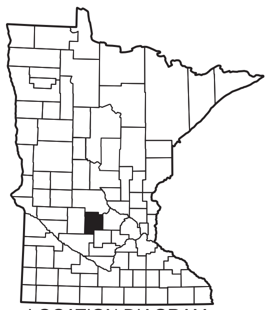
Groundwater Atlas of Meeker County, Minnesota

County Atlas Series C-35, Part B



LOCATION DIAGRAM

Report

To accompany these atlas components:

Plate 6, Water Chemistry

Plate 7, Hydrogeologic Cross Sections, A–A′ through D–D′

Plate 8, Hydrogeologic Cross Sections, E–E′ through H–H′

DEPARTMENT OF NATURAL RESOURCES

St. Paul
2019

mndnr.gov/groundwatermapping

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County Atlas Program

The Minnesota County Atlas series has been produced since 1982. Recent atlases are produced in two parts. Explanations of the history and purpose of the program, atlas applications, user guides, map sales, and descriptions of the components are available online.

Part A Geology was published by the Minnesota Geological Survey (MGS) in 2015 including: Plate 1, Data-Base Map; Plate 2, Bedrock Geology; Plate 3, Surficial Geology; Plate 4, Quaternary Stratigraphy; Plate 5, Bedrock Topography, Depth to Bedrock, and Sand Distribution Model.

Information is available on the Minnesota Geological Survey page (cse.umn.edu/mgs/county-geologic-atlas).

Part B Groundwater was published by the Minnesota Department of Natural Resources (DNR), who expanded on the Part A information after its completion. The groundwater components are described in the introduction of this report.

Information is available on the DNR Groundwater Atlas Program page (mndnr.gov/groundwatermapping).

Technical Reference

Maps were compiled and generated in a geographic information system. Digital data products are available on the DNR Groundwater Atlas Program page (mndnr.gov/groundwatermapping).

Maps were prepared from DNR and other publicly available information. Reasonable effort has been made to ensure the accuracy of the factual data on which the report and map interpretations were based. However, the DNR does not warrant the accuracy, completeness, or any implied uses of these data. Users may wish to verify critical information; sources include both the references here and information on file in the offices of the MGS and the DNR. Every effort has been made to ensure the interpretations conform to sound geologic and cartographic principles. These maps should not be used to establish legal title, boundaries, or locations of improvements.

Base maps were modified from MGS, Meeker County Geologic Atlas, Part A, 2015. Universal Transverse Mercator projection, zone 15N, North American Datum of 1983. North American Vertical Datum of 1988.

GIS and cartography by Randy J. Bradt and Holly Johnson.

Conversion Factors

1 inch per hour = 7.056 x 10^{-6} meter per second

1 part per million = 1 milligram per liter

1 part per billion = 1 microgram per liter

1 milligram per liter = 1000 micrograms per liter

1 gallon per day per foot = 0.1337 $foot^2$ per day

1 $foot^2$ per day = 7.48 gallons per day per foot

Report Contents

Report Figures

Report Tables

Plates (accompanying folded inserts)

Acknowledgments

The author would like to thank the following staff at the Minnesota DNR for their contributions: John Barry, Vanessa Baratta, Wes Rutelonis, Paul Putzier, Ruth MacDonald, Holly Johnson, Todd Petersen, Rachel Lindgren, and Ann Hall. Special thanks also to the following people for taking time to review this report and for providing helpful suggestions: Mike MacDonald, Minnesota Department of Agriculture; Andrew Streitz, Minnesota Pollution Control Agency; James Walsh and John Woodside, Minnesota Department of Health; and Gary Meyers, Minnesota Geological Survey. Editing was by Ruth MacDonald and Holly Johnson.

An additional thank you goes to Scott Alexander from the University of Minnesota for his assistance with the collection and interpretation of the carbon-14 results for this report.

Groundwater Atlas of Meeker County, Minnesota

by Randy J. Bradt

Introduction

This report and the accompanying plates are Part B of the Meeker County Atlas. It describes the groundwater characteristics of the county and was produced by the Minnesota Department of Natural Resources (DNR). It builds on the geology described in Part A, previously published by the Minnesota Geological Survey (MGS).

The purpose of this atlas is to illustrate the hydrogeologic setting, aquifer distribution, pollution sensitivity, groundwater recharge, and subsurface flow of the aquifers within the county. This information can be used to make natural resource and land use decisions that take into account aquifer sensitivity, water quality, and sustainability.

This **report** details the methods, results, and interpretations for the county. **Plate 6** illustrates the water chemistry; **Plates 7 and 8** use hydrogeologic cross sections to show groundwater flow directions and residence time within the aquifers. This introduction gives a summary of the detailed sections that follow.

The **physical setting** of Meeker County in south-central Minnesota contains or intersects parts of four major watersheds. Numerous lakes and rivers provide recreational opportunities for its citizens. Annual precipitation averages 29 inches. Groundwater recharge varies seasonally in response to precipitation with spring and fall typically receiving the greatest amount of groundwater replenishment.

The **geology and physical hydrogeology** (pages 4–20) section describes characteristics of geologic units in the county. Meeker County surficial geologic deposits are predominately unconsolidated glacial loam sediment that are locally overlain by sand and gravel deposits. These sediments overlie a variety of older glacial deposits with total thicknesses varying from tens of feet in the north and northeast to several hundred feet in deep bedrock valleys in the south. Glacial sediment overlie Cretaceous mudstone and sandstone mostly in the eastern half of the county and both overlie Precambrian crystalline bedrock throughout the county.

Aquifers and aquitards are identified by their hydrostratigraphic characteristics and corresponding geologic units from Part A. Groundwater elevation maps give a broad look at the direction of groundwater flow in unconfined conditions (water-table elevation) and confined conditions (potentiometric-surface elevation).

The **water table** (pages 4–8) is a subdued expression of surface topography. Its elevation is highest in the west-central, northwestern, and northern portions of the county and lowest along the larger river valleys that drain surface water generally eastward. At more localized scales, water-table flow is from local highs to river tributaries, lakes, and wetlands. The map for depth to water table shows that the water table is within 10 feet of the surface across most of the county, except in areas of higher topographic relief including the glacial moraines and along the margins of the larger river valley floodplains.

Potentiometric surface maps of **buried sand and gravel aquifers** (pages 9–20) indicate a pattern of generalized groundwater flow toward the larger perennial streams including the Middle Fork Crow, North Fork Crow, South Fork Crow, and Clearwater rivers. Deeper buried sand aquifers show regional groundwater flow to the east and southeast.

The **water chemistry** (pages 21–27 and Plate 6) provides information about the water source, flow path, travel time, and residence time of groundwater. The groundwater chemistry supports the results of the pollution sensitivity models and is used to identify areas of interest, such as those with high pollution sensitivity or elevated levels of potentially harmful chemicals.

- **Surface water connections to groundwater** were evident in a small number of samples from wells mostly south of Litchfield, an area with the greatest concentration of surface-water features. The remaining well samples showed no evidence of surface-water influence.
- **Chloride** from anthropogenic (human) sources was found in a small number of sampled wells. Most of these were from the surficial sand aquifer (ss) and the shallowest buried sand and gravel aquifers (hs and ms).
- **Nitrate** from anthropogenic sources was found in only two wells. Some of the groundwater is too old to have received nitrate from anthropogenic sources, and almost all of the groundwater sampled were devoid of dissolved oxygen which is generally favorable for nitrate removal

(denitrification). Nitrate is more likely to be found in the surficial sand aquifer.

- **Arsenic** concentrations exceeded the maximum contaminant level in about half of the samples. No discernible spatial patterns or correlations were found with specific aquifers. Currently there is no reliable method for predicting which aquifers will have elevated arsenic.
- **Manganese** concentrations equaled or exceeded the Minnesota Department of Health (MDH) Health Based Value for over half of the groundwater samples.
- **Groundwater residence time,** based on tritium data, indicated recent groundwater recharge (less than 60 years old) was mostly limited to aquifers within 100 feet of land surface and rarely beyond a depth of 150 feet. A subset of samples with vintage-age tritium were dated using the carbon-14 method and found to have residence times ranging from approximately 550 to 8,500 years, reflecting the wide range of groundwater conditions in the county.

The **pollution sensitivity** (pages 28–49) or sensitivity of an aquifer is estimated based on the time it takes water to flow through various types and thicknesses of soils and geologic materials. Pollutants are assumed to travel with water at the same rate. The sensitivity is modeled with different methods for the 1) near-surface materials and 2) the buried sand and gravel aquifers and the bedrock surface. The model results are evaluated by comparing the ratings to chemical constituents such as tritium and carbon-14 data for residence time, and to inorganic chemicals for contamination.

Pollution sensitivity of near-surface materials (pages 28–30) is an estimate of the time it takes for water to infiltrate the land surface to a depth of 10 feet. Pollution sensitivity ratings in Meeker County can be broadly grouped:

1. Very low sensitivity is generally found in the southwestern portion of the county where there is clay loam to loam till as well as near the North Fork Crow River where there are silty clay lacustrine sediment.
2. Low sensitivity is associated with loam to sandy loam tills found in most areas of the county except in the southwest.
3. Moderate sensitivity is associated with a variety of loam and sandy loam textured lake sediment. The most extensive deposits are locations east of Litchfield and north of Darwin, and a large area south of Eden Valley.
4. High and very high sensitivity are associated with outwash sand and gravel deposits and deltaic sands in central and northern Meeker County.

Pollution sensitivity of buried aquifers (pages 31–49) varies widely throughout the county and is dependent on the depth of the aquifer and the thickness of overlying aquitard materials. Aquifers closest to the land surface have higher sensitivities over much of their extent. The deeper buried aquifers have little or no elevated sensitivity. Underlying glacial sediment is bedrock, where limited information was available to map aquifers, so the top of bedrock was mapped instead. Pollution sensitivity of the bedrock surface is mostly very low, but there are areas that are rated low to very high in small areas in the north-central and northeastern parts of the county.

Hydrogeologic cross sections (page 50 and Plates 7 and 8) illustrate groundwater flow, residence time, and distribution of chemicals. Cross sections help define areas of interest such as locations of important groundwater recharge, discharge, and sensitivity to pollution. Groundwater flows downward and laterally toward perennial streams that receive groundwater discharge as base flow. Groundwater recharge is enhanced in areas where there is thick surficial sand or where there are multiple stacked buried sands with little or no aquitard materials separating them. In the last 60 years water has recharged to depths ranging from less than 50 feet and up to 172 feet. In most of the county aquitards limit this "younger" water penetration to a depth of 100 feet. Groundwater gradients and sediment textures affect how deep the infiltrating water penetrates. Heavy pumping can artificially enhance gradients resulting in increased recharge rates and greater depth of penetration.

Aquifer characteristics and groundwater use (pages 51–58) summarize specific capacity tests, aquifer tests, water use records, and groundwater level monitoring data for each aquifer. These data can be used to characterize aquifer recharge in the county and plan for new well installations.

Over half of permitted water use is for agricultural crop irrigation with most of the water coming from buried sand and gravel aquifers and the remainder from surficial sand aquifers. Almost a third of the water use is from municipal and other public water supply with buried sand aquifers as the primary source. The remaining water uses include livestock watering, sand and gravel washing, and agricultural food processing.

The DNR has observation wells installed in various parts of the county in order to monitor aquifer water levels. This information helps DNR understand the impacts of groundwater withdrawal to these aquifers and to the natural resources that depend on them. Observed water levels indicate that over time water levels fluctuate from a few to more than 10 feet naturally in response to short and long-term precipitation trends. Aquifers with high-capacity wells are being monitored to ensure that groundwater withdrawal is sustainable and does not impact the aquifers' ability to provide for future generations.

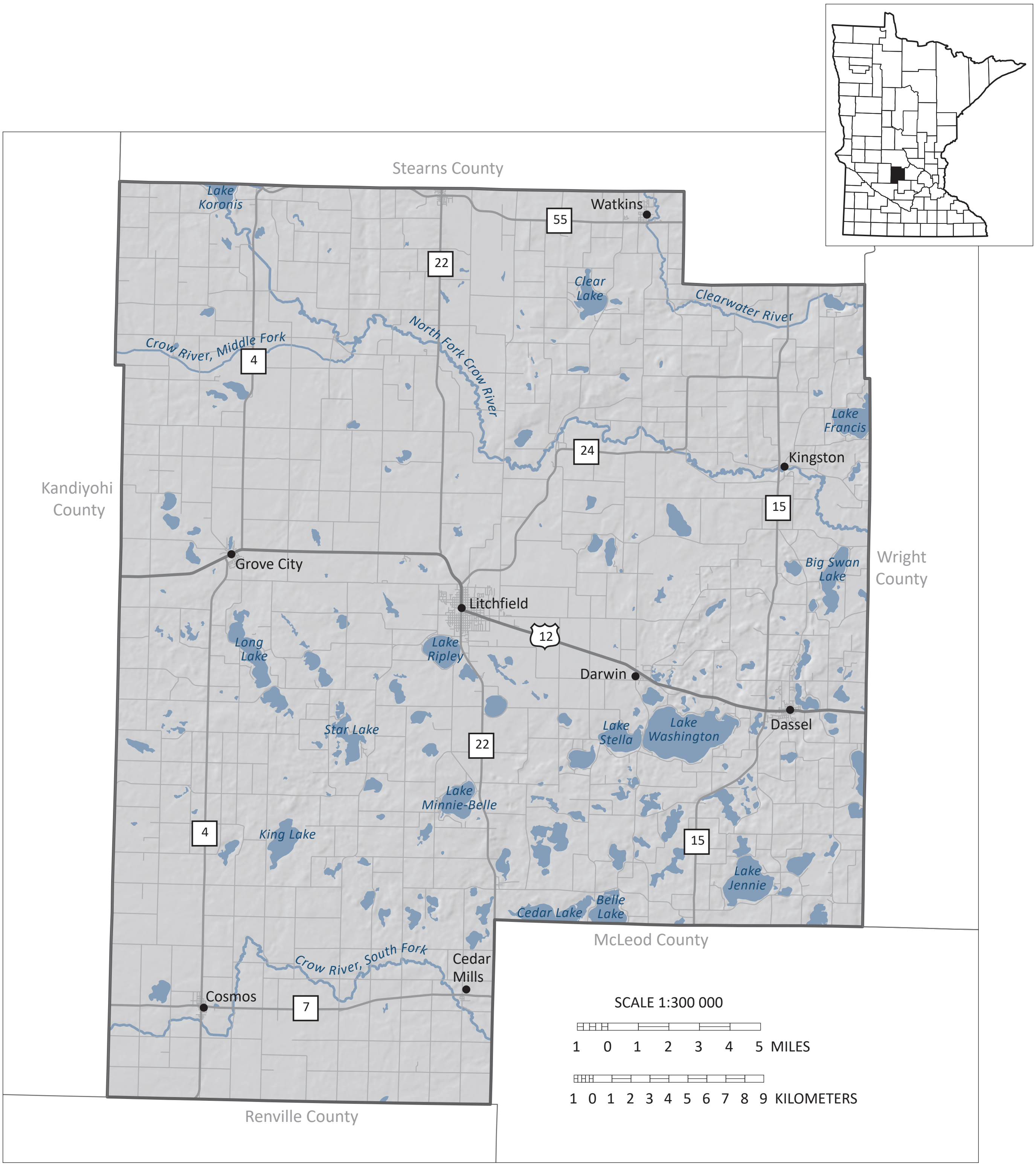


Figure 1. Meeker County, Minnesota

Physical setting and climate

Meeker County is located in south-central Minnesota (Figure 1). It has numerous lakes and the topography ranges from nearly level to rolling terrain. It is approximately 645 square miles in size and is almost 6 percent open water. The population as of July 2017 was 23,131 (U.S. Census Bureau, 2018). Row crop agriculture predominates land use in terms of acreage but the county also has some of the state's largest dairy and poultry operations. The county lies within portions of four major watersheds including: the North Fork Crow River, South Fork Crow River, Sauk River, and Mississippi River–St. Cloud watersheds (Figure 3). The watersheds drain surface waters east and eventually to the Mississippi River. The exception is a small portion of the Sauk River watershed that discharges to the north toward the Sauk River and then northeast to the Mississippi River.

The county is in the northern continental United States and is characterized as a cool sub-humid climate with a large temperature difference between summer and winter. Average temperatures for 1981–2010 are 69 degrees Fahrenheit for summer and 15 degrees for winter (NOAA, 2018). Average annual precipitation is approximately 29 inches, placing it in the middle of the statewide range of 20 to 36 inches.

Geology and physical hydrogeology

Surficial aquifers

Surficial geologic materials in Meeker County consist primarily of sediment of the New Ulm Formation deposited during the Wisconsinan Episode (Part A, Plate 3). Ice carried sediment into the county from two different origins (provenances). The Rainy provenance (northeast of Minnesota) contributed sediment of the Hewitt Formation, carried by the Wadena lobe ice. After its retreat, the Riding Mountain provenance (northwest of Minnesota) contributed New Ulm Formation sediment in three successive advances of the Des Moines lobe (Part A, Plate 3, Figure 3).

These unconsolidated sediment are generally an unsorted mix of sand, silt, and clay sized materials (till). Water does not readily move through this material and therefore till is considered an aquitard. During each ice lobe retreat the meltwaters reworked glacial sediment and deposited sand and gravel. These layers can serve as aquifers if there is sufficient saturated thickness.

The characteristics (areal extent, thickness, and sediment texture) of surficial sand deposits were created from a variety of depositional environments including outwash deposited in streams emanating from the glaciers to lake deltas where sediment-laden streams flowed into glacial Lake Litchfield (Part A, Plate 3).

These characteristics determine whether these deposits are sufficient to provide water for high-capacity wells (irrigation or public water supply) or lower capacity wells for domestic (home) consumption. The lateral extent and thickness of surficial sand deposits are shown in Figure 2.

The thickest and most extensive deposits are in the center of the county where glacial streams deposited sandy sediment in glacial Lake Litchfield, and in the north-central and northwestern portions of the county where glacial stream deposits (outwash) dominate at the land surface. The soils associated with these surficial sands are prone to drought conditions so this area is where most of the irrigation wells are found (see the Water Use section and Figure 41).

Water table

The water table is defined as the surface below which sediment is saturated with groundwater. It occurs in both aquifer and aquitard sediment across the entire county. Although it is shown in the figures as a static surface, it fluctuates over time (Figures 3 and 4).

The water-table maps provide guidance for many applications, but additional site-specific information should be used to refine this information at local scales. Certain conditions affect the fluctuation of the water table and can create locally different results from the maps created for this atlas. Some of these include, but are not limited to, seasonal weather conditions, extent and composition of surficial geology units, land-use practices, vegetation composition and distribution, and pumping of high-capacity wells.

Water-table elevation was estimated from several data sources (Figure 3):

- Elevation of surface-water bodies (e.g., rivers, perennial streams, lakes, and open water wetlands)

- Static water levels in surficial sand wells obtained from the County Well Index database (converted to elevations*)
- Estimates of depth to wet soil conditions from the Natural Resources Conservation Service (NRCS) county soil survey (converted to elevations*)

**Data were converted to elevations using a digital elevation model derived from LiDAR (Light Detection and Ranging) technology.*

The **water table** is generally a subdued expression of the surface topography, with higher elevations in west-central, northwest, and north-central Meeker County. Regionally, water flows southeast to east, eventually discharging to the Mississippi River. Locally, groundwater flows toward lakes, wetlands, and streams including the South Fork Crow, Middle Fork Crow, North Fork Crow, and Clearwater rivers and their tributaries.

The stippled area in Figure 3 shows areas where the surficial sand aquifer is present. Wells in this aquifer include less than 20 percent of the permitted irrigation wells, approximately 1 percent of the domestic wells, and only one public supply well.

Depth to water table (Figure 4) was derived by subtracting the water-table elevation from the land-surface elevation. More details can be found in *Methods for estimating water-table elevation and depth to water table* (DNR, 2016a).

Shallow water-table conditions (0–10 feet) are common in the county. Exceptions include areas where glacial sediment locally form features of high topographic relief or along steep slopes. Where sediment is mapped as sand, it is likely that the depth to water table is deeper (Part A, Plate 3, Surficial Geology). In portions of southwest Meeker County where high topographic features are largely associated with till or lacustrine sediment, the depth to water table may be overestimated. The soils data for these features establishes a water table greater than 5 feet below land surface. However, water-table depths of tens of feet is likely an overestimate of depth to water table caused by contouring data points in lower topographic positions adjacent to these high relief features.

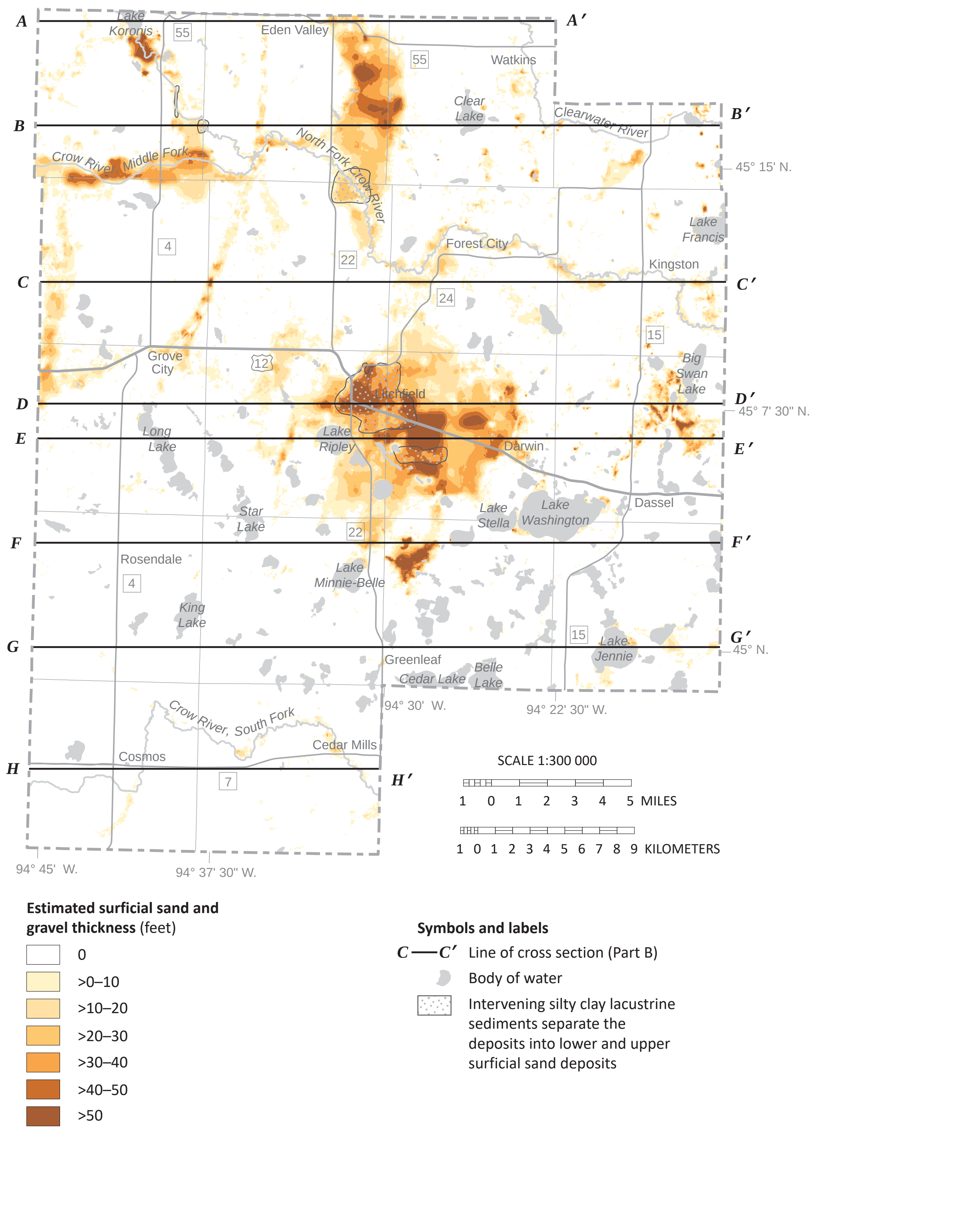


Figure 2. Surficial sand deposits

Mapped extent and thickness of surficial sand and gravel deposits.

