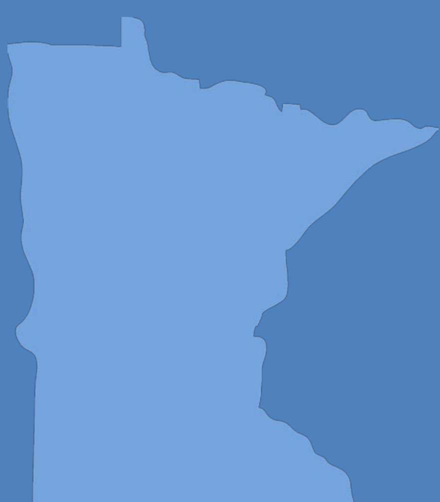
# Groundwater Report – Mississippi River-Headwaters Watershed



Minnesota Pollution Control Agency

January 2017

## Authors

Sophia Vaughan



## Contributors/acknowledgements

The resources for this report were drawn from the Minnesota Pollution Control Agency, Minnesota Department of Natural Resources, Minnesota Department Health, Minnesota Department of Agriculture, University of Minnesota Climatology Working Group, United States Geological Survey, and the United States Department of Agriculture-Natural Resources Conservation Service


The MPCA is reducing printing and mailing costs by using the Internet to distribute reports and information to wider audience. Visit our website for more information.

MPCA reports are printed on 100% post-consumer recycled content paper manufactured without chlorine or chlorine derivatives.


## Editing

David Duffey
Andrew Streitz

## Support

Project dollars provided by the Clean Water Fund; from the Clean Water, Land and Legacy Amendment.



## Minnesota Pollution Control Agency

520 Lafayette Road North | Saint Paul, MN 55155-4194 |

651-296-6300 | 800-657-3864 | Or use your preferred relay service. | Info.pca@state.mn.us


This report is available in alternative formats upon request, and online at www.pca.state.mn.us.


**Document number:** wq-ws1-12

# Contents

# Figures

# I. Introduction

Groundwater reports are detailed reviews on the condition of groundwater within the boundaries of one of the 80 major watersheds in Minnesota. This approach follows the MPCA's 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).

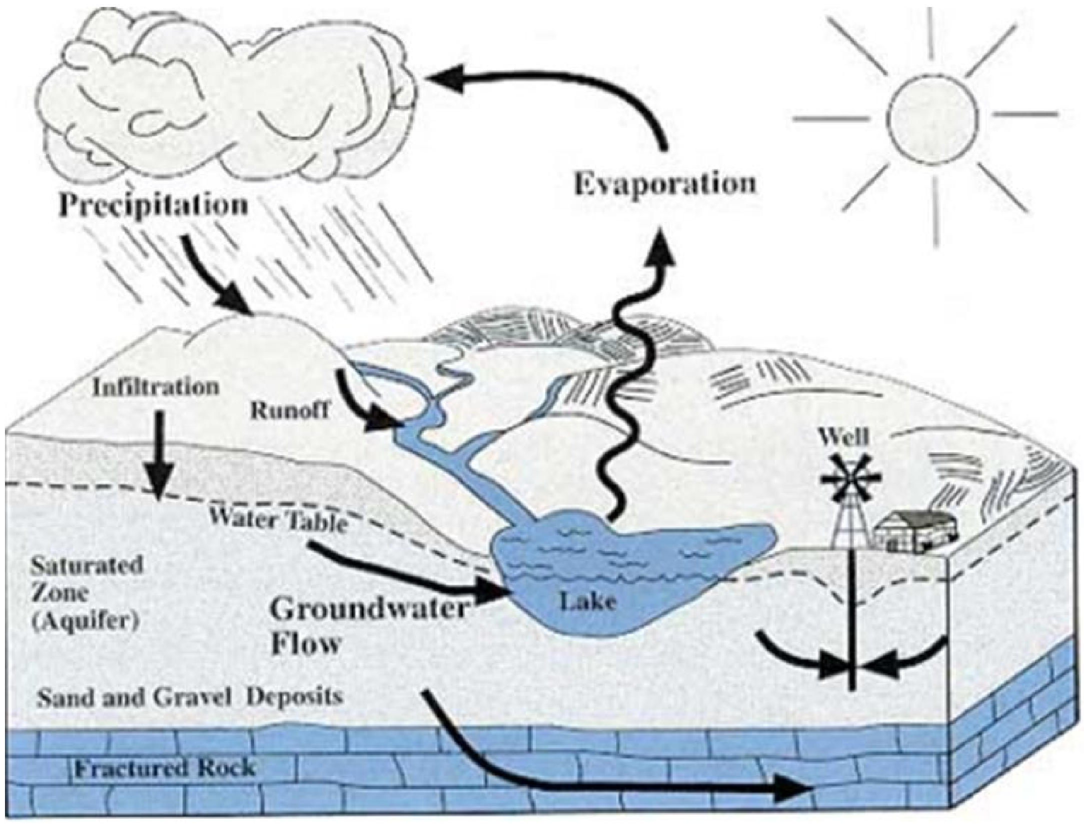



**Figure 1: Simplified hydrologic cycle demonstrating the changing states of water above and below the earth's surface.**

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, 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 Minnesota Pollution Control Agency (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 Minnesota Department of Natural Resources (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 Mississippi River-Headwaters Watershed (HUC 07010101) is located in the northernmost region of the Upper Mississippi River Basin, in north central Minnesota (Figure 2). The watershed is a heavily forested region within the Northern Lakes and Forest Ecoregion, draining an area of 1,961 square miles. The Mississippi River-Headwaters Watershed includes parts of Becker (0.8%), Beltrami (32.9%), Cass (12.2%), Clearwater (9.8%), Hubbard (12.6%), and Itasca (31.6%) counties (USDA, NRCS). Surface waters are abundant with over 1,000 lakes equaling 180,375 acres, approximately 685 river miles, and large riverine wetland areas (MPCA, 2015a). From its source at Lake Itasca in Clearwater County, the Mississippi River runs north-northeast through the watershed, continuing to flow 2,320 miles until it reaches the Gulf of Mexico at New Orleans. The average elevation of the watershed sits at 1,331 feet above sea level, predominately increasing in elevation from east to west (Figure 3).

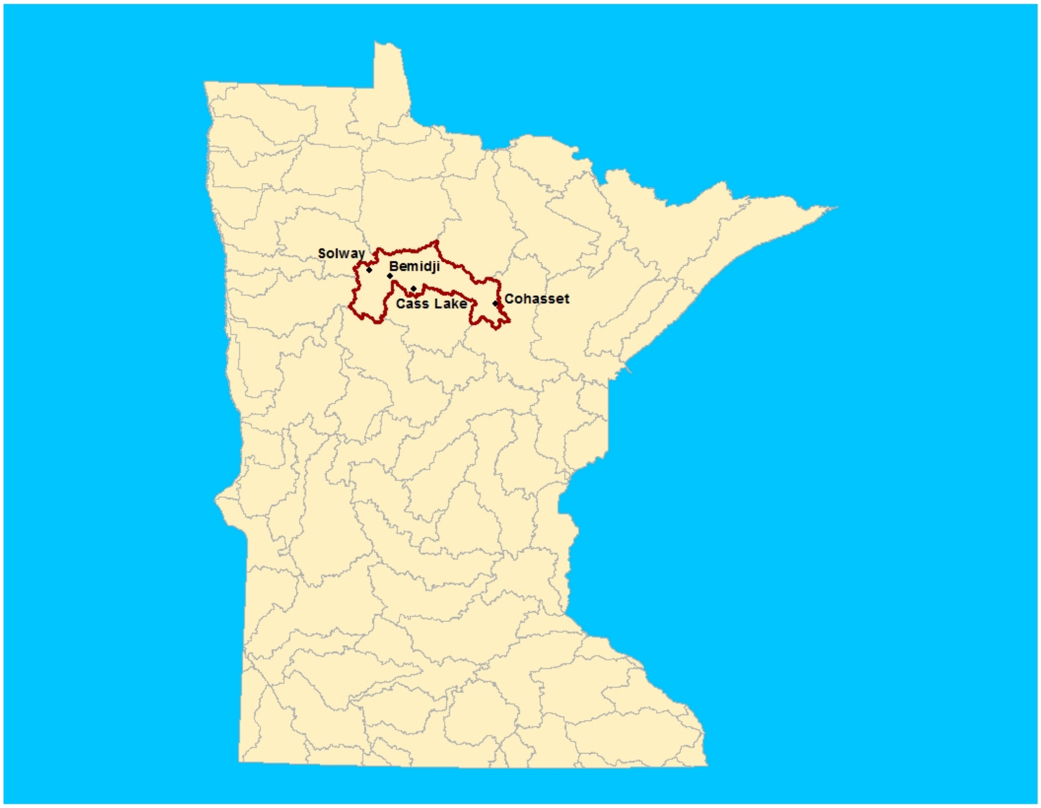



**Figure 2: The location of the Mississippi River-Headwaters Watershed.**

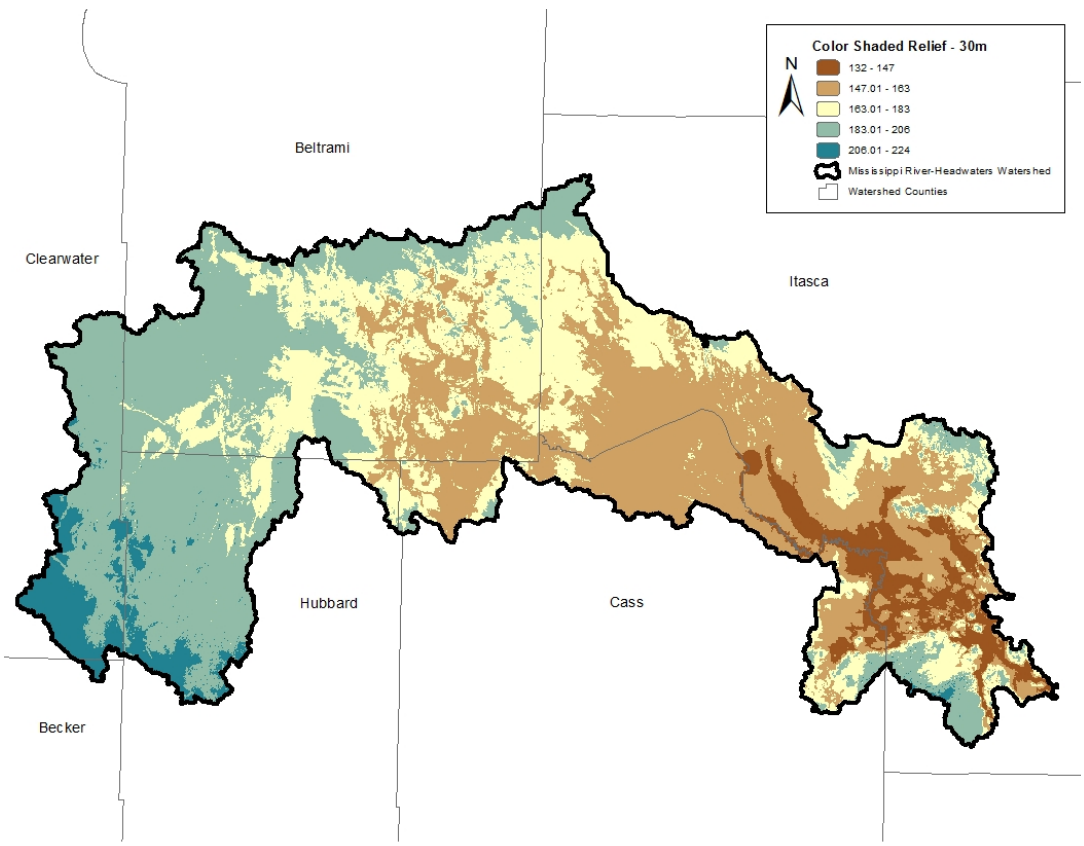



**Figure 3: Mississippi River-Headwaters 8-HUC Watershed Relief (GIS Source: MNDNR).**

## Land use

The land is heavily forested with 44.3% held by private landowners. The remaining land is managed by state (36.1%), county (0.4%), and federal (18%) public land, or held by tribal landowners (0.8%). The land uses and cover include: forest (58%), wetlands (15%), open water (14.3%), grass/pasture/hay (6.4%), and residential/commercial development (2.9%) (Figure 4) (USDA, NRCS). The total population count of the watershed is 48,410 with an estimated 586 farms (USDA, NRCS).

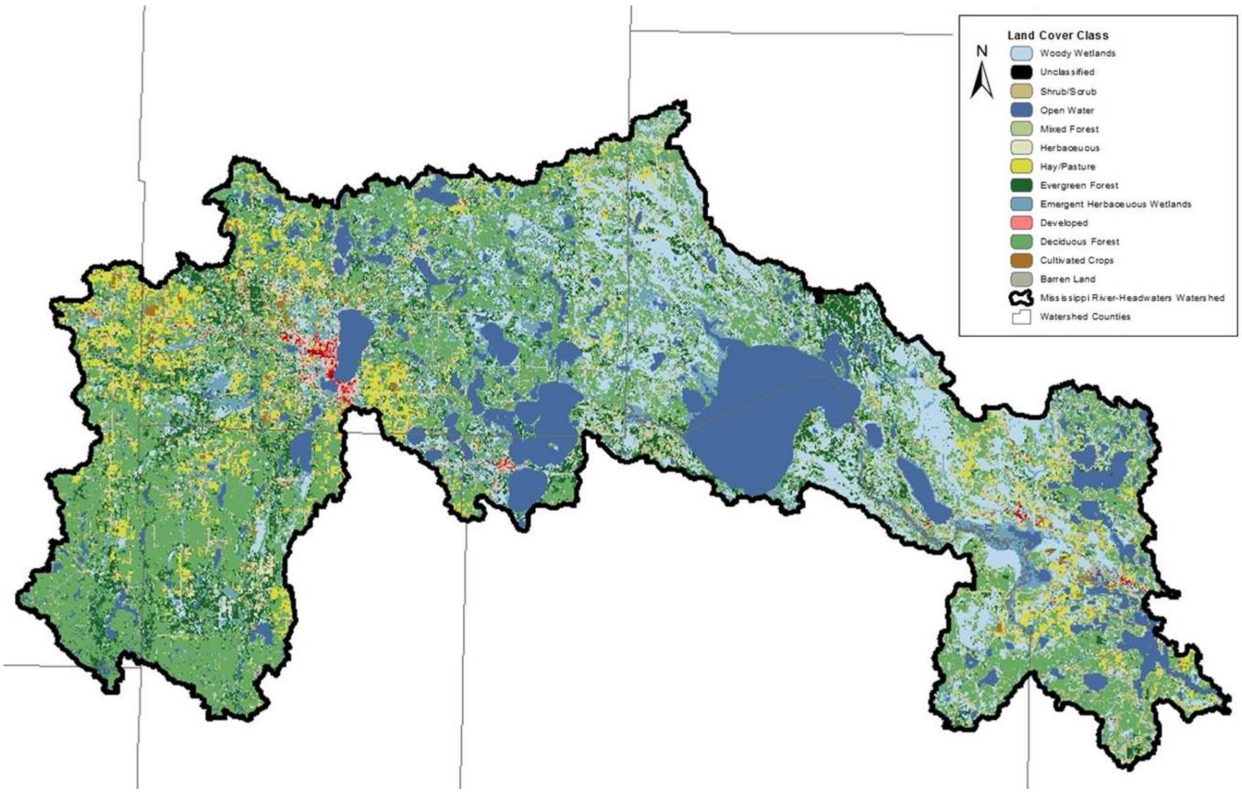



**Figure 4: Land cover in the Mississippi River-Headwaters Watershed (GIS Source: NLCD, 2011).**

## Ecoregion and soils

The watershed is located within the Northern Lakes and Forest Ecoregion. According to the Ecological Classification System, the Mississippi River-Headwaters Watershed lays within the Laurentian Mixed Forest Province and the Northern Minnesota Drift and Lake Plains Section. It predominantly lies within the Chippewa Plains subsection with some portions also lying within the Pine Moraines and Outwash Plains (southwest) and St. Louis Moraines (southeast) subsections (Figure 5).

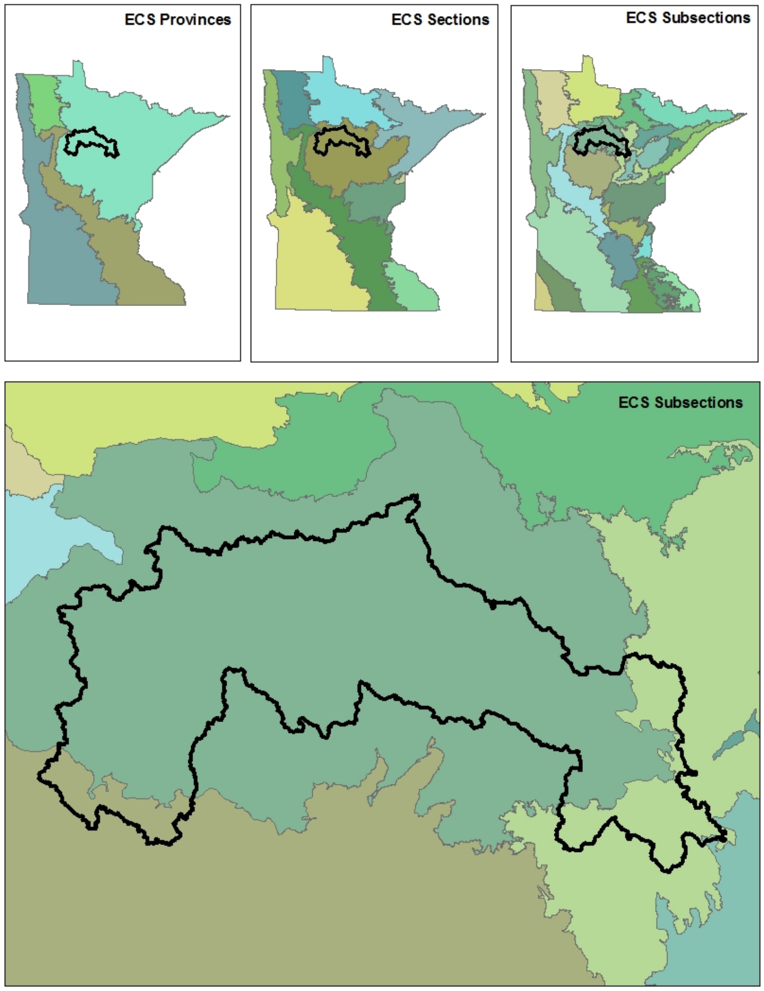



**Figure 5: Three levels of Ecological Classification System for the Mississippi River-Headwaters Watershed.**

The watershed is primarily comprised of calcareous glacial deposits from the Des Moines Lobe and Wadena Lobe (NRCS). The area is made up of alluvium and outwash, Anoka sand plains, forested moraine, northern till, and a number of somewhat poorly drained lakes. The soils consist mainly of Alfisols, with some areas of Entisols and Histosols. Alfisols are formed from weathering processes under forests or mixed vegetation that contribute to a high clay content. This soil is fertile with a high moisture holding capacity, which makes them highly productive for most crops. Entisols are typically found in glacial outwash and alluvium and are characterized as sandy soils that are resistant to weathering. Histosols are formed from vegetation in wet environments, often found in wetlands, marshes or bogs. A more detailed list of the soil types can be found in Figure 6 (below).

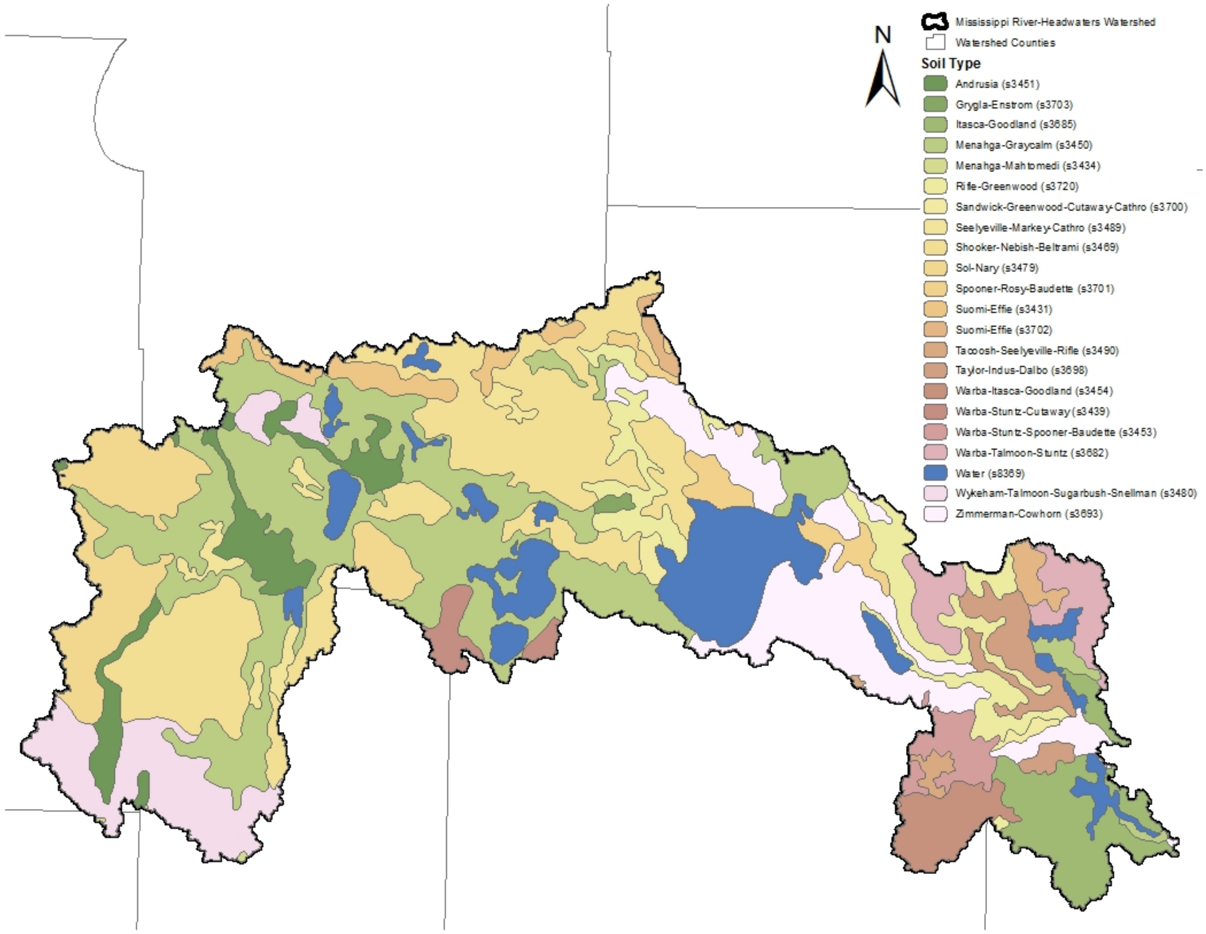



**Figure 6: Soil Classification for the Mississippi River-Headwaters Watershed (GIS Source: USDA NRCS, 2006).**

# II. Climate and precipitation

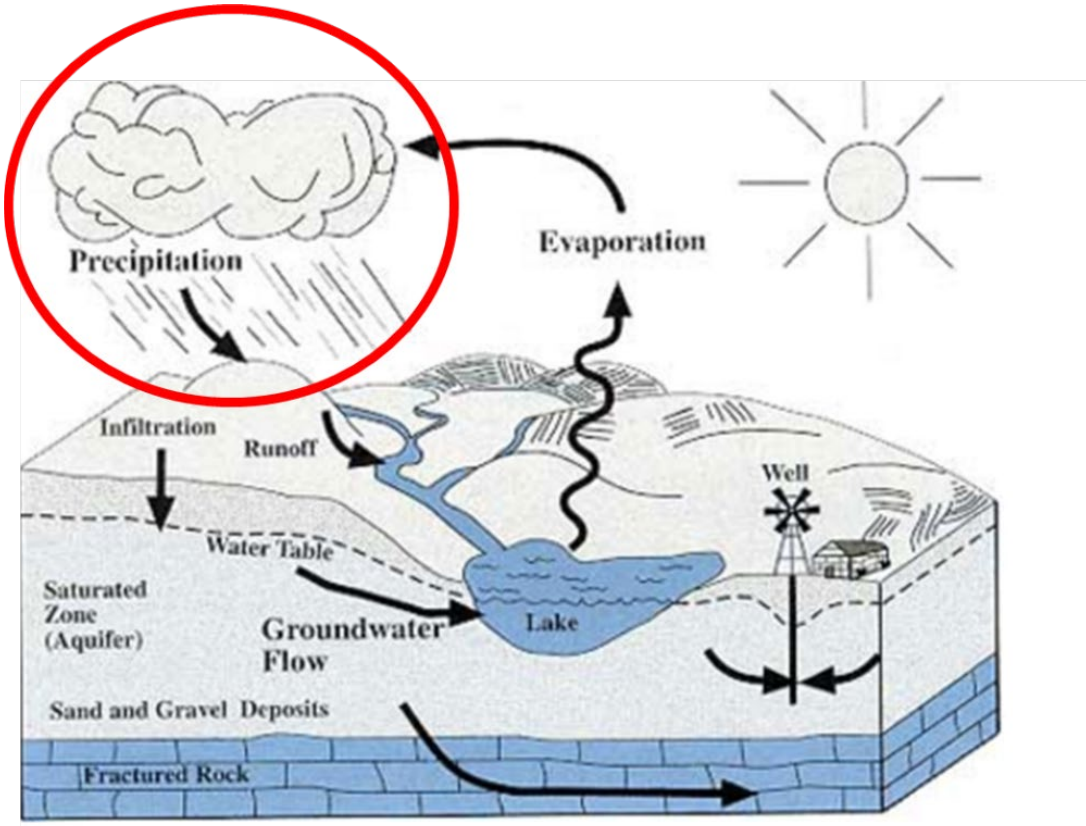



**Figure 7: Precipitation within the hydrologic cycle.**

Minnesota has a continental climate, marked by warm summers and cold winters. The mean annual temperature for Minnesota is 4.6˚C (NOAA, 2016); the mean summer temperature for the Mississippi River-Headwaters Watershed is 18.3˚C and the mean winter temperature is -12.2˚ C (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 majority of the Mississippi River-Headwaters Watershed area received 24 to 28 inches of precipitation in 2014, with a small region in the eastern area that receives 28 to 32 inches of precipitation. The display on the right shows the amount that precipitation levels departed from normal. For the Mississippi River-Headwaters area it displays that precipitation ranged from two inches below normal to two inches above normal in 2014.

