiration definition

Evapotranspiration (ET) is the sum of evaporation and transpiration. ET can come from surface water bodies, the ground surface, and evaporation from the capillary fringe in the near surface water table, and the transpiration of groundwater by plants whose roots draw water from the capillary fringe. Transpiration is mostly derived from the evaporation of water from plant leaves, and accounts for roughly 10% of the moisture in the atmosphere, with the other 90% coming from evaporation from surface water bodies (USGS, 2015b).

Evapotranspiration variation across Minnesota

Regarding evapotranspiration in Minnesota, the MNDNR describes this process as:

> The presence of moist versus dry air masses also helps to determine the atmosphere's ability to absorb water vapor evaporating from soil and open-water surfaces, or transpiring from leaf surfaces. Western Minnesota, more frequently under the influence of dry air masses, has higher evapotranspiration rates than the eastern half of the state. Temperature plays an important role in determining the amount of energy available for evapotranspiration. Because spatial temperature patterns are determined mainly by latitude, southern Minnesota experiences more evapotranspiration than in the north.

Due to its position in the continent, Minnesota is located on the boundary between the semi-humid climate regime of the eastern U.S., and the semi-arid regime to the west. Semi-humid climates are areas where average annual precipitation exceeds average annual evapotranspiration, leading to a net surplus of water. In semi-arid areas, evapotranspiration exceeds precipitation on average, creating a water deficit. In Minnesota, the boundary between the climate regimes cuts the State roughly into east-west halves, as seen in an analysis of the difference between annual precipitation and evapotranspiration in Figure 41 (MNDNR, 2015g).

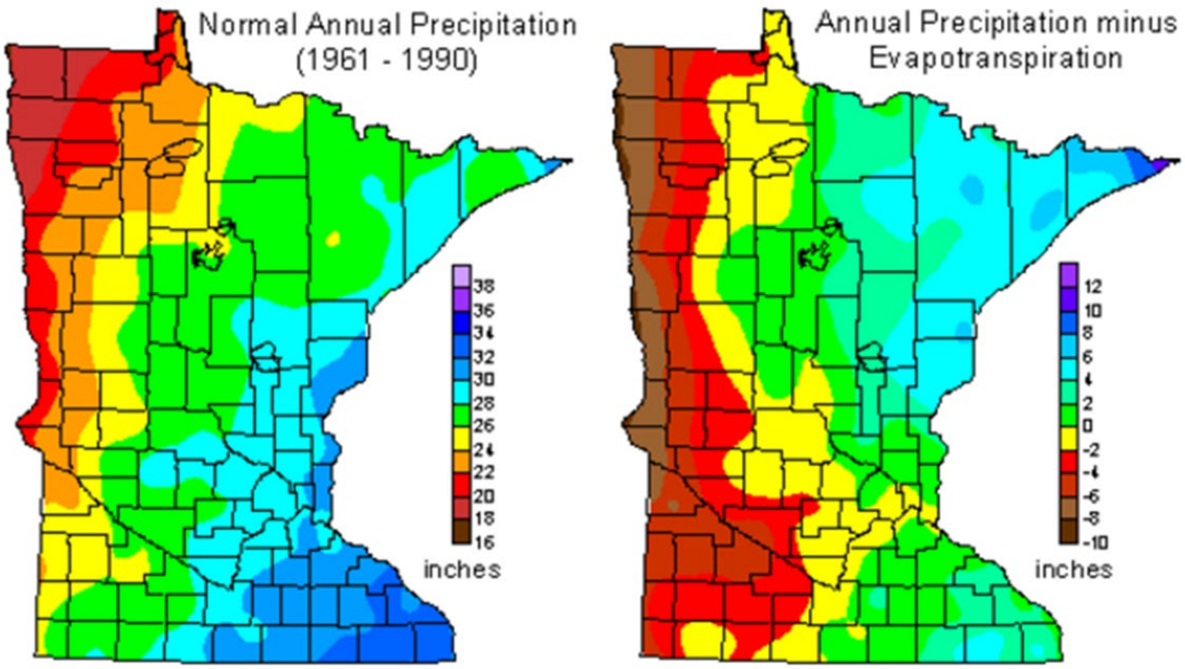

Figure 41: Minnesota annual precipitation and precipitation minus evapotranspiration (1961-1990)

VII. Conclusion: Statement of groundwater condition

For this report, the key issues that will be focused on are the surface water quality and groundwater protection. According to the USDA NRCS, the County Soil and Water Conservation Districts within the Lake Superior North Watershed identified and listed issues they believe should be considered as top priority for conservation and cost sharing efforts (USDA NRCS). Those issues include: soil quality (excessive erosion), woodland management, surface water quality (nutrients and priority pollutants), surface and groundwater quality and quantity, shoreline management and wetland management.