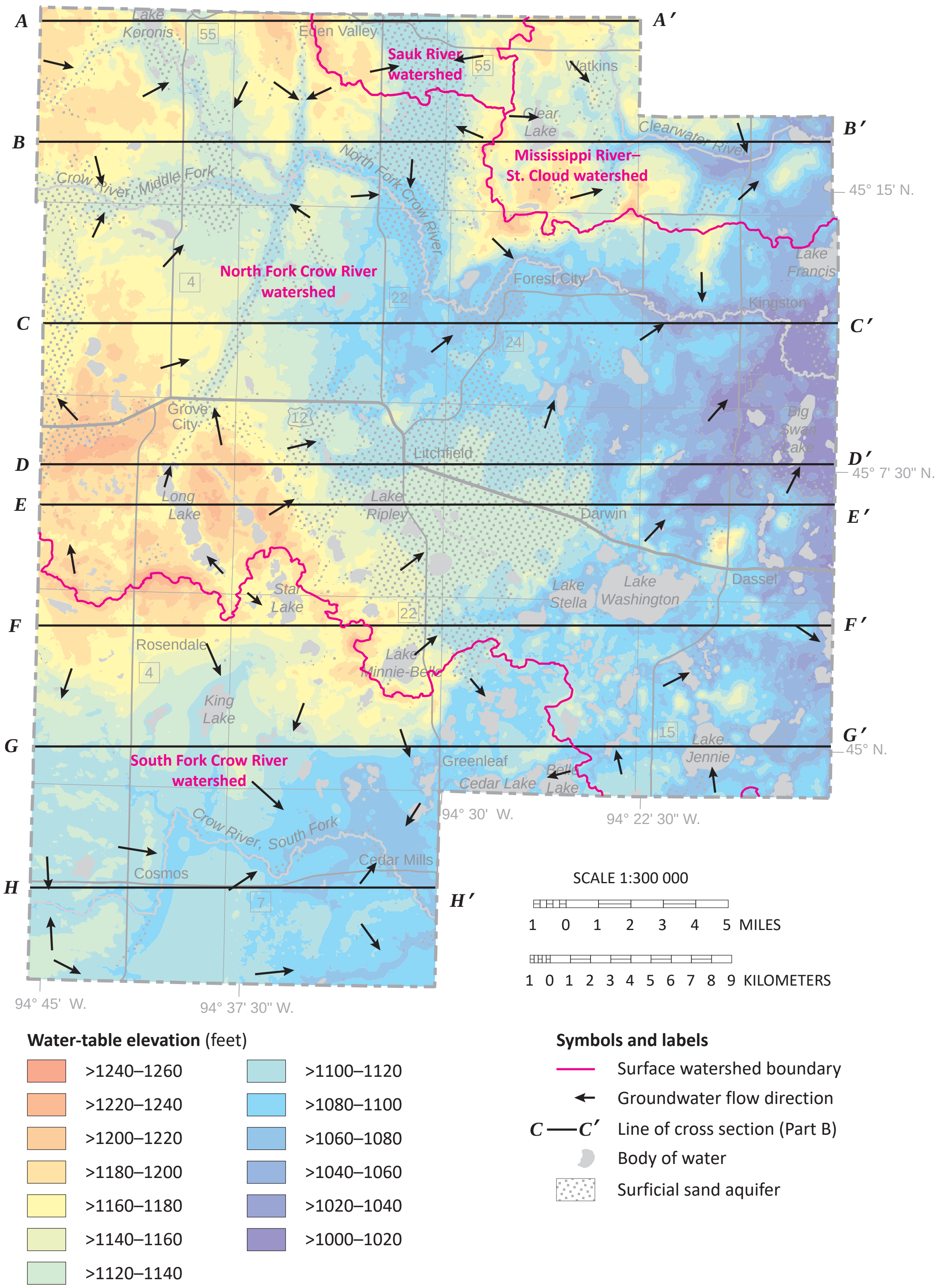


Figure 3. Water-table elevation

The water table is a subdued expression of the county's topography. Groundwater flows from topographic highs toward lakes, major rivers, and their tributaries.

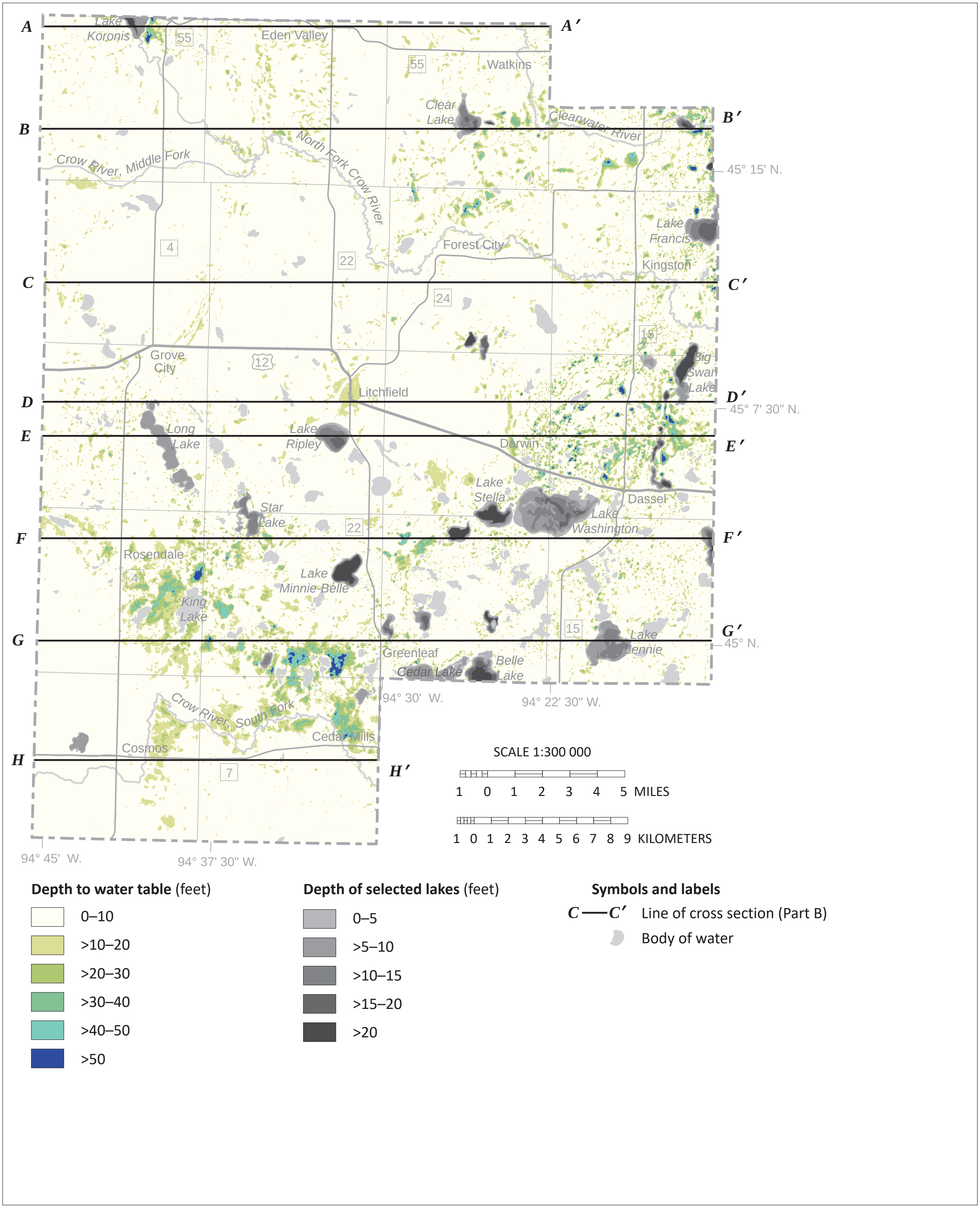


Figure 4. Depth to water table

Shallow water-table conditions (0–10 feet) are common in the county. Deeper conditions of greater than 10 feet to the water table are present in the hummocky terrain in southern and eastern Meeker County. Most lakes and wetlands are visible expressions of the water table.

Buried aquifers

Sand and gravel

In Meeker County over 95 percent of the wells are completed within the buried sand and gravel aquifers. Beneath the surficial geologic deposits are alternating layers of older sand, gravel, and fine-grained deposits from previous glacial advances. Combined thickness of unconsolidated sediment varies from less than 50 feet thick in the northeast to almost 700 feet thick in the deep bedrock valleys near Cedar Mills. Within the glacial sediment are discontinuous buried sand and gravel aquifers with individual thickness seldom exceeding 30 feet.

The naming convention for the buried sand and gravel aquifers in this atlas is based on the underlying till unit described in the associated geologic atlas (Part A).

The stratigraphic column correlates the glacial geologic units from Part A with the hydrogeologic units of Part B (Figure 5). Part A descriptions are generally classified *sand and gravel* or *till or lake clay.* These are converted into the hydrogeologic descriptions of aquifer or aquitard, respectively.

The stratigraphic units are shown as follows:

- Aquifers are shown with patterns.
- Aquitards are shown as shades of gray, representing the relative hydraulic conductivity. Lighter shades represent units with more sand, implying a higher hydraulic conductivity. The shades of gray are based on the average sand content of the aquitard, which is determined from the matrix texture (portion that is less than 2 millimeter grain size).
- Units of undifferentiated sediment with an unknown or unnamed texture are shown in brown.

In this atlas, the ***buried sand and gravel*** aquifers will be referred to as ***buried sand*** aquifers.

	Part A	Part B
silt and clay[1]		sc1
surficial sand and gravel[2]		ss1
silt and clay[1]		sc
surficial sand and gravel[2]		ss
Heiberg (till)	nht	nht
sand and gravel	nts	nts
Villard (till)	nt	nt
sand and gravel	*ms*	ms
Moland (till)	*mt*	mt
sand and gravel	*hs*	hs
Hewitt (till)	*hwt*	hwt
sand and gravel	*scs*	scs
Sauk Centre (till)	*sct*	sct
sand and gravel	*mls*	mls
Meyer Lake (till)	*mlt*	mlt
sand and gravel	*gs3*	gs3
Good Thunder, Unit 3 (till)	*gt3*	gt3
sand and gravel	*gs4*	gs4
Good Thunder, Unit 4 (till)	*gt4*	gt4
sand and gravel	*gs5*	gs5
Good Thunder, Unit 5 (till)	*gt5*	gt5
sand and gravel	*wrs*	wrs
Rainy (till)	*wrt*	wrt
sand and gravel	*wes*	wes
Elmdale (till)	*wte*	wte
sand and gravel	*vs*	vs
Winnepeg (till)	*vt*	vt
undifferentiated sand and gravel	*psu*	psu
undifferentiated sediment	*pu*	pu

Percent sand in aquitard

>50% and ≤60%	
>40% and ≤50%	
>30% and ≤40%	
≤30%	

[1]Defined by one or a combination of the map units: ac, ll, pe, nl, nvs, nva, nvt, nhs. In cross sections, these units are only shown where associated with surficial sand and gravel units.

[2]Defined by one or a combination of the map units: al, ls, eo, ng, ns, nlg, nd, ni, hwi.

Figure 5. Hydrostratigraphy of Quaternary unconsolidated sediment

Bedrock

Less than five percent of wells are completed in bedrock and most of those are in the Cretaceous aquifer (Part A, Plate 2). Cretaceous bedrock are made up of interbedded sandstone, siltstone, and mudstone, and are divided into the Dakota Formation (Kd) and the Cretaceous undifferentiated (Ka), with the Dakota Formation offering the best opportunity for water supply. Cretaceous bedrock is generally found in the eastern half of the county and overlies the Precambrian crystalline bedrock. The Precambrian is a complex assemblage of igneous and metamorphic rocks and does not function as an aquifer except where porosity has developed by fracturing or weathering.

Potentiometric surfaces

Potentiometric surface maps show the direction of groundwater flow. In confined aquifers, pressure causes the water level in a well to rise above the aquifer. These levels are contoured to create a map of the potentiometric surface for each aquifer. The resulting elevation maps of groundwater levels show changes in water levels similar to how topographic maps show changes in land-surface elevations.

The potentiometric surface of an aquifer represents the potential energy that is available to move groundwater. As groundwater moves from higher to lower potentiometric elevations it flows perpendicular to the contours. Flow directions are shown on the maps.

Groundwater flows from recharge areas through the aquifer to discharge locations within a wide continuum of depth, distance, and time. High elevation areas on the potentiometric surface can indicate important recharge areas. Flow into, through, and out of shallow aquifers can take days to weeks to travel distances of up to a mile while flow in deeper aquifers can take centuries to millennia to travel dozens of miles. River valleys are typical examples of lower elevation discharge areas.

Potentiometric surface maps were created (Figures 6 through 15) using static water-level data from the County Well Index (CWI), measurements made by DNR staff, and river elevation points along the major rivers and streams. The CWI records represent various climatic and seasonal conditions over more than four decades ending in 2016. This data variability creates some uncertainty in potentiometric surface elevations. Perennial river and stream elevation points are included because these features can be groundwater discharge locations, and represent approximate groundwater elevations.

Potentiometric surface maps were not generated for the nts and psu aquifers due to their limited extent and lack of well data.

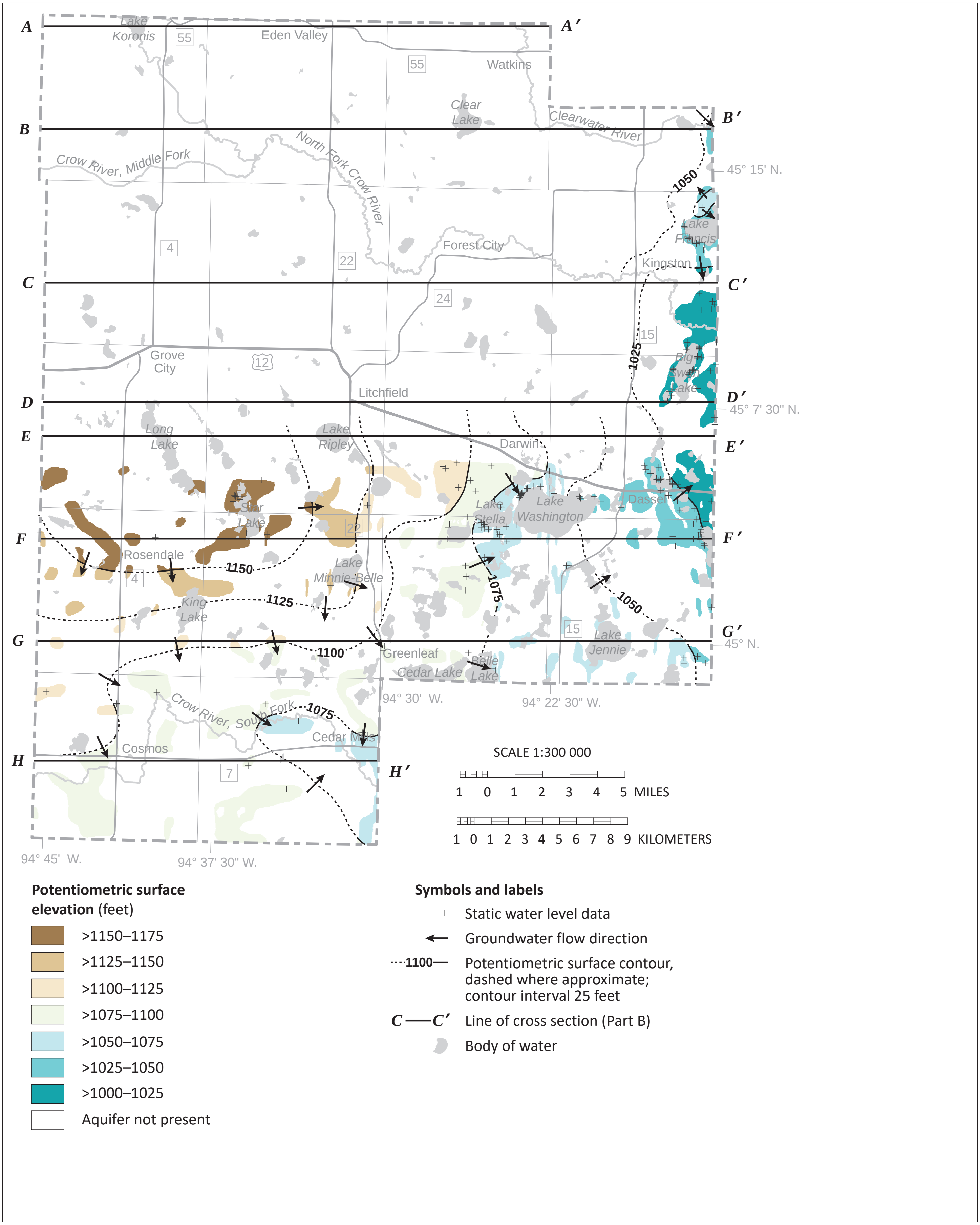


Figure 6. Potentiometric surface of the ms buried sand aquifer

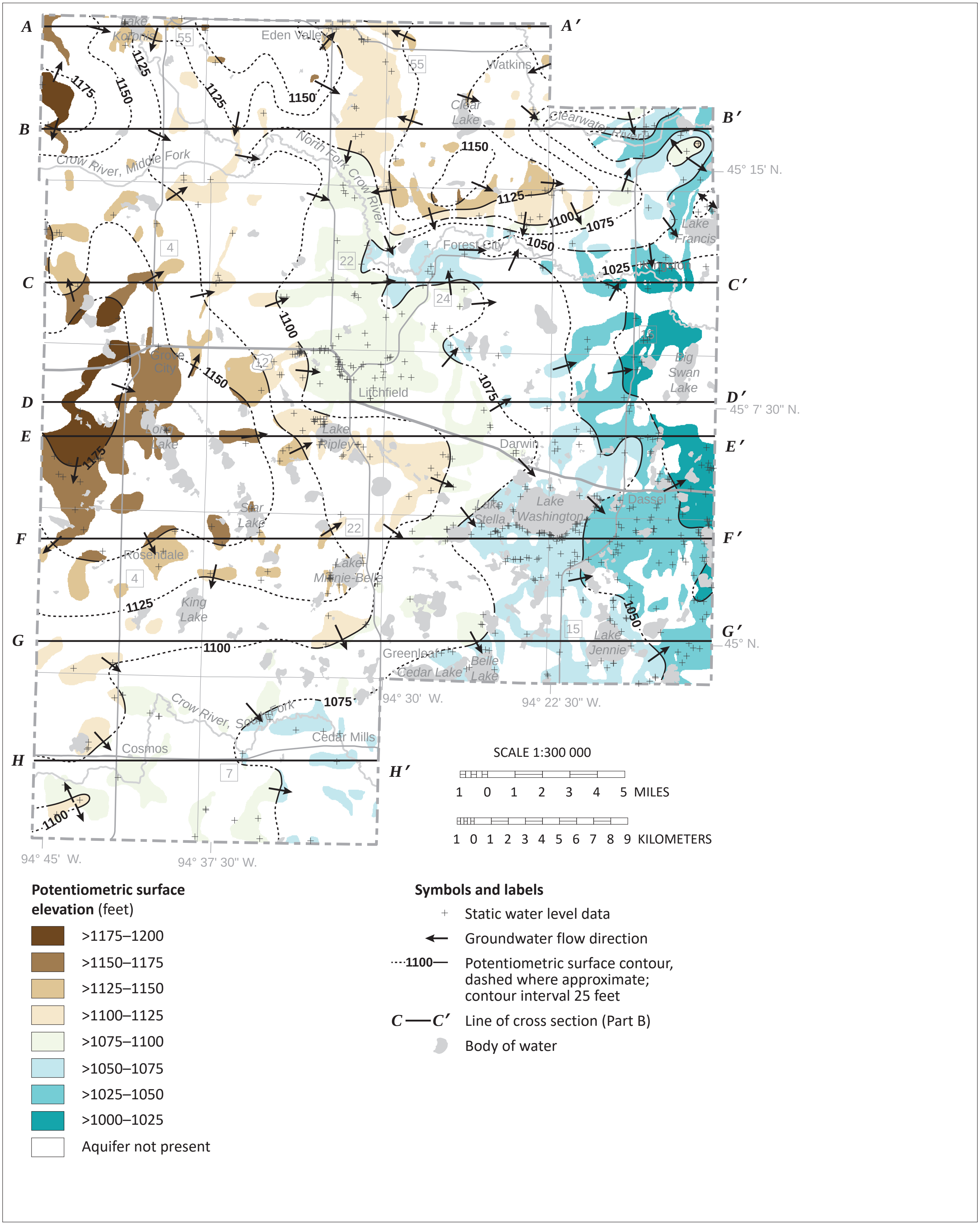
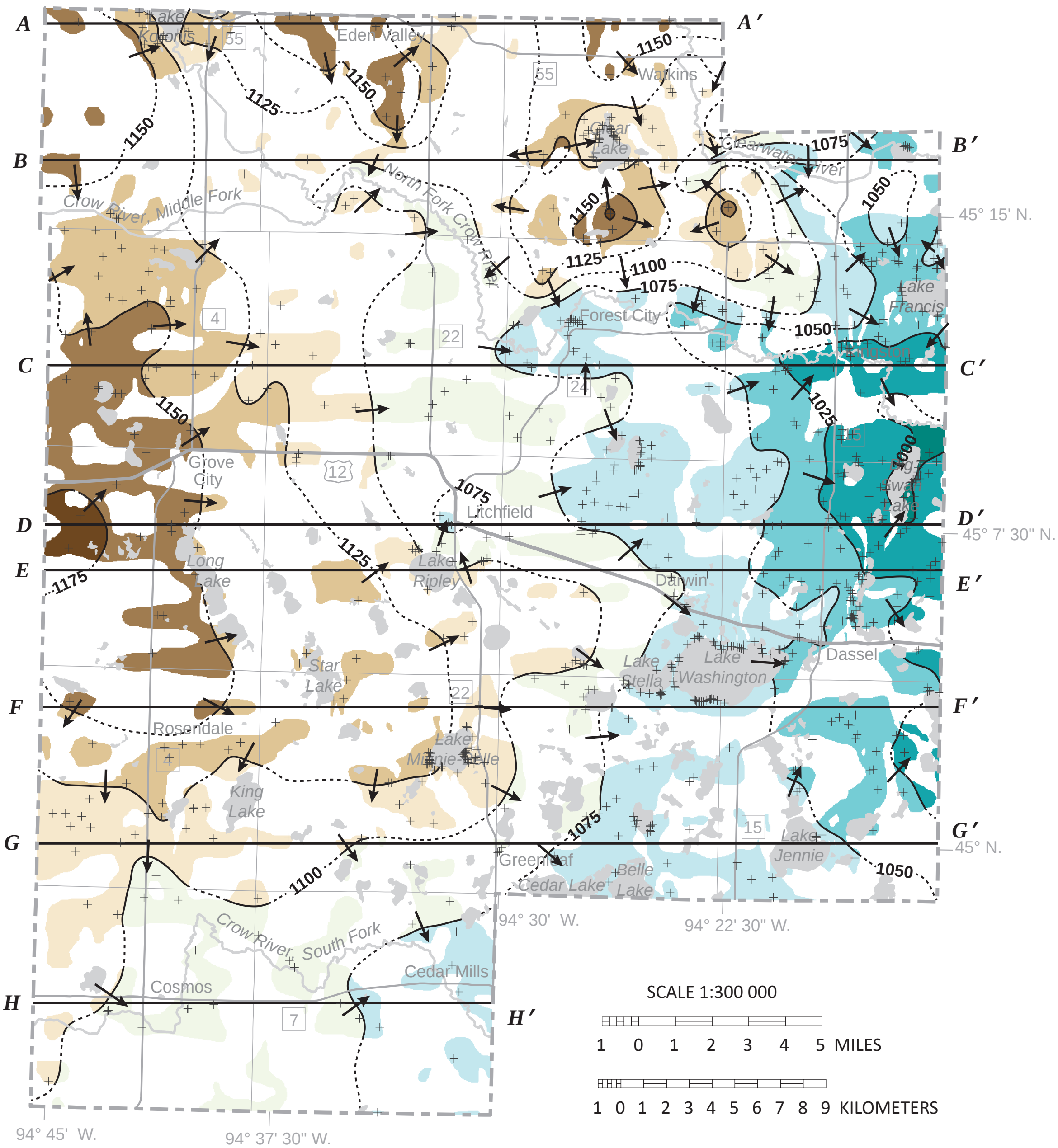