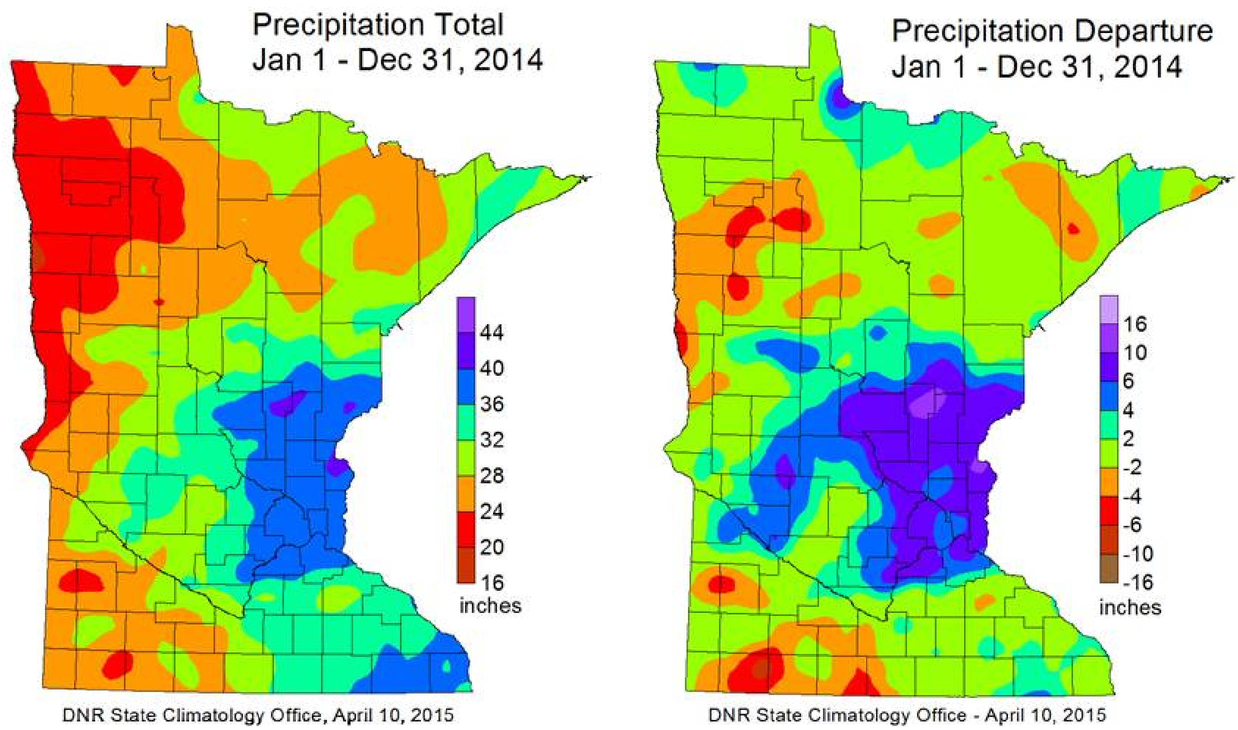



**Figure 8: Statewide precipitation levels during 2014 (Source: MNDNR State Climatology Office, 2015).**

The Mississippi River-Headwaters Watershed is located in the north central precipitation region. Figure 9 and 10 (below) display the areal average representation of precipitation in north central 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 north central region display no significant trend over the last 20 years. However, precipitation in north central 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.

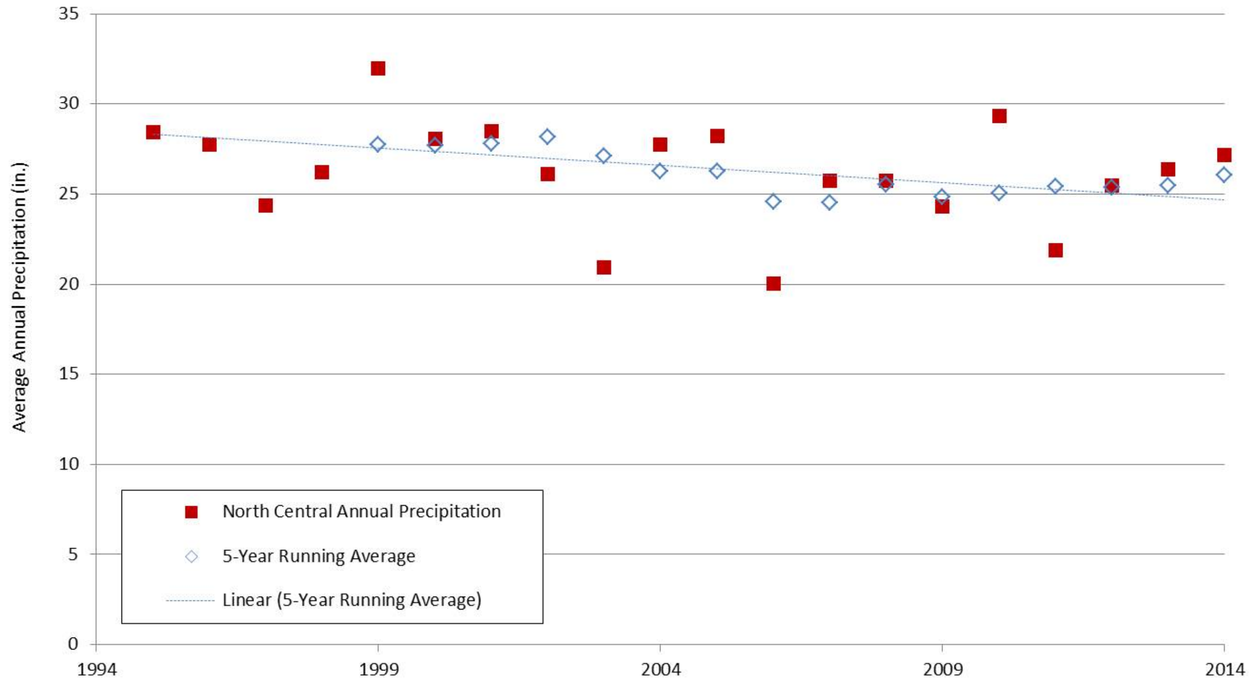



**Figure 9: Precipitation trends in North Central Minnesota (1995-2014) with five-year running average.**

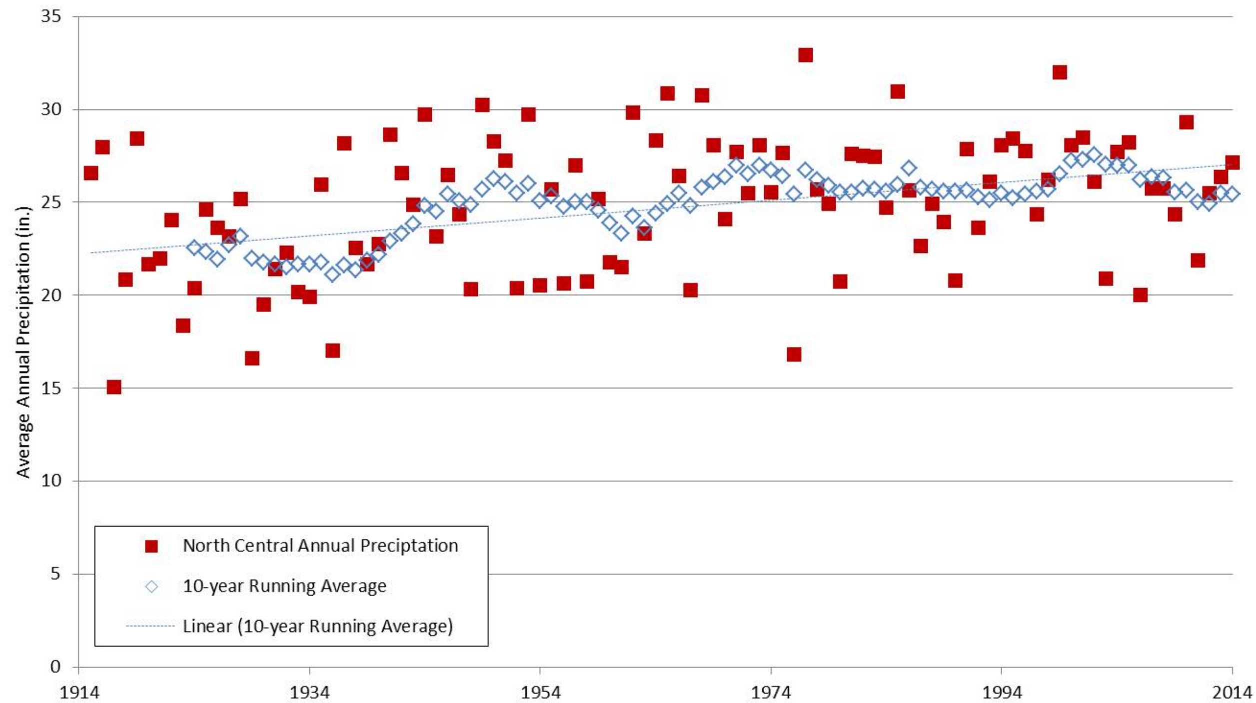



**Figure 10: Precipitation trends in North Central Minnesota (1915-2014) with 10-year running average.**

# III. Surface water hydrology

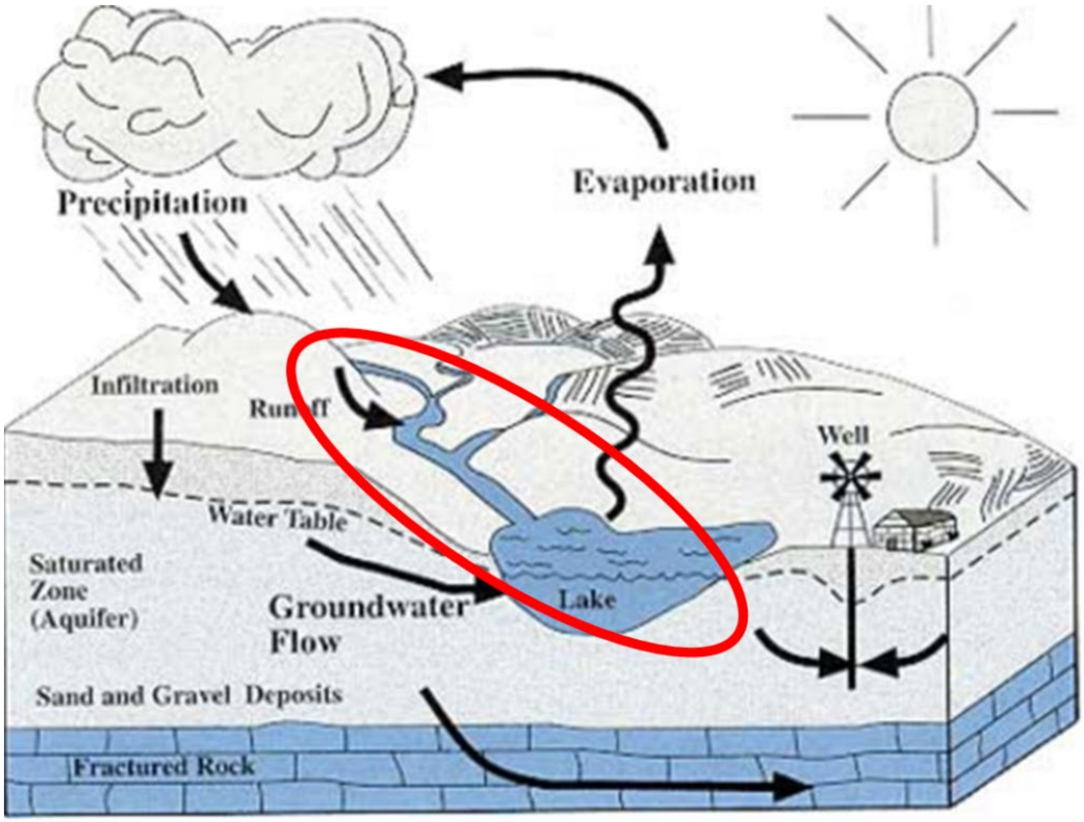



**Figure 11: Surface water within the hydrologic cycle.**

The Mississippi River-Headwaters Watershed is considered a water-rich area with 685.05 total river miles and over 1,000 lakes, as well as groundwater springs and large riverine wetland areas (MPCA, 2015a). As the watershed is named for, Mississippi River begins its 2,320-mile descent into the Gulf of Mexico at Lake Itasca in Clearwater County. Other major rivers in the watershed include Deer River, Leech Lake River, Schoolcraft River, Third River, Turtle River and the Vermillion River and major lakes include Lake Itasca, Ball Club, Cass Lake, Deer Lake, Lake Bemidji, Lake Winnibigoshish, and Pokegama Lake (MPCA, 2015a).

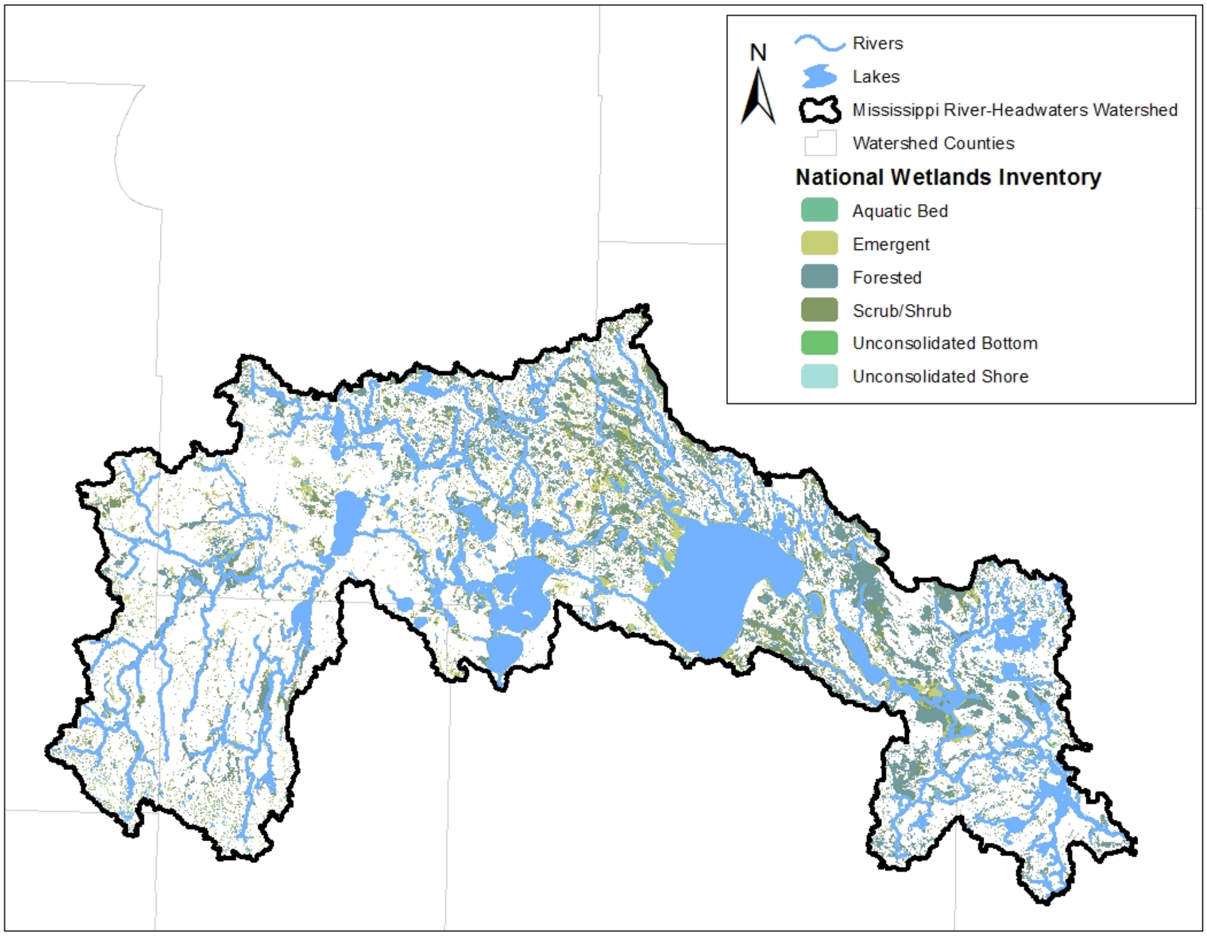



**Figure 12: Lakes, wetlands, and waterbodies in the Mississippi River-Headwaters Watershed.**

## Streamflow

Streamflow data from the United States Geological Survey's (USGS) real-time streamflow gaging stations for two steam sites along the Mississippi River were 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 Mississippi River near Bemidji, Minnesota 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 1995 to 2015, excluding 2002 due to lack of data, for the same water body. The data appear to be increasing in July and August, but not at a statistically significant rate. Annual and summer monthly mean streamflow is displayed in Figure 15 and 16 for the Mississippi River at Ball Club, Minnesota during the water year 2008 to 2014. Although both appear to be increasing during this time period, there is no statistically significant trend, primarily due to insufficient number of years' worth of data. By way of comparison at a state level, summer month flows have declined at a statistically significant rate at a majority of streams selected randomly for a study of statewide trends (Streitz, 2012). For additional streamflow data throughout Minnesota, please visit the USGS website: http://waterdata.usgs.gov/mn/nwis/rt.