Surface water quality

Surface water quality can be degraded by a number of different factors, including, but not limited to, atmospheric deposition, sedimentation from eroded soils, excess nutrients from runoff from nearby farm fields or impervious surfaces from urban areas, flow alteration or variability, point and nonpoint sources, septic systems and landfill disposal. According to the MPCA's surface water impairment list, the North Superior Watershed included a total of 106 impairments, with 1 stream reach and 95 lakes (10 lakes had two impairments) (MPCA, 2015d). The primary impairment is mercury in fish tissue (88.7%), followed by mercury in water (9.4%), one occurrence of turbidity (in the stream reach), and one occurrence of PCB in fish tissue. For more information impaired waters, please refer to the MPCA's Guidance Manual for Assessing the Quality of Minnesota Surface waters for the Determination of Impairment, 305(b) Report and 303(d) List: https://www.pca.state.mn.us/sites/default/files/tmdl-guidancemanual04.pdf.

Mercury has been a rising issue for human consumption of fish due to the bioaccumulation of this element and its associated compounds, which can cause damage to the central nervous system (MPCA, 2007). Research has identified that 70% of mercury deposition in Minnesota is anthropogenic while 30% is natural from atmospheric deposition (MPCA, 2007). In 2007, the U.S Environmental Protection Agency approved the Minnesota's Statewide Mercury Total Maximum Daily Load study, which allocated reduction shares to 90% federal and 10% state. The state is working on the long-term goal to reduce the mercury concentration in water bodies by reducing state emissions by 93% (MPCA, 2007).

Groundwater protection

Groundwater protection should be considered both for quantity and quality. Quantity is based on the amount of water withdrawn versus the amount of water being recharged to the aquifer. High capacity groundwater withdrawals in the watershed have increased from 7.8 million gallons in 1994 to 10.1 million gallons in 2013. Population increase has created more urbanization and development, especially for water supply for private consumption and non-crop irrigation for golf courses. It is estimated that the development pressure is moderate where land usage is being converted from timberland, resorts and lakeshore into home and recreation development (Figure 42) (USDA NRCS). This increase in development for recreation can also be seen with an increase in non-crop irrigation for golf courses special categories, such as snow and ice making, which has significantly increased ($p=0.001$) from 1994 to 2013.

Figure 42: Aerial view of Grand Marais, Minnesota in eastern Lake Superior North Watershed

While the amount of water being withdrawn from aquifers has increased greatly over time, there are no groundwater wells in the watershed designated to track the water levels needed to estimate any drawdown. Although fluctuations due to seasonal variations are common, the watershed has high rates of potential groundwater recharge to surficial materials (Figure 43). When comparing the location of the permitted groundwater withdrawals, they are primarily correlated with areas of higher potential recharge. At this stage, aquifer drawdown is not a concern; however, if water usage and land use conversion continue to increase, the probability of the water table being drawn downward also increases. It is for this reason that the MNDNR monitors and takes precautions when permitting water use appropriations.