Figure 7. Potentiometric surface of the hs buried sand aquifer



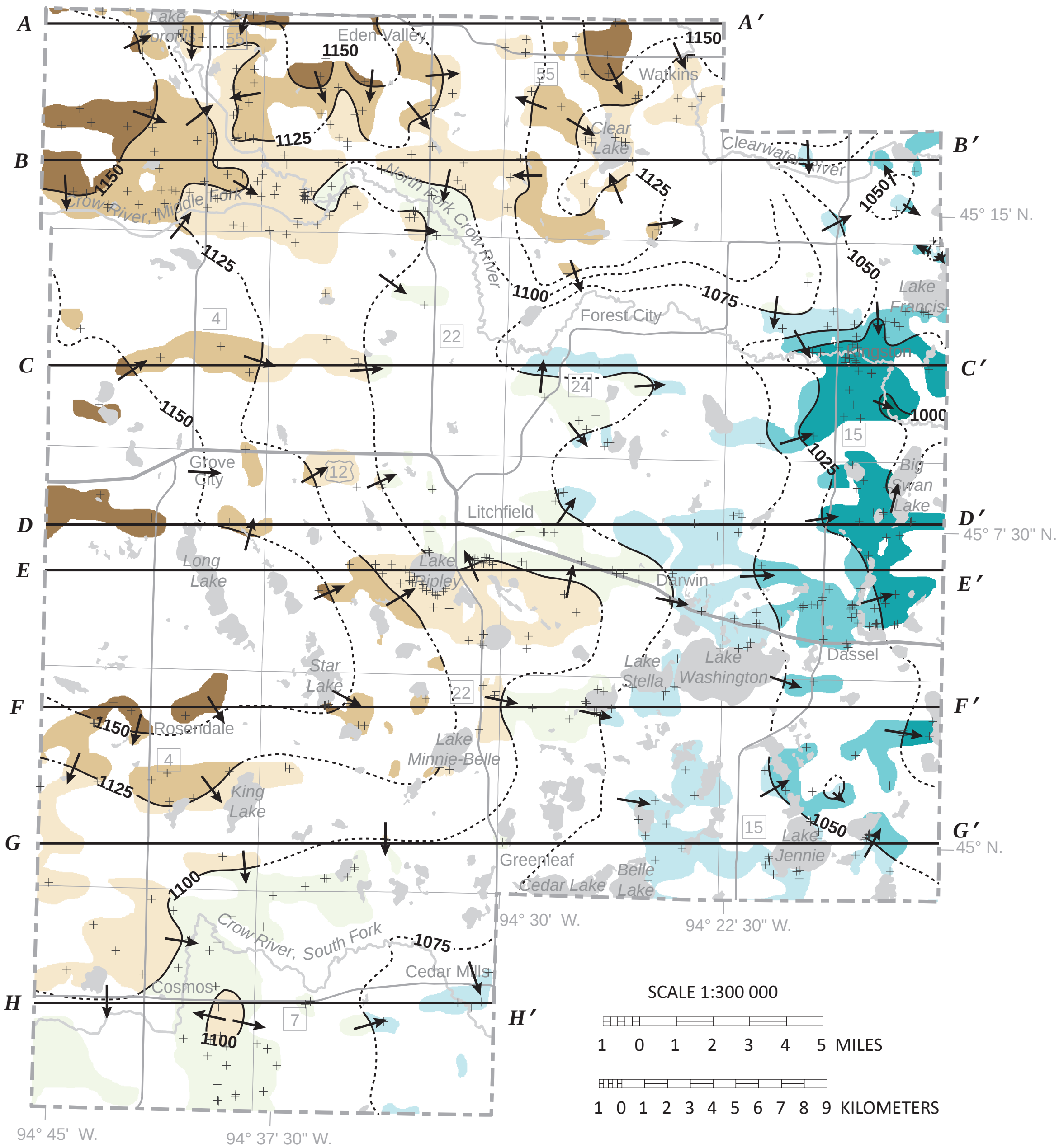
Potentiometric surface elevation (feet)

- >1175–1200
- >1150–1175
- >1125–1150
- >1100–1125
- >1075–1100
- >1050–1075
- >1025–1050
- >1000–1025
- >975–1000
- Aquifer not present

Symbols and labels

- \+ Static water level data
- Groundwater flow direction
- ····1100— Potentiometric surface contour, dashed where approximate; contour interval 25 feet
- *C*—*C′* Line of cross section (Part B)
- Body of water

Figure 8. Potentiometric surface of the scs buried sand aquifer



Potentiometric surface elevation (feet)

- >1150–1175
- >1125–1150
- >1100–1125
- >1075–1100
- >1050–1075
- >1025–1050
- >1000–1025
- >975–1000
- Aquifer not present

Symbols and labels

- Static water level data
- Groundwater flow direction
- 1100 Potentiometric surface contour, dashed where approximate; contour interval 25 feet
- C—C′ Line of cross section (Part B)
- Body of water

Figure 9. Potentiometric surface of the mls buried sand aquifer

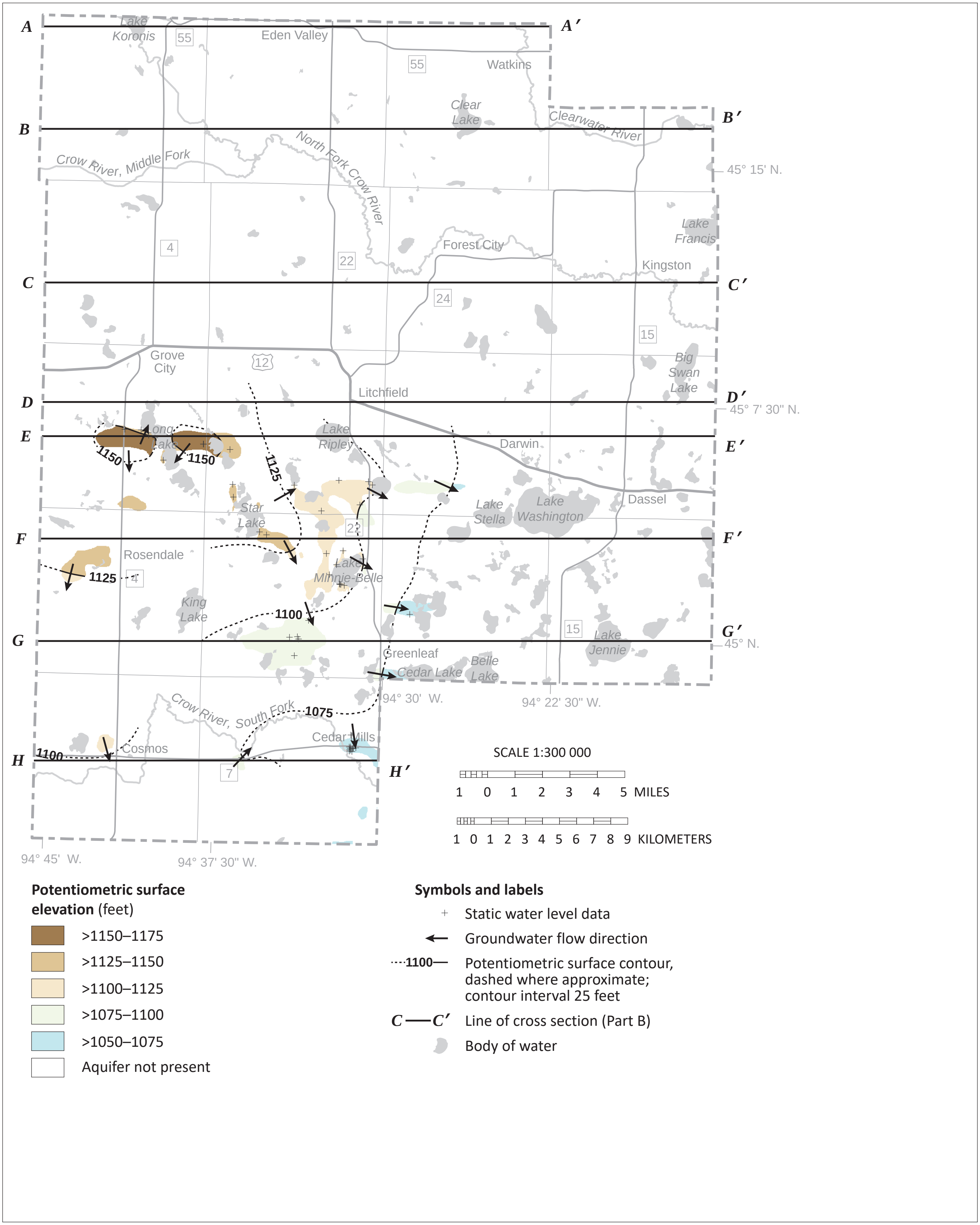


Figure 10. Potentiometric surface of the gs3 buried sand aquifer

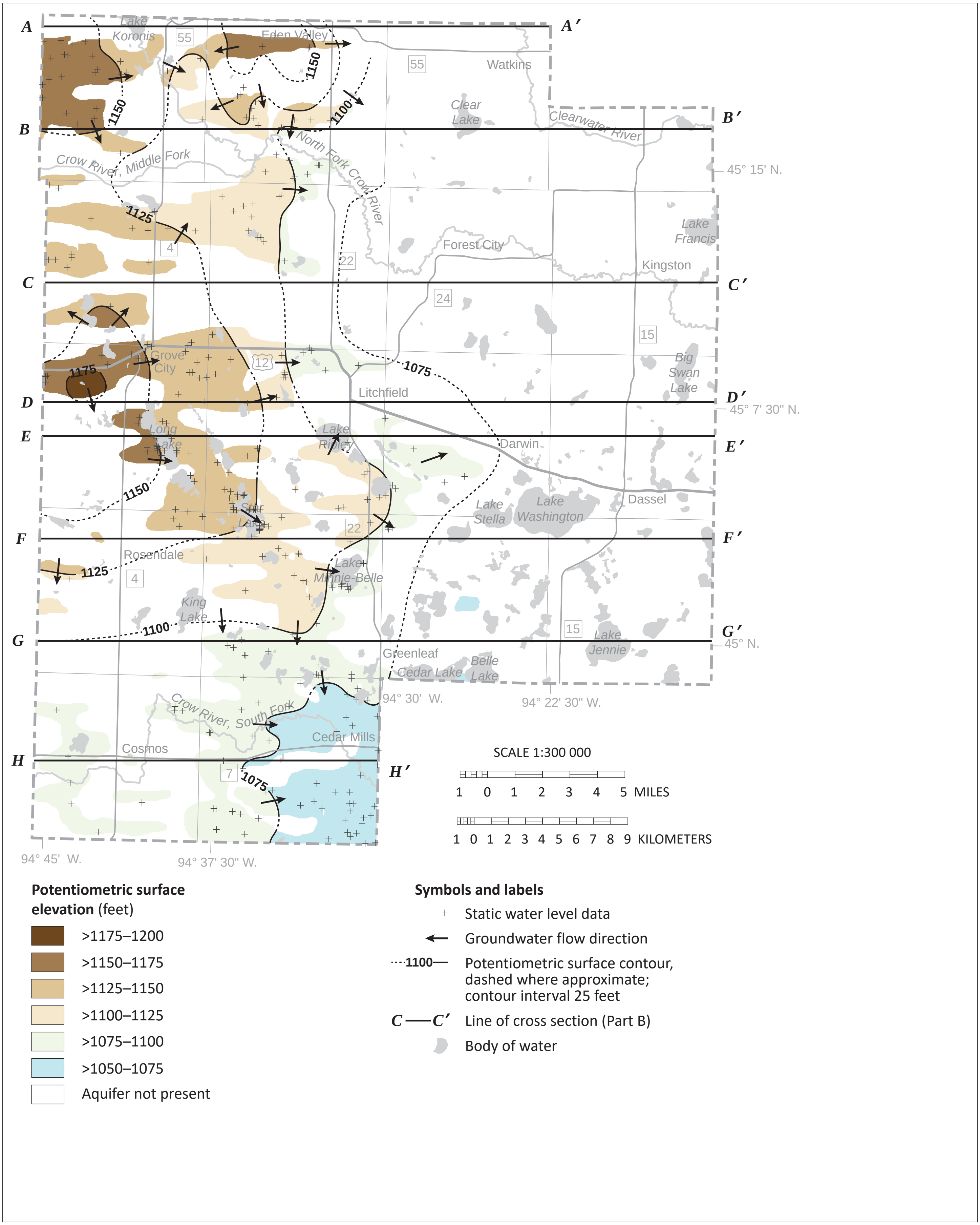


Figure 11. Potentiometric surface of the gs4 buried sand aquifer

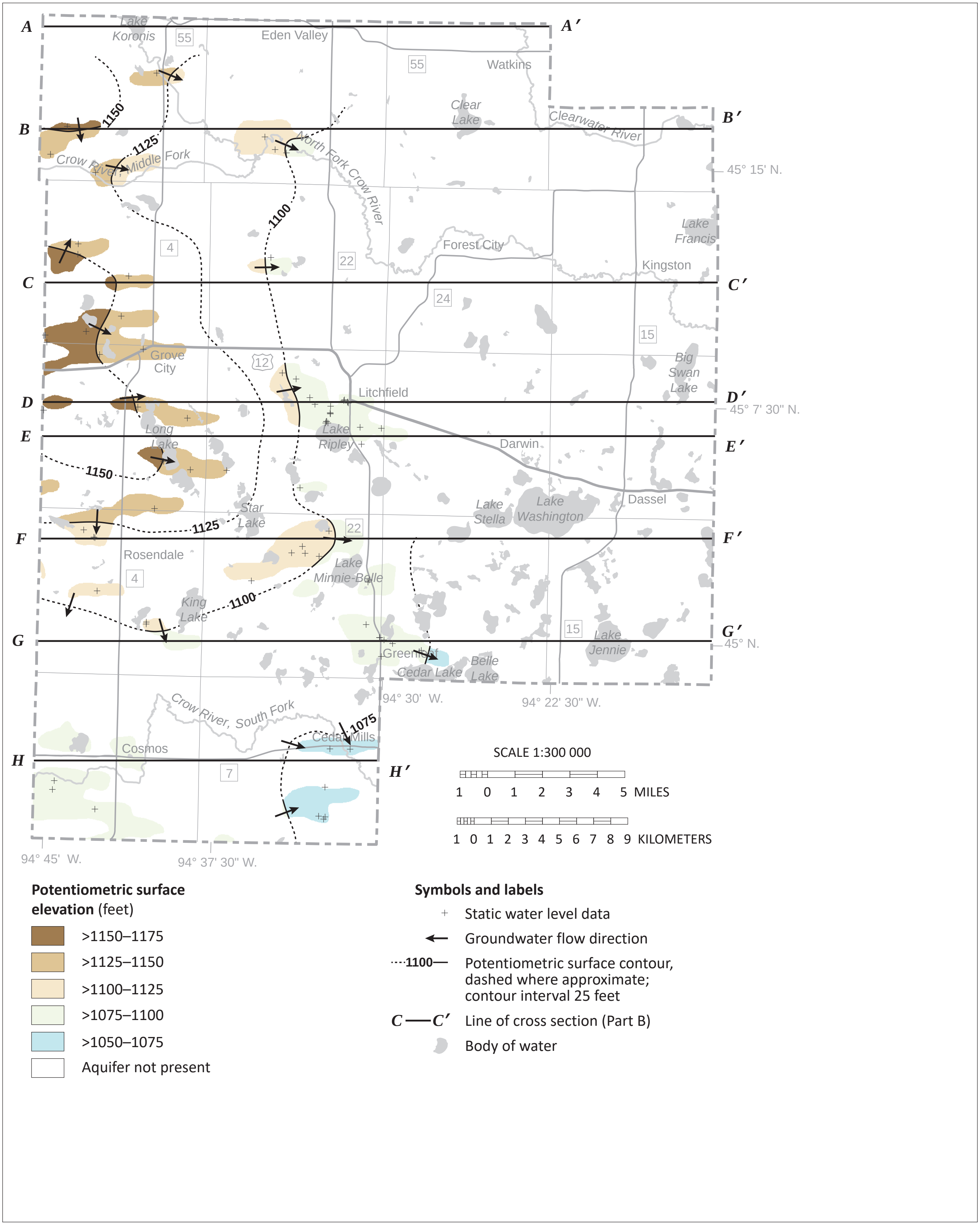
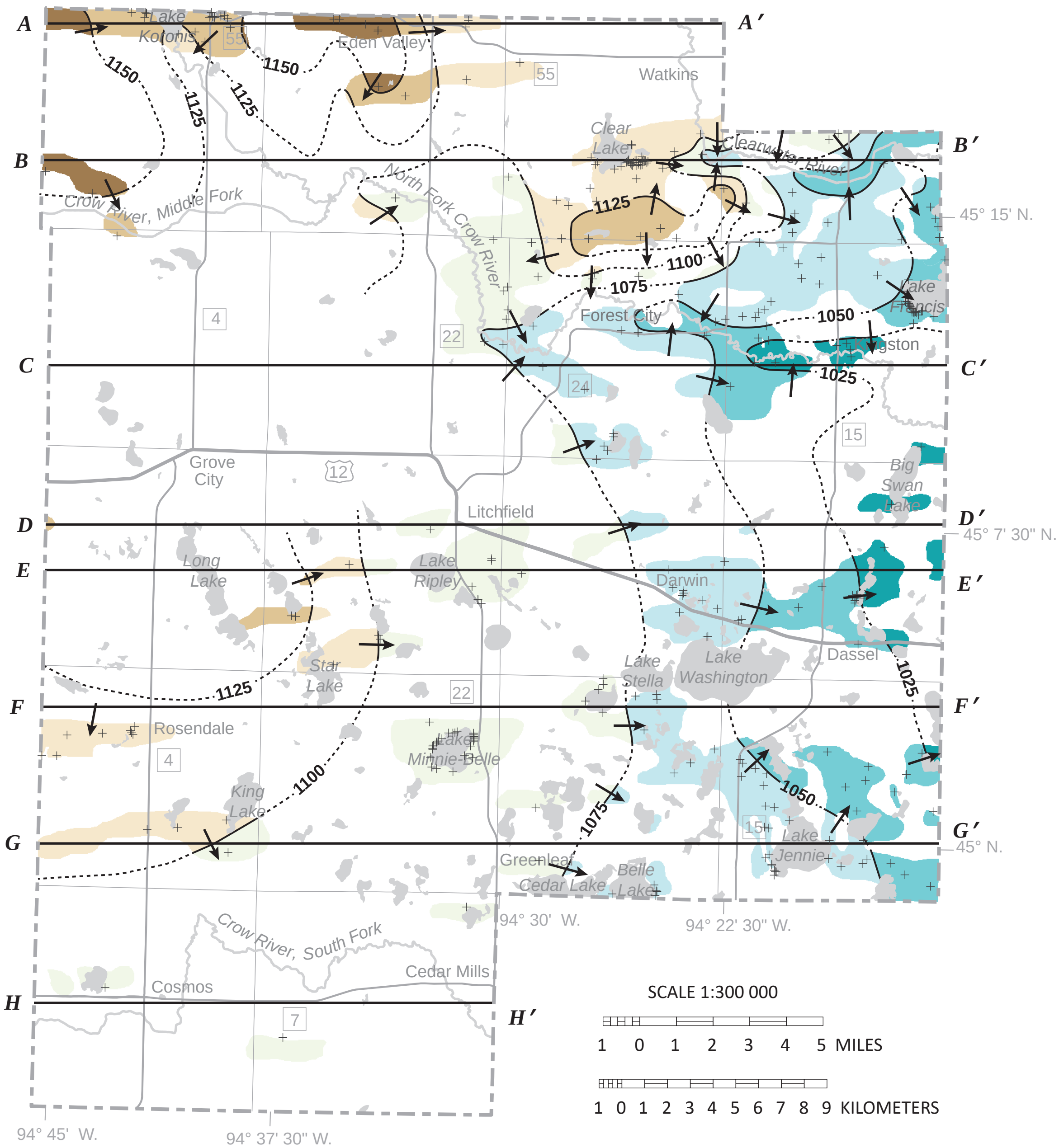


Figure 12. Potentiometric surface of the gs5 buried sand aquifer



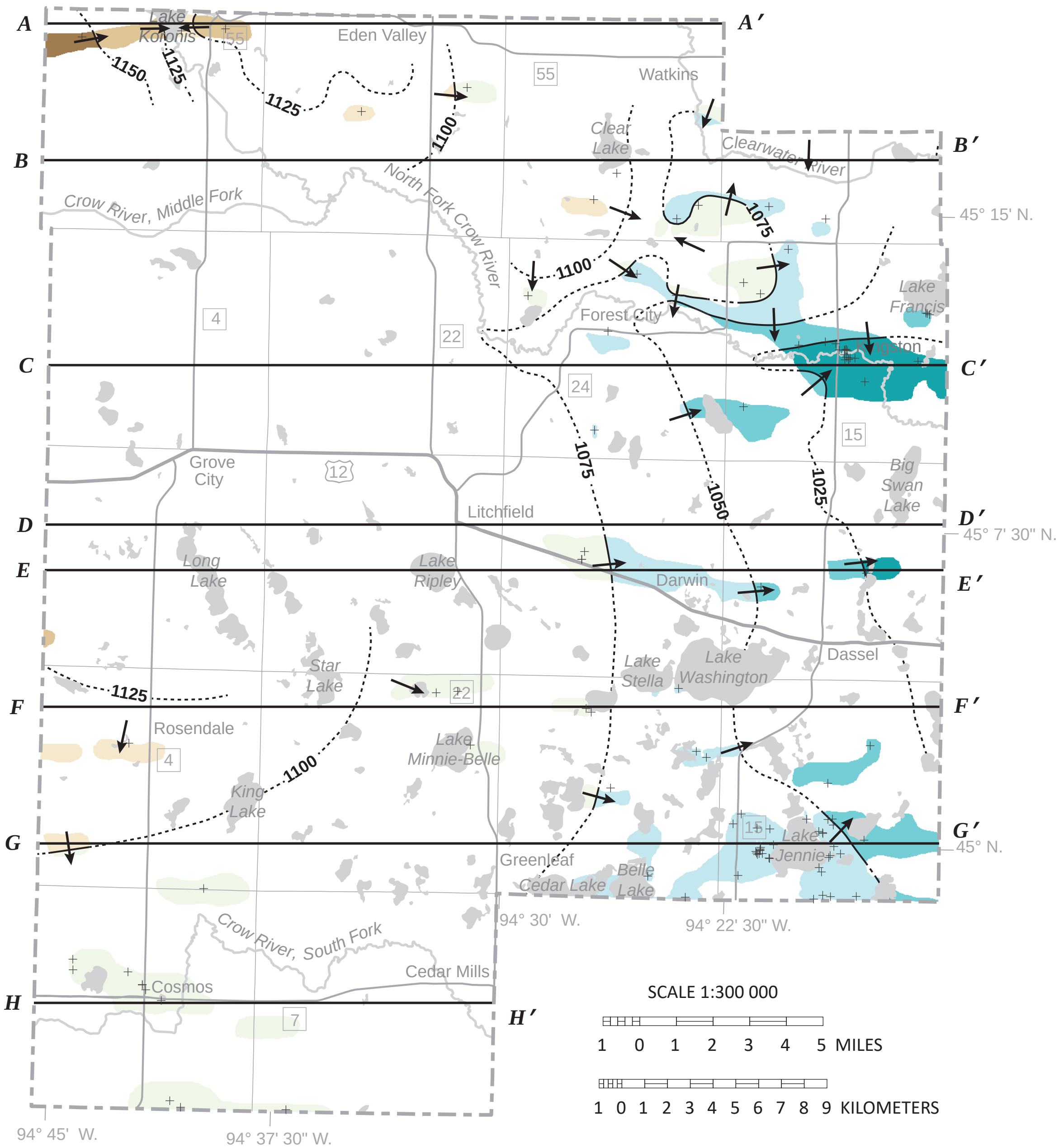
Potentiometric surface elevation (feet)