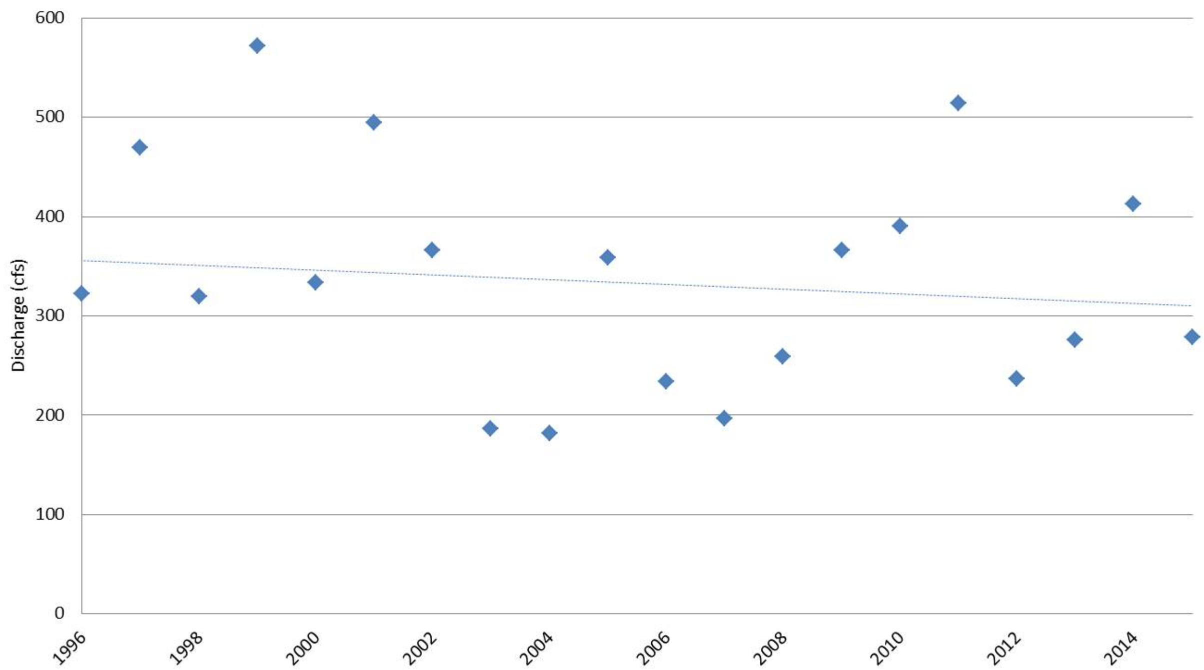



**Figure 13: Annual mean discharge for Mississippi River near Bemidji, MN (1996-2015).**

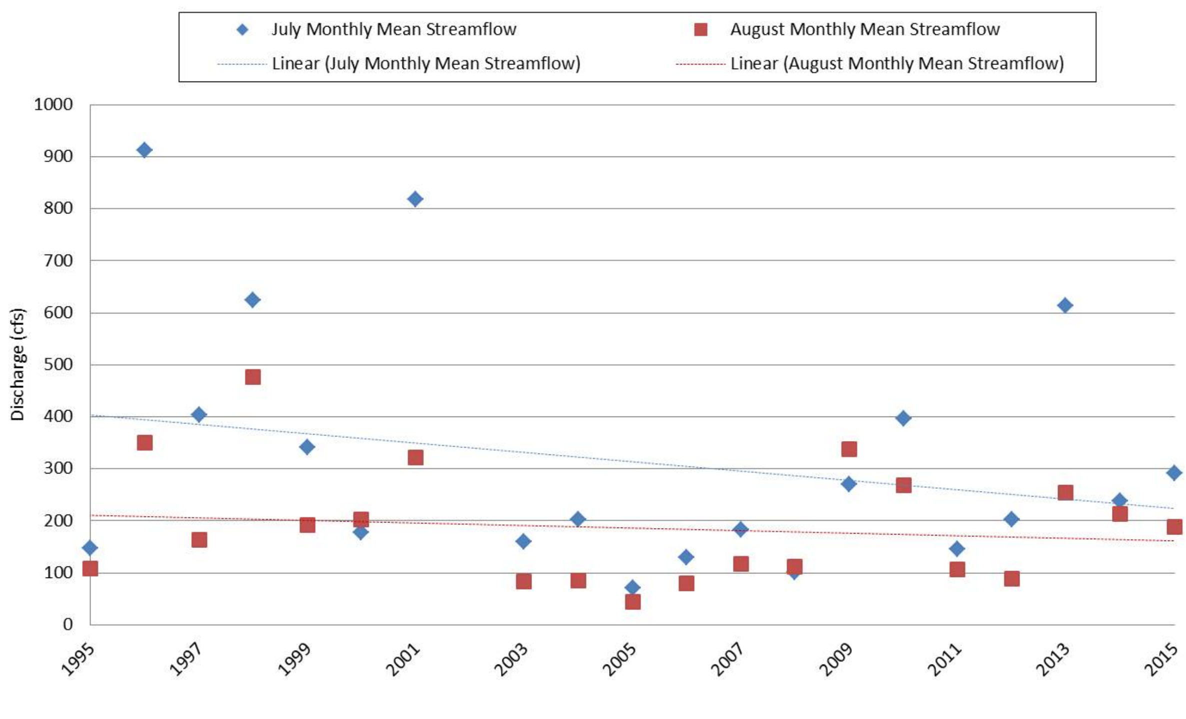



**Figure 14: Mean monthly discharge for Mississippi River near Bemidji, MN (1995-2015).**

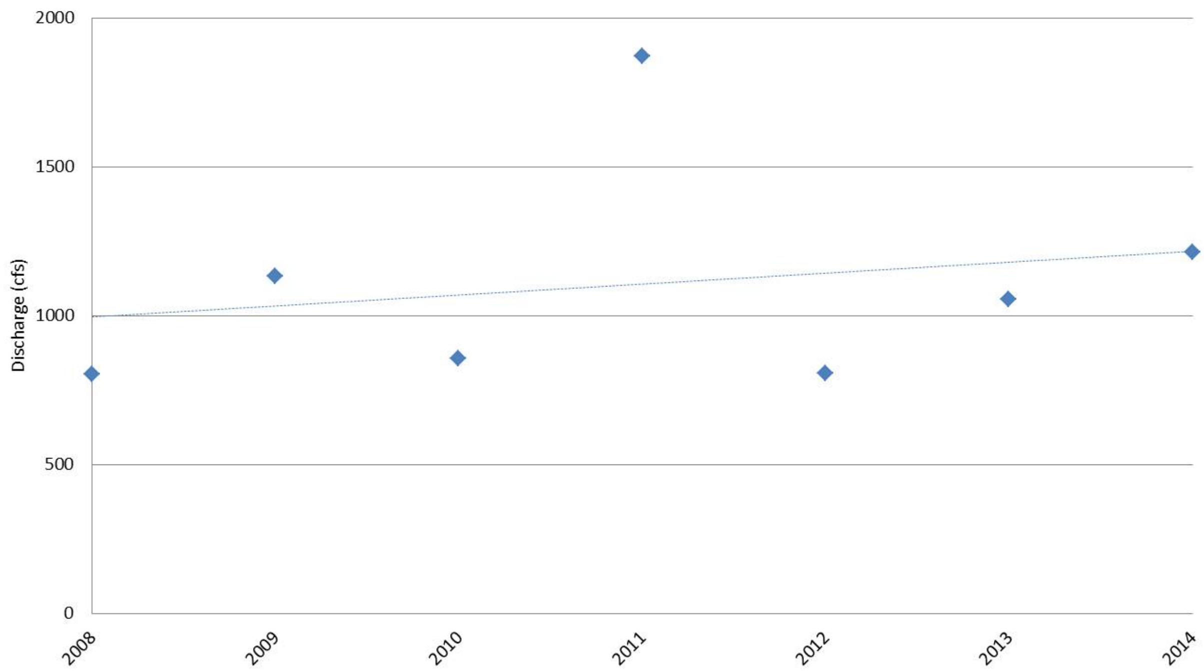



**Figure 15: Annual mean discharge for Mississippi River at Ball Club, MN (2008-2014).**

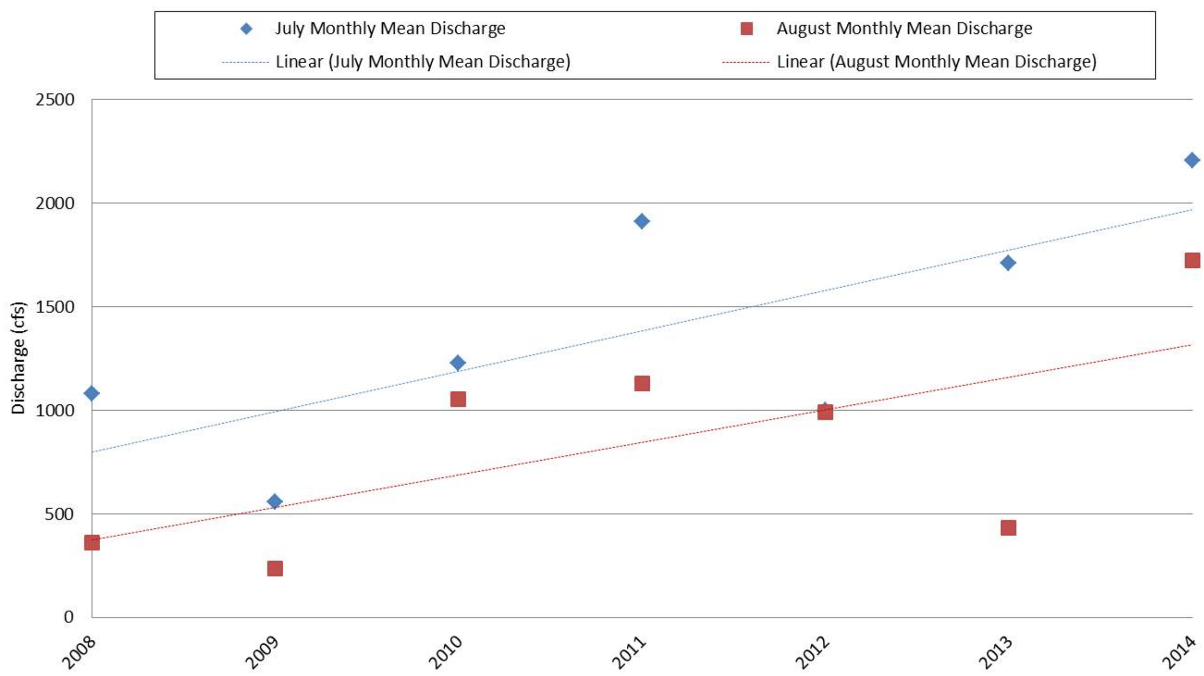



**Figure 16: Mean monthly Discharge for Mississippi River at Ball Club, MN (2008-2014).**

## Lake levels

Lake Plantagenet (Inventory Number 29015600) in Hubbard County is located near Bemidji in the western region of the watershed (Figure 17). The area of the lake is 2,511 acres with a maximum depth of 65 feet and an average lake water level elevation of 1342.88 (MPCA, 2015b). The lake's use classification is 2B, 3C, which is defined as a healthy warm water aquatic community; industrial cooling and materials transport use without a high level of treatment. The overall condition is described as "suitable for swimming and wading, with good clarity and low algae levels throughout the open water season" (MPCA, 2015b).

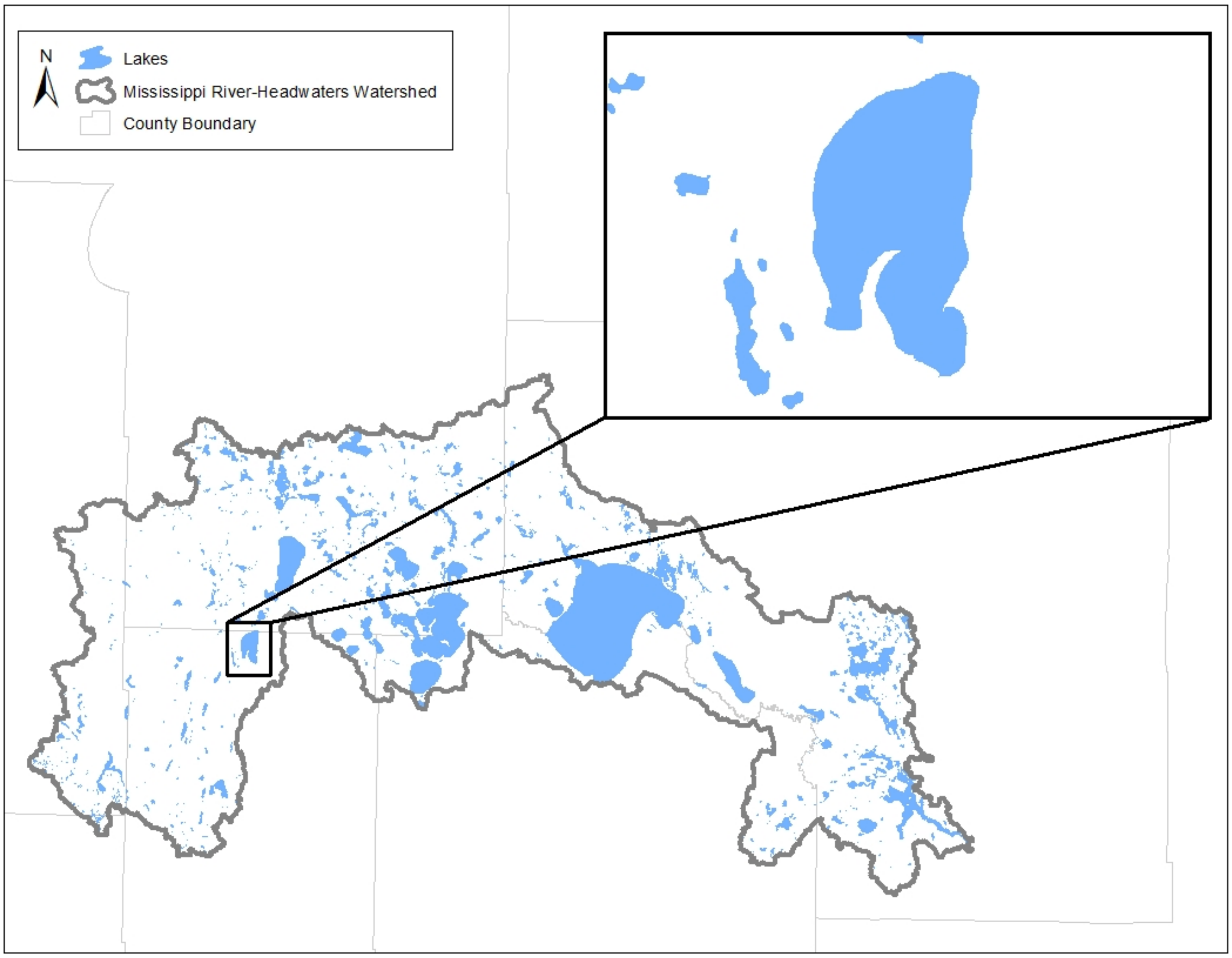



**Figure 17: Lake Plantagenet within Mississippi River-Headwaters Watershed.**

A 2012 survey by the MNDNR determined the average water clarity to be 3.25 feet, which is considered poor water clarity, and the littoral area to be 986 acres (MNDNR, 2015b). The lakeshore consisted of moderate development, one active resort and two public boat landings. Lake Plantagenet is well connected to many lakes downstream via the Schoolcraft River system. This connectivity allows significant fish migration between Lake Plantagenet and Lake Bemidji (MNDNR, 2015b). The MNDNR has maintained fish populations via alternate year stocking of walleye fry and muskellunge fingerlings over the last 10 years (MNDNR, 2015b). The lake has also been identified as a trophy muskellunge lake, which can cause higher fishing pressure for this species. However, 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 18). Lake elevation data can be found from the MNDNR Lake Finder website: http://www.dnr.state.mn.us/lakefind/index.html.

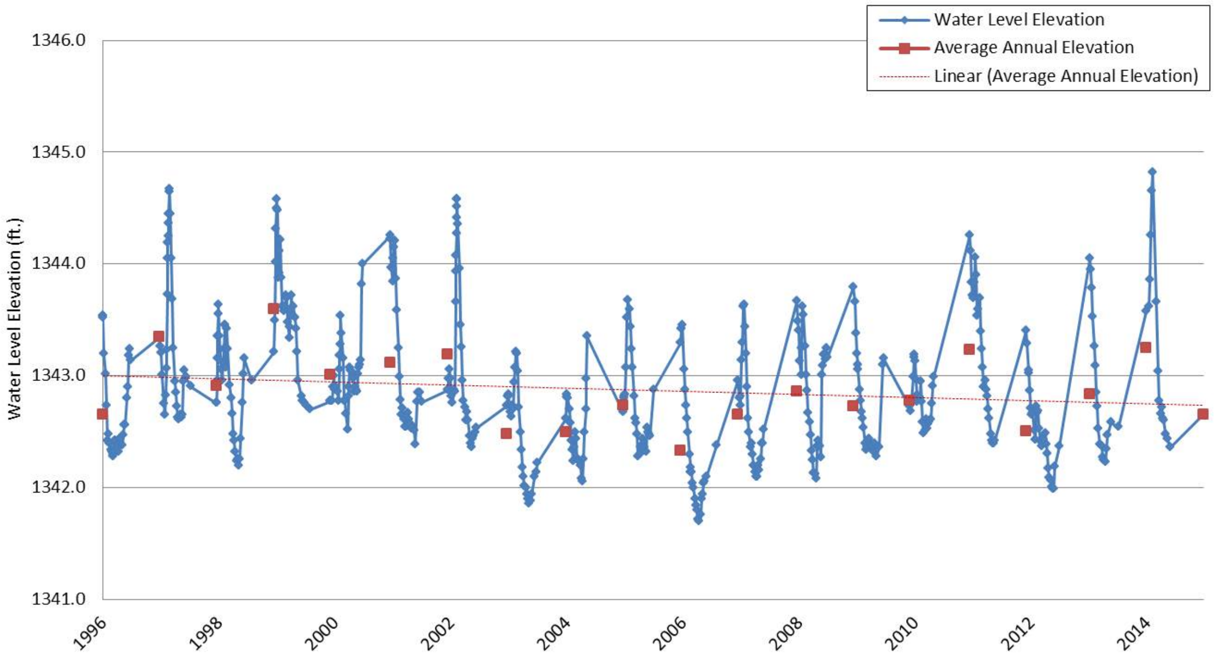



**Figure 18: Lake Plantagenet water level elevations (1996-2015).**

Dixon Lake (Inventory Number 31092100) in Itasca County is located near Squaw Lake in the central area of the watershed (Figure 19). The area of the lake is 550 acres with a maximum depth of 29 feet and an average lake water level elevation of 1302.39 (MPCA, 2015c). The lake's use classification is 2B, 3C; but the overall condition is described as "not always suitable for swimming and wading due to low clarity or excessive algae caused by the presence of nutrients, such as phosphorus in the water" (MPCA, 2015c).

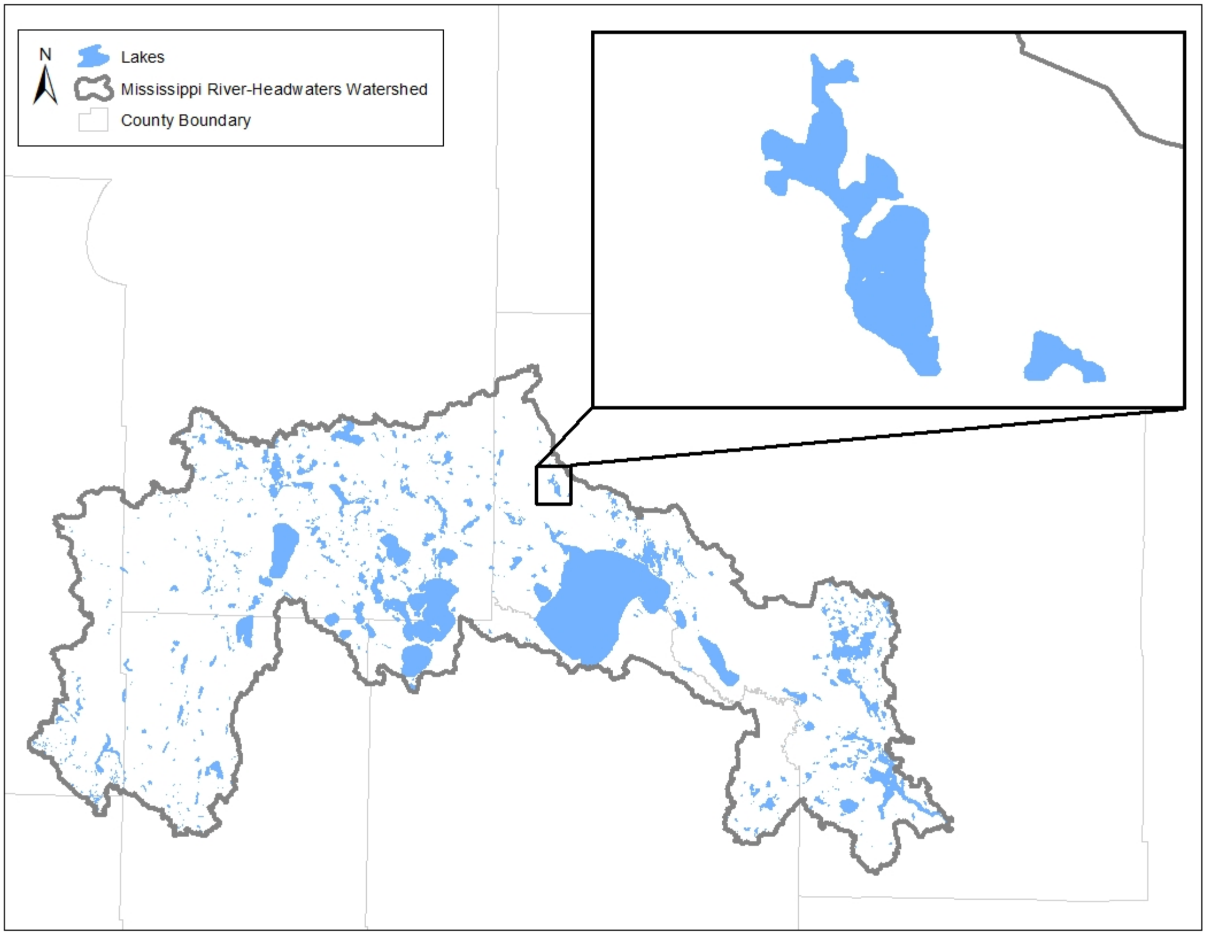



**Figure 19: Dixon Lake within the Mississippi River-Headwaters Watershed.**

A 2009 survey by the MNDNR determined Dixon Lake to be a moderately sized eutrophic lake with average water clarity of 5.7 feet (moderate water clarity) and a littoral area of 478 acres (MNDNR, 2015c). The lake has four inlets: Third River, Otter Creek, Sioux Lake Creek, and Unnamed Creek. Third River also acts as the outlet on the south end of the lake (MNDNR, 2015c). The MNDNR has stocked the lake with walleye fry over the last 10 years and black crappie has also been a primary management species for this lake. The MPCA identified Dixon Lake as impaired for aquatic recreation in 2007 for nutrient/eutrophication biological indicators and for aquatic consumption for mercury in fish tissue in 2011 (MPCA, 2015c). Over the last 20 years, lake level elevation has remained constant, altering for seasonal fluctuations (Figure 20).

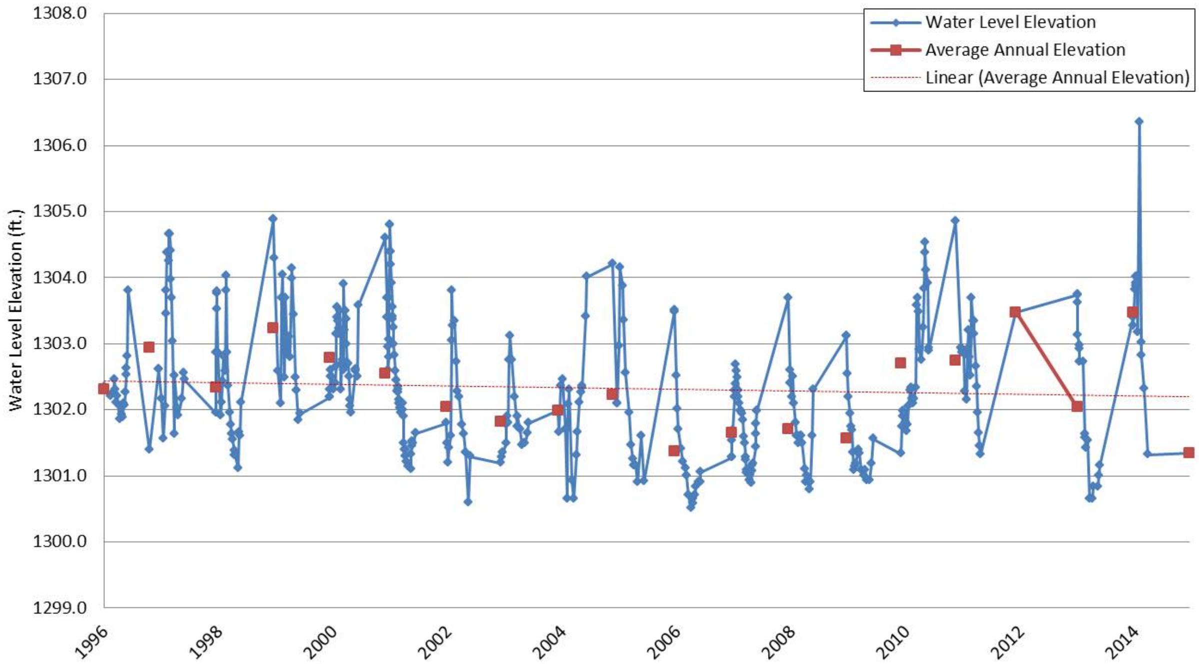



**Figure 20: Dixon Lake water level elevations (1996-2015).**

Siseebakwet Lake, also referred to as Sugar Lake (Inventory Number 31055400), in Itasca County is located near Grand Rapids in the eastern area of the watershed (Figure 21). The area of the lake is 1,205 acres with a maximum depth of 105 feet and an average lake water level elevation of 1329.53 (MPCA, 2015d). The lake's use classification is 2B, 3C; and the overall condition is described as "suitable for swimming and wading, with good clarity and low algae levels throughout the open water season" (MPCA, 2015d).

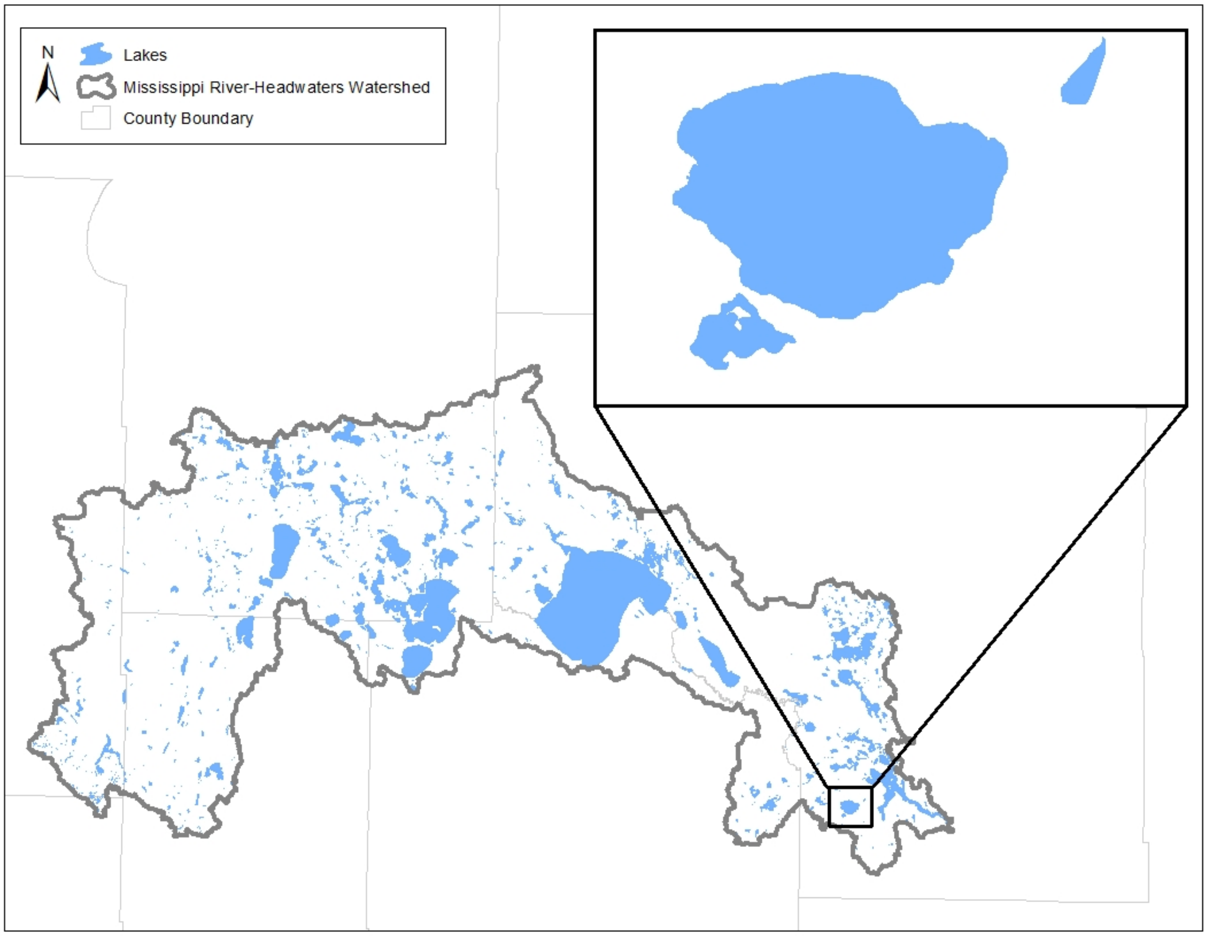



**Figure 21: Siseebakwet Lake within Mississippi River-Headwaters Watershed.**

In 2012, the MNDNR conducted a fisheries lake survey that determined that the lake had an average water clarity of 13.3 feet and a littoral area of 292 acres (MNDNR, 2015d). The lakeshore is heavily developed, but is broken up by stands of bulrush and one county owned public access. The lake has two inlets: the Sugar Brook from the west connecting Little Siseebakwet and Spring Lake, and an unnamed channel from the southwest connecting South Sugar Lake and Siseebakwet Lake. Sugar Brook also acts as the outlet on the northeast end and connects the lake to Pokegama Lake near Grand Rapids (MNDNR, 2015d). The MNDNR has stocked the lake with walleye with varying rates and frequencies; however, since 2007 the MNDNR has alternated stocking years at a rate of two pounds per littoral acre (584 pounds) (MNDNR, 2015d). The lake has also met all aquatic consumption and recreation standards during MPCA's water quality assessments (MPCA, 2015d). Over the last 20 years, lake level elevation has remained constant, altering only for seasonal fluctuations (Figure 22).