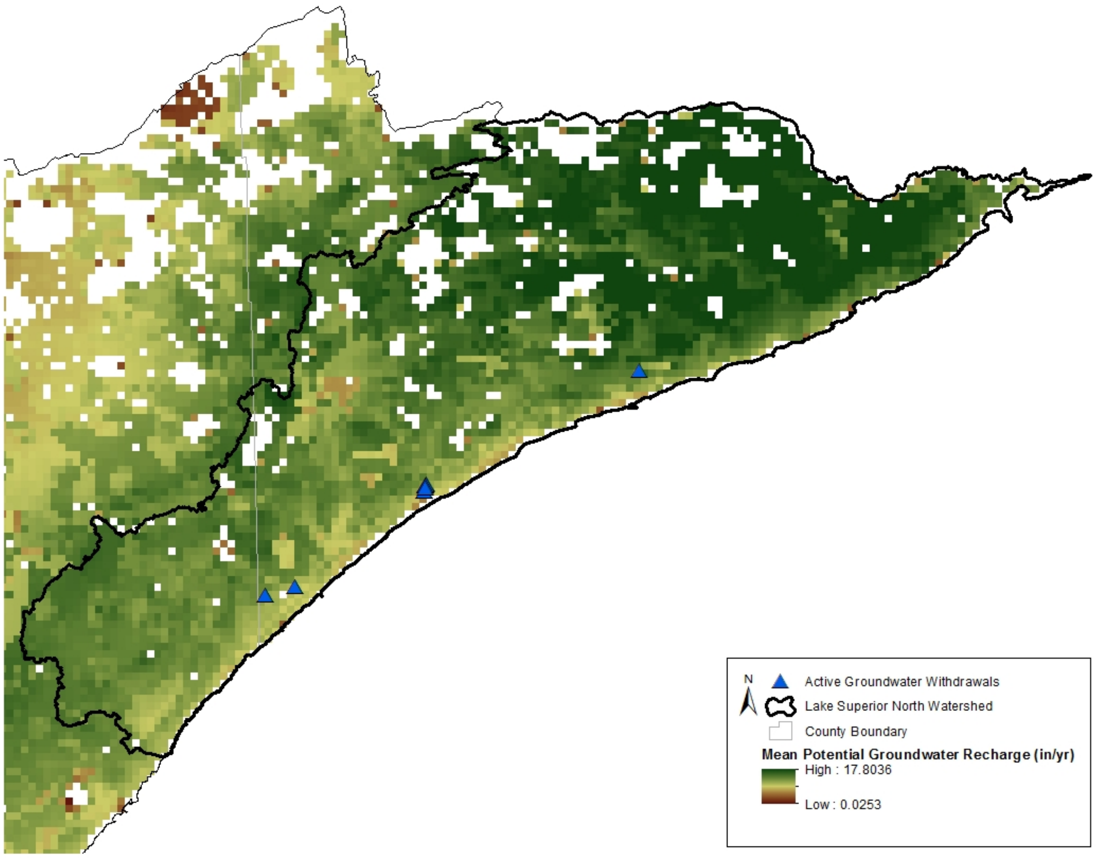

Figure 43: Mean potential groundwater recharge and groundwater permit locations in the Lake Superior North Watershed

Groundwater quality is based on the sensitivity of the aquifers and the effects of naturally occurring and anthropogenic constituents found in the water. Factors affecting aquifer sensitivity include: 1) whether the aquifer is shallow or deep, 2) whether the aquifer is unconfined or confined, 3) the material of the aquifer, and 4) groundwater recharge rates. Typically, aquifers that are shallow, unconfined, low clay content with cobbles and gravel materials and high recharge tend to have greater sensitivity to contamination. Sources of contamination can be naturally occurring, such as atmospheric deposition or weathering processes, or anthropogenic influences, such as leaking storage tanks, septic systems, landfills, uncontrolled hazardous waste, and chemical applications to agricultural landscapes or for deicing roads, parking lots, or sidewalks. The MPCA's WIMN program has identified a number of these potentially contaminated sites and facilities within the Lake Superior North Watershed. These types of sites include feedlots, hazardous waste, investigation and cleanup, solid waste, and tanks and leaks sites that have been identified as a potential, current or past contamination site or a site that is not a contamination risk, but required an environmental permit or registration from the MPCA (Figure 44). There is only one feedlot in the watershed, but it is located in an area that has been identified as having medium to high groundwater contamination susceptibly. Due to the area not being classified as good farmable soils, there are 22 farms located in the watershed with a total animal count of 198 (USDA NRCS). These are low enough values that they should not be a concern, but it is important to identify that a high number of livestock and poultry can increase the risk of water pollution, especially in areas of increased contamination susceptibility.