- >1150–1175
- >1125–1150
- >1100–1125
- >1075–1100
- >1050–1075
- >1025–1050
- >1000–1025
- Aquifer not present

Symbols and labels

- + Static water level data
- ← Groundwater flow direction
- ····1100— Potentiometric surface contour, dashed where approximate; contour interval 25 feet
- *C*——*C′* Line of cross section (Part B)
- Body of water

Figure 13. Potentiometric surface of the wrs buried sand aquifer



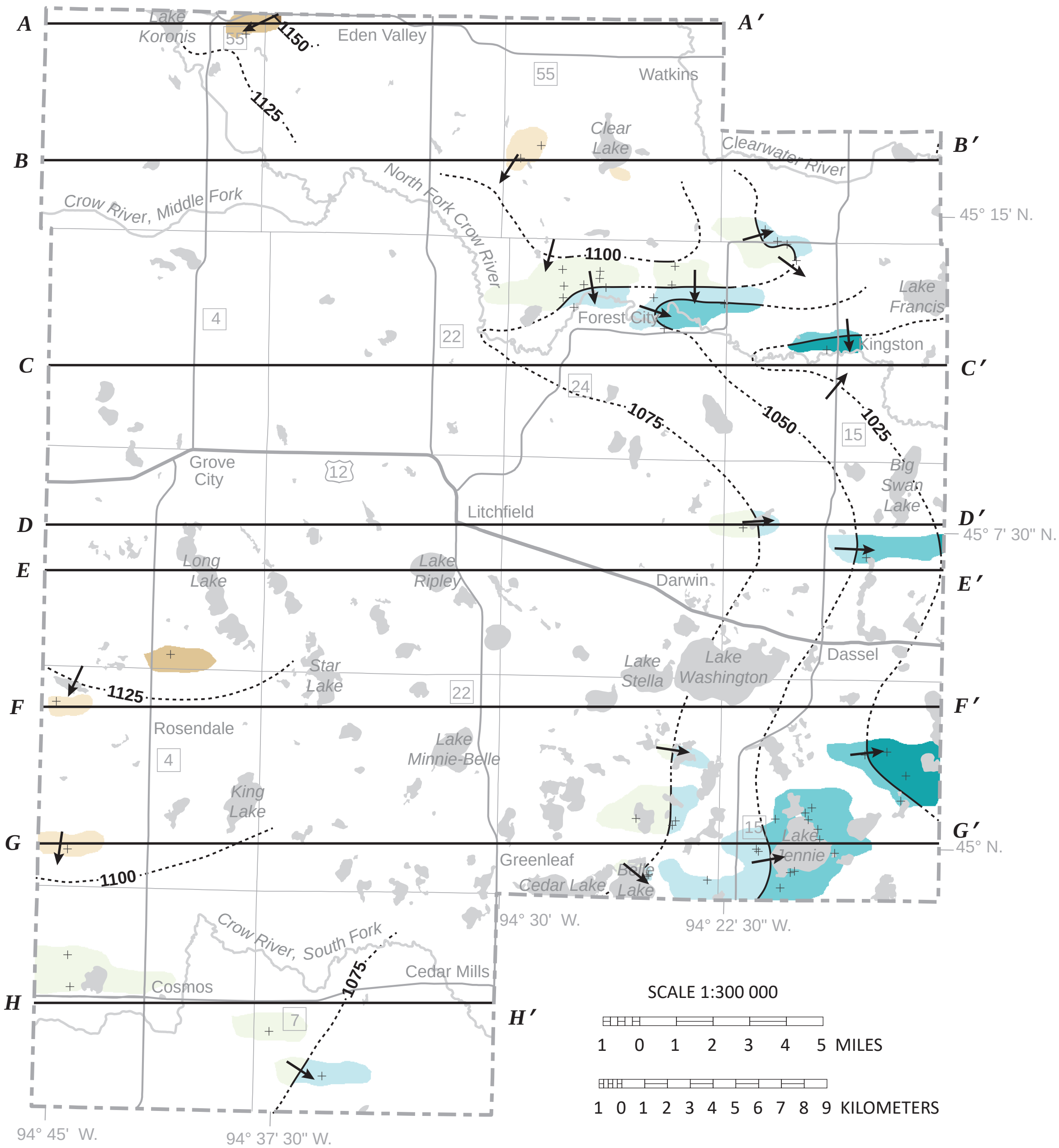
Potentiometric surface elevation (feet)

- >1150–1175
- >1125–1150
- >1100–1125
- >1075–1100
- >1050–1075
- >1025–1050
- >1000–1025
- Aquifer not present

Symbols and labels

- \+ Static water level data
- ← Groundwater flow direction
- ····1100— Potentiometric surface contour, dashed where approximate; contour interval 25 feet
- *C*——*C′* Line of cross section (Part B)
- Body of water

Figure 14. Potentiometric surface of the wes buried sand aquifer



Potentiometric surface elevation (feet)

- >1150–1175
- >1125–1150
- >1100–1125
- >1075–1100
- >1050–1075
- >1025–1050
- >1000–1025
- Aquifer not present

Symbols and labels

- Static water level data
- Groundwater flow direction
- ·····1100— Potentiometric surface contour, dashed where approximate; contour interval 25 feet
- *C*——*C′* Line of cross section (Part B)
- Body of water

Figure 15. Potentiometric surface of the vs buried sand aquifer

Water chemistry (Plate 6)

Precipitation or surface water seeps through the soil layer and into the pores and crevices of aquifers and aquitards. The water moves in complicated but definable patterns: into the aquifers as recharge, through the aquifers, and out of the aquifers as discharge.

The types of dissolved elements and compounds in groundwater provide information about the recharge areas, the geologic layers that the water flowed through, and approximately how long the water has been underground (residence time). Water chemistry is used to provide information such as the following.

- Groundwater **recharged** from surface water can be identified from the effect of evaporation on the isotopes of hydrogen and oxygen.
- Groundwater **residence time** is estimated from tritium and carbon-14 isotopes. Tritium is used to identify water that has moved into the subsurface since the 1950s. Carbon-14 is used to determine groundwater residence times of centuries to millennia.
- Concentrations of select **chemical elements** above their drinking water standard can indicate areas where groundwater consumption is a potential concern to human health.

Water sampling

To better understand groundwater movement and pollution sensitivity in the county, samples were collected from wells in aquifers most important for domestic water supply. Wells were selected based on their aquifer characteristics and distribution and were sampled according to the protocols outlined in Appendix A. Chemical data from well-water samples were used along with physical measurements (static water level and aquifer tests) to understand water movement.

An ideal well-sampling network for the county atlas is distributed evenly across the county, includes populated areas, and targets surface-water and groundwater interaction around lakes and larger rivers. The network sampled for this atlas depends on citizen willingness to participate. Approximately 1000 well owners were contacted for permission to sample. County atlas protocol is to collect samples from approximately 90 of those wells.

The DNR collected water samples and standard field parameters from 89 wells and 10 lakes. The analytical results from these samples were combined with historical chemistry data from the Minnesota Department of Health (MDH) that included 47 well samples and 1 surface-water sample.

Groundwater recharge sources

Chemical changes occur as water moves from precipitation to groundwater. These can help determine whether groundwater was recharged directly from precipitation, surface water, or a mixture of the two. Stable isotopes of oxygen and hydrogen were used for determining groundwater and surface-water interactions (Kendall and Doctor, 2003). Oxygen and hydrogen each have two main stable isotopes: ^{18}O and ^{16}O, and ^{2}H and ^{1}H. The different masses cause each to evaporate at a different rate, which results in fractionation, leaving behind different ratios of heavy to light isotopes. This results in isotopic signatures unique to groundwater with different recharge sources.

- Groundwater recharged directly from **precipitation** has a **meteoric isotopic signature.** The water infiltrated directly into the ground, leaving the isotopic ratio unchanged.
- Groundwater recharged from **surface water** such as lakes or open-water wetlands has an **evaporative isotopic signature.** This water has been subjected to fractionation where light isotopes evaporated into the atmosphere, leaving water enriched in heavier isotopes.

To identify the source (precipitation or surface water) of a groundwater sample, oxygen and hydrogen isotopic data are plotted against each other. The x-axis represents the oxygen isotope value ($\delta^{18}O$) and the y-axis represents the hydrogen isotope value ($\delta^{2}H$). The measured ratio in the sample is divided by the ratio in a standard. The standard used was Vienna Standard Mean Ocean Water (VSMOW).

Definition of delta (δ)

The stable isotope composition of oxygen and hydrogen are reported as δ values. δ ($^{0}/_{00}$) = (R_x/R_s-1)*1000 where R represents the ratio of the heavy to light isotope, 18O/16O or 2H/1H; R_x represents the ratio of the sample; and R_s represents the ratio in VSMOW. Delta values are reported in units of parts per thousand ($^{0}/_{00}$ or permil) relative to VSMOW.

Results

County results were compared to the **global meteoric water line** (GWML) developed from precipitation data from around the world (Craig, 1961). County well samples plot primarily along this line, indicating that most of the groundwater is recharged by precipitation directly infiltrating into the subsurface (Figure 16).

Ten lakes were sampled for stable isotopes and their results plotted to establish a range of evaporative signatures for comparing against groundwater samples, and to establish the local evaporation line.

Most of the $\delta^{18}O$ lake values ranged from -2.6 to -4.8 compared to the groundwater values that ranged between -10.8 and -8.4. Koronis Lake fell between these at -6.56. This comparatively lighter lake value suggests less evaporation from the lake and therefore a shorter residence time for the water. The reason for this could be that Koronis Lake has a much larger contributing watershed than the other lakes sampled and a large watershed to lake area ratio; both can contribute to shorter residence times. Another possibility is that Koronis Lake receives a proportionally larger contribution of groundwater than the other sampled lakes.

Lake recharge is evident in 10 well samples that plot along the evaporation line. The three groundwater samples that plot farthest from the GMWL along the evaporation line are completed in aquifers that likely receive a significant portion of their recharge from lake water. Two of these samples are adjacent to Star Lake located approximately 5 miles southwest of Litchfield. The proportion of lake water recharge is greater in the 65-foot-deep well compared to the 130-foot-deep well as shown by the position of each sample along the evaporation line in Figure 16. The proportions of meteoric and lake water could not be estimated since a lake sample was not collected for comparison. However, stable isotope values for similar lakes suggest the majority of recharge to these wells is from the lake.

The third sample is from a 151-foot-deep well adjacent to Lake Jennie located in far southeast Meeker County. Since a stable isotope sample was collected for Lake Jennie, a two component linear mixing model (Katz, B.G. 1998) was used to approximate the proportion of lake recharge to the well estimated to be around 75 percent.

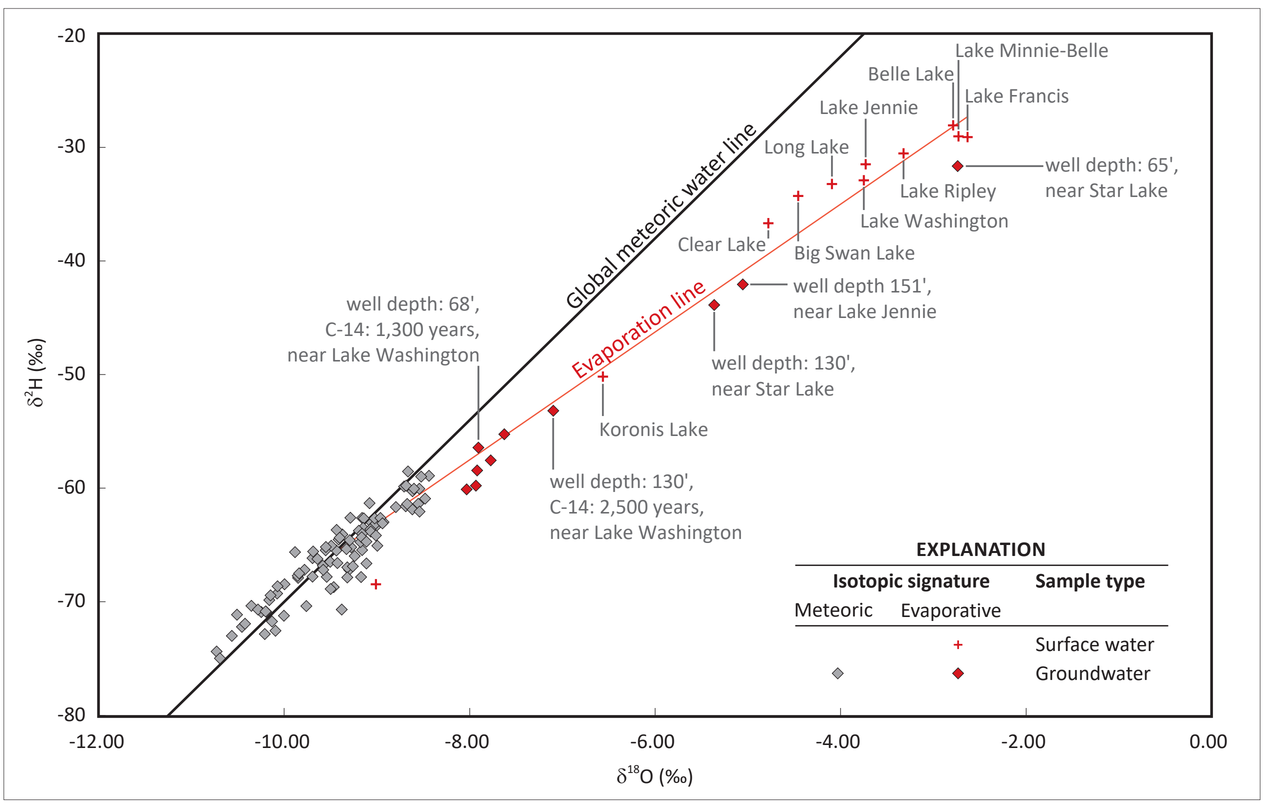


Figure 16. Stable isotope values from water samples

The global meteoric water line (GMWL) represents precipitation values. The GMWL was developed using precipitation samples from around the world and is described by the following equation: $\delta^2H = 8.0\ \delta^{18}O + 10.0$. Groundwater from direct infiltration of precipitation generally plots along or close to the global meteoric water line. Groundwater samples from 88 of the 98 wells plot along this line.

Meteoric waters that undergo evaporation are increasingly enriched in the heavier isotopes (fractionation) resulting in divergence away from and below the GMWL, along **the evaporation line.** Ten lake and ten groundwater samples were used to develop the local evaporation line. The evaporation line represents isotopic fractionation due to evaporation and is described by the following equation: $\delta^2H = 5.6\ \delta^{18}O - 12.5$.

Groundwater residence time indicators

Groundwater residence time is the approximate time that has elapsed since water infiltrated the land surface to the time it was pumped from a well or discharged to a lake, river, wetland, or spring. Short residence time generally suggests short travel paths and/or high recharge rates; long residence time suggests long travel paths and/or lower recharge rates. The residence time of groundwater was estimated for this atlas using isotopic analysis of the radioactive isotopes of hydrogen (tritium) and carbon (carbon-14).

Tritium

- Groundwater residence time was interpreted from the concentration of tritium. Although tritium is a naturally occurring isotope of hydrogen, atmospheric concentrations greatly increased from atmospheric testing of nuclear weapons between 1953 and 1963 (e.g., Alexander and Alexander, 1989). Tritium concentrations were used to estimate groundwater residence time using the known half-life of 12.32 years (Lucas and Unterweger, 2000). The concentrations are presented in tritium units (TU) and are referred to as tritium age in the following categories.
- **Cold War era**: water entered the ground from the peak period of atmospheric tritium concentration from nuclear bomb testing, 1958–1959 and 1961–1972 (greater than 15 TU).
- **Recent**: water entered the ground since about 1953 (8 to 15 TU).
- **Mixed**: water is a mixture of recent and vintage (greater than 1 TU to less than 8 TU).
- **Vintage**: water entered the ground before 1953 (less than or equal to 1 TU).

Historical data (sample dates 1998–2016) are used in the residence time interpretations of this report and are classified according to Table B-2 in Appendix B.

Carbon-14

Ten previously sampled wells with vintage tritium-age water were sampled a second time and analyzed for the carbon-14 (^{14}C) isotope to estimate longer residence times. This naturally occurring isotope has a half-life of 5,730 years, and is used to estimate groundwater residence time ranging from 100 to greater than 40,000 years (Alexander and Alexander, 1989).

Inorganic chemistry of groundwater

Water dissolves minerals in the soil, sediment, and bedrock as soon as precipitation infiltrates the soil layer and becomes groundwater. Its chemistry changes as water moves along its flow paths. Water quality evaluations describe contaminants that are potentially harmful (natural or anthropogenic) and that affect aesthetics. The following guidelines are used in this atlas.

U.S. Environmental Protection Agency

(EPA 2017 July, EPA 2017 March)

Maximum Contaminant Level (MCL): legally enforceable federal standards that apply to public water systems, to limit the levels of contaminants in drinking water.

Maximum Contaminant Level Goal (MCLG): nonenforceable health goals set on possible health risks from exposure over the course of a lifetime.

Secondary Maximum Contaminant Level (SMCL): nonenforceable guidelines for contaminants that may cause aesthetic effects or taste and odor problems in drinking water.

Minnesota Department of Health

(MDH, 2012a)

Health Risk Limit (HRL): the concentration of a groundwater contaminant, or a mixture of contaminants, that can be consumed with little or no risk to health and which has been promulgated under rule.

Health Based Value (HBV): derived using the same algorithm as HRLs. However, they have not yet been promulgated as rules.

The major cations and major anions results are reported in units of parts per million (ppm). Trace elements such as arsenic and manganese are reported in units of parts per billion (ppb). The following chemicals are naturally occurring, though the presence or elevated concentrations of some may be due to anthropogenic sources. Drinking water standards were developed for those chemicals that pose potential health risks.

Chemical descriptions

Calcium, magnesium, and sodium cations and bicarbonate anions are dissolved out of the glacial sediment and bedrock by groundwater. The calcium, magnesium, and bicarbonate constituents are derived from limestone and dolomite bedrock sources (Hem, 1985) and are common in groundwater in glacial sediment aquifers. Bicarbonate is also derived from carbon dioxide present in the atmosphere and in soil above the water table. Sodium is often present in deep aquifers or at mineral interfaces. As groundwater moves through sediment, calcium and magnesium ions in solution are exchanged for sodium ions adsorbed on clay surfaces (Hounslow, 1995).

Sulfate (SMCL 250 ppm) is largely naturally occurring. Common sources of sulfate are dissolution of gypsum and oxidation of sulfide minerals. High concentrations in groundwater can negatively affect taste and may act as a laxative.

Chloride (SMCL 250 ppm, elevated ≥ 5 ppm) can occur naturally from deep sources such as residual brine, or it may come from anthropogenic sources including road salts, water softener salts, and fertilizers. (Davis and others, 1998; Panno and others, 2006; Mullaney and others, 2009). In Meeker County, chloride/bromide ratios equal or exceeding 250 indicate that chloride is likely from an anthropogenic source, and less than 250 are from natural sources.

Nitrate-nitrogen (nitrate) (MCL and HRL 10 ppm, elevated ≥ 1 ppm) can occur naturally at low concentrations but elevated concentrations can indicate impacts from fertilizer and animal or human waste. Nitrate concentrations lessen with time (denitrification) when there is little oxygen in the groundwater. In Minnesota, groundwater with long residence time typically has little available oxygen and low to no nitrate. (MDH, 1998; Wilson, 2012).

Arsenic (MCL 10 ppb; MCLG 0) is a naturally occurring element that has been linked to negative health effects, including cancer. The MDH advises domestic well owners to treat drinking water if arsenic is detected at any level (MDH, 2018a). Current science cannot predict which wells will have high arsenic concentrations, therefore newly constructed drinking-water wells are tested for arsenic (Minnesota Administrative Rules 4725.5650, 2008).

The factors affecting elevated arsenic concentrations in groundwater are not completely understood. There is a strong correlation with glacial sediment derived from rocks northwest of Minnesota (Erickson and Barnes, 2005a). High arsenic concentrations are believed to be caused by naturally-occurring arsenic-bearing minerals that are associated with small shale particles in these tills. Some of this arsenic was previously released and then adsorbed to surfaces of mineral crystals and other small particles during earlier oxidizing conditions. This surface-adsorbed arsenic (the most chemically available form) is released to groundwater under reducing conditions (Erickson and Barnes 2005b; Nicholas and others, 2011; Thomas, 2007). Research also indicates that arsenic concentrations are increased in wells that have short-screened sections near the boundary of an aquifer and aquitard (Erickson and Barnes, 2005a; McMahon, 2001).

Manganese (HBV 100 ppb; SMCL 50 ppb) is a naturally occurring element that is beneficial to humans at low levels, but high levels may harm the nervous system (MDH, 2018b). In addition to health effects, concentrations above the SMCL can cause negative secondary effects such as poor taste, odor, and water discoloration (stained laundry and plumbing fixtures).

Organic chemicals were not a part of this investigation but can be found in reports from other state agencies (pesticides and their breakdown products, solvents, degreasers, etc.).

Results

Chloride

Of the 103 wells sampled, 21 had elevated levels, 7 suggest an anthropogenic source, and 14 suggest a natural source. Of the 21 elevated samples, 16 wells are completed in the shallower ss, hs, ms, and scs aquifers at depths less than 100 feet below land surface. The sample with the highest naturally elevated chloride (151 ppm) came from a 203-foot-deep well in the Dakota aquifer (Kd) in far northeastern Meeker County. This sample had vintage tritium-age water and a chloride/bromide ratio of 177.

Nitrate

Of the 107 wells sampled, 2 had elevated levels; 1 was completed in the hs aquifer and the other in the surficial sand (ss) aquifer. Both wells are shallow (54 and 61 feet, respectively) and have mixed tritium-age water indicating it is more recently recharged. The general absence of nitrate is not surprising because all but three of the wells sampled for dissolved oxygen were anoxic (very low dissolved oxygen), indicating potential denitrifying conditions in the aquifer.

Arsenic

Of the 118 wells sampled for arsenic, 45 percent exceeded the MCL. No discernible spatial patterns or correlations with specific aquifers were found. Arsenic levels statewide are above the MCL in an average of 10 percent of the private wells sampled by the MDH from August 2008 through March 2016 (MDH, 2018c).

Manganese

Of the 104 wells sampled for manganese, 62 percent exceeded the HBV. No discernible spatial patterns or correlations were found with specific aquifers. Concentrations above the HRL were found in most of the aquifers sampled.

Statewide, manganese concentrations were greater than the HBV in drinking-water wells for 57 percent of water-table aquifers and 63 percent of buried sand aquifers sampled (MDH, 2012b). Although there are no clear patterns of manganese distribution across most of Minnesota, the MDH has found that southeastern Minnesota tends to have low levels of manganese (below 50 ppb) and southwestern Minnesota tends to have higher levels (some over 1,000 ppb).

Piper diagram: major cations and anions

Descriptions

The Piper diagram is useful for showing multiple chemistry results and for observing trends in major ions. It has three components: a cation triangle, an anion triangle, and a central diamond. Every sample is represented by three data points: one in each triangle and one in the diamond grid.

On both of the ternary diagrams (triangles), major ions are plotted as percentages of milliequivalents per liter (meq/l) of total cations or total anions. The lower left ternary diagram compares the major cations: calcium, magnesium, and sodium plus potassium. The lower right ternary diagram compares the major anions: bicarbonate, sulfate, and chloride plus nitrate. The data points in the two ternary diagrams are then projected onto the diamond grid to show the overall chemical characteristics of the groundwater. The dashed arrows show an example of this relationship on the Piper diagram in Figure 17.

A water type is assigned to the samples by plotting each on a Piper diagram. This represents a water sample relative to the most common ionic constituents in natural waters. The relative proportions differ depending on the water's original interaction with the atmosphere, any subsequent interactions with anthropogenic sources, and the aquifer.