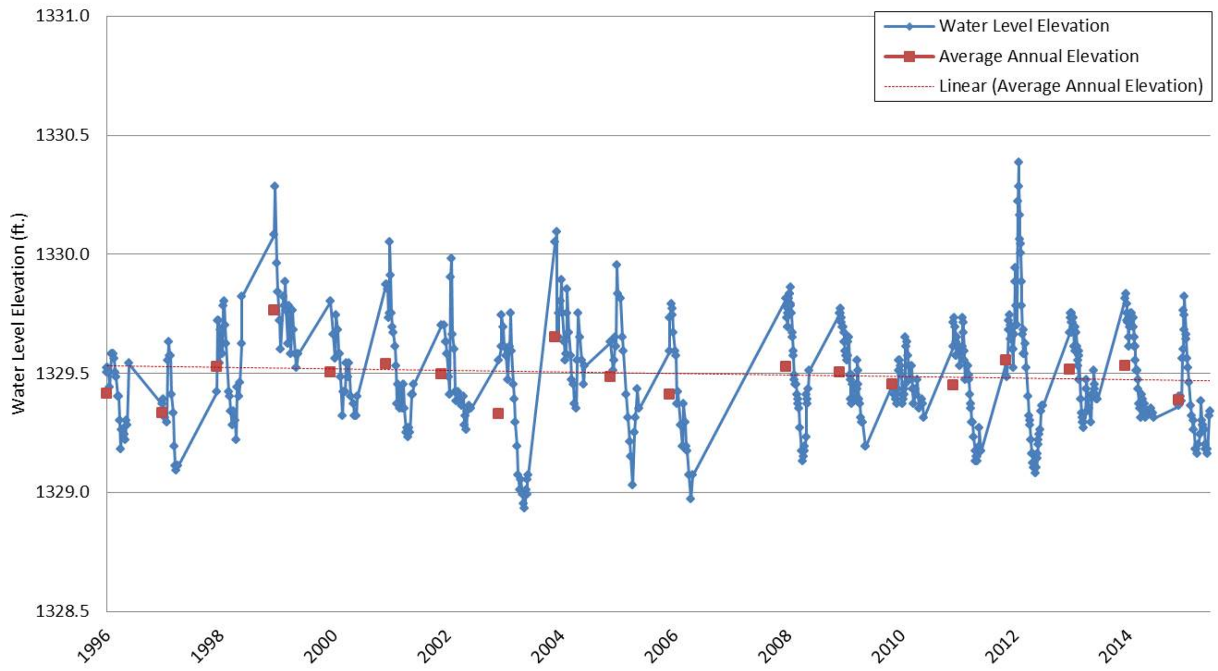



**Figure 22: Siseebakwet Lake water level elevations (1996-2015).**

# IV. Hydrogeology

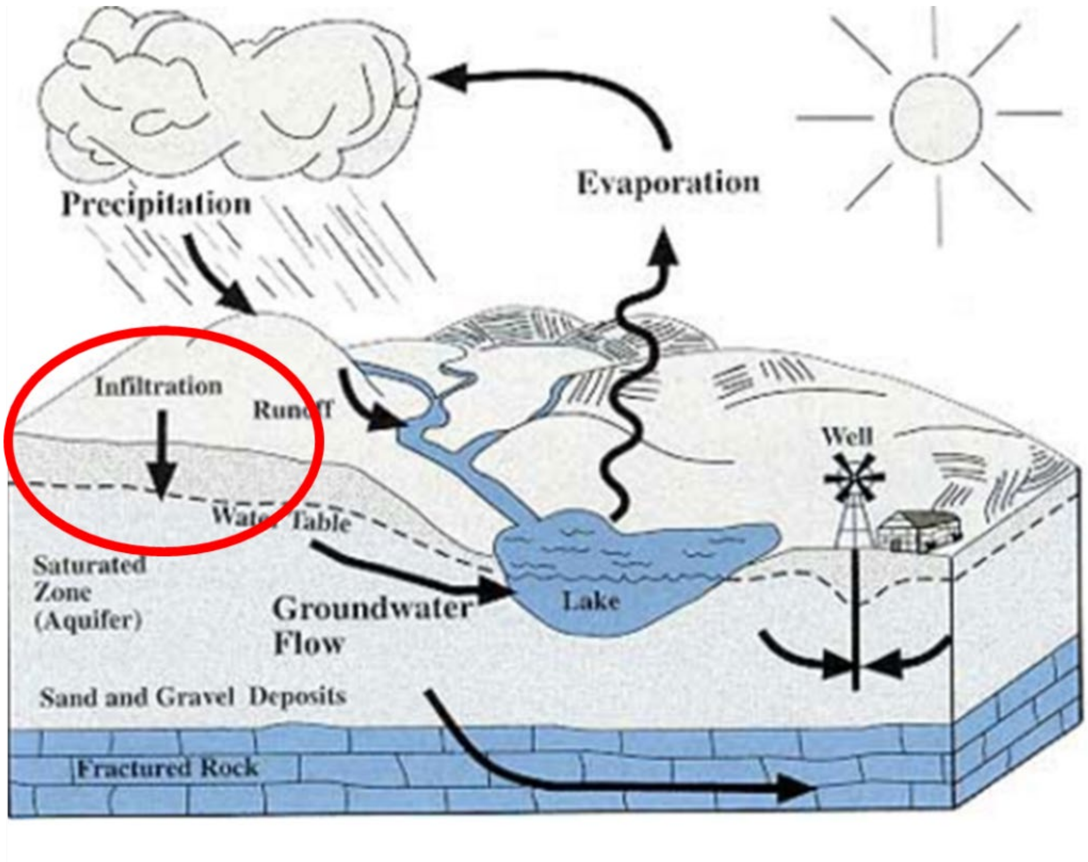



**Figure 23: Groundwater within the hydrologic cycle.**

Hydrogeology is the study of the interaction, distribution, and movement of groundwater through the rocks and soil of the earth. The geology of a region strongly influences the quantity of groundwater available, the quality of the water, the sensitivity of the water to pollution, and how quickly the water will be able to recharge and replenish the source aquifer. This branch of geology is important to understand as it indicates how to manage groundwater withdrawal and land use and can determine if mitigation is necessary.

## 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 the Mississippi River-Headwaters Watershed, Becker, Hubbard, and Cass counties are in progress while Itasca, Beltrami, and Clearwater counties have not yet begun. Therefore, there is no County Geologic Atlas information available for this watershed at this time. For additional 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 much of the Mississippi River-Headwaters Watershed and is the parent material for the soils that have developed since glaciation. The depth to bedrock ranges from exposure at the surface to over 890 feet and 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 Des Moines and Wadena lobes. The glacial sediments can be grouped by material texture: 1) sand and gravel outwash, 2) calcareous till, 3) non-calcareous till, and 4) peat (Figure 24).

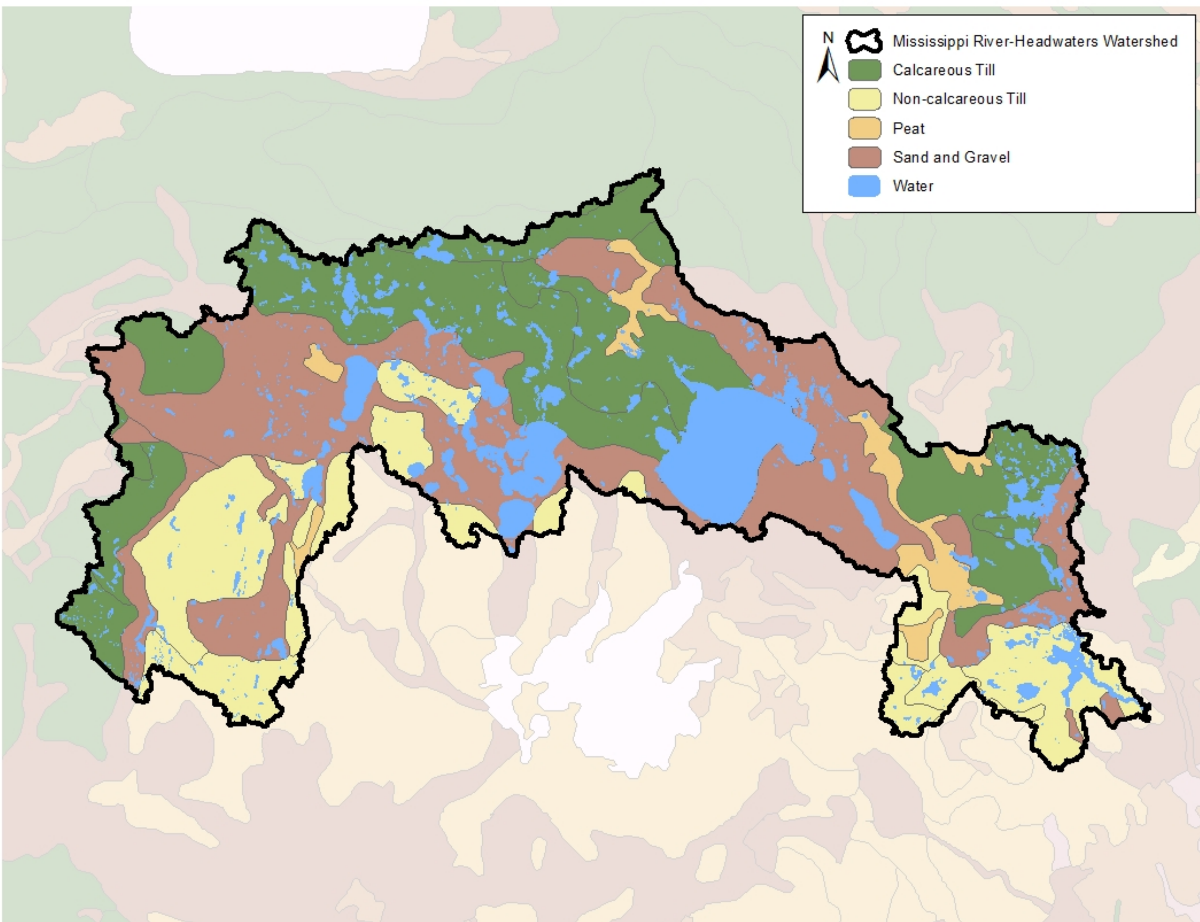



**Figure 24: Quaternary geology, glacial sediments within the Mississippi River-Headwaters Watershed (GIS Source: MGS, 1982).**

Bedrock is the main mass of rocks that form the Earth, located underneath the surficial geology and can only be seen in only a few places where weathering has exposed the bedrock. The bedrock geology of the Mississippi River-Headwaters Watershed includes Precambrian crystalline rocks and Cretaceous rocks in the southeast region of the watershed (Figure 25). The uppermost bedrock is the cretaceous bedrock, which is the youngest pre-glacial deposit layer, and is described as sandstone layers interbedded with thick layers of shales and are often used as the local water source (MNDNR, 2001). The cretaceous bedrock located within this watershed is the the Coleraine Formation, which is an iron-ore conglomerate (coarse-grained clastic sedimentary rock), sandstone, shale and lignite of marine origin. The Precambrian bedrock covers the extent of the watershed, is comprised of the Superior Province, and displays evidence of volcanic activity. The main terrane groups include Animikie Group: Thomson Formation and Virginia Formation (mudstone and greywacke), Biwabik Iron Formation (basal conglomerate) and Pokegama Quartzite (conglomerate, siliceous mudstone), the Wawa Subprovince, the Wawa and Wabigoon Subprovince (mafic metavolcanic rocks, calc-alkalic volcanic and volcaniclastic rocks. In addition, foliated to gneissic terrane includes tonalite, diorite and granodiorite, massive to weakly foliated areas include granitic and granitoid intrusions, and other mafic intrusion with pyroxenite, peridotite, gabbro and lamprophyre are prevalent throughout the watershed.

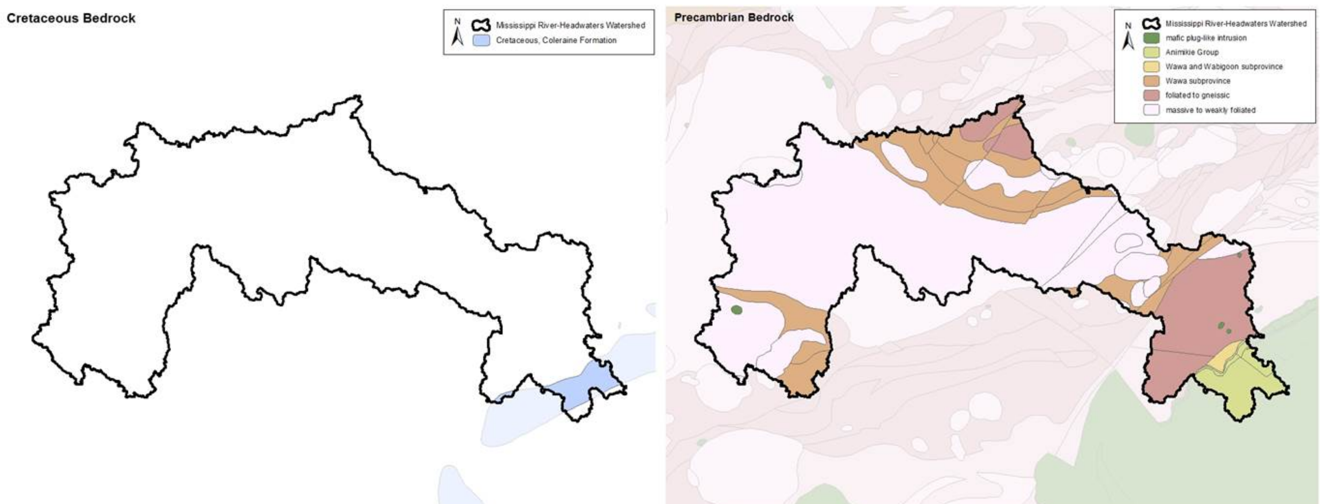



**Figure 25: Bedrock geology of the Mississippi River-Headwaters Watershed: Cretaceous and Precambrian (GIS Source: MGS, 2011).**

## 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 26). 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.

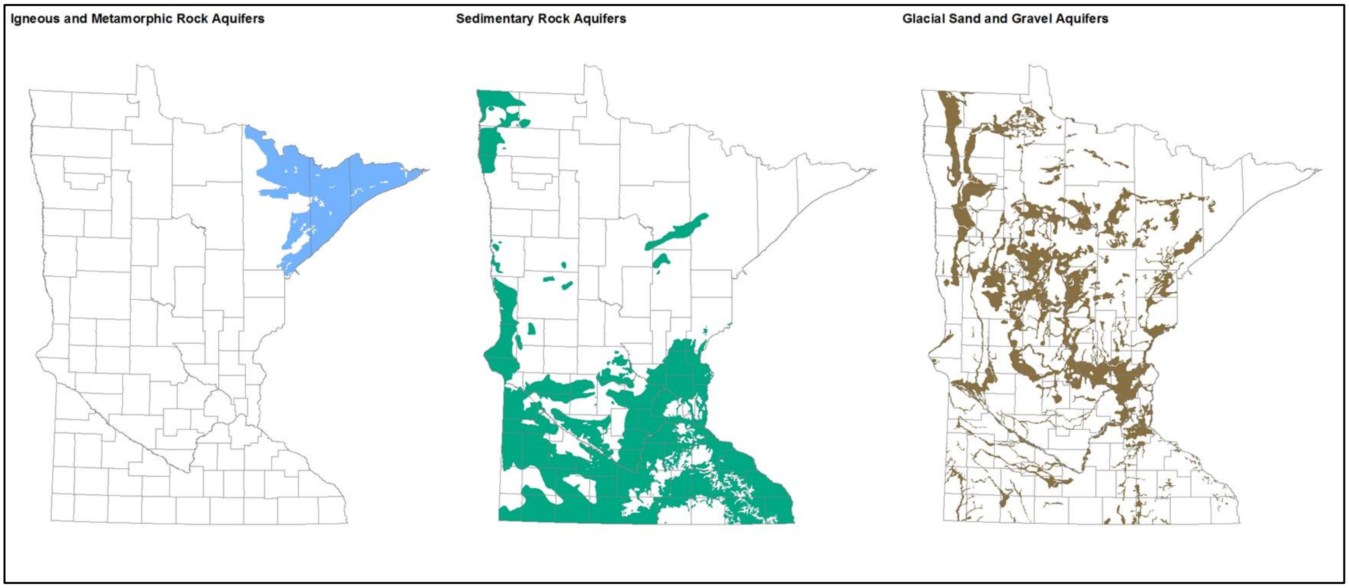



**Figure 26: Minnesota's three basic types of aquifers (MPCA, 2005).**

This region contains four main types of aquifers, including Quaternary aquifers: buried sand and gravel, surficial sand and gravel aquifers, and underlying bedrock aquifers: Precambrian aquifers, and Cretaceous aquifers. These four aquifers are vital groundwater sources. The buried sand and gravel aquifers include the Quaternary Buried Artesian Aquifer (QBAA), the Quaternary Buried Unconfined Aquifer, and the Quaternary Buried Undifferentiated Aquifer. It is from these aquifers that the majority of wells in this region of Minnesota yield the greatest amount of groundwater (MPCA, 1999a). 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. For the Mississippi River-Headwaters Watershed, the QWTA and QBAA aquifers are the primary sources for groundwater withdrawal with at least 40 and 35%, respectively.

# 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 DNR 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, 2015d).

Since bedrock aquifers are typically covered with thick till, they would normally be 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 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 Mississippi River-Headwaters 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 coarse-scale planning tool. According to this data, the Mississippi River-Headwaters Watershed is estimated to have primarily high to highest contamination susceptibility (Figure 27) (Porcher, 1989).

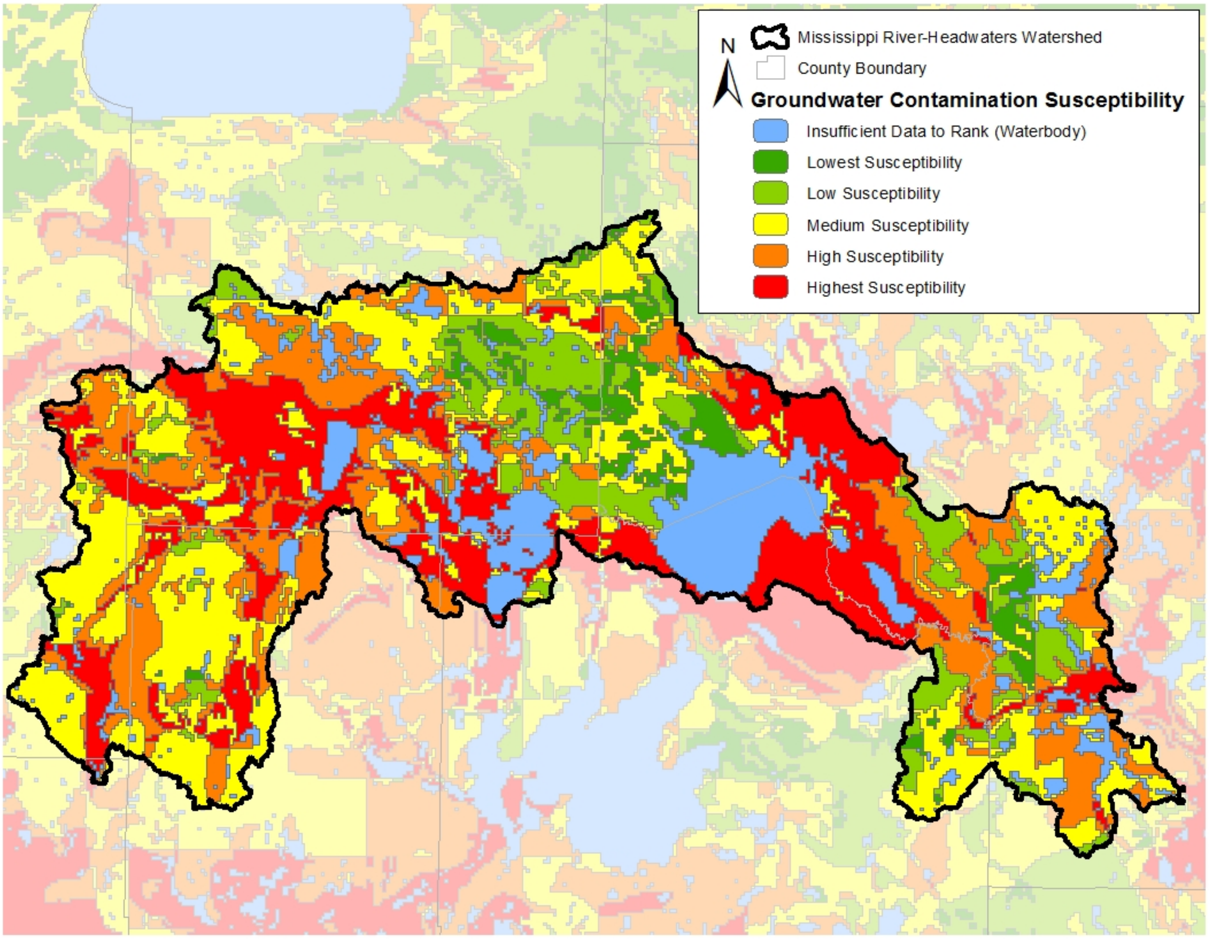



**Figure 27: Groundwater contamination susceptibility for the Mississippi River-Headwaters Watershed (GIS Source: MPCA, 1989).**

# Groundwater provinces

The Mississippi River-Headwaters falls within one of Minnesota's six Groundwater Provinces: the Central Province (Figure 28), which is characterized by "sand aquifers in generally thick sandy and clayey glacial drift overlying Precambrian and Cretaceous bedrock" (MNDNR, 2001). As discussed, this province's water sources are made up of Precambrian bedrock, some Cretaceous shale and sandstone in limited areas, and overlying sandy unconsolidated sediments.

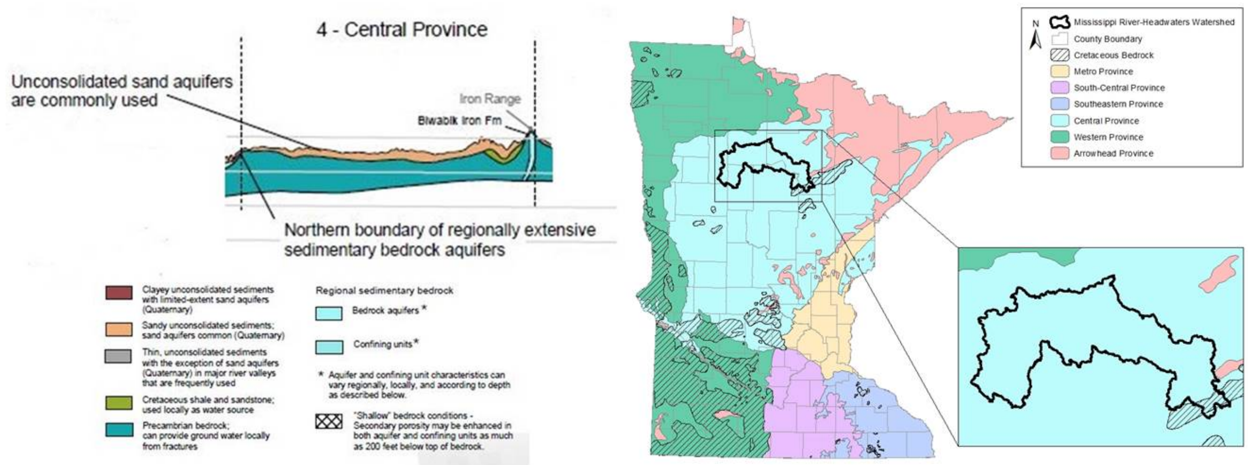



**Figure 28: Central Province generalized cross section (Source: MNDNR, 2001).**

# 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 USGS 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 28). 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 Mississippi River-Headwaters Watershed, the average annual potential recharge rate to surficial materials ranges from 0.4 to 13.4 inches per year, with an average of 5.2 inches per year (Figure 29). The statewide average potential recharge is estimated to be 4 inches per year with 85% of all recharge ranging from 3 to 8 inches per year (Figure 30). When compared to the statewide average potential recharge (Figure 31), the Mississippi River-Headwaters Watershed receives a higher percent of grid cells on average of potential recharge, mostly likely attributed to the variability of the surficial sediment distribution of the area.