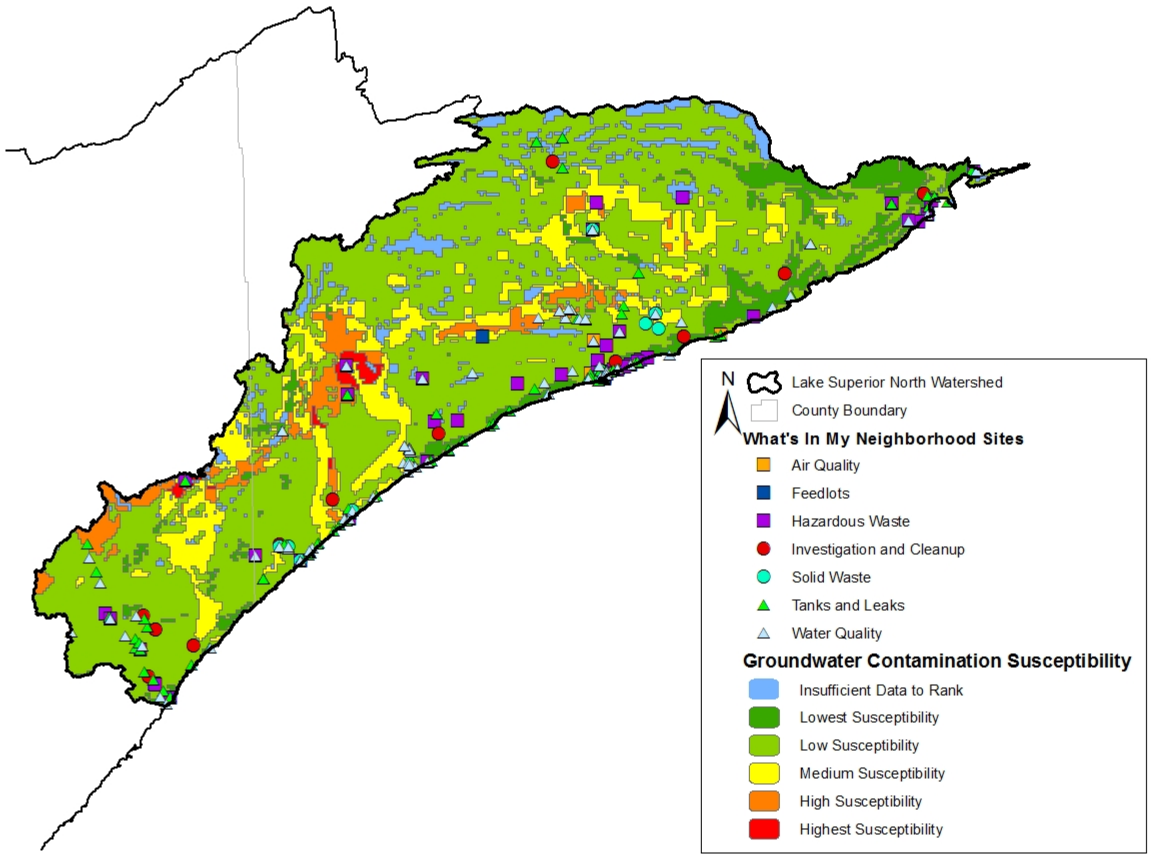

Figure 44: Groundwater contamination susceptibility and WIMN sites within the Lake Superior North Watershed

The watershed is located within the Northeast Hydrogeologic Region. During the MPCA's baseline study, the groundwater quality in this region was determined to be good when compared to other regions with similar aquifers. Although exceedances were found for different constituents within the regions, including arsenic, the primary source of contamination was due to geology. At this time, there is very little monitoring being conducted in this area by the MPCA or MDA. The MDH determined that there were some exceedances of the 10 micrograms per liter MCL of arsenic in private wells by county, ranging from 2.1% to 11.6% per county.

Recommendations

As often is the situation, additional monitoring would benefit the understanding of the health of the watershed, especially its groundwater resources. Expansion of the MPCA's Ambient Groundwater Network would benefit the watershed by providing current monitoring of the surficial groundwater specific to the watershed. Greater monitoring efforts increase understanding and aid in identifying the extent of issues that may be present and the risks that may be associated with them.

As population and development grows, so too do irrigation and water supply demands. The MNDNR permits and tracks water use by permit holder and rising demand suggests that the Department be cautious in granting future permits. Another factor to consider is climate change. Climate change is stimulating changes in precipitation, seasonal length, and droughts, which all can contribute to alterations in groundwater availability. The current state of the Lake Superior North Watershed is in good health and is able to maintain the current demand, but with changes in demand and climate, the status quo may not be sustainable.

VIII. References

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