Results

Water types were interpreted from clusters of sample concentrations with a similar range of values. The naming convention used the two principal end members in the cation and anion groups (Back, 1966; Wilson, 2012). The first accounted for 50 percent or more of the total and the second for at least 10 percent. The majority of Meeker County samples classify as calcium-magnesium bicarbonate, calcium-sodium-bicarbonate, and calcium-magnesium-bicarbonate-sulfate-type waters. These water types are common in Minnesota. Three samples plot outside the typical chemical range of Meeker County groundwater, indicated with numbers 1 through 3 on Figure 17.

Two of the atypical samples were collected from the scs aquifer near the cities of Cosmos and Kingston with well depths of 109 and 86 feet, respectively. In the well near Cosmos, sulfate is the major anion, not bicarbonate. This difference likely reflects groundwater recharge through till that has a greater proportion of sulfide sources.

The sample near Kingston is not very deep, but older water with a longer flow path is suggested by the vintage tritium age and the degree of cation exchange with sodium on the cation ternary diagram. The location of this site is in a valley associated with the Crow River, and it is possible that there is upwelling of older water at this location.

A third sample is classified as a sodium-calcium-mixed anion-type water collected from a Dakota aquifer (Kd) well at a location just northeast of Watkins. Several of the chemical parameters analyzed represent maximum values compared to values in the county. This suggests that sediment may contain residual saline brines.

On the cation ternary diagram there appears to be a relationship between percent sodium and groundwater age. A red line separates samples that have less than 10 percent meq/l sodium from those with a greater percentage. The 41 samples above the 10 percent threshold are of vintage tritium age. Of the samples with less sodium, half have a vintage tritium age, and the rest have a mixed or recent tritium age.

Cation exchange is the likely mechanism where sodium adsorbed on the clay-size fraction of the glacial till likely exchanges with dissolved calcium and magnesium ions in groundwater as the water slowly moves through these lower permeability units.

On the anion ternary diagram there are six samples highlighted with yellow that have elevated nitrate or elevated chloride with chloride/bromide ratios indicating anthropogenic sources. Samples plotting toward the chloride plus nitrate axis are commonly mixed and recent tritium age. One exception is a vintage tritium-age sample (number 3 on Figure 17) collected from a Dakota aquifer (Kd) that has elevated chloride (151 ppm), but a chloride/bromide ratio indicating a natural chloride source.

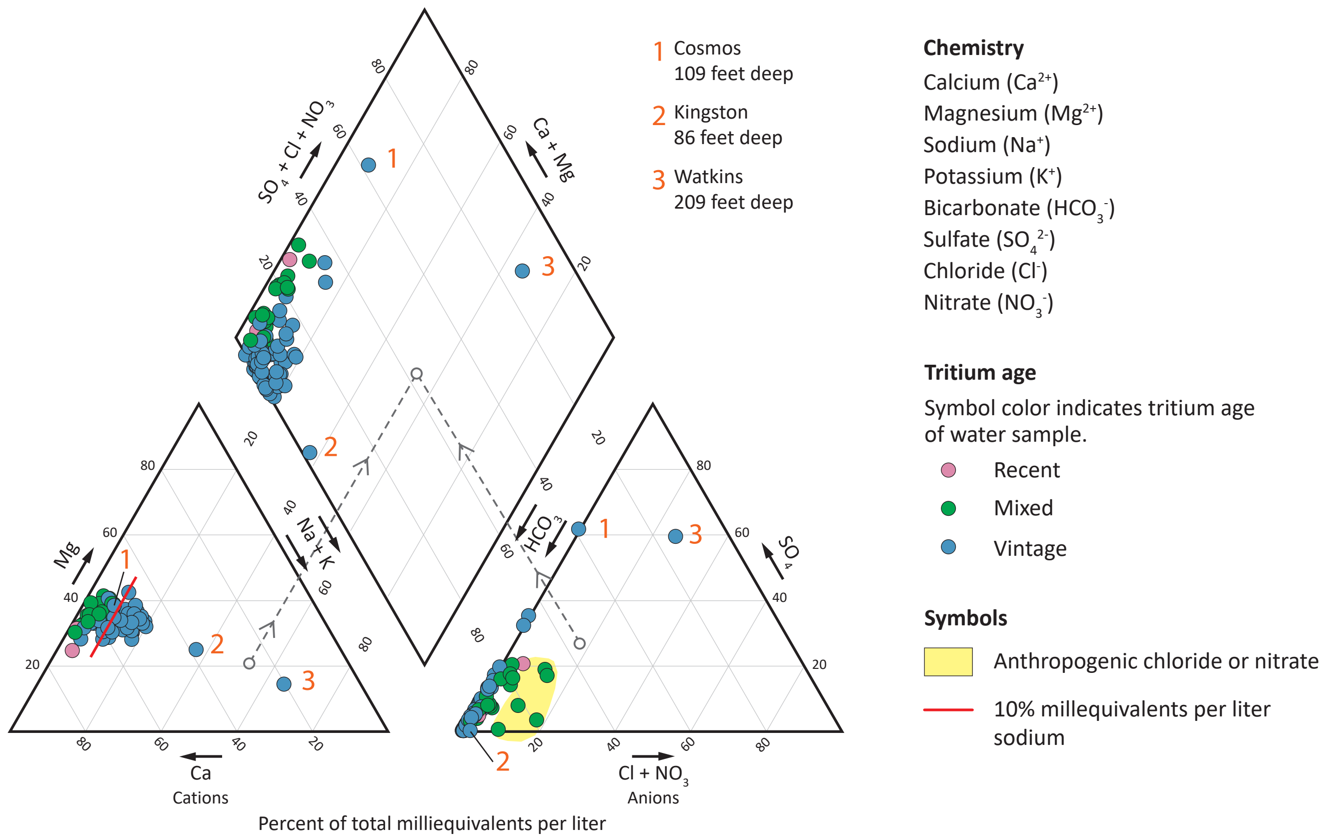


Figure 17. Piper diagram of DNR groundwater samples

Comparison of the relative proportions of cations and anions in groundwater from all the wells sampled by the DNR. The cations and anions are shown in the left and right triangles, respectively. The center diamond shows a composite of cations and anions. Groundwater residence time generally increases as sodium exchanges with calcium and magnesium on the cation diagram. Samples with elevated nitrate or chloride are typically associated with mixed and recent tritium-age water as shown on the anion diagram.

Pollution sensitivity

Pollution sensitivity is defined as the potential for groundwater to be contaminated because of the properties of the geologic material. Migration of contaminants dissolved in water flowing through unsaturated and saturated sediment is a complex process that is typically affected by biological degradation, oxidizing or reducing conditions, and other factors. The methods used to interpret pollution sensitivity included the following general assumptions:

- Flow paths are vertical and downward from the land surface through the soil and underlying sediment to an aquifer.
- A contaminant is assumed to travel at the same rate as water.
- A dissolved contaminant that is moving within water from the surface is not chemically or physically altered over time.

River valleys can be important groundwater discharge areas (see "Hydrogeologic cross sections"). Local upward groundwater movement is characteristic of these areas and the actual pollution sensitivity may be less than rated.

Two models were used to estimate the pollution sensitivity, based on the different properties of the aquifer materials or the thickness of the geologic layers. The following assumptions were applied.

- **Near-surface materials** (to a depth of 10 feet): sediment texture is the primary property used to create a sensitivity map. The permeability of the sediment matrix texture is estimated based on hydrologic theory and empirical data to establish a downward flow rate. The vertical travel time is then estimated using the downward flow rate multiplied by the vertical travel distance.
- **Buried aquifers**: sediment above and between buried sand aquifers is fine grained with low hydraulic conductivity. The method only considers the cumulative thickness of fine-grained sediment overlying aquifers. It does not consider differences in sediment texture or permeability of aquitard materials.

The model results are evaluated by comparing select chemistry from mapped aquifers.

The central concept for both types of pollution sensitivity maps is the relative rate of groundwater movement. This is described as infiltration in the unsaturated zone, and recharge in the saturated zone. Areas of high sensitivity can be areas of high recharge. In addition to soil properties, land cover also affects potential recharge (Smith and Westenbroek, 2015).

Near-surface materials

Methods

The pollution sensitivity of near-surface materials is an estimate of the time it takes for water to infiltrate the land surface, travel through the unsaturated zone, and reach the water table, which is assumed to be 10 feet below land surface. The first 3 feet is assumed to be soil; the next 7 feet (3–10 feet) is assumed to be surficial geological material. If there are no soil data, the transmission rate is based on 10 feet of the surficial geologic unit.

The transmission rate will vary depending on the texture. Coarse-grained materials generally have faster transmission rates than fine-grained materials. The two primary inputs used to estimate transmission rate are the hydrologic soil group and the surficial geologic matrix texture. Attributes of both are used to estimate the time of travel (Table 1) (Natural Resources Conservation Service, 2016; Part A, Plate 3).

The time of travel through near-surface sediment varies from hours to approximately a year (Figure 18).

- Areas with a relatively short travel time (hours to a week) are rated high sensitivity.
- Areas with a longer travel time (weeks to a year) are rated low or very low.
- Areas with travel times of more than a year are rated ultra low. There are no ultra low areas in this county.

Further details are available in *Methods to estimate near-surface pollution sensitivity* (DNR, 2016b).

Results

Very low sensitivity is associated with clayey till deposits (nht) covering the southwest portion of the county (Figure 19). Glacial and post-glacial silty clay deposits scattered throughout the county are also mapped with very low sensitivity with the largest mapped features located in proximity to the North Fork Crow River along cross section C–C′.

Low sensitivity is associated with loam and sandy loam tills that cover large portions of the county with the exception of the southwest corner. Together, very low and low sensitivity encompass approximately 78 percent of the county.

Moderate sensitivity is mostly associated with a variety of loam and sandy loam textured lake sediment. The most extensive deposits include locations east of Litchfield and north of Darwin, and a large area south of Eden Valley.

High sensitivity is mostly associated with glacial outwash sand and gravel in the central and northern portions of the county. These deposits are typically found in glacial and modern drainageways, including the North Fork Crow River and Middle Fork Crow River. There is also a large deposit of glacial Lake Litchfield deltaic sands near Litchfield and Darwin.

Table 1. Transmission rates used to assess the pollution sensitivity rating of near-surface materials

Hydrologic Soil Group (0–3 feet)		Surficial Geologic Texture (3–10 feet)		
Group*	**Transmission rate (in/hr)**	**Classification**	**Transmission rate (in/hr)**	**Surficial geology map unit (Part A, Plate 3)**
A, A/D	1	gravel, sandy gravel, silty gravel	1	hwi, nd, ng, ni, nlg
		sand, silty sand	0.71	eo, ls
B, B/D	0.50	silt, loamy sand	0.50	al, ns
		sandy loam, peat	0.28	hwt, nhs, nvs, pe
C, C/D	0.075	silt loam, loam	0.075	nva, nvt
		sandy clay loam	0.035	Not mapped in county
D	0.015	clay, clay loam, silty clay loam, sandy clay, silty clay	0.015	ac, ll, nht, nl
--	--	glacial lake sediment of Lake Agassiz	0.000011	Not present in county

Note that peat is used as an overlay on the map due to variable and typically unknown thicknesses.
*The Natural Resources Conservation Service (NRCS) defines hydrologic soil groups primarily based on texture and the occurrence of low permeability layers (Natural Resources Conservation Service, 2009).
Group A: water is freely transmitted. Soils are more than 90 percent sand and gravel.
Group B: soils are less permeable but water transmission is still unimpeded.
Group C: water transmission is somewhat restricted.
Group D: water movement is restricted or very restricted.

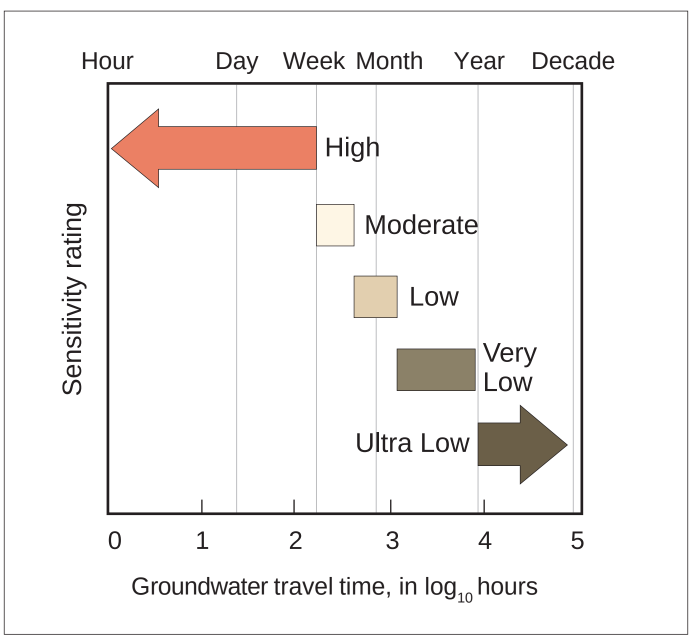
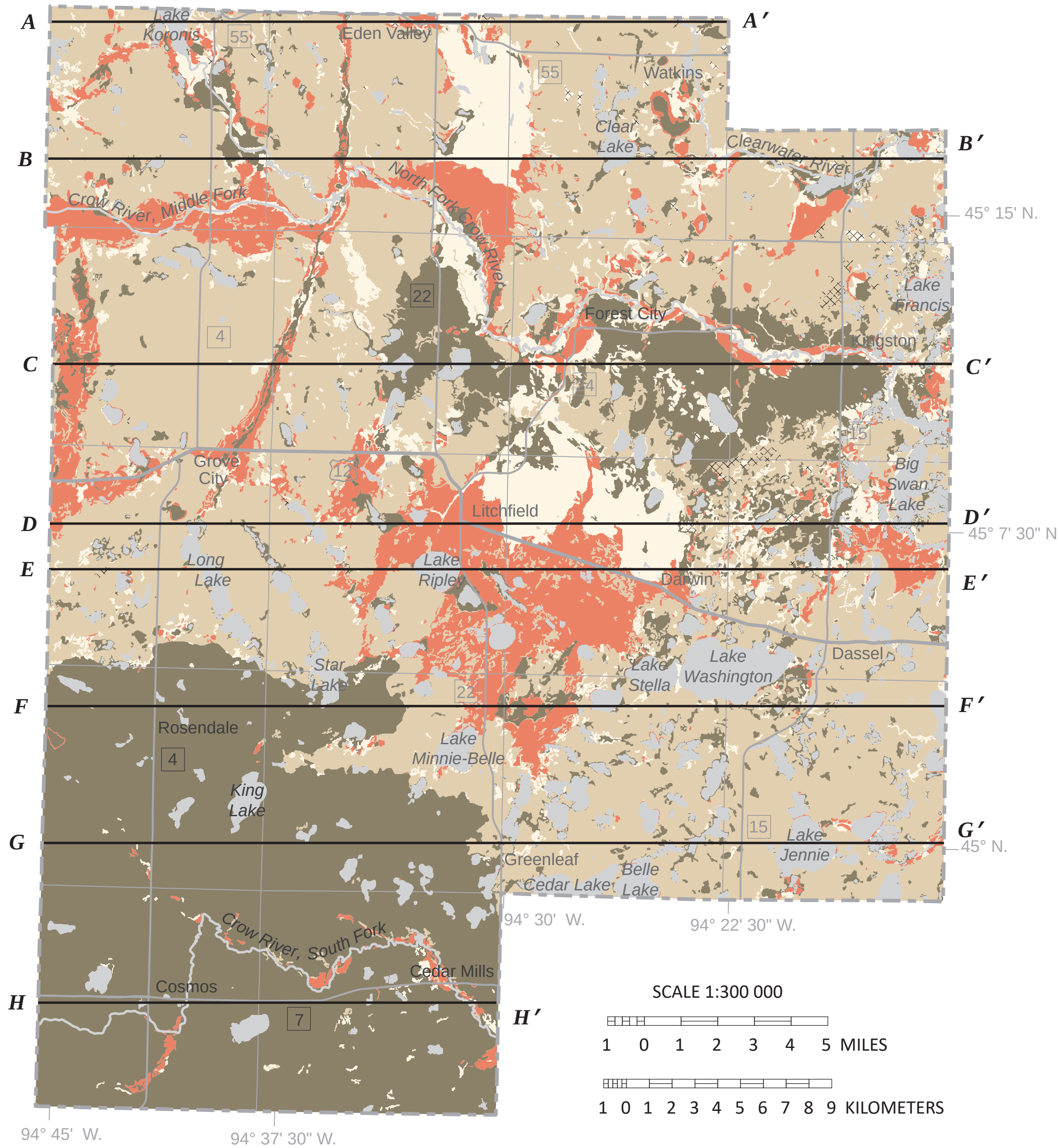


Figure 18. Pollution sensitivity rating of near-surface materials



Estimated vertical travel time through near-surface materials

- High: hours to a week
- Moderate: a week to weeks
- Low: weeks to months
- Very Low: months to a year

Symbols and labels

- *C*——*C′* Line of cross section (Part B)
- Body of water
- Peat

Figure 19. Pollution sensitivity of near-surface materials

Estimated vertical travel time to an assumed 10-foot deep water table.

Buried sand aquifers and bedrock surface

Methods

The sensitivity rating for the buried sand aquifers and the bedrock surface is based on estimated vertical travel times defined by the Geologic Sensitivity Workgroup (1991). Travel time varies from hours to thousands of years. Areas with ratings of high or very high have relatively short travel times of less than a few years. Areas rated low or very low have estimated travel times of decades or longer (Figure 20).

The DNR developed a pollution sensitivity model that represents how precipitation infiltrates the land surface and recharges portions of deeper aquifers. The central concept is that focused (relatively rapid) recharge occurs where aquifers overlap and are connected by complex pathways. The model assumes that the thickness of fine-grained sediment overlying an aquifer is inversely proportional to the sensitivity of an aquifer. The thicker the fine-grained sediment, the longer it takes for water to move through it (Figure 21).

Geographic Information Systems (GIS) software was used to calculate cumulative thickness of the low-permeability sediment layers in the county. Thicknesses of 10 feet or less were rated very high sensitivity, thicknesses greater than 40 feet were rated very low, and thicknesses between 10 and 40 were given intermediate ratings. More details are available in *Procedure for determining buried aquifer and bedrock surface pollution sensitivity based on cumulative fine-grained sediment thickness* (DNR, 2016c).

The model results were combined with groundwater flow directions (derived from potentiometric surfaces) to help understand the distribution of particular chemical constituents. The pollution sensitivity values and spatial distributions were compared to the tritium age of groundwater.

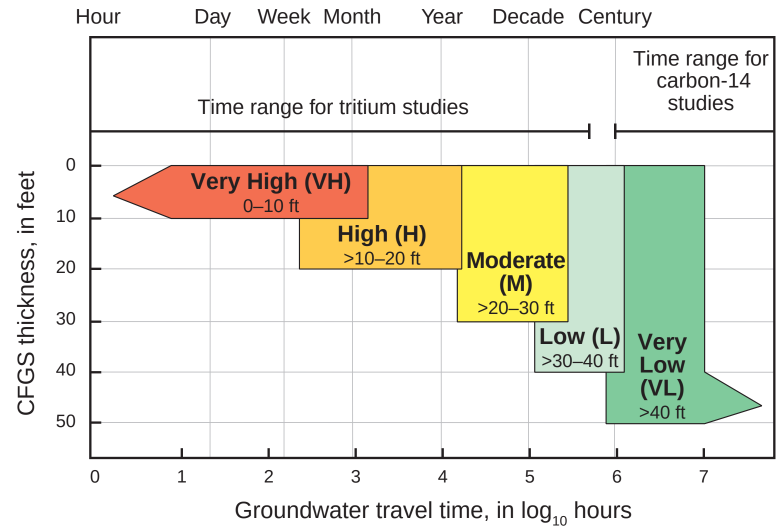


Figure 20. Geologic sensitivity rating for the buried sand aquifers and the bedrock surface

Sensitivity is defined by estimated vertical travel time. The numbers following each rating represent the *cumulative fine-grained sediment* (CFGS) thickness overlying an aquifer.

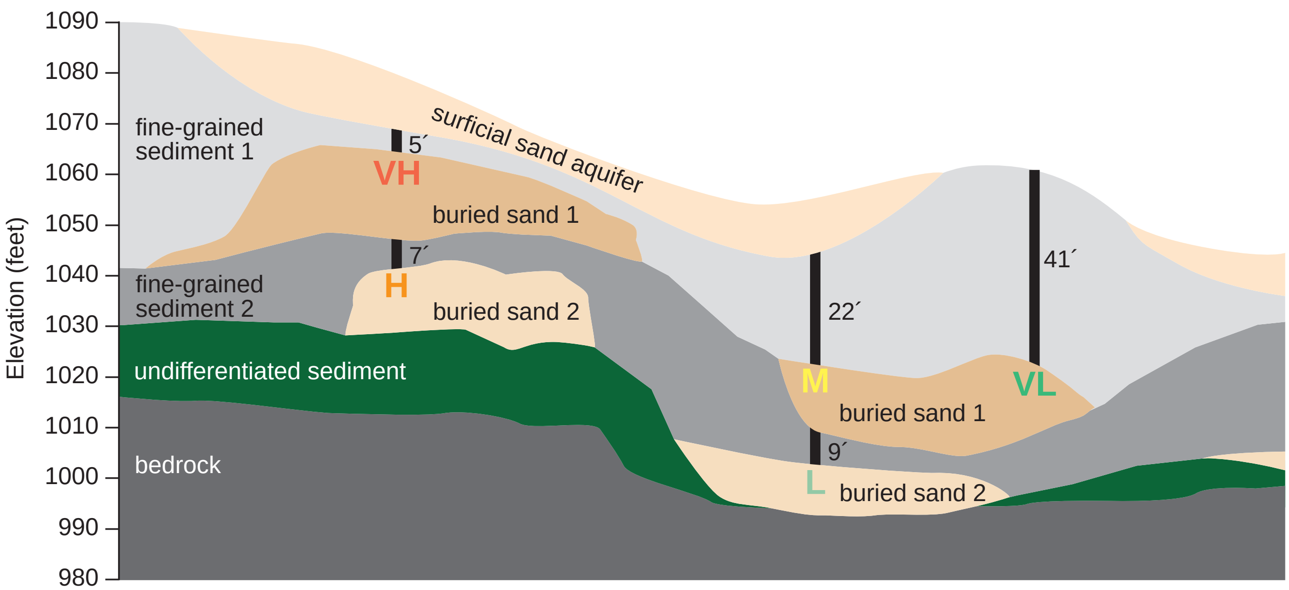


Figure 21. Cross section showing examples of pollution sensitivity ratings

Sensitivity ratings are based on the cumulative thickness of overlying fine-grained sediment. Each vertical black line is labeled with the thickness of fine-grained sediment. The letter at the base of the line indicates the sensitivity rating.

Groundwater conditions

Groundwater recharge, presumed flow paths, and discharge can be evaluated using the combination of groundwater residence time, equipotential contours, water chemistry, and relative hydraulic conductivity. The following conditions provide a way of linking pollution sensitivity with residence time and anthropogenic indicators (tritium, anthropogenic chloride and nitrate).

(1) Water from the surface moves through a thin layer of overlying fine-grained material to an underlying aquifer.

(2) Groundwater moves from an overlying surficial aquifer to a buried aquifer.

(3) Groundwater moves from an overlying buried aquifer to an underlying buried aquifer.

(L) Groundwater flows laterally.

(P) Tritium concentration may be artificially elevated by high capacity pumping.

(U) Groundwater flowpath is unknown.

(D) Groundwater discharges to a surface-water body.

In general, conditions 1, 2, 3, and the associated tritium-age water (recent and mixed) match the type of vertical groundwater flow and focused recharge that is assumed in the pollution sensitivity model. These conditions provide some validation of the model in areas of moderate to very high sensitivity.

Limitations of the model are represented by conditions L (lateral) and U (unknown). Condition L indicates that recent or mixed tritium-age water is assumed to be flowing laterally from upgradient sources. Condition U indicates the model can't explain the origin of recent or mixed tritium-age water in deep, isolated, or protected settings.

The conditions are displayed on the pollution sensitivity figures and cross section plates. Conditions vary across the state and may not be present in every county.