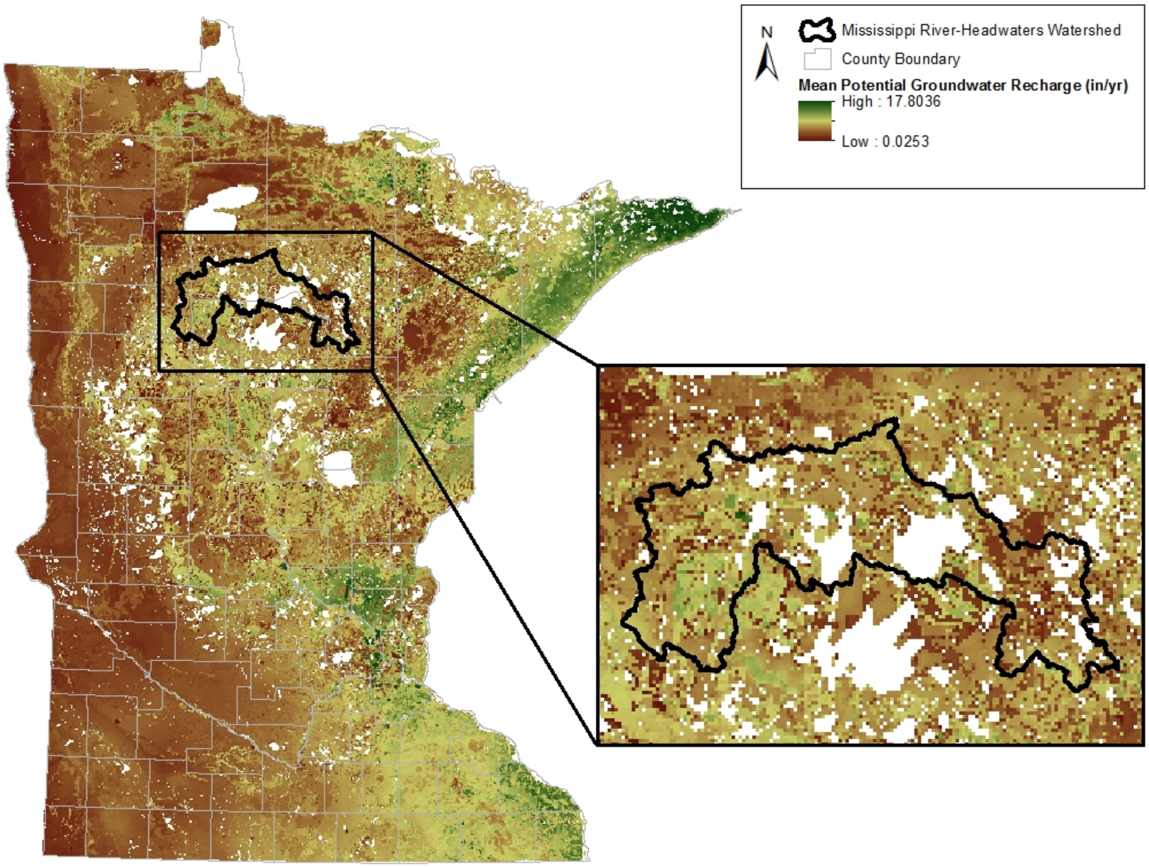



**Figure 29: Average annual potential recharge rate to surficial materials in Mississippi River-Headwaters Watershed (1996-2010).**

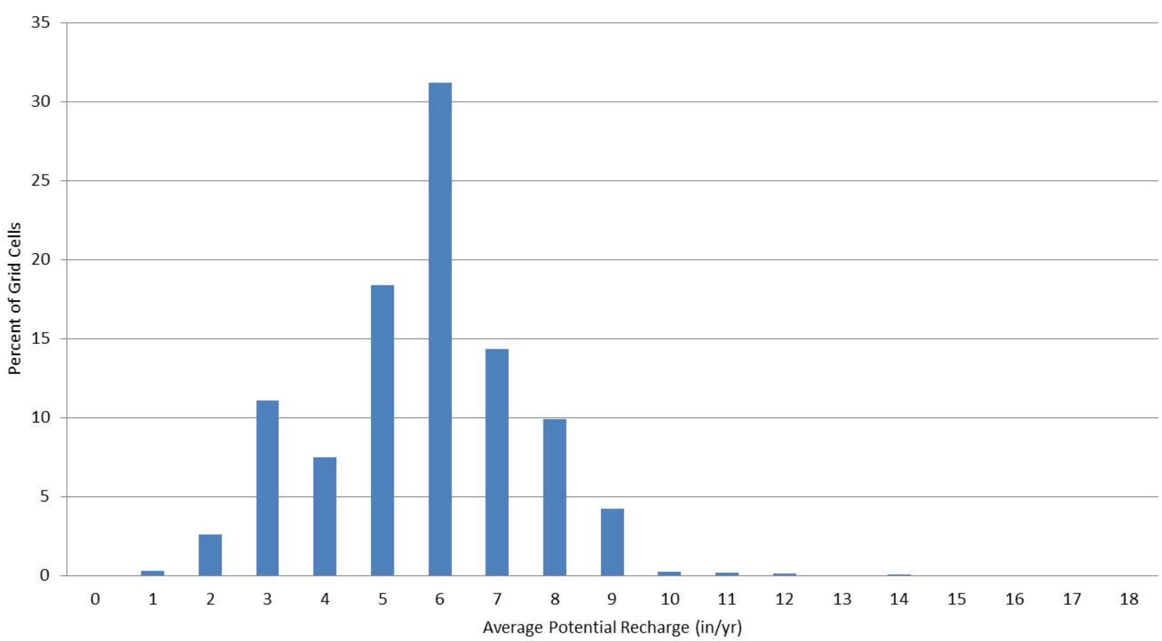



**Figure 30: Average annual potential recharge rate percent of grid cells in the Mississippi River-Headwaters Watershed (1996-2010).**

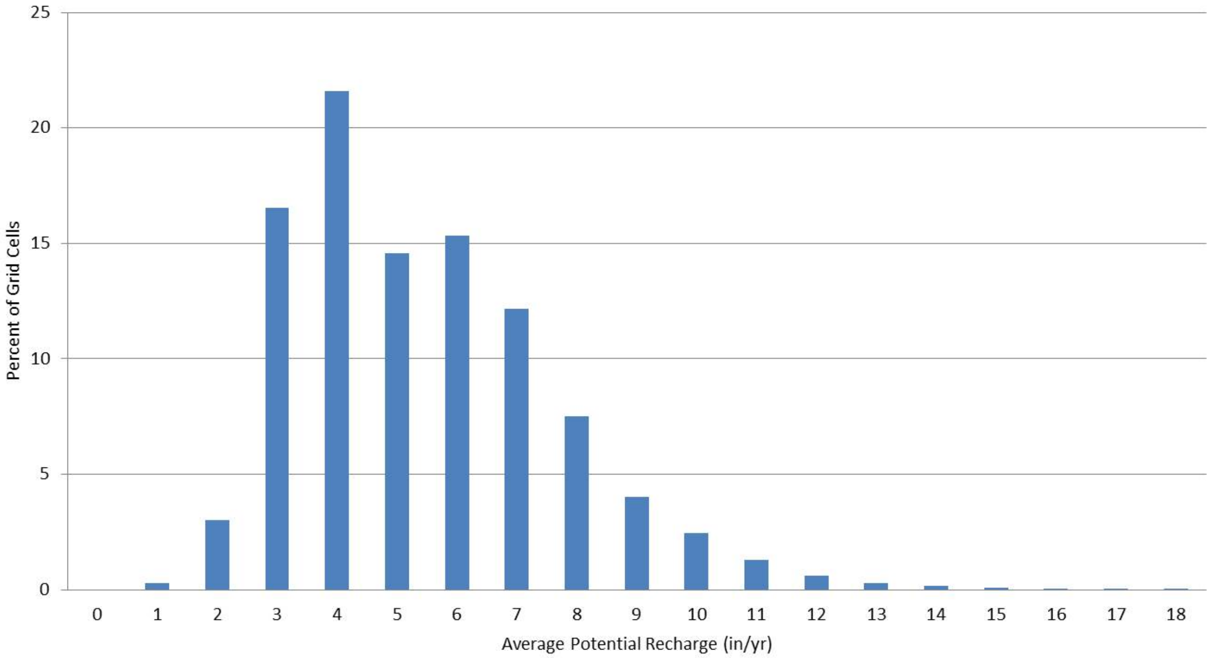



**Figure 31: Average annual potential recharge rate percent of grid cells statewide (1996-2010).**

# V. Groundwater quality

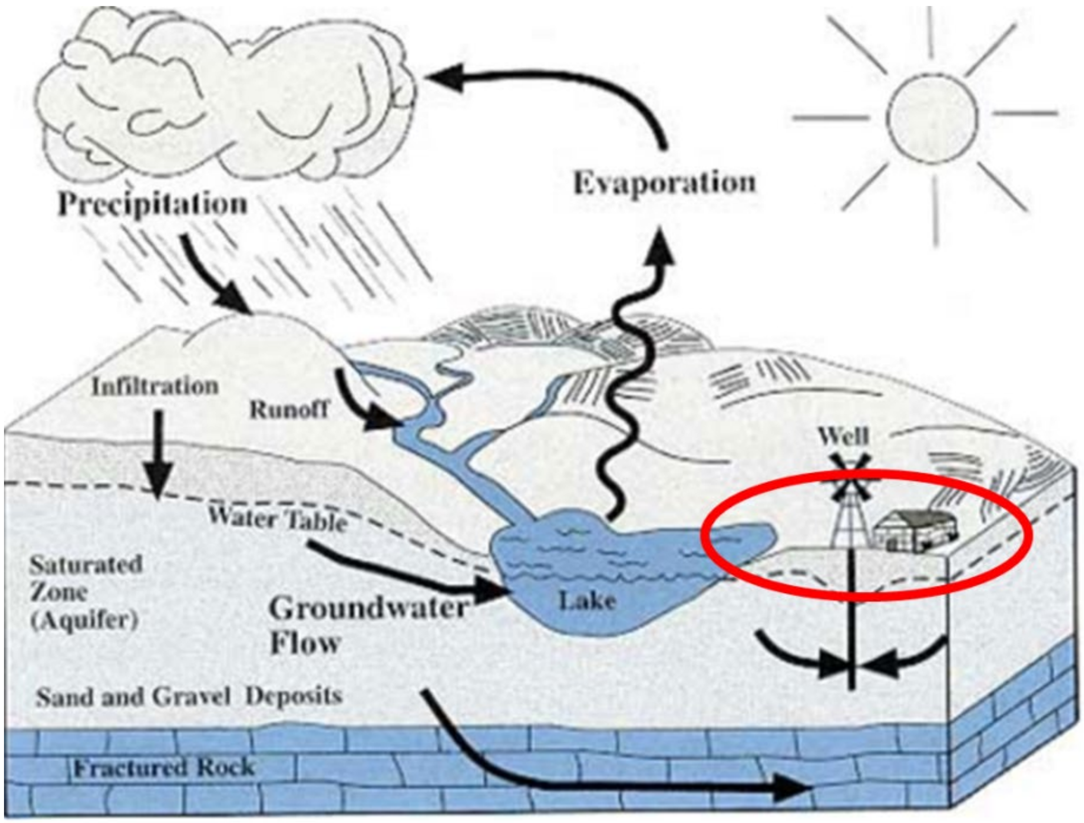



**Figure 32: Groundwater quality within the hydrologic cycle.**

## 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 MPCA'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.

There are currently 19 MPCA Ambient Groundwater Monitoring well (18 monitoring, 1 domestic) within the Mississippi River-Headwaters Watershed. Figure 33 displays the locations of ambient groundwater wells within and around the specified watershed. Data collection ranged from 2004 to 2015; however, the majority of the wells were added in 2010. Therefore, data analysis was conducted on the current MPCA Ambient Groundwater Wells from 2010 to 2015.

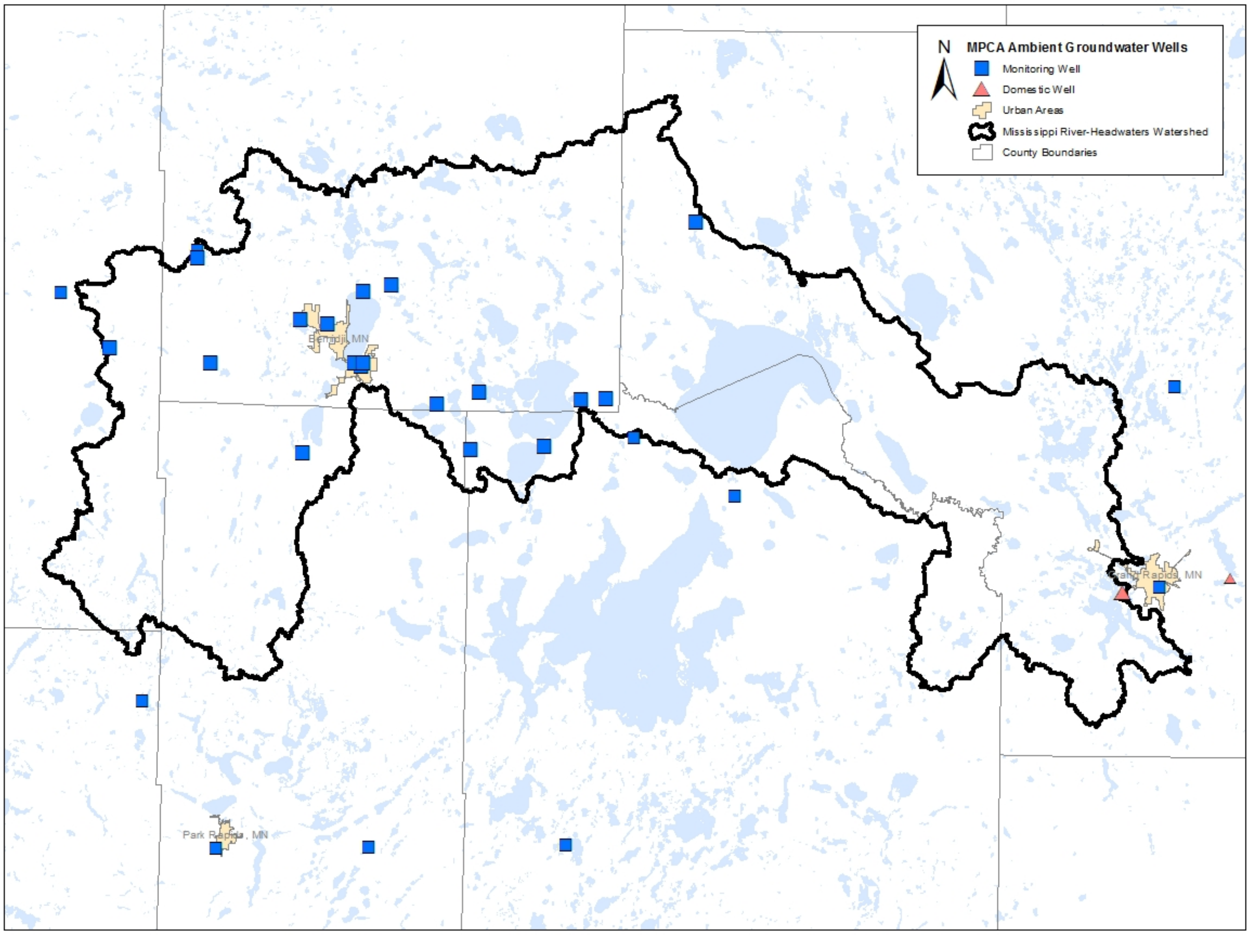



**Figure 33: MPCA ambient groundwater monitoring well locations near the Mississippi River-Headwaters Watershed (2015).**

The three chemicals focused on for the ambient groundwater quality data were arsenic, nitrate, and chloride for frequency and exceedances in drinking water standards (Figure 34). Arsenic is primarily naturally forming from the weathering of mineral deposits, but it can be dangerous for human consumption due to its toxicity. Wells with a detection frequency of arsenic within the Mississippi River-Headwaters Watershed was reported in 59.8% of wells from 2010 to 2015.The MCL for arsenic in drinking water was set by the U.S. Environmental Protection Agency (EPA) as 10 micrograms per liter. Only one well within the watershed has consistently exceeded the MCL during this time period, which is most likely attributed to the presence of clay deposits, resulting in low dissolved oxygen levels. Nitrate, a form of nitrogen, has a MCL of 10 milligrams per liter. This limit is primarily set for the risk of methemoglobinemia (blue-baby syndrome) in infants under the age of six months. Nitrate detection frequency occurred 70.6% of the time, within one exceedance of the MCL in one well near Bemidji in 2010. Chloride has become an increasing concern in developed areas where salt is used as a deicing agent, which may cause higher chloride concentrations and can affect the taste of drinking water (Kroening & Ferrey, 2013). Chloride has a secondary MCL set as 250 milligrams per liter for taste. Chloride detection frequency within the watershed was 92.2% of the time with one occurrence exceeding the secondary limit in one well near Bemidji in 2014.

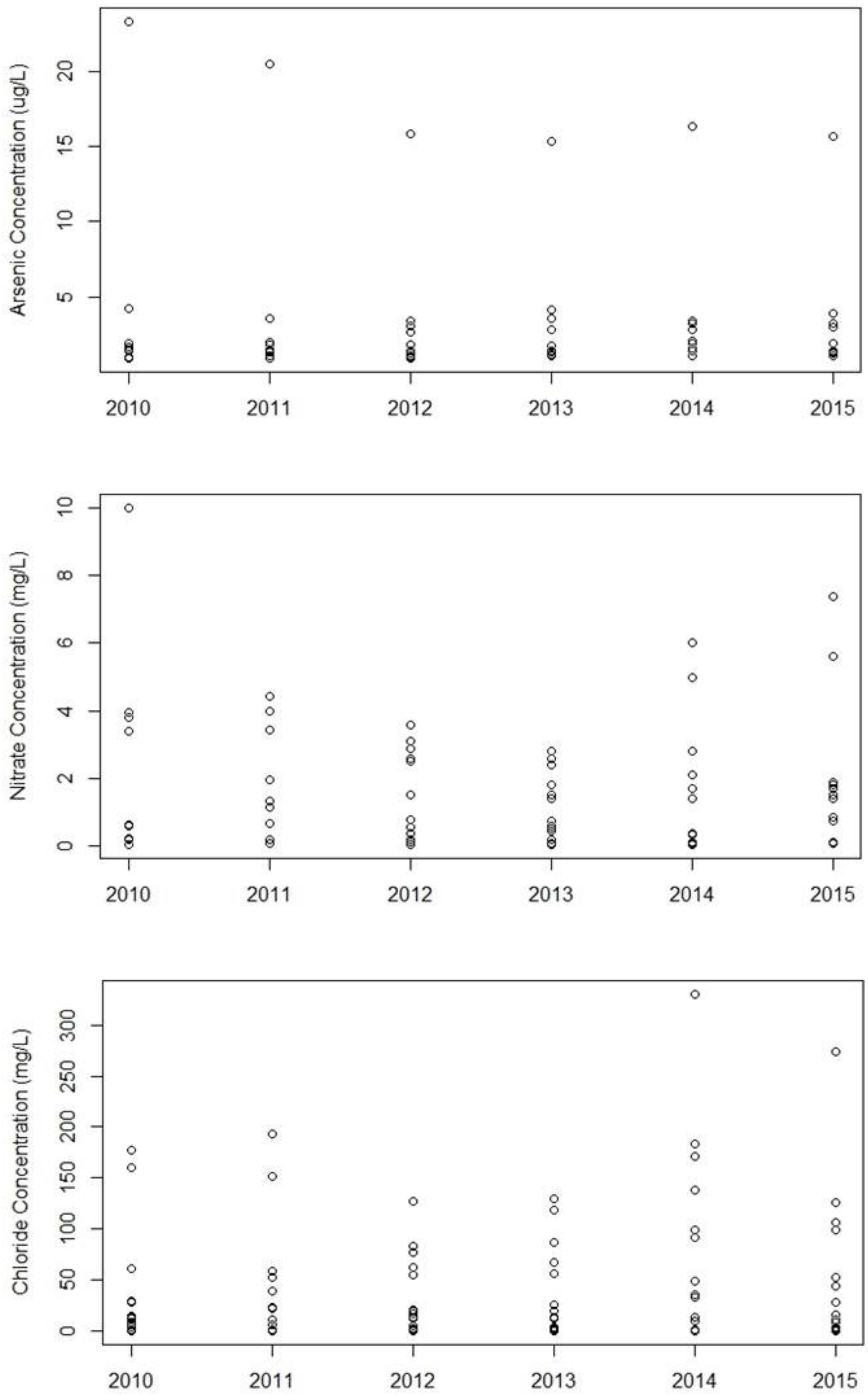



**Figure 34: Ambient groundwater monitoring detections of arsenic, nitrate and chloride in samples from the Mississippi River – Headwaters watershed (2010-2015).**

## 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 Mississippi River-Headwaters Watershed lies within three of those regions, with the upper west half within the Northwest Region, the upper eastern half within the Northeast Region, and the lower end of the watershed within the North Central Region (Figure 35). Due to the small portion of the watershed within the North Central Region, this report will focus on the findings from the Northeast and Northwest Hydrogeologic Regions.

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 criteria in arsenic, beryllium, boron, manganese and selenium (MPCA, 1999a). The groundwater quality in the Northwest Region had a tendency of greater concentrations of most chemicals when compared to similar aquifers statewide. Exceedances of drinking water criteria were found in arsenic, barium, boron, manganese, molybdenum, nitrate and selenium (MPCA, 1999b). The exceedances identified were contributed to natural sources, such as geology, residence times and well construction. Volatile organic compounds were also detected in both regions with the most commonly detected compounds associated with fuel oils, gasoline and well disinfection (MPCA, 1999a; MPCA, 1999b).

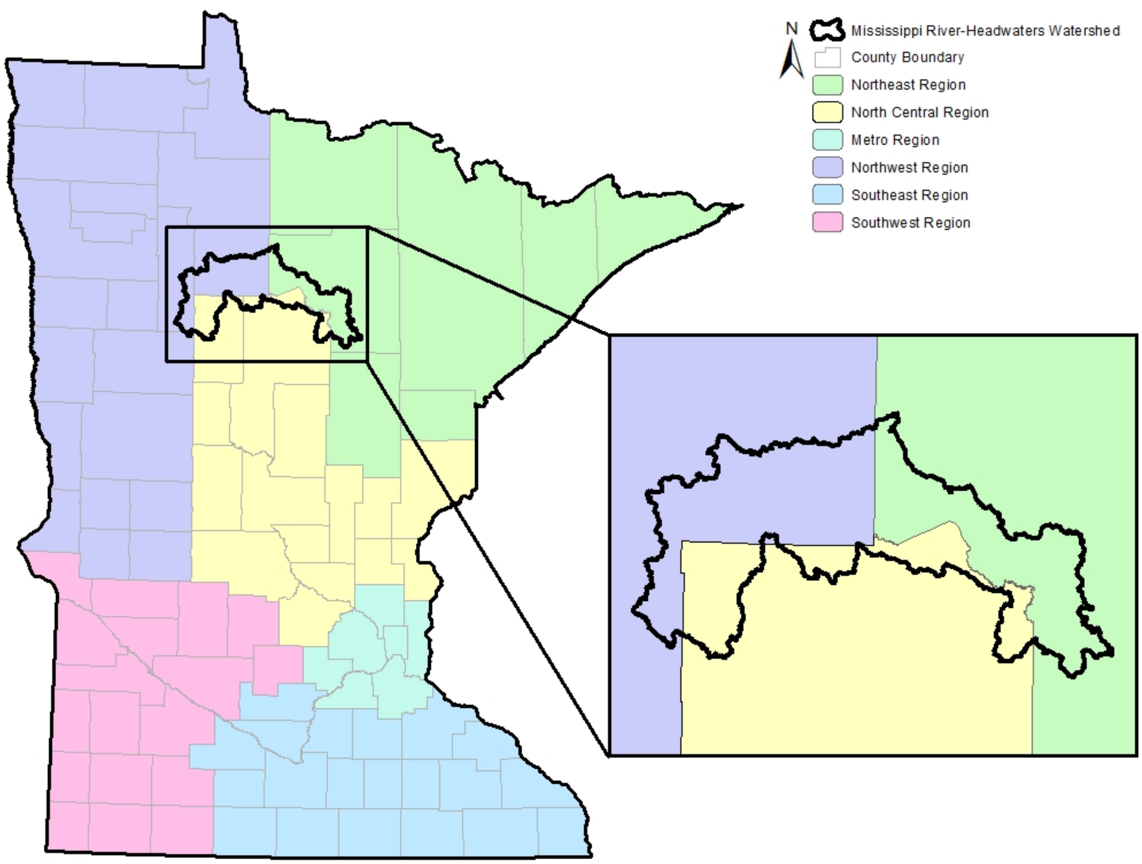



**Figure 35: Mississippi River-Headwaters Watershed within the MPCA hydrogeologic regions.**

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, consisting of 10 regional water quality monitoring networks that are referred to as Pesticide Monitoring Regions (PMRs), which are based on agricultural practices and hydrologic/geologic characteristics (MDA, 2015). The Mississippi River-Headwaters Watershed lies within the regional water quality monitoring networks for Region 2 (PMR 2) and Region 4 (PMR 4). PMR 2 is also referred to as the North Central Region and PMR4 is referred to as the Central Sands. The majority of the watershed is within PMR 2, with only small areas in the lower and southwest reaches of the watershed within PMR 4.

The Monitoring and Assessment Unit (MAU) of the MDA sampled 166 sites throughout Minnesota for pesticides in groundwater in 2015. However, PMR 2 is not monitored for groundwater due to the minimal agricultural chemicals usage in heavily forested areas (MDA, 2015). Although there are no groundwater sampling sites located within the Mississippi River-Headwaters Watershed, some wells throughout the state detected up to five common detection pesticides or degradates in 2014 (Figure 36). These detections included acetochlor, alachlor, atrazine, metolachlor and metribuzin, but none that exceeded drinking water standards for human consumption (MDA, 2015).

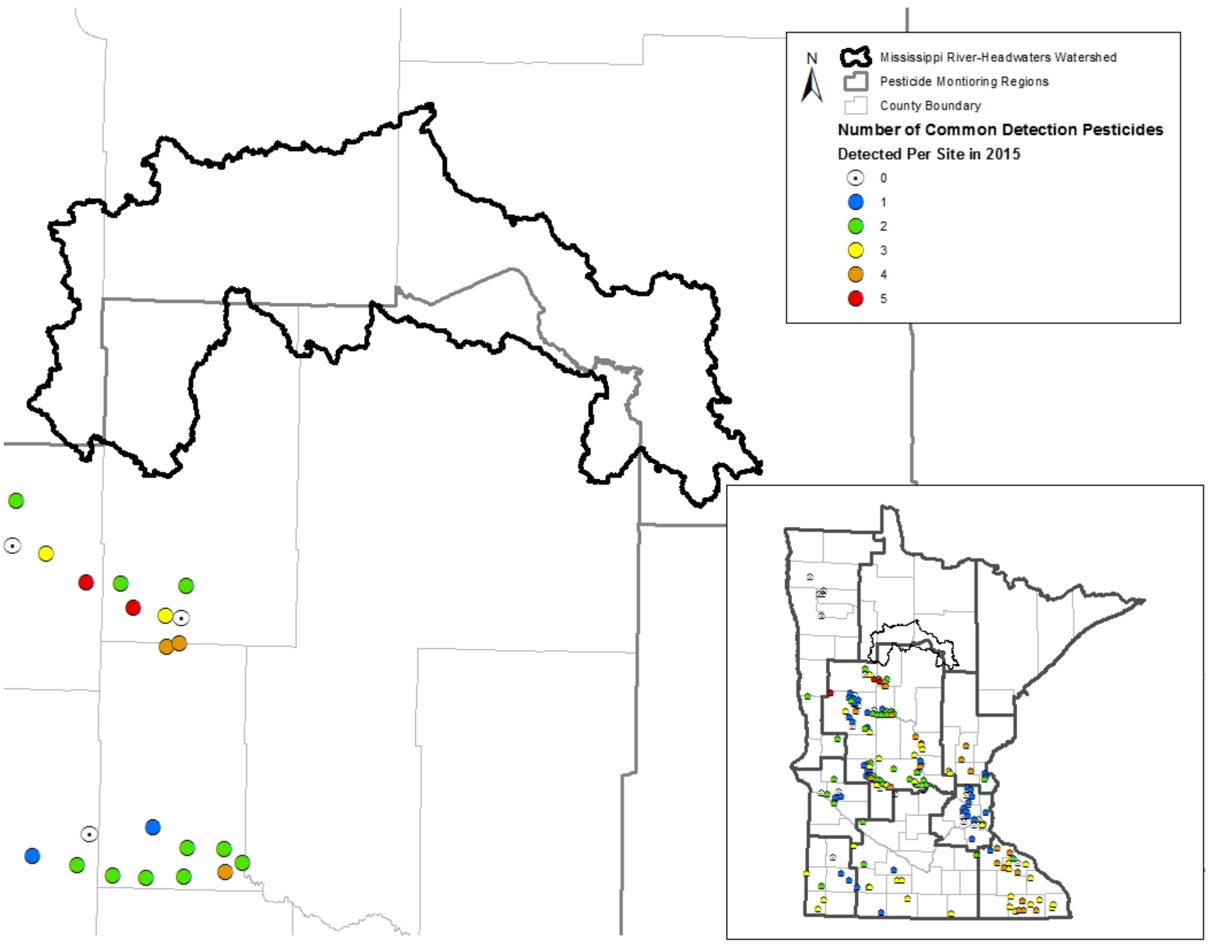



**Figure 36: MDA pesticide detections and the Mississippi River-Headwaters Watershed (Source: MDA, 2015).**

Another source of information on groundwater quality comes from the Minnesota Department of Health (MDH). Mandatory testing for arsenic of all newly constructed wells has found that 10.7% of all wells installed from 2008 to 2015 have arsenic levels above the MCL for drinking water (MDH, 2015). In the Mississippi River-Headwaters Watershed, the majority of new wells are within the water quality standards for arsenic levels, but there are 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 5 to greater than 20% exceedances. By county, the percentages of wells identified with concentrations exceeding the MCL are as follows: Clearwater (10.5%), Beltrami (10.2%), Itasca (5.4%), Cass (4.2%) and Hubbard (1.9%) (MDH, 2015) (Figure 37). Becker County has 25.3% of wells within the county that exceed the MCL, but the area of the county within the watershed is minimal and would inaccurately represent the watershed. For more information on arsenic in private wells, please refer to the MDH's website:
http://www.health.state.mn.us/divs/eh/wells/waterquality/arsenic.html.

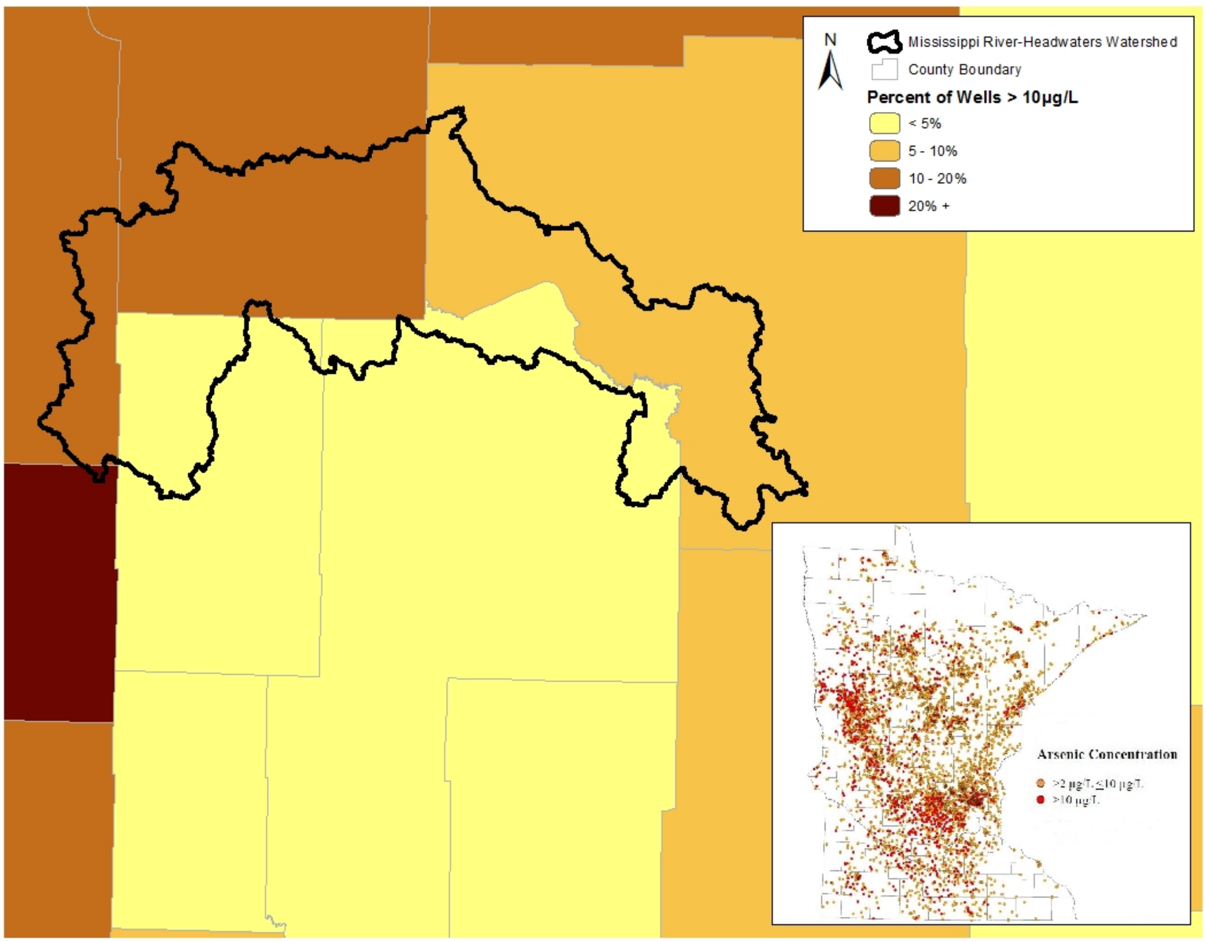



**Figure 37: Percent wells with arsenic occurrence greater than the MCL per county for the Mississippi River-Headwaters Watershed (2008-2015) (Source: MDH, 2015)**

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 Mississippi River-Headwaters Watershed, there are currently 1,723 sites identified by WIMN: 499 hazardous waste sites, 497 tanks and leaks, 460 water quality sites, 132 investigation and cleanup sites, 84 feedlots sites, 28 air quality sites, and 23 solid waste sites (Figure 38). For more information regarding WIMN, refer to the MPCA webpage at [http://www.pca.state.mn.us/index.php/data/wimn-whats-in-my-neighborhood/whats-in-my-neighborhood.html](http://www.pca.state.mn.us/index.php/data/wimn-whats-in-my-neighborhood/whats-in-my-neighborhood.html).

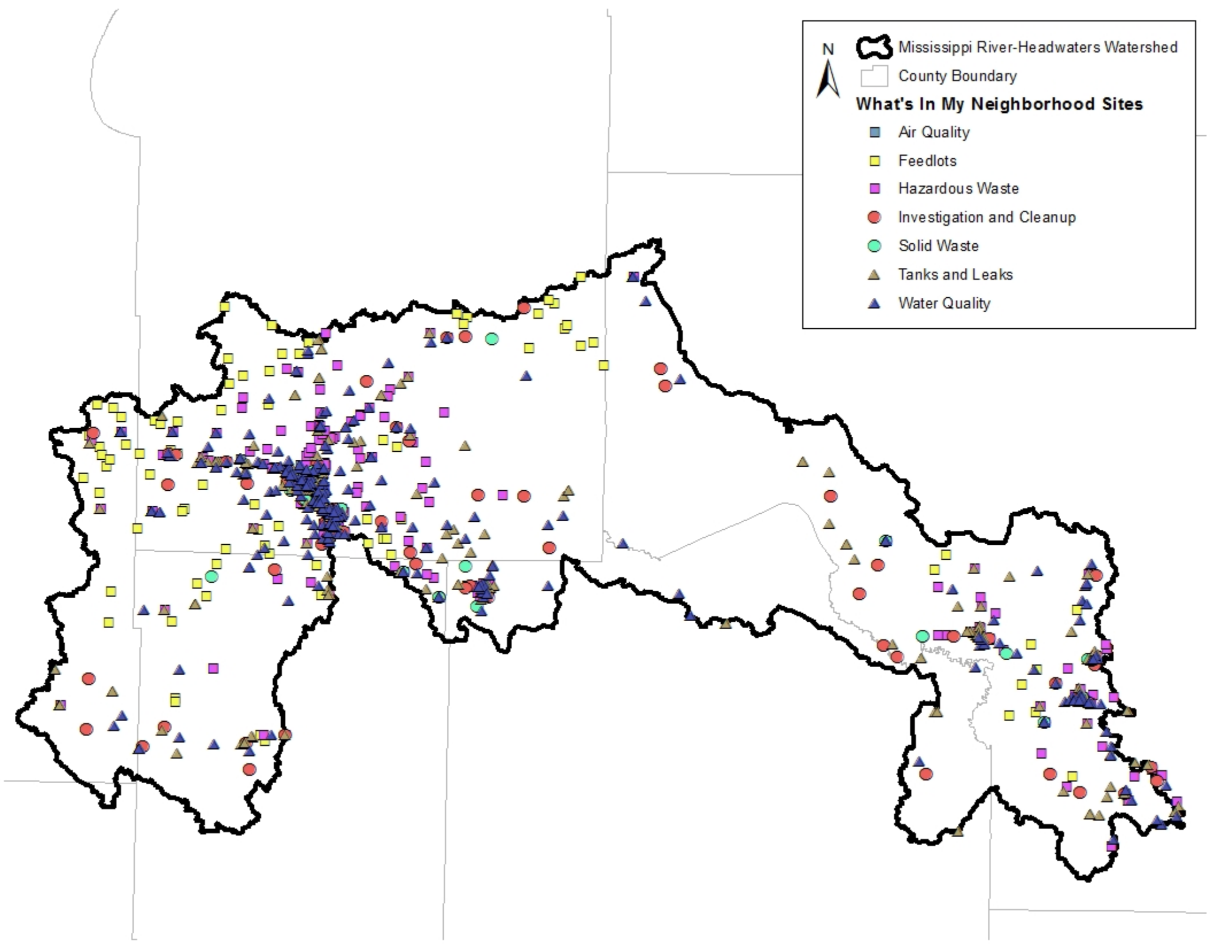



**Figure 38: "What's In My Neighborhood?" site programs and locations for the Mississippi River-Headwaters Watershed.**

# VI. Groundwater quantity

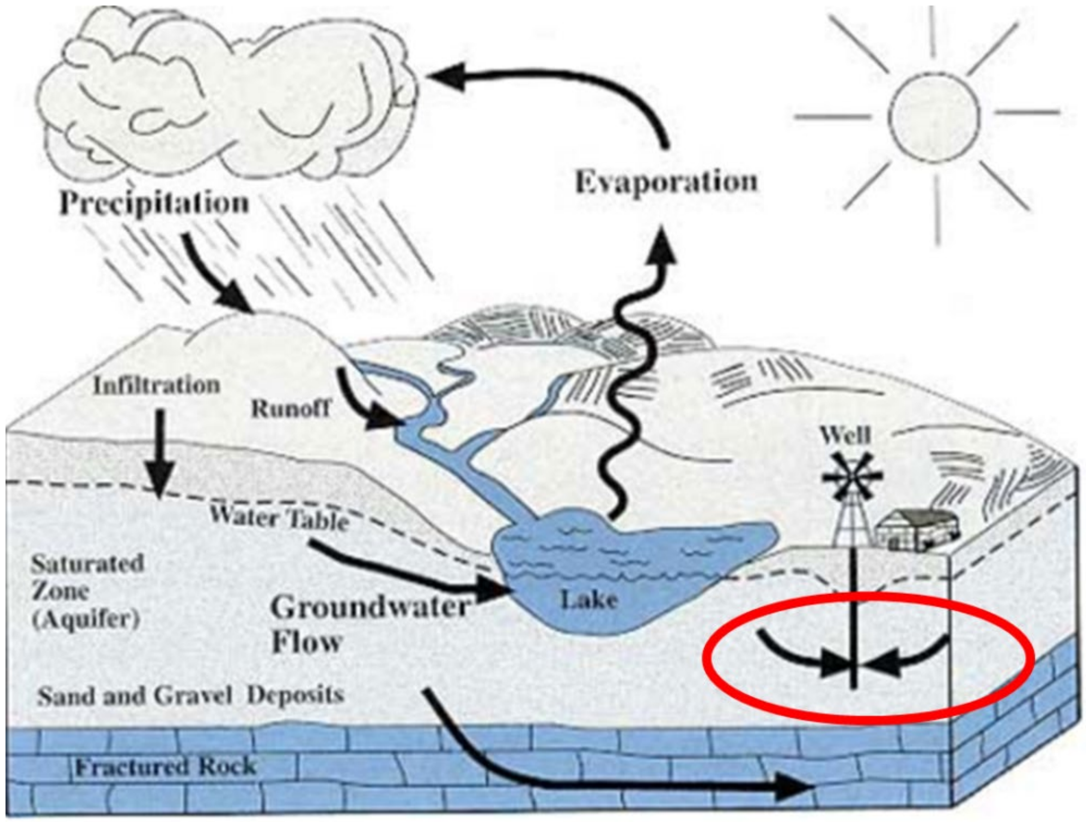



**Figure 39: Groundwater quantity within the hydrologic cycle.**

## Groundwater and surface water withdrawals

The MNDNR permits all high capacity water withdrawals where the pumped volume exceeds 10,000 gallons per day or one million gallons per year. Permit holders are required to track water use and report back to the MNDNR annually. 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, 2015e). According to the most recent USGS site-specific water-use data system (SWUDS), in 2013 the withdrawals within the Mississippi River-Headwaters Watershed are primarily utilized for power generation (98.3%). The remaining withdrawals include: water supply (municipal and private) (1.1%), non-crop irrigation (0.21%), agricultural irrigation (0.14%), special categories including pollution containment, dust control, construction non-dewatering and others (0.12%), industrial processing (0.07%), water level maintenance (0.01%) and heating and cooling purposes (0.03%) (Figure 40). From 1994 to 2013, withdrawals associated with industrial processing have increased significantly (p=0.001), while non-crop irrigation and water supply have also slightly increased (p=0.05). All other categories have remained relatively constant over this time period.

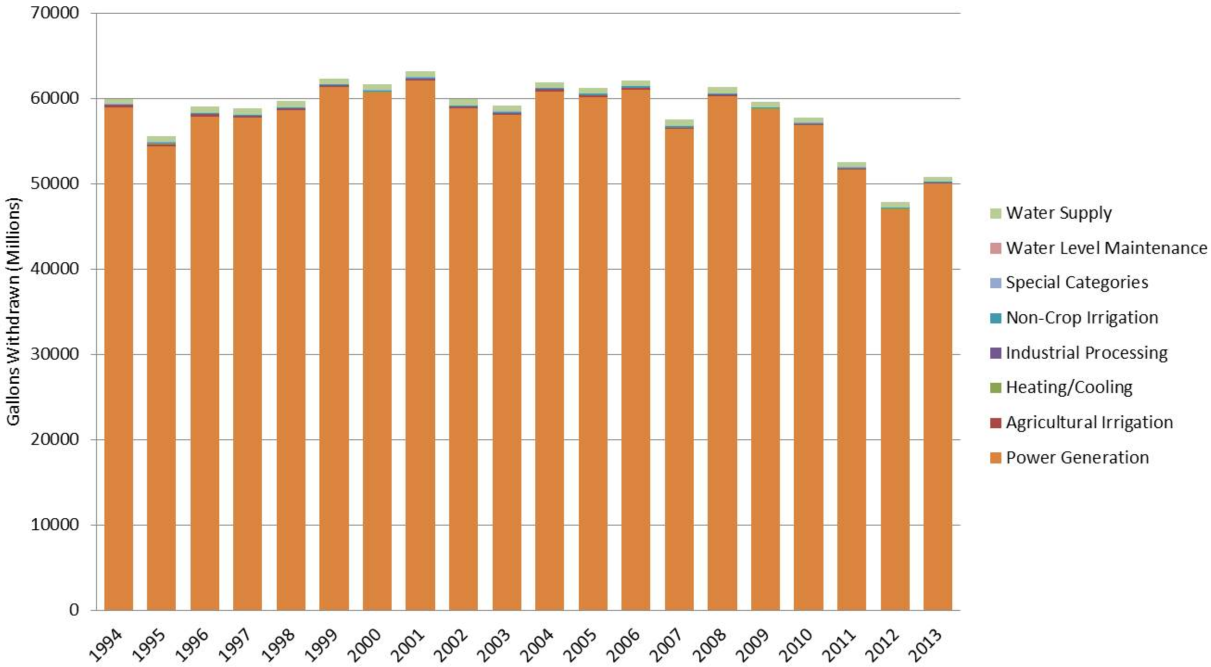



**Figure 40: Groundwater and surface water permitted withdrawals by category in the Mississippi River-Headwaters Watershed (1994-2013).**

Figure 41 displays total high capacity groundwater and surface water withdrawal locations within the watershed with active permit status in 2013. During 1994 to 2013, groundwater withdrawals within the Mississippi River-Headwaters Watershed exhibit a decreasing withdrawal trend (p=0.01) (Figure 42), and while surface water withdrawals appears to be decreasing, there is no statistically significant trend (Figure 43). Quaternary water table aquifer (QWTA) withdrawals, which account for approximately 21% of all groundwater withdrawals, emulate the overall groundwater withdrawal trend with a slight decrease over this time period (p=0.1) (Figure 44).

The change in high capacity 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 43, pumping a reported amount of approximately 1.0 billion gallons of water, while in 2013, the number of quantities reported with active permits increased to 66, but amount of water pumped decreased to 902.1 million gallons of water. For surface water withdrawals in 1994, the number of active permit holders with reported quantities was 19 and withdrew 58.9 billion gallons, while in 2013, the number of active permit holders increased to 25, but the amount withdrawn decreased to 49.9 billion gallons for the year.