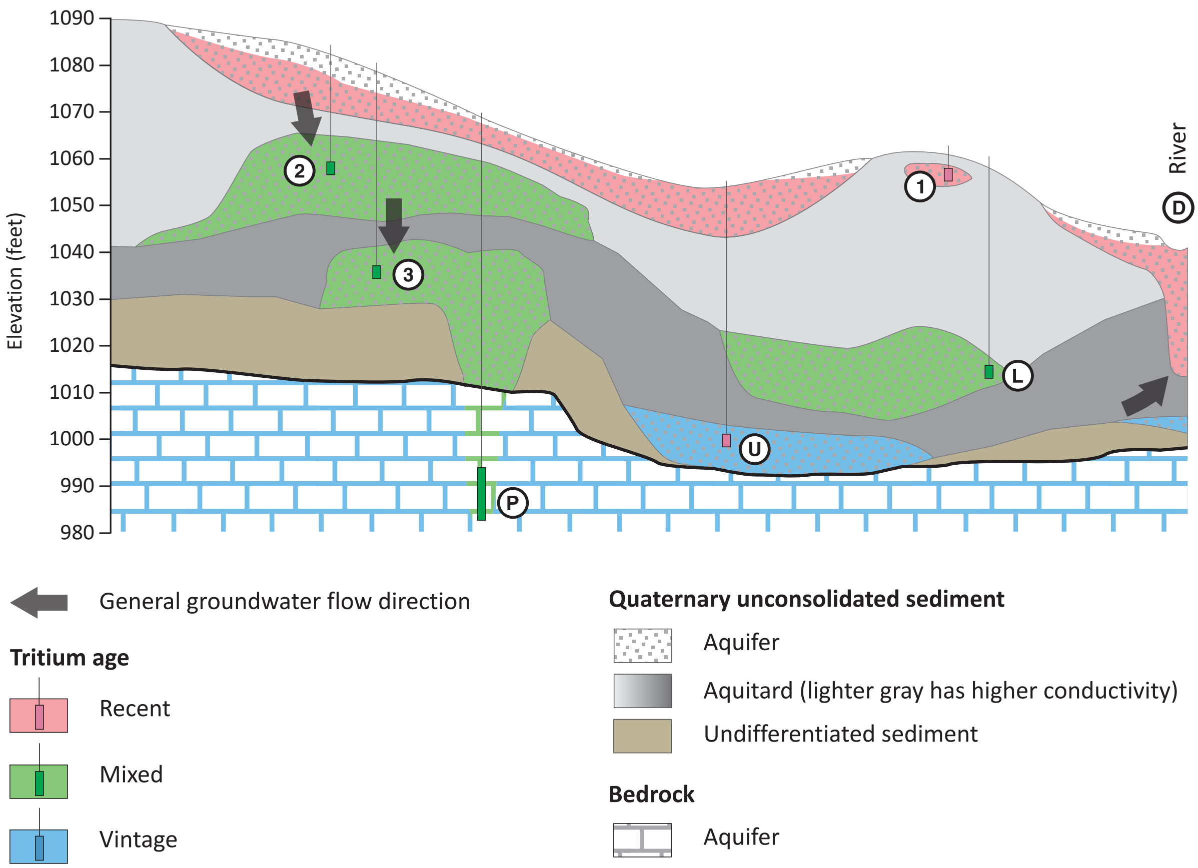


Figure 22. Hypothetical cross section illustrating groundwater conditions

This cross section shows interpretations of why tritium might be present in groundwater samples exposed to different groundwater conditions.

Results

This section describes the pollution sensitivity for the buried aquifers in stratigraphic order from youngest to oldest, and includes the depth, thickness, and spatial distribution. The model information is compared with the tritium age of groundwater and the presence or absence of other anthropogenic chemical indicators (nitrate and chloride). Higher sensitivity is associated with the following results.

- Tritium age is recent or mixed.
- Nitrate concentrations ≥ 1 ppm.
- Chloride concentrations ≥ 5 ppm with chloride/bromide ratios ≥ 250.

nts aquifer (Figure 23)

This aquifer is limited to the southwest portion of the county. The majority of the aquifer ranges in depth from 0–50 feet, with a mean depth of 24 feet. Only three wells in the county are completed in this aquifer. None were sampled for chemistry.

Its proximity to the land surface and lack of thick overlying till results in overall higher pollution sensitivity ratings. The buried portions of the aquifer are predominately overlain by till of the Heiberg Member (nht). The clay loam to loam texture of the nht provides a protective layer where the thickness is sufficient.

ms aquifer (Figure 24)

This aquifer is limited to the southern portion of the county, along with a narrow band extending north along the eastern edge of the county. The majority of the aquifer ranges in depth from 10–100 feet, with a mean depth of 61 feet. Approximately 5 percent of the wells in the county are completed in this aquifer.

Chemistry: 8 samples were collected and analyzed for tritium, nitrate, and chloride. Results for tritium age: 1 mixed and 7 vintage. Results for nitrate: 0 contained elevated nitrate. Results for chloride: 1 contained elevated chloride from an anthropogenic source.

The mixed tritium-age sample is located approximately 4 miles southwest of Litchfield in an area mapped as very low sensitivity. The aquifer has an area of higher sensitivity less than 1 mile upgradient from the well which may be the source of the mixed tritium-age water. Of the 7 vintage tritium-age samples, 4 are in very low sensitivity areas, and 3 are in higher sensitivity areas. Loam to sandy loam textured Villard Member till (vt) immediately overlies this aquifer throughout its extent. Higher sensitivity ratings are primarily due the proximity to the land surface and to connections to the overlying nts aquifer. In the southwest, the pollution sensitivity ratings are mostly very low and low due to the additional protection provided by the clay loam to loam textured Heiberg Member till (nht).

Vintage tritium-age water was found in three wells located in areas of higher sensitivity. Two of the wells are located on the west shore of Lake Francis and the southern shore of Little Swan Lake. The absence of tritium at these sites may be due to weak vertical downward gradients or vertically upward gradients bringing deeper older water to the aquifer. The site on Lake Francis had a carbon-14 residence time of 700 years. The meteoric signatures are consistent with groundwater flow toward the lake from adjacent uplands. A third well is located on the western shores of Collinwood Lake in southeastern Meeker County. This is in an area of moderate sensitivity immediately adjacent to, and downgradient from, a large area of very low sensitivity, where the vintage tritium-age water likely originates.

hs aquifer (Figure 25)

This aquifer occurs throughout the county with the majority of the aquifer ranging in depth from 10–100 feet, with a mean depth of 61 feet. Approximately 16 percent of the wells in the county are completed in this aquifer.

Chemistry: Of the 31 total samples collected, 29 were analyzed for tritium with the following results: 4 recent, 11 mixed, and 14 vintage. Of the 25 samples analyzed for nitrate, 1 was elevated. Of the 24 samples analyzed for chloride, 11 were elevated. Five of these were anthropogenic chloride and 6 were from natural sources.

Pollution sensitivity ratings are generally very low in the southern half and moderate to very high in the northern half. The southern half has at least two tills overlying the aquifer, the loam to sandy loam textured Molland Member (mt) and the clay loam to loam Villard Member (vt). An additional till (Heiberg Member till (nht)) is also present in the southwest. In the north, protection of the hs aquifer is limited to deposits of the vt resulting in less protection and higher pollution sensitivity.

Three of the four recent tritium-age samples are from wells located near Eden Valley in areas mapped moderate to very high sensitivity, which fits the sensitivity model. A fourth sample located in Dassel in a very low sensitivity area is likely receiving lateral recharge from an area of very high sensitivity located approximately 1,000 feet upgradient of this well. Nine of the 11 samples with mixed tritium age were from wells less than 100 feet deep located either in areas with mixed sensitivity, or in very low sensitivity areas downgradient from areas of higher sensitivity.

Two of the mixed tritium-age samples are located in very low sensitivity areas with no adjacent higher sensitivity. Tritium was not expected in either of these wells, which include a 132-foot-deep City of Litchfield production well and a 127-foot-deep U.S. Geological Survey (USGS) monitoring well 1,500 feet to the southeast. These two wells and others are the focus of a groundwater sustainability study looking at recharge through glacial tills (Witt, 2017). In this study there are two well nests spaced approximately 2,400 feet from each other. The study concluded that recharge rates through the till aquitard at the two locations were significantly different with aquifer recharge estimates of approximately 3 years at one location and over 1,000 years at the other.

The 14 vintage tritium-age samples are from wells that are mostly found in areas mapped with very low or low sensitivity which is consistent with the sensitivity model. One of these wells is located just over 2 miles southeast of Darwin, and had a carbon-14 residence time of 1,300 years providing additional confirmation for the very low sensitivity rating.

scs aquifer (Figure 26)

The extent of this aquifer is the greatest of the buried sand aquifers. The majority of the aquifer ranges in depth from 40–140 feet, with a mean depth of 91 feet. Approximately 24 percent of the wells in the county are completed in this aquifer.

Chemistry: Of the 32 total samples collected from this aquifer, 30 were analyzed for tritium with the following results: 1 recent, 10 mixed, and 19 vintage. Of the 27 samples analyzed for nitrate and chloride, none were elevated for nitrate, 3 were elevated for chloride from natural sources.

Pollution sensitivity for this aquifer is primarily very low, with areas of higher sensitivity mostly limited to the north and east. Of the 11 recent and mixed samples, 8 are in very low sensitivity areas where tritium was not expected. The source of tritium is unknown since there are no nearby higher sensitivity areas where lateral flow may have sourced the mixed and recent tritium. One explanation for the elevated tritium levels is that there may be unidentified sand bodies that enhance recharge rates to these buried sands. Another possibility is well conditions that allow water from above the aquifer to enter the well. The deepest of these wells is a 156-foot-deep municipal well that may have enhanced vertical recharge due to long duration high-capacity pumping that brought mixed tritium-age water to a greater depth. The remaining 3 samples were generally consistent with the model sensitivity, or were reasonable based on lateral flow from nearby areas of higher sensitivity.

Of the 19 vintage tritium-age samples, 16 were located in very low sensitivity areas. The other 3 sites are located in areas where pollution sensitivity was either low or moderate. One of these is 1.5 miles west of Kingston near the North Fork Crow River where downward vertical gradients may be weak or even upward to provide base flow to the river. This could explain the vintage tritium-age water in a higher sensitivity area. A second site less than 3 miles southeast of Kingston near Collinwood Creek is located in a medium sensitivity area immediately downgradient from a larger area of very low sensitivity. The last site is just east of Eden Valley in a low sensitivity area with higher sensitivity in the area. Three of the vintage samples also had carbon-14 residence times ranging from 1,200 to 2,500 years, consistent with the very low sensitivities of those locations.

mls aquifer (Figure 27)

This aquifer has widespread discontinuous deposits throughout the county. The majority of the aquifer ranges in depth from 70–180 feet, with a mean depth of 125 feet. Approximately 14 percent of wells in the county are completed in this aquifer.

Chemistry: All of the 18 samples collected from this aquifer were analyzed for tritium with the following results: 6 mixed and 12 vintage. Of the 16 samples analyzed for nitrate and chloride, none were elevated for nitrate, 2 were elevated for chloride from natural sources.

Very low sensitivity is the dominant rating with higher sensitivities accounting for less than 2 percent by area. Locations of these higher sensitivities are mostly limited to small areas in parts of northern and far eastern Meeker County.

All of the samples collected were in very low sensitivity areas. For the 6 samples with mixed tritium-age water, the source of tritium is mostly unknown. One well is on the eastern border of Kingston with low mixed tritium, suggesting mixing of recent or mixed tritium-age water with vintage tritium-age water. Another well located approximately 3.5 miles southeast of Eden Valley has low mixed tritium compared to an adjacent well in the same aquifer approximately ¼ mile upgradient that has vintage tritium-age water and a carbon-14 residence time of 550 years. A well just over 4 miles southwest of Litchfield has mixed tritium-age water. This well has a strong evaporative signature suggesting that a significant portion of recharge is coming from nearby Star Lake. The mapped aquifer extends upgradient from the well and beneath Star Lake and may have a better connection to the lake than would be indicated by the very low sensitivity. Another well located almost 4 miles west of Eden Valley has mixed tritium-age water with no clear recharge source identified. Upgradient recharge is coming from areas to the north in Stearns County that are not mapped for pollution sensitivity. A public supply well in Dassel has high mixed tritium-age water that contrasts with a second public supply well in the same aquifer ¼ mile to the south that has vintage tritium-age water. Well conditions that allow water from above the aquifer to enter the well may be occurring at this well. Mixed tritium-age water analyzed in a well located approximately 1.5 miles east of Eden Valley may be getting lateral recharge from an upgradient higher sensitivity area approximately ¼ mile to the east. The remaining 12 wells were found to have vintage tritium-age water consistent with the very low sensitivity.

gs3 aquifer (Figure 28)

This aquifer is located in the southwestern portion of the county. The majority of the aquifer ranges in depth from 120–240 feet, with a mean depth of 181 feet. The aquifer has very low pollution sensitivity. Approximately 1 percent of the wells in the county are completed in this aquifer.

Chemistry: Of the 2 samples collected, both had vintage tritium age and neither were elevated for nitrate or chloride.

gs4 aquifer (Figure 29)

This aquifer is primarily limited to the western portion of the county. The majority of the aquifer ranges in depth from 110–250 feet, with a mean depth of 193 feet. Approximately 9 percent of the wells in the county are completed in this aquifer.

Chemistry: Of the 10 samples collected from this aquifer, 9 were analyzed for tritium and all were vintage. Of the 8 samples analyzed for nitrate and chloride, none were elevated.

All of the samples were collected in very low sensitivity areas. Three had carbon-14 residence times of 5,500–8,500 years, consistent with the very low sensitivity of that area.

This aquifer is mapped as very low sensitivity except for one location in the far northwestern portion where the North Fork Crow River has removed most of the overlying protective till.

gs5 aquifer (Figure 30)

This aquifer is primarily limited to the western portion of the county. The majority of the aquifer is deeper than 180 feet, with a mean depth of 239 feet. Approximately 2 percent of the wells in the county are completed in this aquifer.

Chemistry: Of the 4 samples collected, 2 were analyzed for tritium age; both were vintage. Of the 2 samples analyzed for nitrate, none were elevated. No samples were analyzed for chloride.

All samples were collected at locations identified as very low sensitivity.

wrs aquifer (Figure 31)

This aquifer consists of widespread discontinuous deposits within the county except for the west-central region. The majority of the aquifer is deeper than 90 feet, with a mean depth of 179 feet. Approximately 8 percent of the wells in the county are completed in this aquifer.

Chemistry: All 11 samples collected were analyzed for tritium age with the following results: 1 mixed and 10 vintage. All 11 samples were analyzed for nitrate and chloride. None were elevated for nitrate; 1 was elevated for chloride, likely from natural sources.

The samples were from areas with very low sensitivity. The one mixed sample is from the shallowest well (106 feet) just east of Eden Valley. Approximately 1.5 miles northeast of Kingston is a 128-foot-deep well that had a carbon-14 residence time of 1,400 years, which is consistent with the very low sensitivity of that area.

Most of the aquifer is characterized as having a very low sensitivity rating. The exceptions are small areas in the north-central and northeast portions.

wes aquifer (Figure 32)

This aquifer consists of widespread discontinuous deposits except for the west-central region of the county. The majority of the aquifer is deeper than 140 feet, with a mean depth of 219 feet. Approximately 3 percent of the wells in the county are completed in this aquifer.

Chemistry: Of the 6 samples collected from this aquifer, 5 were analyzed for tritium age and all were vintage. Of the 4 samples analyzed for nitrate, none were elevated. Of the 3 samples analyzed for chloride, none were elevated.

Pollution sensitivity is very low with the exception of three small areas in northern and northeastern Meeker County

vs aquifer (Figure 33)

This aquifer consists of widespread discontinuous deposits across the county except for the central, west-central, and northwest portions. The majority of the aquifer is deeper than 160 feet, with a mean depth of 233 feet. Approximately 1 percent of the wells in the county are completed in this aquifer.

Chemistry: No samples were collected in this aquifer.

Pollution sensitivity is very low, except for a small area 3.7 miles northeast of Forest City.

psu aquifer (Figure 34)

This aquifer is found as a few scattered deposits in the southwest and southeast. The majority of the aquifer is deeper than 270 feet, with a mean depth of 336 feet. Only 2 wells in the county are completed in this aquifer.

Chemistry: No samples were collected from this aquifer.

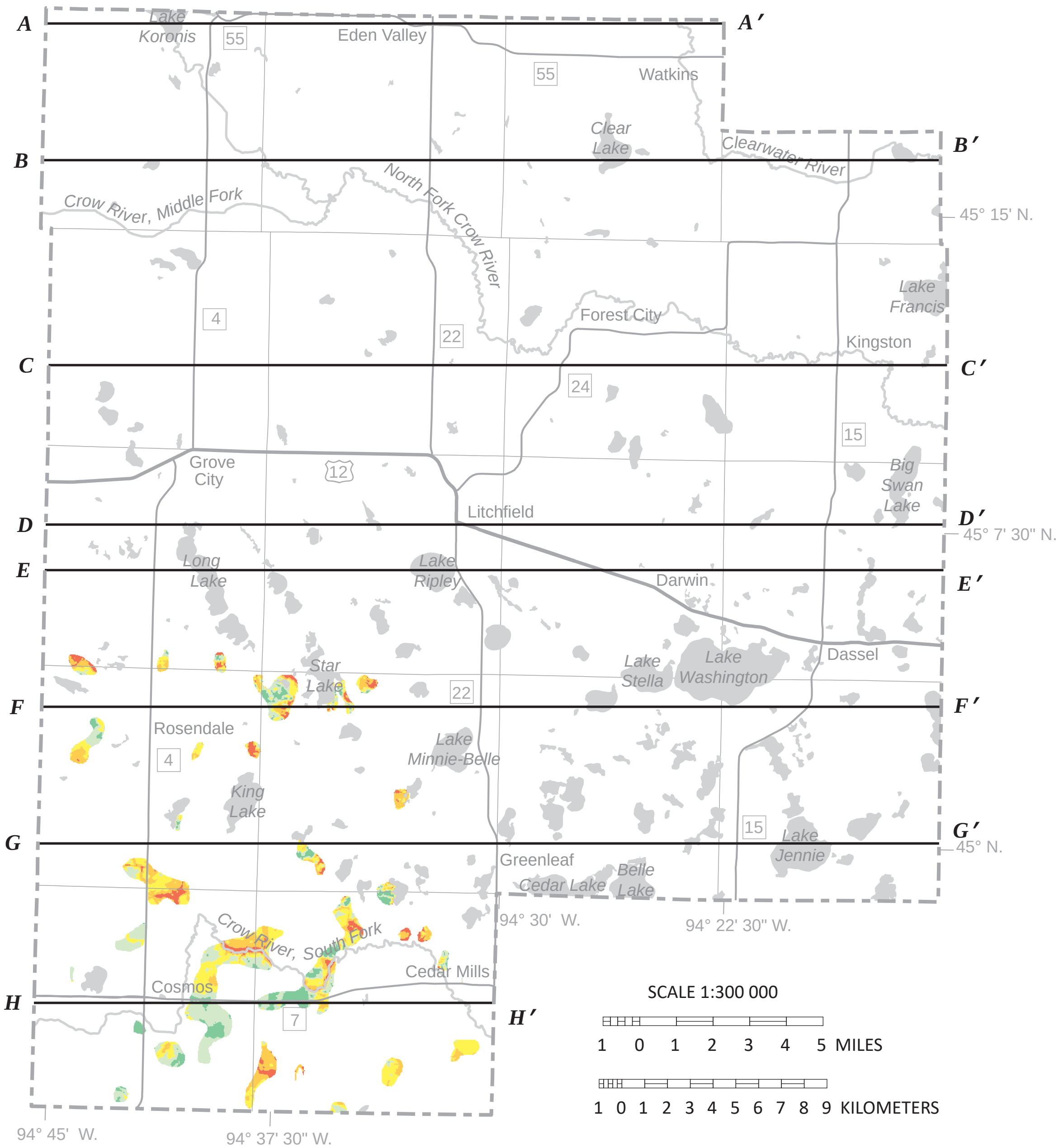
Pollution sensitivity is very low.

Bedrock surface (Figure 35)

Bedrock wells range from 76–750 feet in depth. Approximately 3 percent of the wells in the county are completed in a bedrock aquifer.

Chemistry: Of the 2 samples collected from a bedrock aquifer, both were vintage, consistent with their very low sensitivity locations. Both samples were analyzed for nitrate and chloride. Neither was elevated for nitrate. One was elevated for chloride from a natural sources.

Most of the bedrock wells are completed in sedimentary Cretaceous deposits located in the east and north-central portions. The Dakota aquifer (Kd) is found mostly in the northern portion. The Cretaceous undifferentiated unit (Ka) is located in the southeastern portion of the county and in the deep bedrock valley trending to the north, with some overlap in the center of the county. A small number of wells are completed in low permeability Precambrian bedrock. Pollution sensitivity of the bedrock surface is generally very low with the exception of a few small areas in the north-central and northeast.



Pollution sensitivity rating

Estimated vertical travel time.

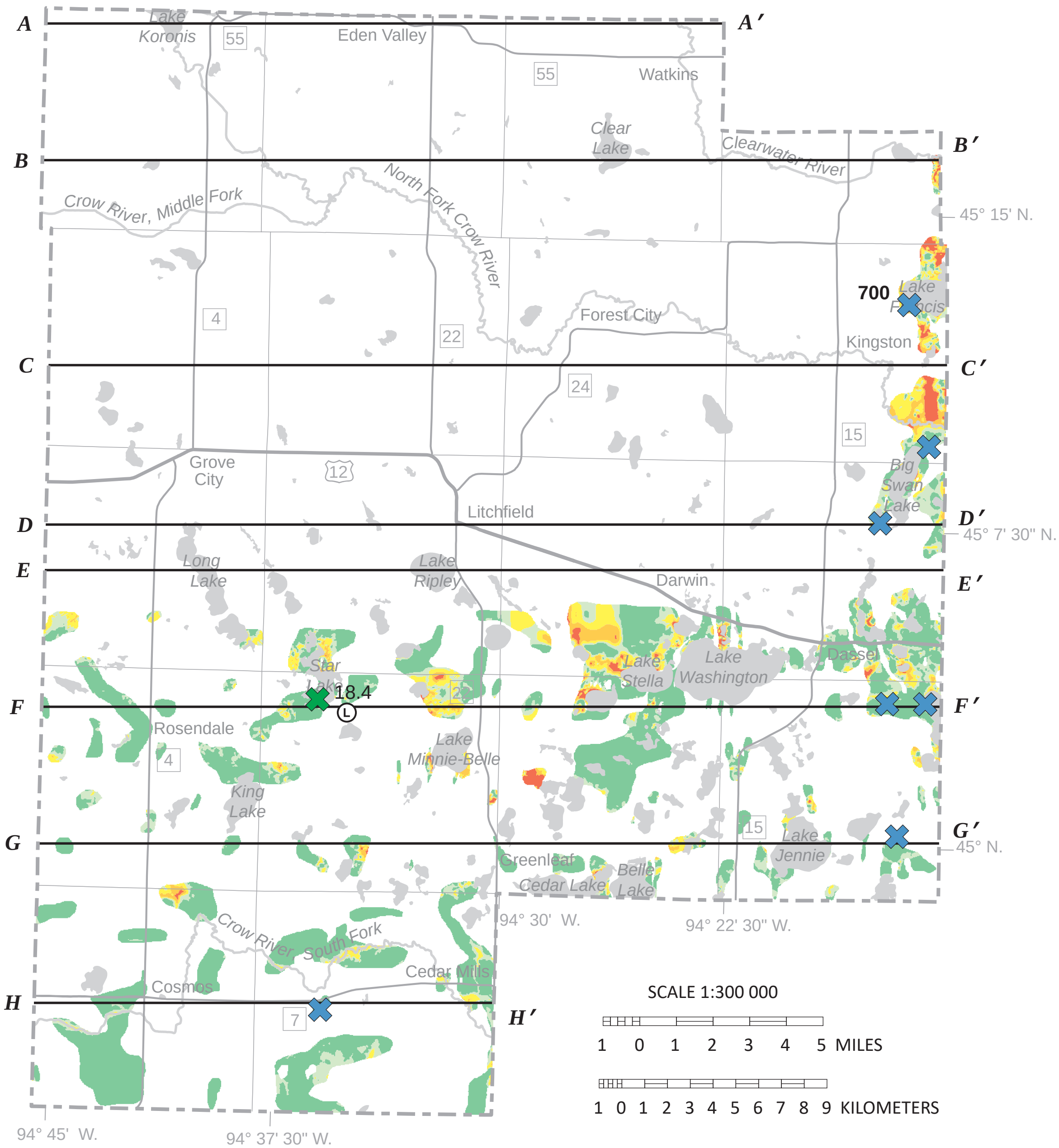
- Very High: hours to months
- High: weeks to years
- Moderate: years to decades
- Low: decades to a century
- Very Low: a century or more

Symbols and labels

C——*C′* Line of cross section (Part B)

Body of water

Figure 23. Pollution sensitivity of the nts aquifer



Pollution sensitivity rating

Estimated vertical travel time.

- Very High: hours to months
- High: weeks to years
- Moderate: years to decades
- Low: decades to a century
- Very Low: a century or more

Tritium age

Symbol color indicates tritium age of water sample.

- Mixed
- Vintage

Symbols and labels

18.4 Chloride: if shown, concentration is ≥5 ppm. (* naturally elevated)

700 Carbon-14 (^{14}C): estimated groundwater residence time in years.

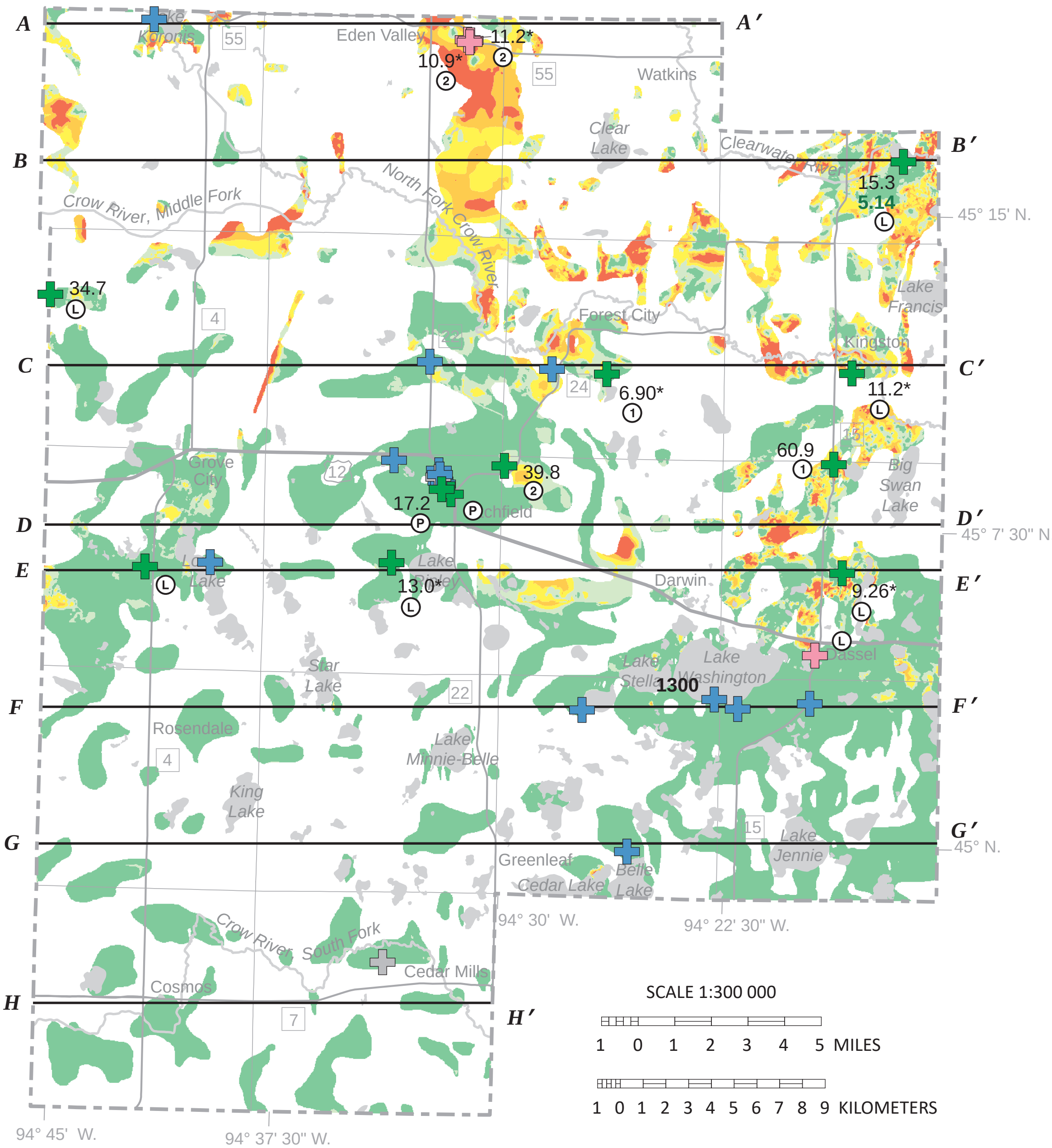
C—*C′* Line of cross section (Part B)

Body of water

Groundwater conditions

Ⓛ Groundwater flows laterally.

Figure 24. Pollution sensitivity of the ms aquifer



Pollution sensitivity rating

Estimated vertical travel time.

- Very High: hours to months
- High: weeks to years
- Moderate: years to decades
- Low: decades to a century
- Very Low: a century or more

Tritium age

Symbol color indicates tritium age of water sample.

- Recent
- Mixed
- Vintage
- Not sampled for tritium.

Symbols and labels

9.26*	Chloride: if shown, concentration is ≥5 ppm. (* naturally elevated)
5.14	Nitrate: if shown, concentration is ≥1 ppm.
1300	Carbon-14 (^{14}C): estimated groundwater residence time in years.
C—C′	Line of cross section (Part B)
	Body of water

Groundwater conditions

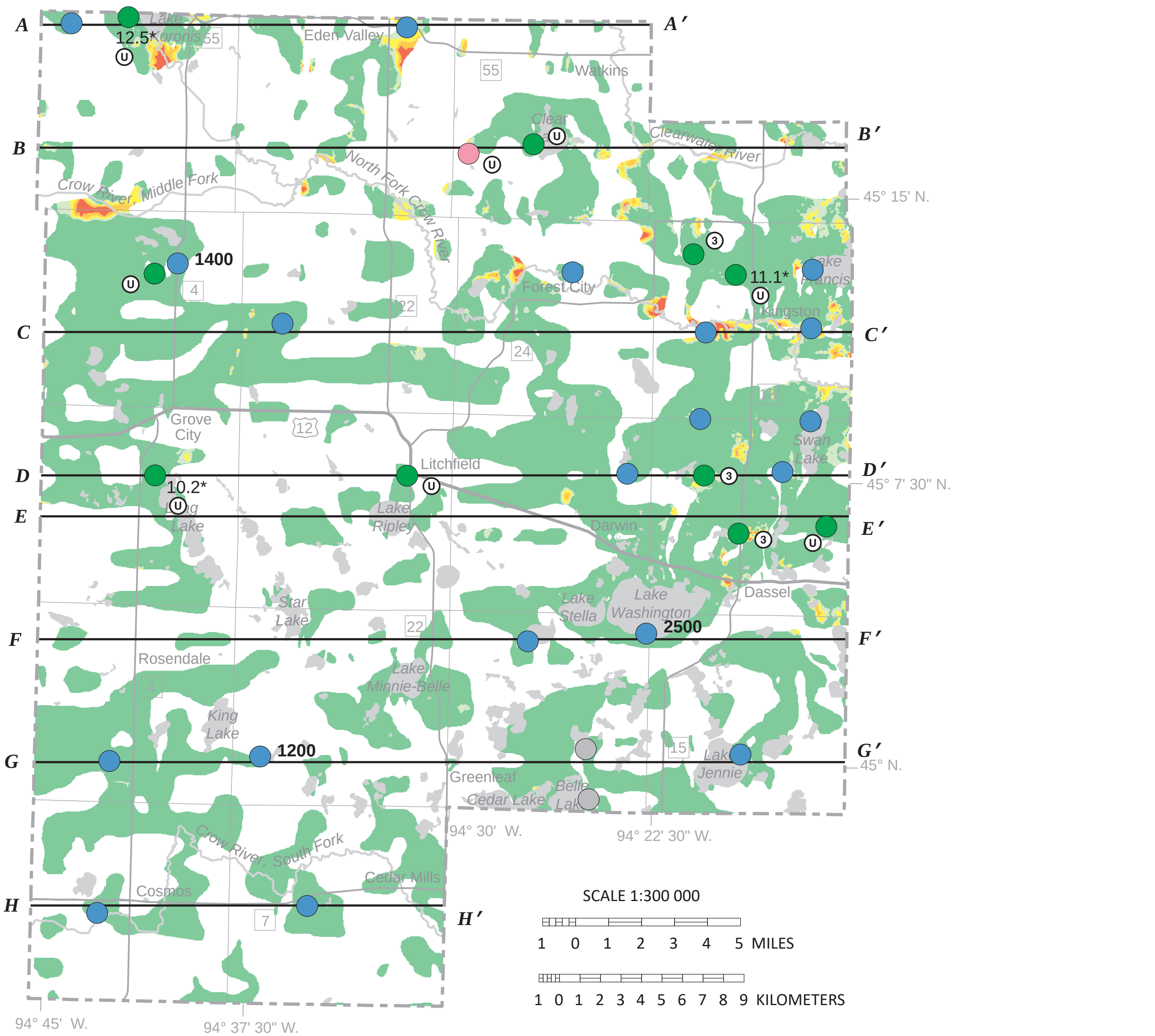
① Water from the surface moves through a thin layer of overlying fine-grained material to an underlying aquifer.

② Groundwater moves from an overlying surficial aquifer to a buried aquifer.

Ⓛ Groundwater flows laterally.

Ⓟ Tritium concentrations may be artificially elevated by high capacity pumping.

Figure 25. Pollution sensitivity of the hs aquifer



Pollution sensitivity rating

Estimated vertical travel time.

- Very High: hours to months
- High: weeks to years
- Moderate: years to decades
- Low: decades to a century
- Very Low: a century or more

Tritium age

Symbol color indicates tritium age of water sample.

- Recent
- Mixed
- Vintage
- Not sampled for tritium.

Symbols and labels

11.1* Chloride: if shown, concentration is ≥5 ppm. (* naturally elevated)

1400 Carbon-14 (^{14}C): estimated groundwater residence time in years.

C —— C′ Line of cross section (Part B)

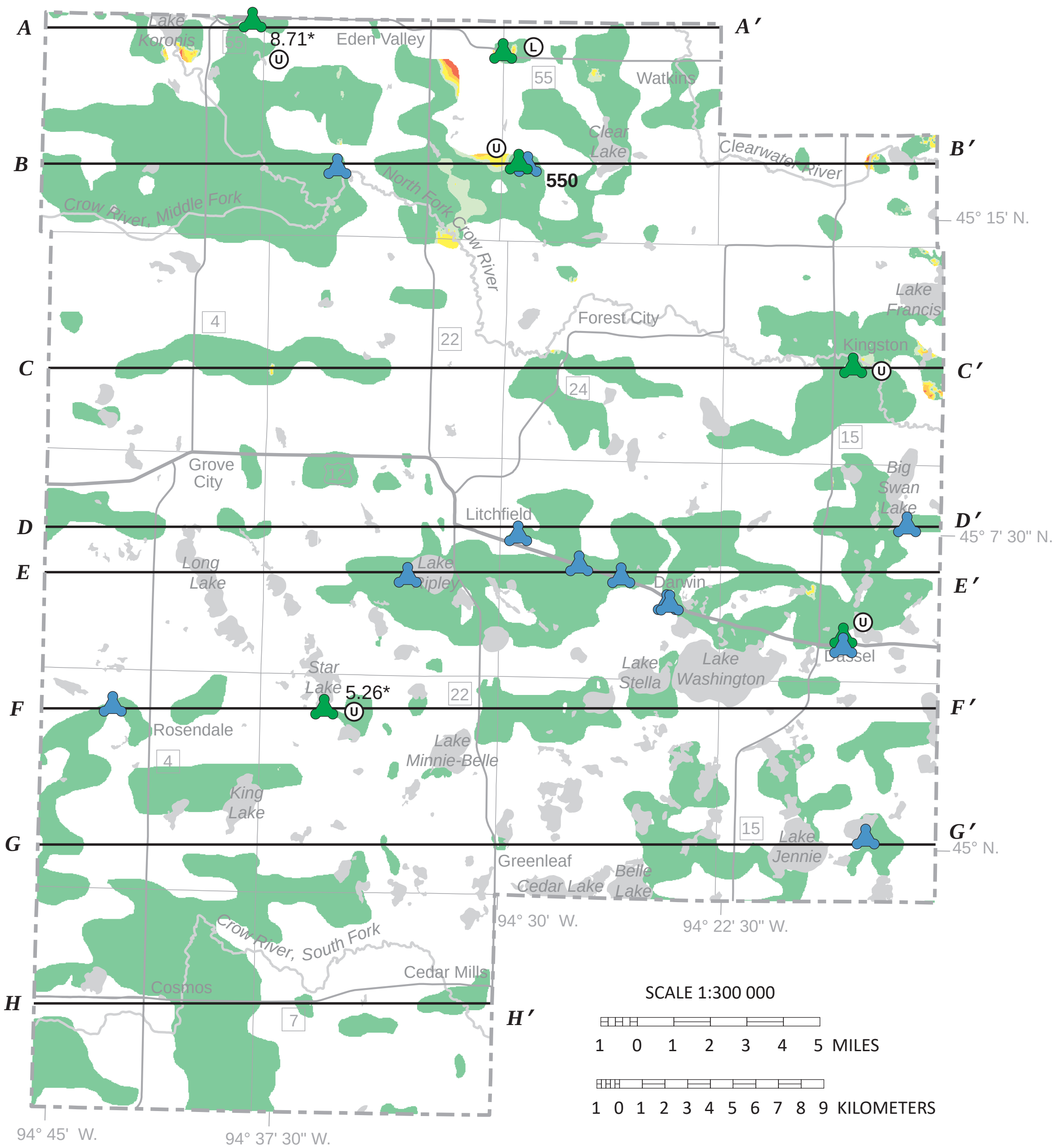
Body of water

Groundwater conditions

(3) Groundwater moves from an overlying buried aquifer to an underlying buried aquifer.

(U) Groundwater flowpath is unknown.

Figure 26. Pollution sensitivity of the scs aquifer



Pollution sensitivity rating

Estimated vertical travel time.

- Very High: hours to months
- High: weeks to years
- Moderate: years to decades
- Low: decades to a century
- Very Low: a century or more

Tritium age

Symbol color indicates tritium age of water sample.

- Mixed
- Vintage

Symbols and labels

5.26* Chloride: if shown, concentration is ≥5 ppm. (* naturally elevated)

550 Carbon-14 (^{14}C): estimated groundwater residence time in years.

C—*C′* Line of cross section (Part B)

Body of water

Groundwater conditions

Ⓛ Groundwater flows laterally.

Ⓤ Groundwater flowpath is unknown.

Figure 27. Pollution sensitivity of the mls aquifer

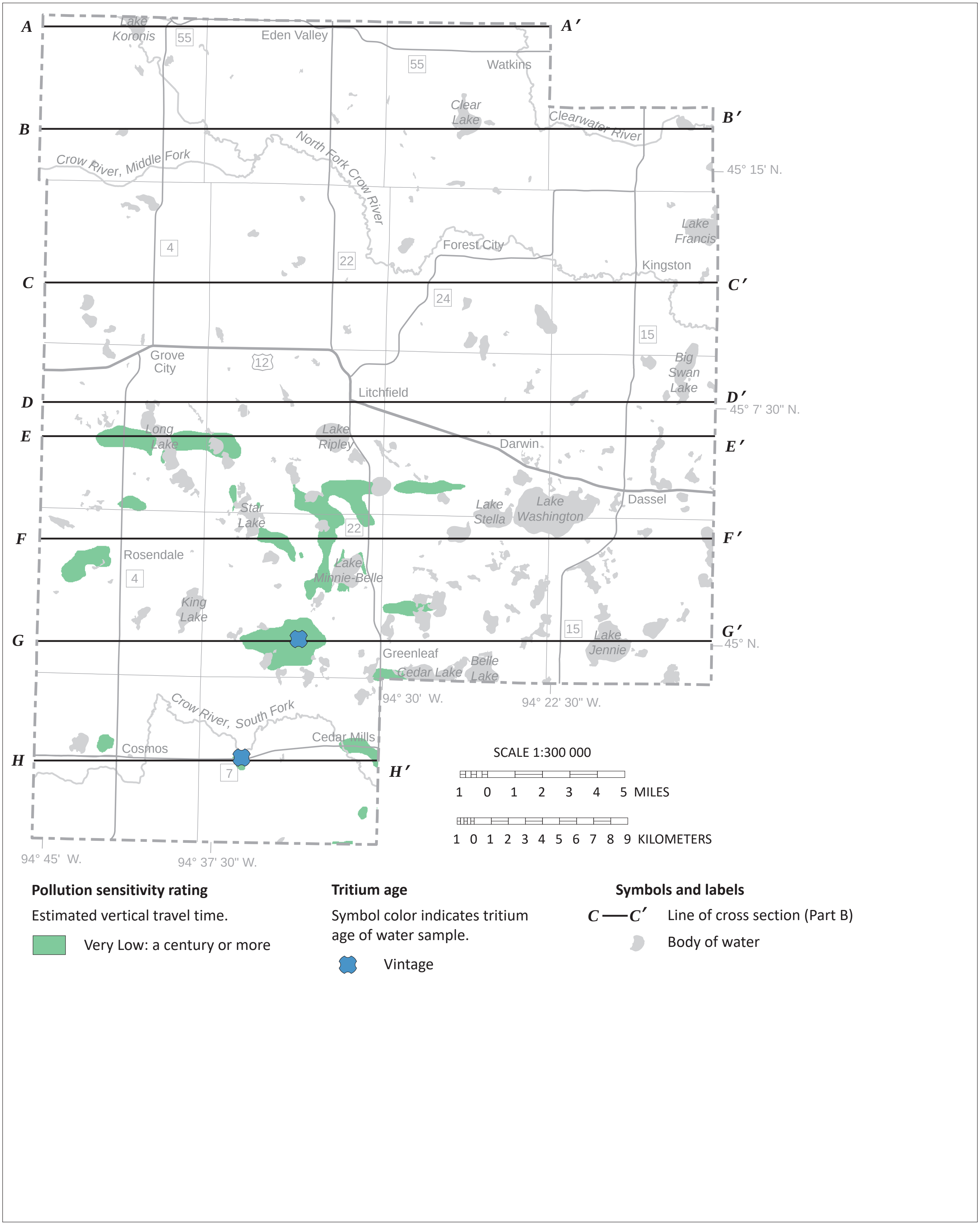
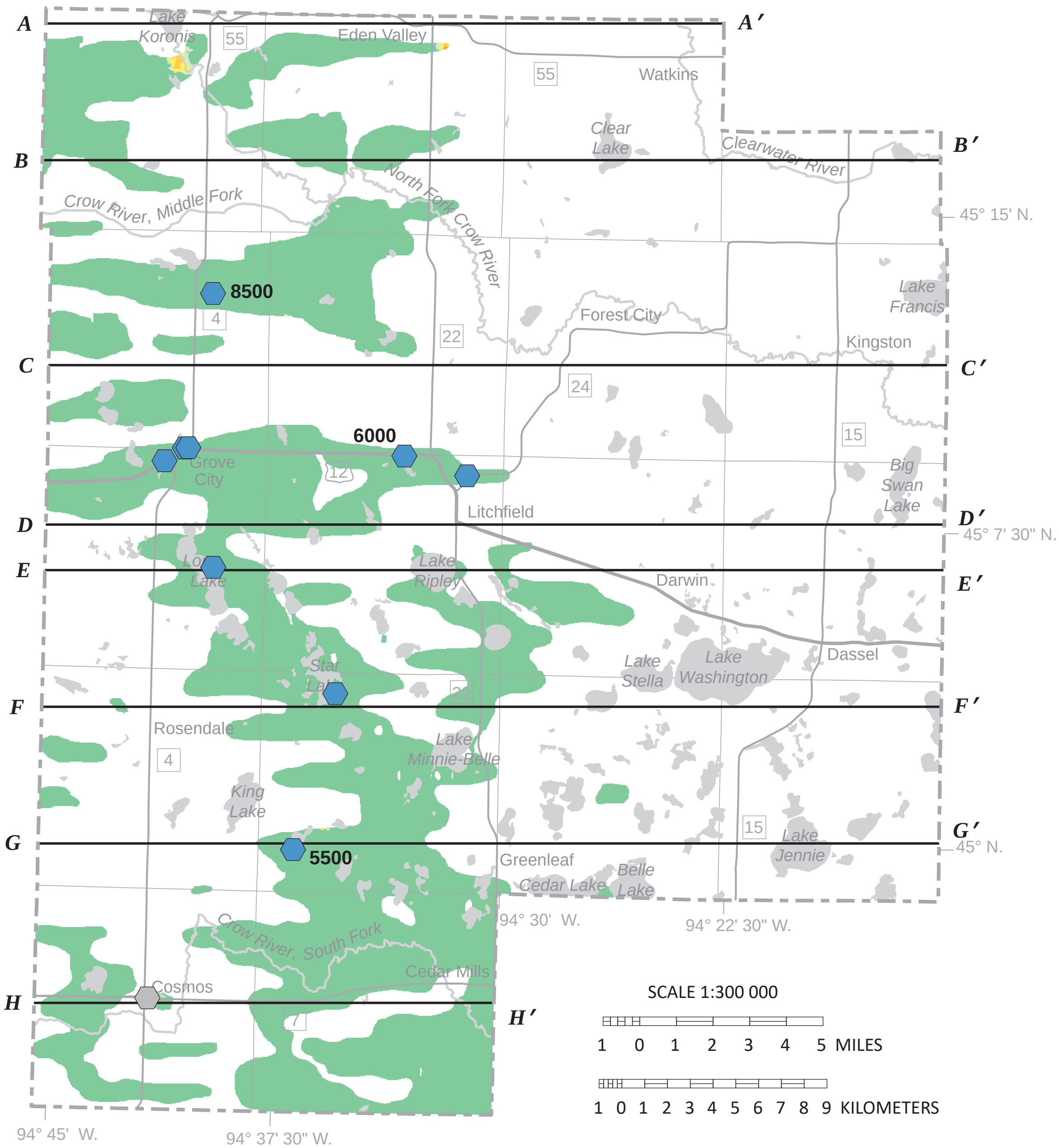


Figure 28. Pollution sensitivity of the gs3 aquifer



Pollution sensitivity rating

Estimated vertical travel time.