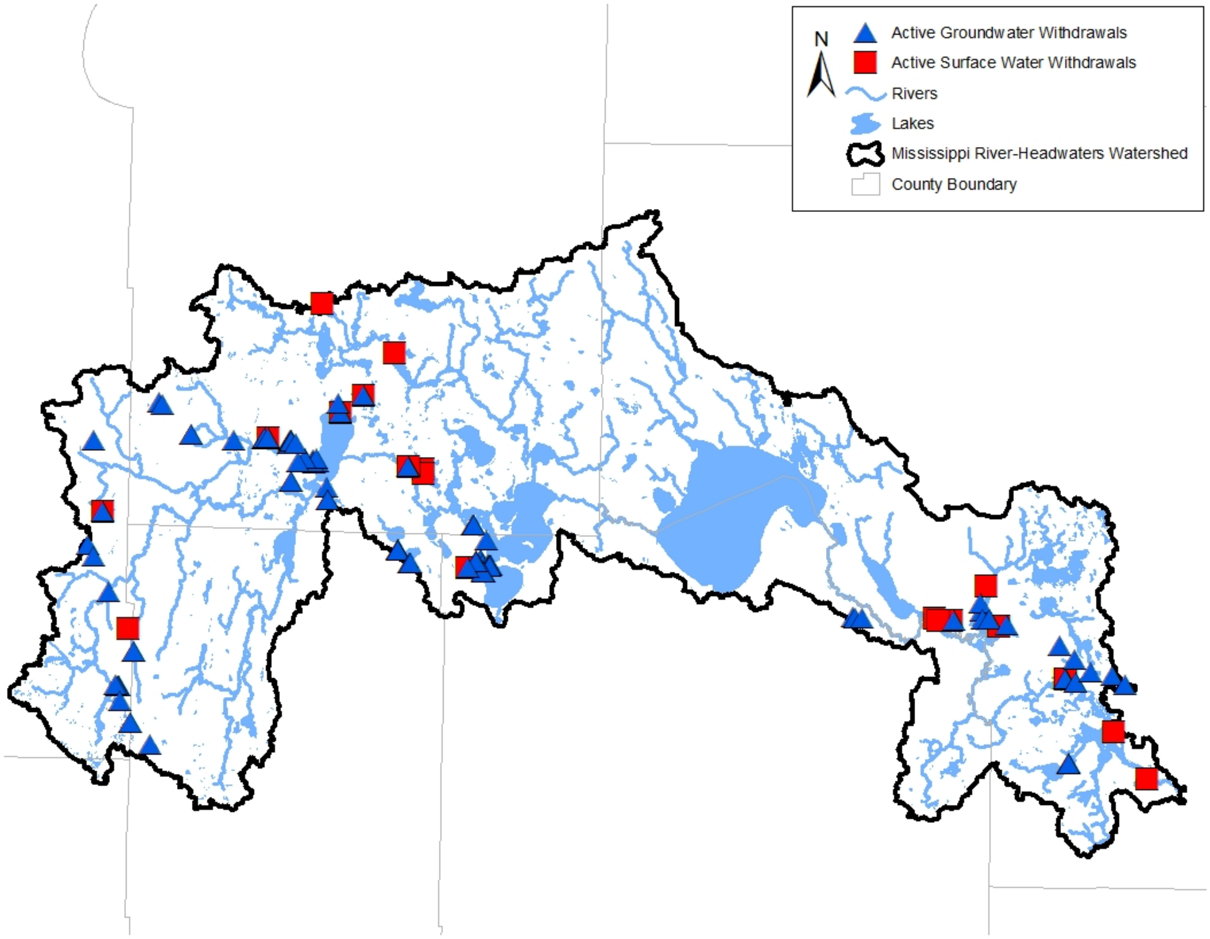



**Figure 41: Locations of active status permitted high capacity withdrawals in 2013 within the Mississippi River-Headwaters Watershed.**

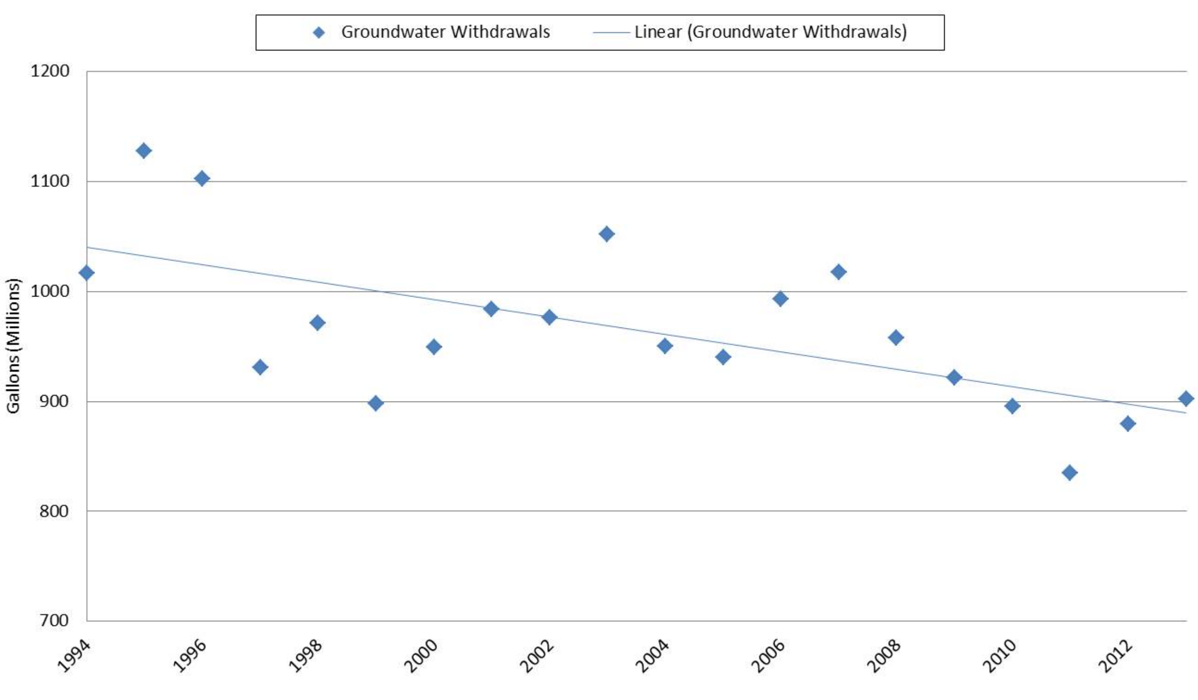



**Figure 42: Total annual groundwater withdrawals in the Mississippi River-Headwaters Watershed (1994-2013).**

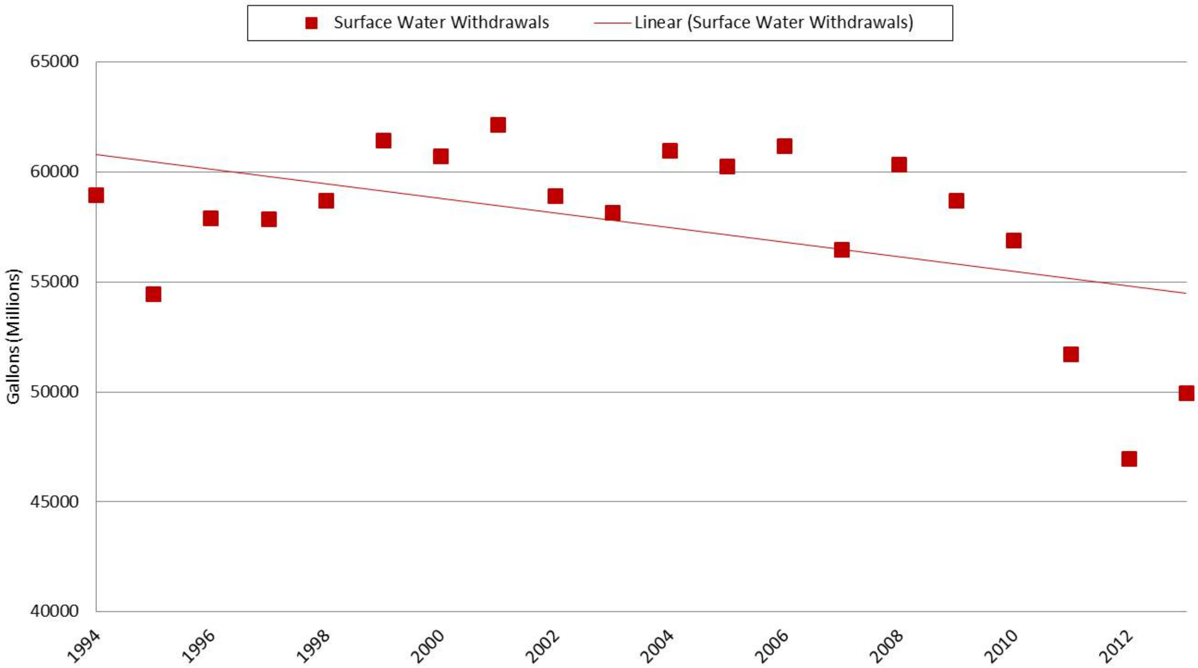



**Figure 43: Total annual surface water withdrawals in the Mississippi River-Headwaters Watershed (1994-2013).**

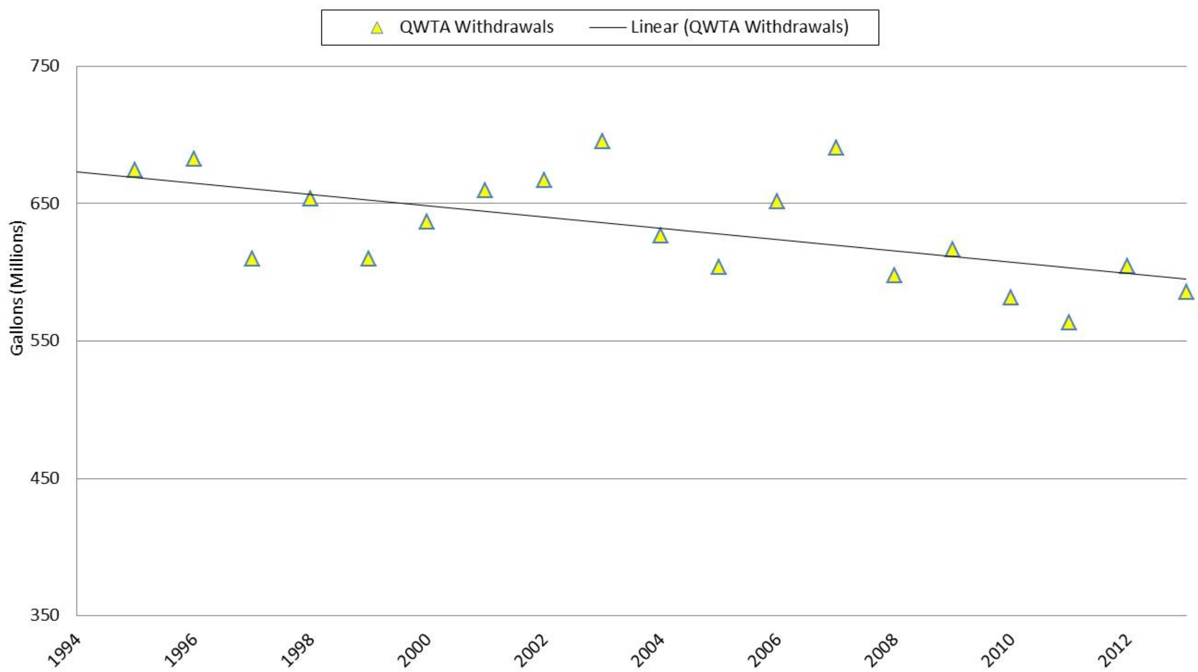



**Figure 44: Total annual quaternary water table withdrawals in the Mississippi River-Headwaters Watershed (1994-2013).**

## 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.

Four MNDNR observation wells (29036, 29050, 11014 and 4025) within the Mississippi River-Headwaters Watershed were chosen based on data availability and geologic location as representative of depth to groundwater throughout the watershed (Figure 45). Depth to Water (DTW) was collected on a monthly basis and the average annual DTW was calculated.

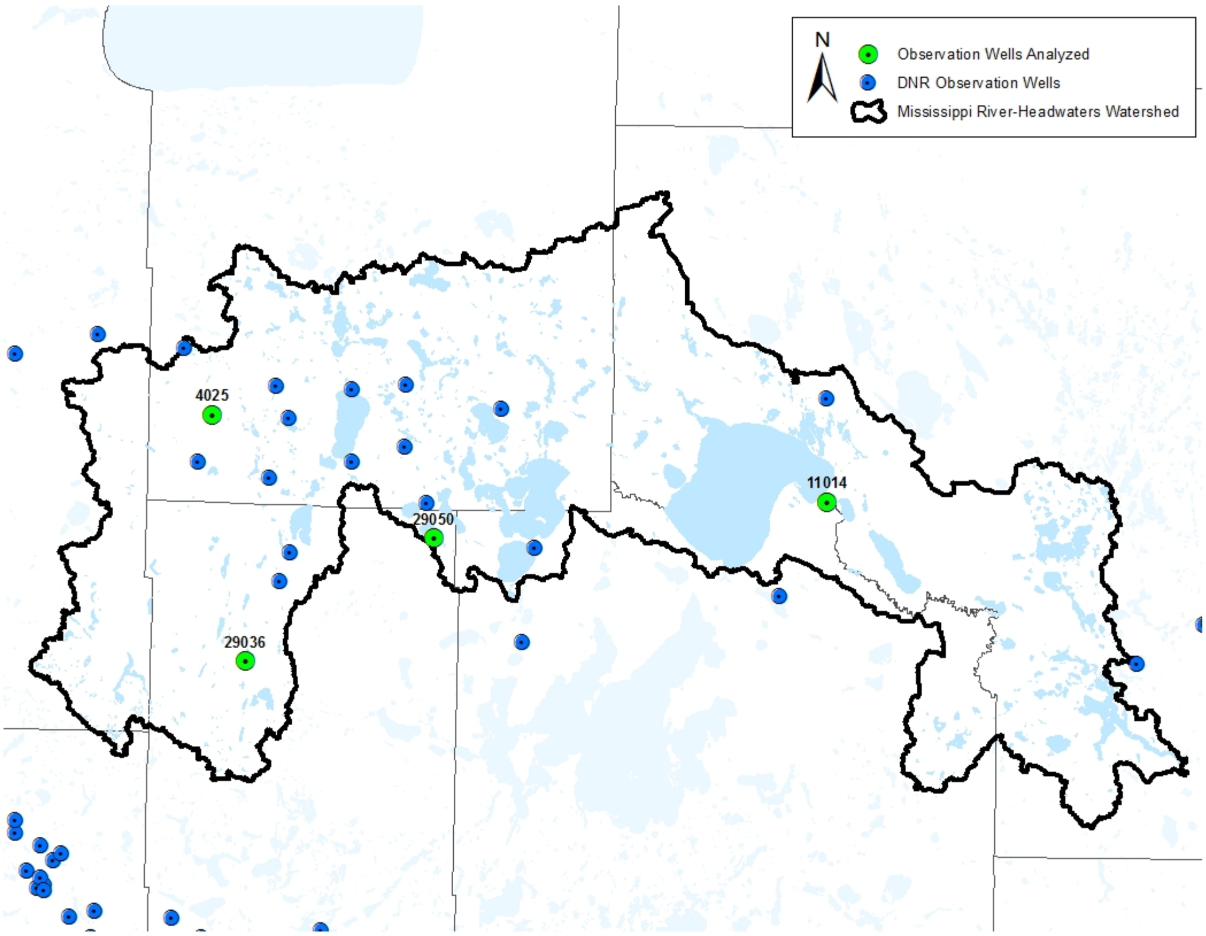



**Figure 45: MNDNR water table observation well locations within the Mississippi River-Headwaters Watershed.**

Observation well 29036 located near Laporte in the southwest area of the watershed exhibits a decreasing trend of the water table level (p=0.05) over the last 20 years (1996-2015) (Figure 46). Similarly, 29050 near Cass Lake in the central area (Figure 47) and 11014 near Bena in the eastern area (Figure 48) also exhibit a trend in decreasing water levels (p=0.1). Observation well 4025 near Solway in the northwest region displays no statistical trend in depth to groundwater on an average annual basis (Figure 49).

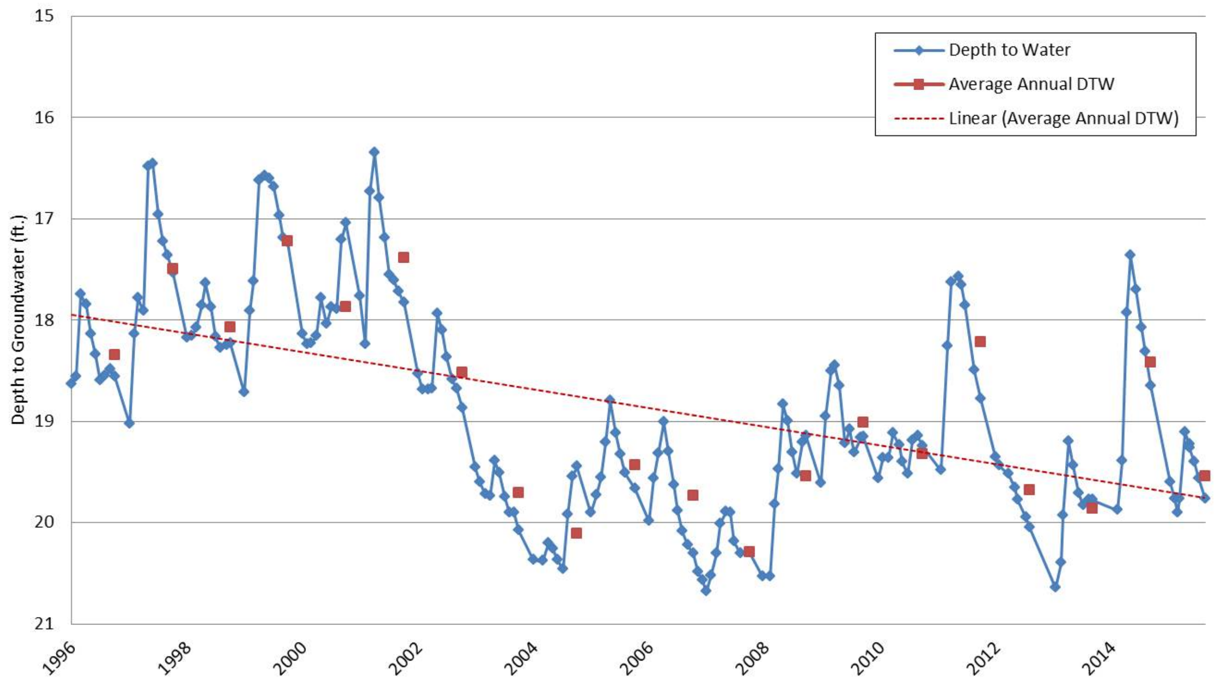



**Figure 46: Depth to groundwater for Observation Well 29036 near Laporte (1996-2015).**

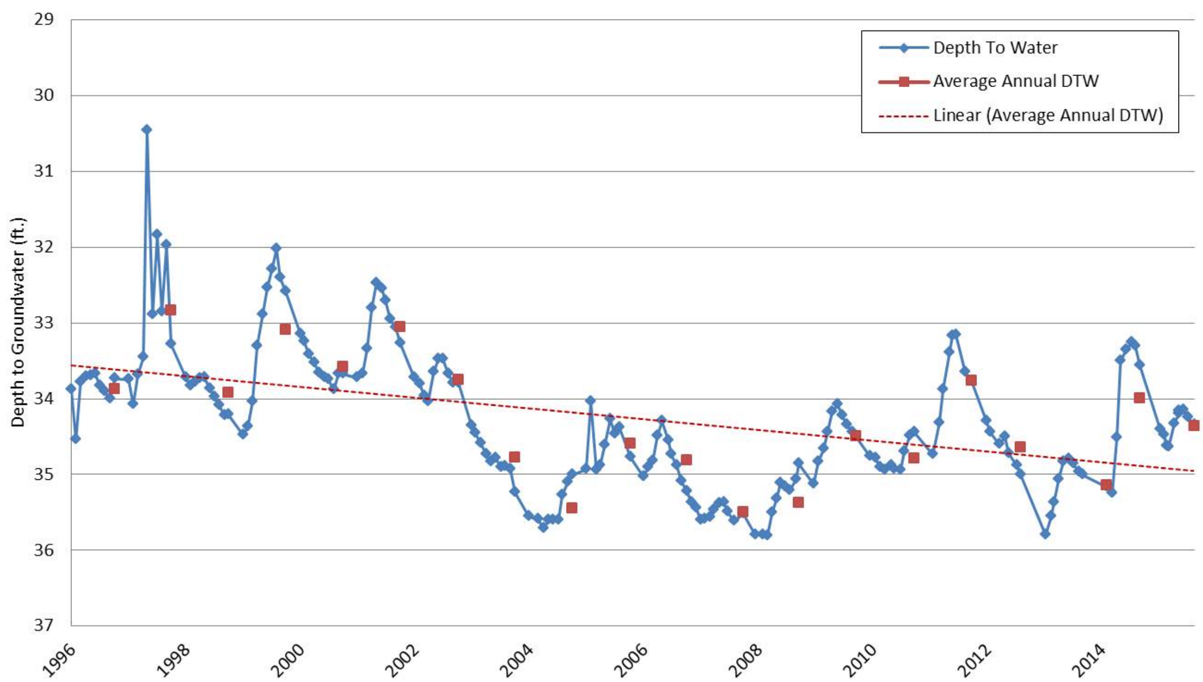



**Figure 47: Depth to groundwater for Observation Well 29050 near Cass Lake (1996-2015).**

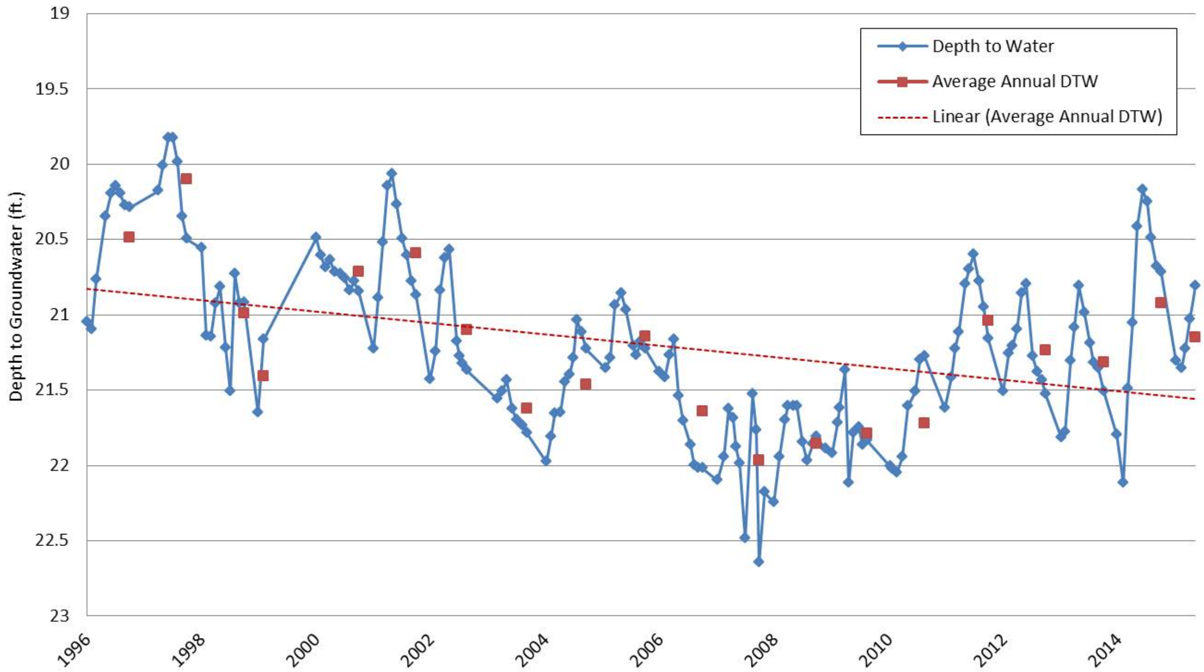



**Figure 48: Depth to Groundwater for Observation Well 34002 near Belgrade (1996-2015).**

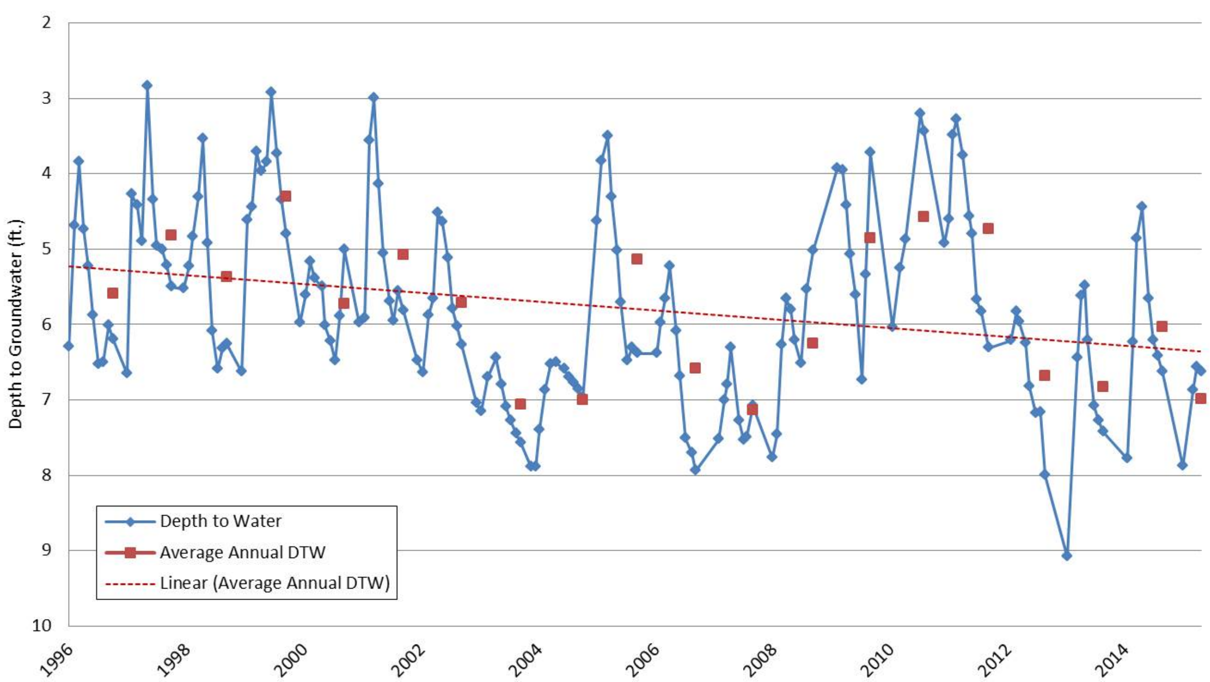



**Figure 49: Depth to groundwater for observation well 4025 near Solway (1996-2015).**

# VII. Evapotranspiration

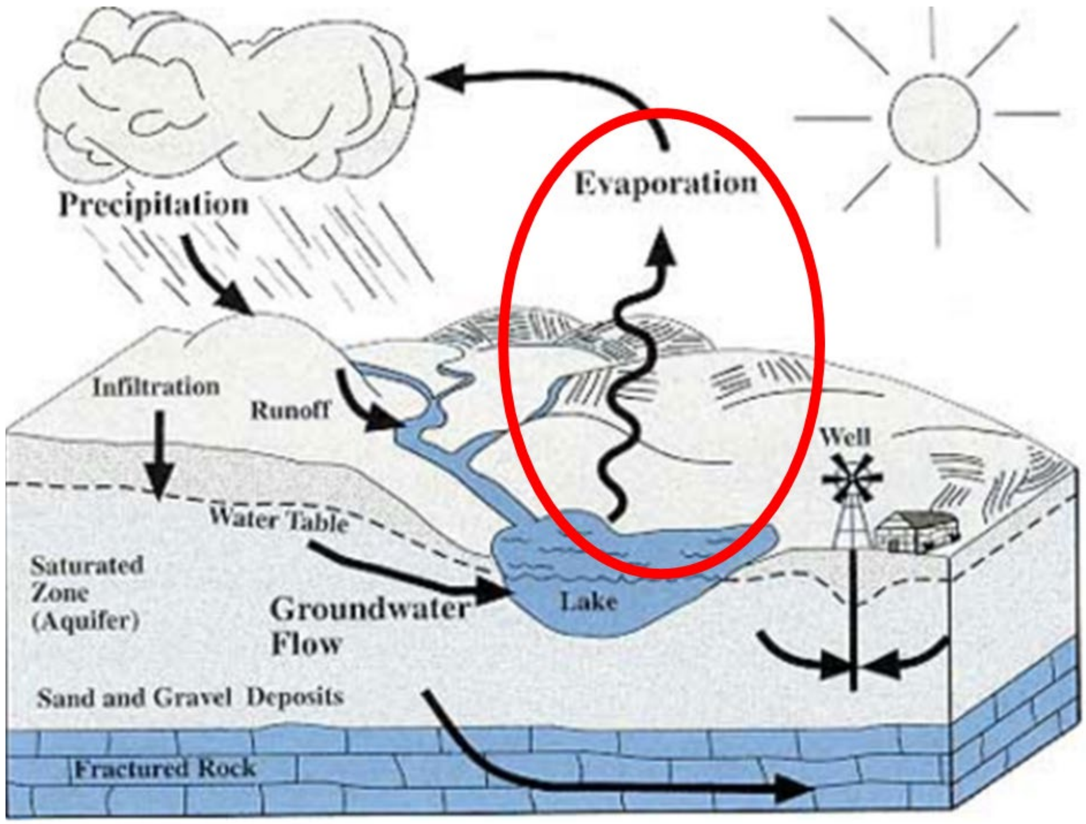



**Figure 50: Evapotranspiration within the hydrologic cycle.**

## Evapotranspiration definition

Evapotranspiration (ET) is the sum of evaporation and transpiration. ET can come from surface water bodies, the ground surface, 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 United States, 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 51 (MNDNR, 2015f).

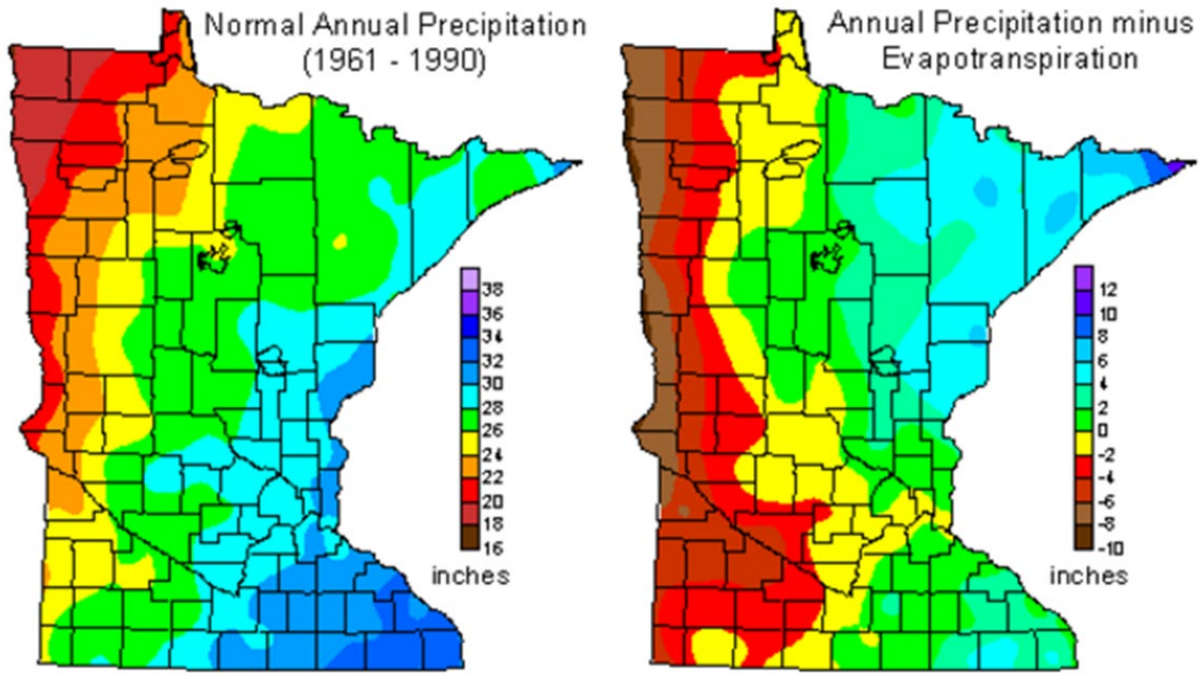



**Figure 51: Minnesota annual precipitation and precipitation minus evapotranspiration (1961-1990).**

# VIII. Conclusion: statement of groundwater condition

For this report, the key issues that will be focused on are surface water quality and groundwater protection. According to the USDA NRCS, the County soil and water conservation districts within the Mississippi River-Headwaters 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 sheet and rill erosion), woodland management, surface water quality (nutrients and priority pollutants), pasture and grazing land management, groundwater quality (nutrients, organics, animal and human wastewater management) and wetland management.

## Surface water quality

According to the MPCA's surface water impairment list for 2012, the Mississippi River-Headwaters Watershed included a total of 59 lakes and 4 stream reaches that were identified as impaired (MPCA, 2015e). The primary impairment for river/stream reaches is insufficient dissolved oxygen and for lakes is mercury 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 chemical that 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 EPA 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).

Although nutrients, such as nitrogen and phosphorus, are necessary for stream health, excess levels can cause algal blooms, which decrease the amount of light and dissolved oxygen available for aquatic plants and organisms. Dissolved oxygen, a function of atmospheric pressure, water temperature, and dissolved substances in the water, is a vital constituent for aquatic health and water quality. Two primary sources for depleted oxygen levels include excess nutrient runoff and soil erosion (causing turbidity) from agricultural landscapes into nearby waterbodies. The total number of acres treated within in the Mississippi River-Headwaters Watershed with one or more chemicals, including insecticides, herbicides, wormicides and fruiticides is 18,238 acres, or approximately 1.5% of the watershed (USDA NRCS). This is a small percentage of the watershed, but should be monitored and mitigated due to low dissolved oxygen levels in stream reaches. Turbidity is caused from suspended sediments in the water column, often from soil erosion, that can block light and limit the photosynthesis process. Soil erosion has been calculated and predicted to be between 0.106 and 0.253 tons per acre per year for the watershed (Humburg & Herman) and has been ranked as a moderate to high concern for the watershed (USDA, NRCS).

## 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. Groundwater withdrawals in the watershed have decreased by nearly 10% from 1994 to 2013. However, water table elevations in MNDNR observation wells have displayed decreasing trends over the most recent 20 years of data collected. It is estimated that the development pressure is moderate in some parts of the watershed where land is converted from farms and timberland to recreation and country homes (USDA NRCS). This increase in development is also seen with a slight increase in non-crop irrigation (golf course, athletic field and landscape irrigation) and water supply (p=0.05). Therefore, although overall groundwater withdrawals have been decreasing, the watershed's water table has been exhibiting signs of decline. While fluctuations due to seasonal variations are normal, long term changes in elevations should not be ignored. The potential groundwater recharge to surficial materials throughout the watershed ranges from very low to very high, with an average of 5.2 inches per year. When comparing the location of the permitted groundwater withdrawals, many locations are correlated with areas of medium to low potential recharge (Figure 52).

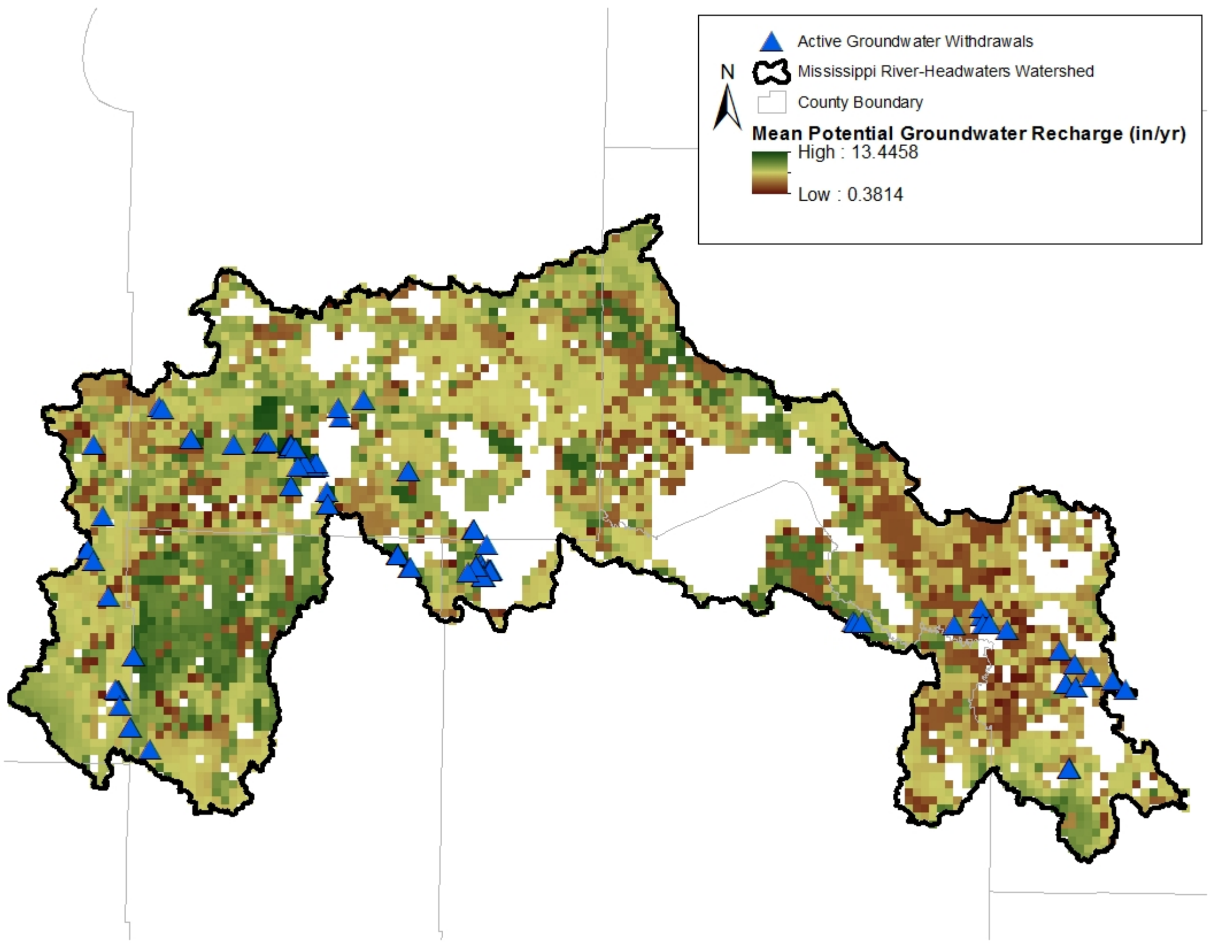



**Figure 52: Mean potential groundwater recharge and groundwater permit locations within the Mississippi River-Headwaters Watershed.**

The groundwater quality of the watershed appears to be good. The MPCA monitors 19 wells within the watershed, 18 monitoring wells and 1 domestic well. The purpose of this network is to investigate the background chemistry and impact of chemicals on the groundwater. Statistical analysis was completed on these wells for 117 different constituents and parameters to determine concentration, frequency and possible trends. Arsenic, nitrate and chloride detection frequency for 2010 to 2015 was 59.8, 70.6 and 92.2% of wells, respectively. Only one well had consistent high levels of arsenic, which is likely due to the presence of a clay layer and low dissolved oxygen levels. Nitrate exceeded the MCL, and chloride exceeded the secondary MCL only once, both in the same well near Bemidji at different times. Other sources of groundwater quality data were limited due to the high forested/low agricultural land use for this 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, have 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. Although the ambient groundwater quality data appears to be good, the MPCA's WIMN program has identified a number of potentially contaminated sites and facilities within the Mississippi River-Headwaters 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 53). Due to the higher levels of groundwater contamination susceptibility throughout the watershed, it is important to continue to monitor these potentially harmful sites in order to inhibit possible water pollution.

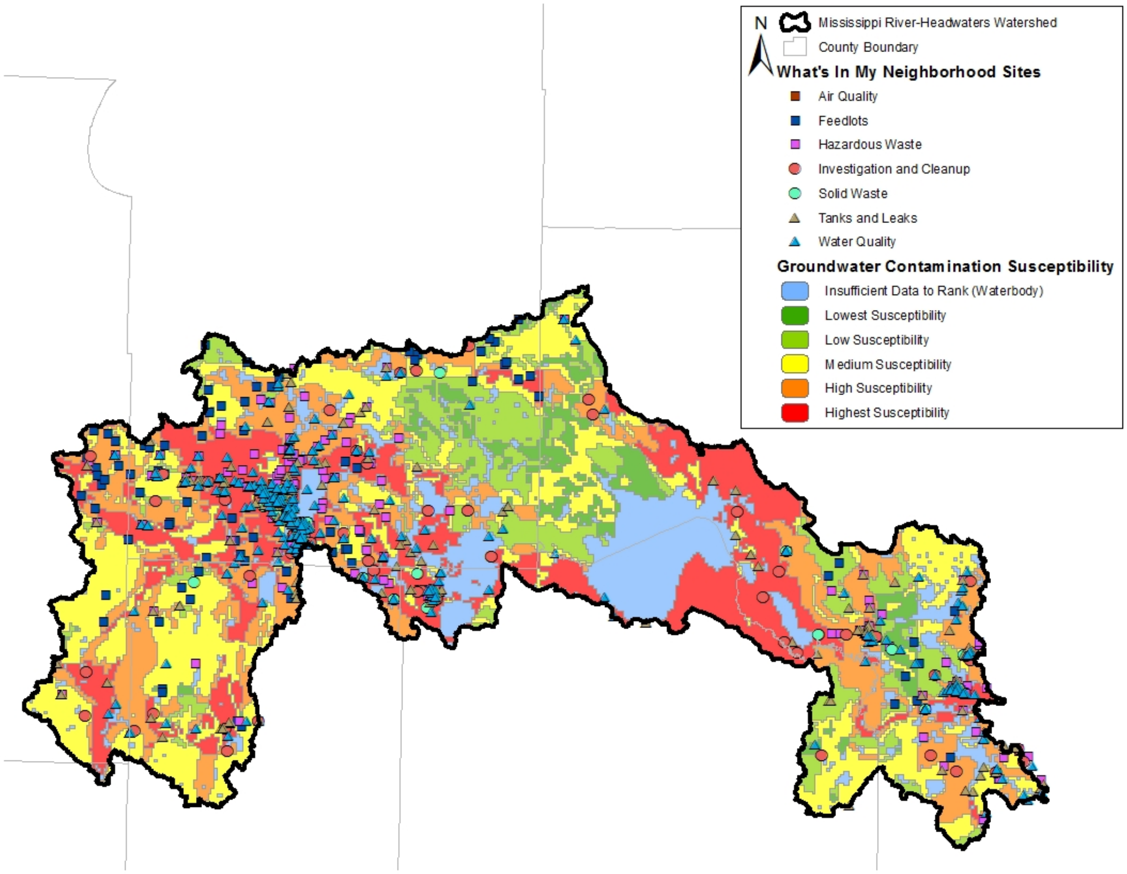



**Figure 53: Groundwater contamination susceptibility and WIMN sites within the Mississippi River-Headwaters Watershed.**

# Recommendations

Overall, the groundwater quality of the watershed appears to be healthy, with few exceedances of chemicals of interest and concern. Additional and continued monitoring will benefit the understanding of the health of the watershed and its groundwater resources and aid in identifying the extent of the issues present and risk associated. Increased localized monitoring efforts will help accurately define the risks and extent of any issues within the watershed. Adoption of best management practices will benefit both surface and groundwater. These practices, such as planting cover crops, replacing aging septic systems as well as controlling feedlot runoff and chemical application, will help prevent and mitigate negative impacts in the future.

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 MNDNR be cautious in granting future permits. Another factor to be considered when determining sustainable withdrawals over time 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 Mississippi River-Headwaters Watershed is stable and able to maintain the current demand, but with demand and climate fluctuations in the future, this assumption should be reassessed.

# IX. References


Humburg, J. and Herman, T. (2013), Mississippi Headwaters Watershed. Retrieved from http://wiki.sdstate.edu/User:Suzette.Burckhard/Hydrology_Class_Watershed_Wiki/Mississippi_Headwaters_Watershed

Kroening, S. and Ferrey, M. (2013), The Condition of Minnesota's Groundwater, 2007-2011. Document number: wq-am1-06

Minnesota Department of Agriculture: Pesticide and Fertilizer Management (2015), 2014 Water quality Monitoring Report. MAU-15-101.

Minnesota Department of Health (2015), Private Wells - Arsenic. Retrieved from https://apps.health.state.mn.us/mndata/webmap/wells.html

Minnesota Department of Natural Resources (2001), Figure 1: Minnesota Ground Water Provinces. Retrieved from http://files.dnr.state.mn.us/natural_resources/water/groundwater/provinces/gwprov.pdf

Minnesota Department of Natural Resources: State Climatology Office (2003), Climate. Retrieved from http://www.dnr.state.mn.us/faq/mnfacts/climate.html

Minnesota Department of Natural Resources: State Climatology Office (2015), Annual Precipitation Maps. Retrieved from http://climate.umn.edu/doc/annual_pre_maps.htm

Minnesota Department of Natural Resources (2015a), Surface-water watersheds vs. ground-water watersheds. Retrieved from http://www.dnr.state.mn.us/watersheds/surface_ground.html

Minnesota Department of Natural Resources (2015b), Fisheries Lake Survey: Plantagenet. Retrieved from http://www.dnr.state.mn.us/lakefind/showreport.html?downum=29015600

Minnesota Department of Natural Resources (2015c), Fisheries Lake Survey: Dixon. Retrieved from http://www.dnr.state.mn.us/lakefind/showreport.html?downum=31092100

Minnesota Department of Natural Resources (2015d), Fisheries Lake Survey: Siseebakwet (Sugar). Retrieved from http://www.dnr.state.mn.us/lakefind/showreport.html?downum=31055400

Minnesota Department of Natural Resources (2015e), Groundwater pollution sensitivity. Retrieved from http://www.dnr.state.mn.us/waters/groundwater_section/mapping/sensitivity.html

Minnesota Department of Natural Resources (2015f), Water use- Water Appropriations Permit Program. Retrieved from http://www.dnr.state.mn.us/waters/watermgmt_section/appropriations/wateruse.html

Minnesota Department of Natural Resources (2015g), Climate's Impact on Water Availability; evapotranspiration. Retrieved from http://www.dnr.state.mn.us/climate/water_availability.html

Minnesota Geological Survey (1982), S-01 Geologic Map of Minnesota, Quaternary Geology. Using: *ArcGIS* [GIS software]. Version 10.3.1. Redlands, CA: Environmental Systems Research Institute. Retrieved from http://www.mngs.umn.edu/service.htm

Minnesota Geological Survey (2011), Geologic Map of Minnesota-Bedrock Geology S-21. Using: *ArcGIS* [GIS software]. Version 10.3.1. Redlands, CA: Environmental Systems Research Institute. Retrieved from http://www.mngs.umn.edu/service.htm

Minnesota Pollution Control Agency (1999a), Baseline Water Quality of Minnesota's Principal Aquifers: Region 1, Northeast Minnesota.

Minnesota Pollution Control Agency (1999b), Baseline Water Quality of Minnesota's Principal Aquifers: Region 3, Northwest Minnesota.

Minnesota Pollution Control Agency (2007), Minnesota Statewide Mercury Total Maximum Daily Load. Document number: wq-iw4-01b.

Minnesota Pollution Control Agency (2009), Watershed Approach to Condition Monitoring and Assessment. Document number: wq-s1-27.

Minnesota Pollution Control Agency (2015a), Mississippi River - Headwaters. Retrieved from https://www.pca.state.mn.us/water/watersheds/mississippi-river-headwaters

Minnesota Pollution Control Agency (2015b), Plantagenet: 3 MI S of Bemidji (Lake). Retrieved from http://cf.pca.state.mn.us/water/watershedweb/wdip/waterunit.cfm?wid=29-0156-00

Minnesota Pollution Control Agency (2015c), Dixon: 7 MI W of Squaw Lake (Lake). Retrieved from http://cf.pca.state.mn.us/water/watershedweb/wdip/waterunit.cfm?wid=31-0921-00

Minnesota Pollution Control Agency (2015d), Siseebakwet: 8 MI SW of Grand Rapids (Lake). Retrieved from http://cf.pca.state.mn.us/water/watershedweb/wdip/waterunit.cfm?wid=31-0554-00

Minnesota Pollution Control Agency (2015e), Maps of Minnesota's Impaired Waters and TMDLs. Retrieved from https://www.pca.state.mn.us/water/maps-minnesotas-impaired-waters-and-tmdls

Minnesota Pollution Control Agency (2015f), Statewide Mercury Reduction Plan. Retrieved from https://www.pca.state.mn.us/water/statewide-mercury-reduction-plan

Porcher, E. (1989), Ground Water Contamination Susceptibility in Minnesota (revised edition), Minnesota Pollution Control Agency, St. Paul, MN, 29 p.

Streitz, A. (2011). The Role of Groundwater in Watershed Studies. *Minnesota Ground Water Association Newsletter, 30*(4), 15-19. Retrieved from http://www.mgwa.org/newsletter/mgwa2011-4.pdf

United States Department of Agriculture, Natural Resources Conservation Service (No Date), Rapid Watershed Assessment: Mississippi Headwaters, (MN) HUC: 07010101. Retrieved from http://www.nrcs.usda.gov/Internet/FSE_DOCUMENTS/nrcs142p2_022926.pdf

United States Geological Survey (2007), Ground Water Recharge in Minnesota. Retrieved from http://pubs.usgs.gov/fs/2007/3002/pdf/FS2007-3002_web.pdf

United States Geological Survey (2015a), Aquifers and Groundwater. Retrieved from http://water.usgs.gov/edu/earthgwaquifer.html

United States Geological Survey (2015b), Evapotranspiration, the water cycle. Retrieved from http://water.usgs.gov/edu/watercycleevapotranspiration.html

Zhang, H. (1998), Geologic Atlas of Stearns County, Minnesota: Hydrogeology of the Quaternary Water Table System. County Atlas Series, Atlas C-10, part B, Plate 8 of 10, Hydrogeology of the Quaternary Water-table System.