- Very High: hours to months
- High: weeks to years
- Moderate: years to decades
- Low: decades to a century
- Very Low: a century or more

Tritium age

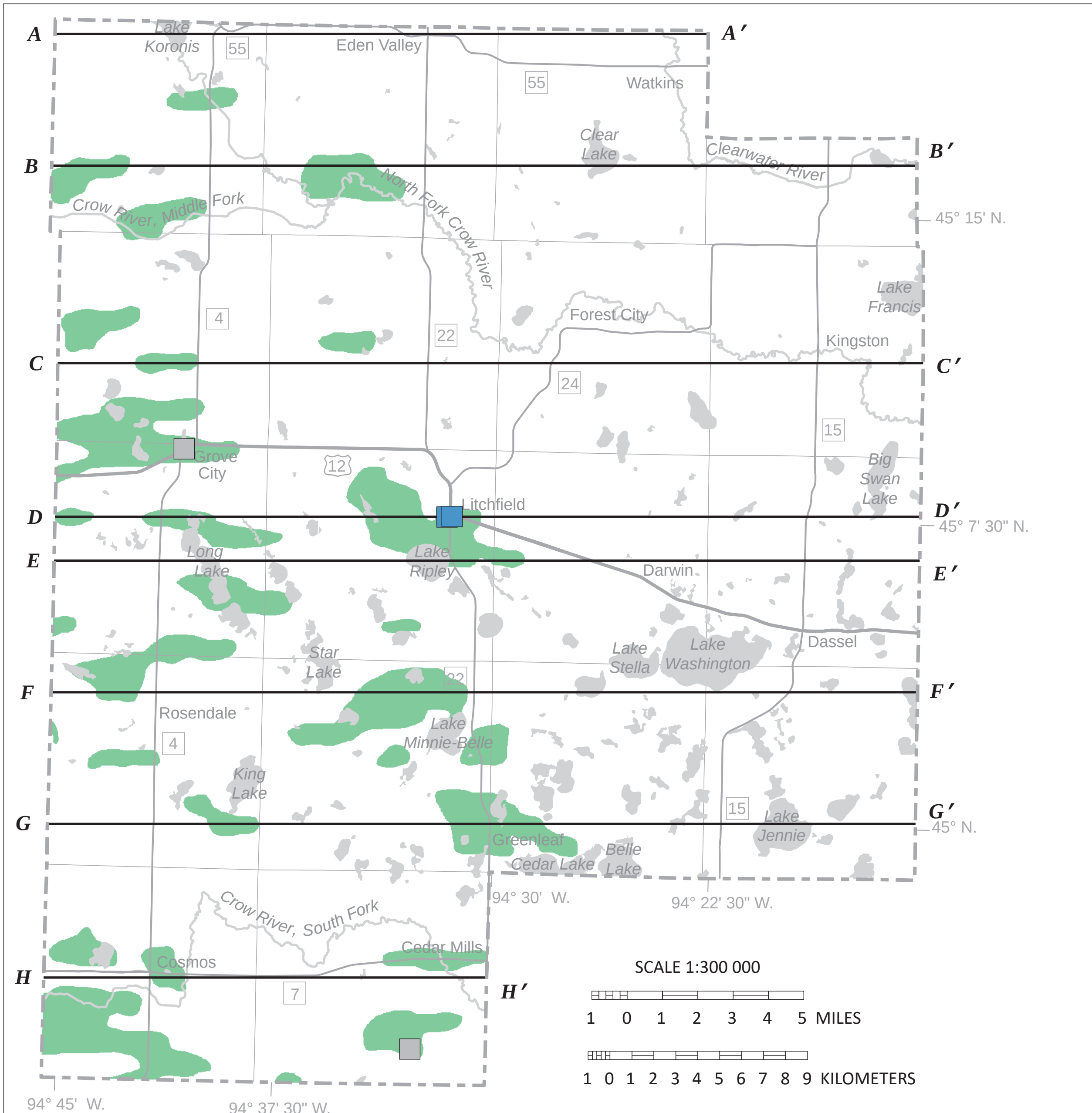
Symbol color indicates tritium age of water sample.

- Vintage
- Not sampled for tritium.

Symbols and labels

- **6000** Carbon-14 (^{14}C): estimated groundwater residence time in years.
- *C —— C′* Line of cross section (Part B)
- Body of water

Figure 29. Pollution sensitivity of the gs4 aquifer



Pollution sensitivity rating

Estimated vertical travel time.

Very Low: a century or more

Tritium age

Symbol color indicates tritium age of water sample.

Vintage

Not sampled for tritium.

Symbols and labels

C—C′ Line of cross section (Part B)

Body of water

Figure 30. Pollution sensitivity of the gs5 aquifer

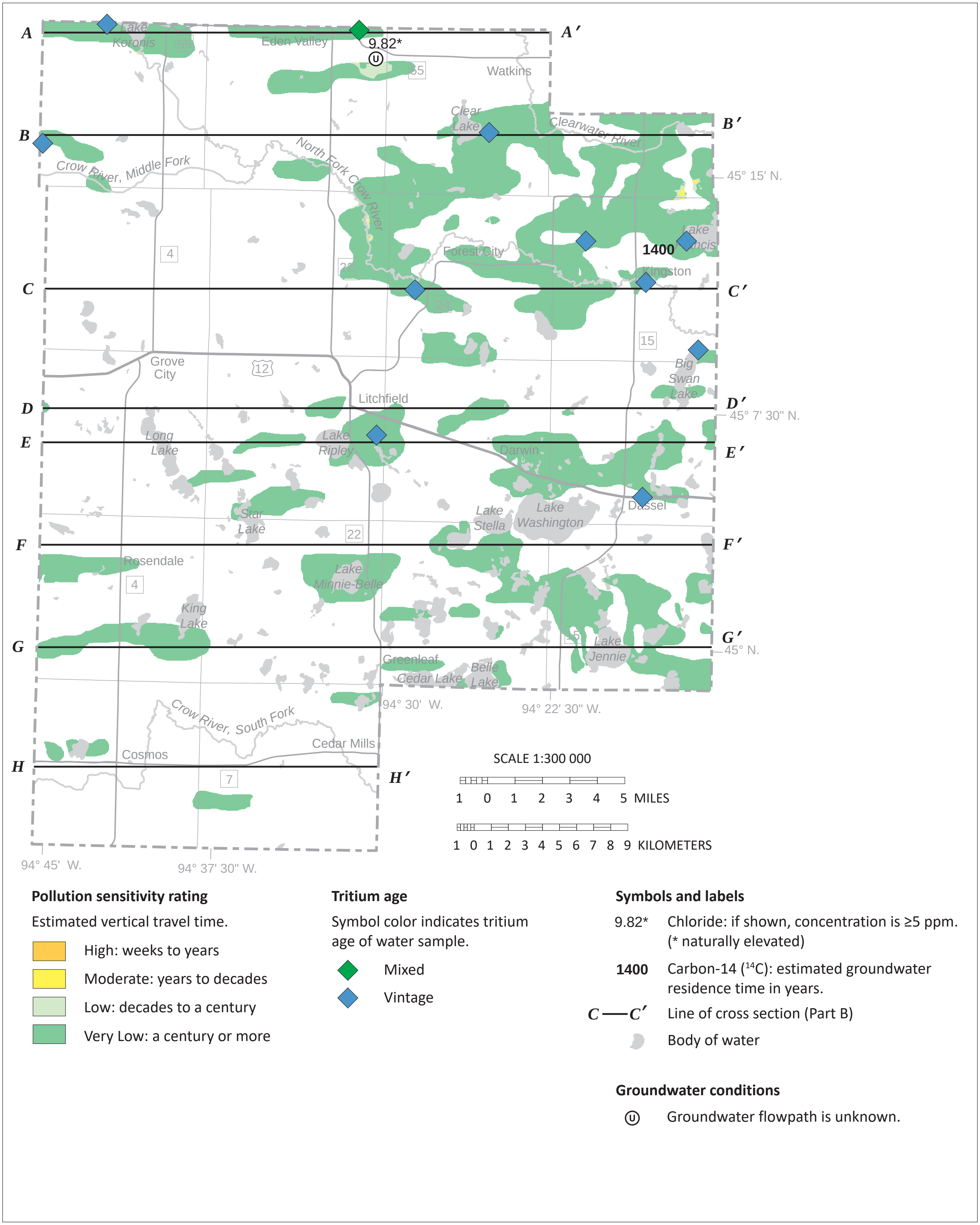


Figure 31. Pollution sensitivity of the wrs aquifer

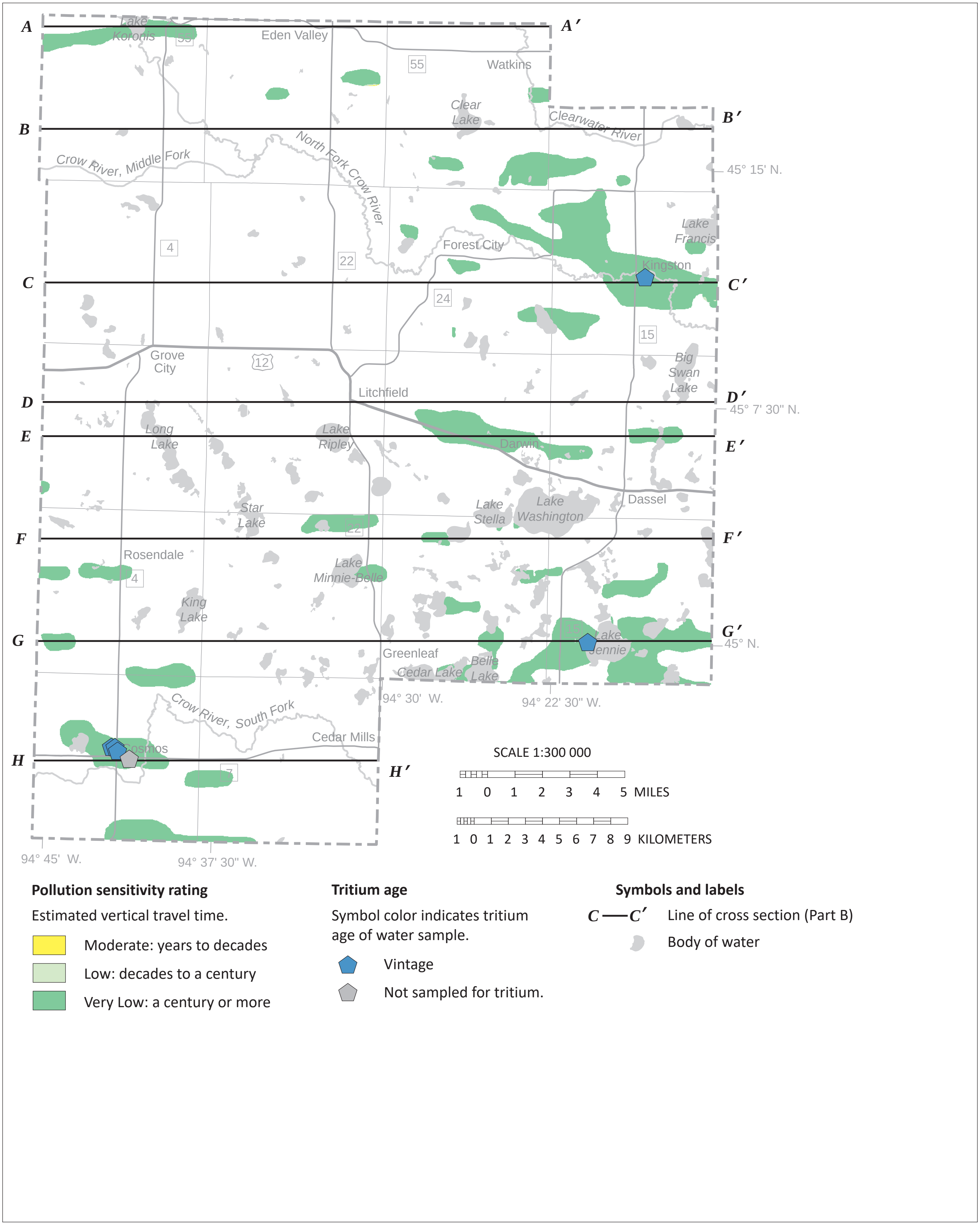
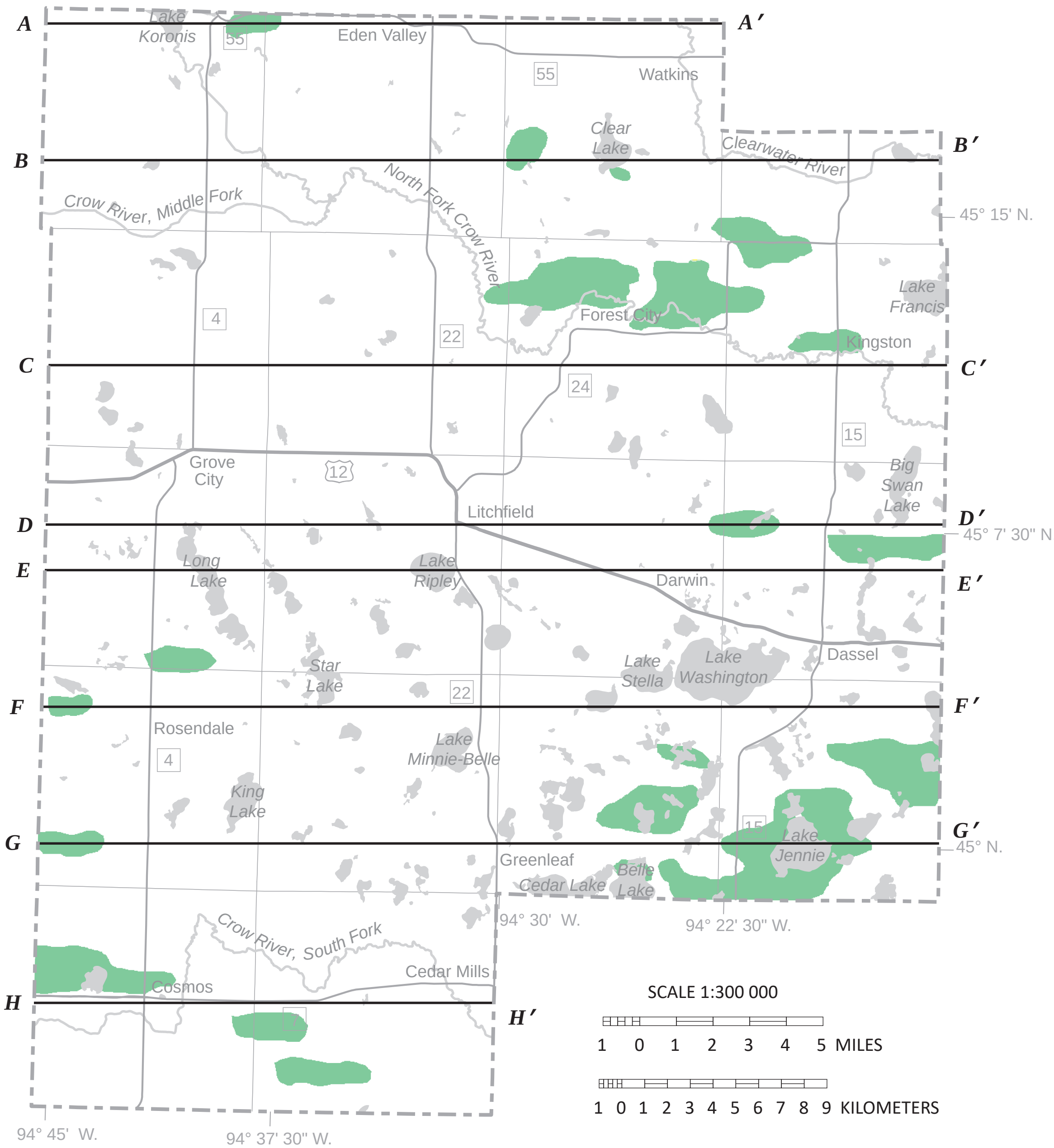


Figure 32. Pollution sensitivity of the wes aquifer



Pollution sensitivity rating

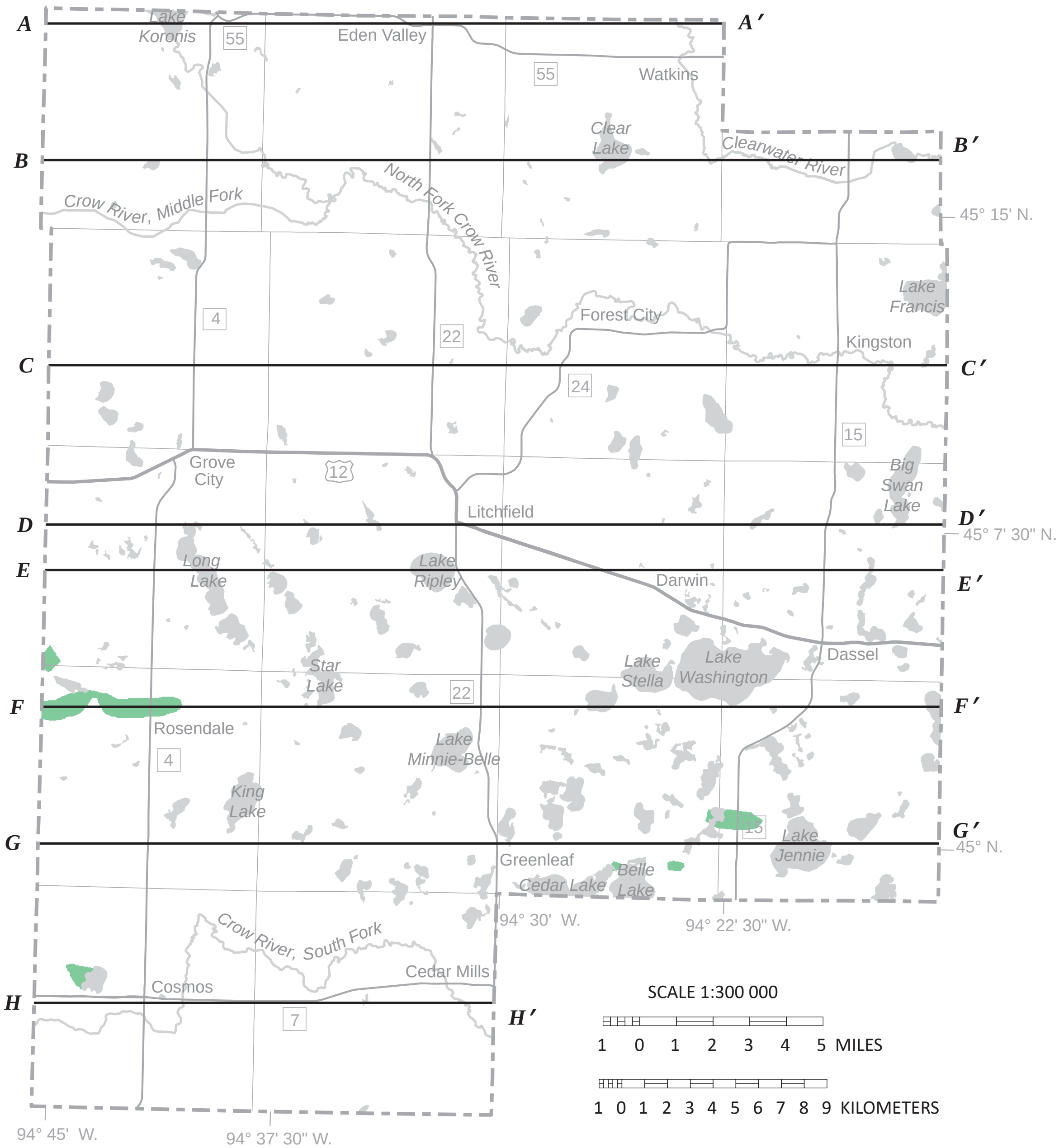
Estimated vertical travel time.

- Moderate: years to decades
- Low: decades to a century
- Very Low: a century or more

Symbols and labels

- C —— C′ Line of cross section (Part B)
- Body of water

Figure 33. Pollution sensitivity of the vs aquifer



Pollution sensitivity rating

Estimated vertical travel time.

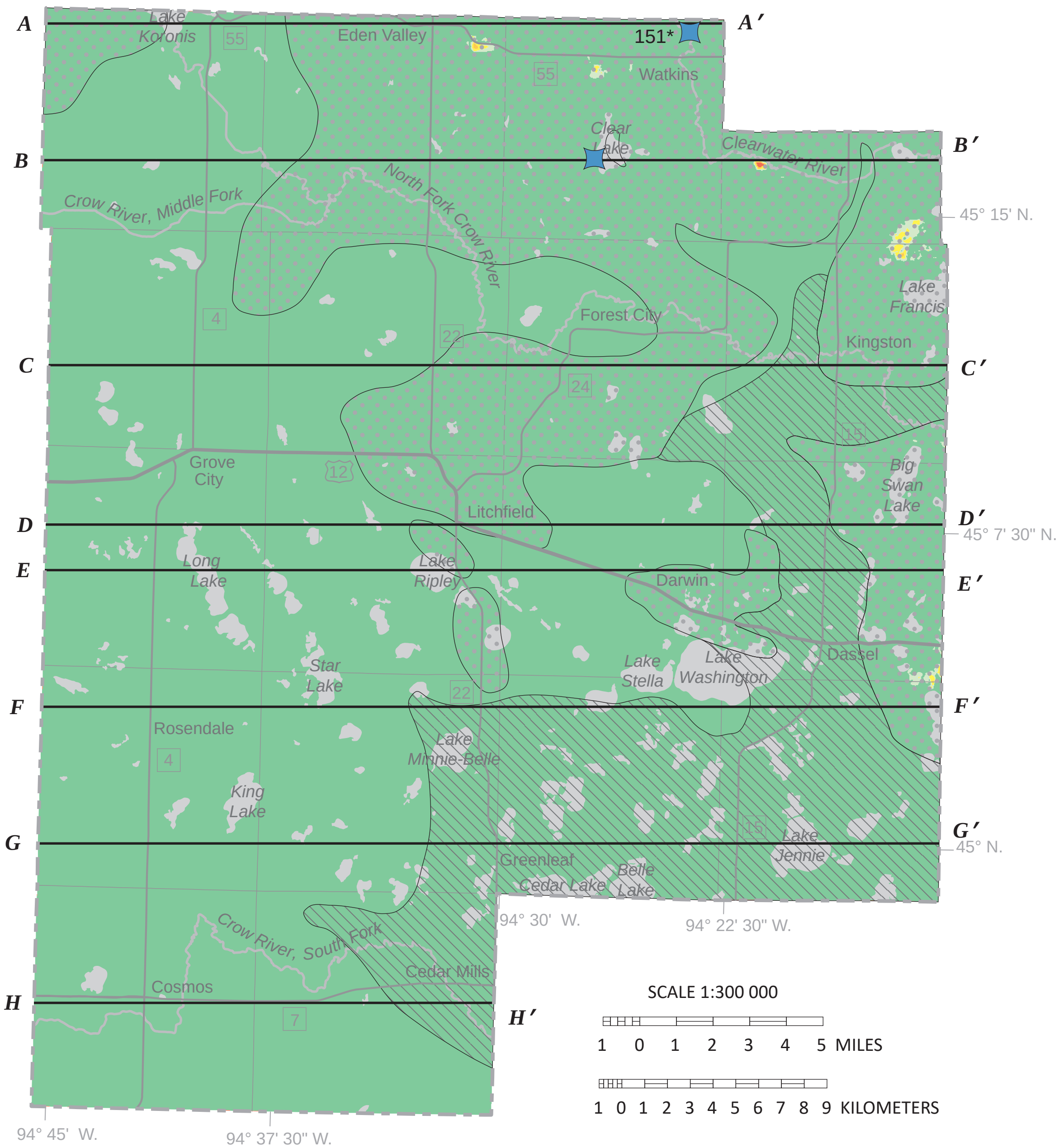
Very Low: a century or more

Symbols and labels

C —— C′ Line of cross section (Part B)

Body of water

Figure 34. Pollution sensitivity of the psu aquifer



Pollution sensitivity rating

Estimated vertical travel time.

- Very High: hours to months
- High: weeks to years
- Moderate: years to decades
- Low: decades to a century
- Very Low: a century or more

Tritium age

Symbol color indicates tritium age of water sample.

- Vintage

Symbols and labels

- 151* Chloride: if shown, concentration is ≥5 ppm. (* naturally elevated)
- C — C′ Line of cross section (Part B)
- Body of water

Bedrock geology

- Dakota Formation (Kd)
- Cretaceous undifferentiated (Ka)
- Precambrian crystalline bedrock

Figure 35. Pollution sensitivity of the bedrock surface

Hydrogeologic cross sections (Plates 7 and 8)

The hydrogeologic cross sections shown on Plates 7 and 8 illustrate the horizontal and vertical extent of aquifers and aquitards, the relative hydraulic conductivity of aquitards, general groundwater flow direction, areas of groundwater recharge and discharge, and groundwater residence time. The cross sections were chosen to display most of the chemistry data and to illustrate a variety of recharge examples.

The eight cross sections were selected from a set of 50 regularly-spaced (1 kilometer) west-to-east cross sections created by the MGS. Each was constructed in GIS using a combination of well data from CWI and sections of Part A: Bedrock Geology (Plate 2), Surficial Geology (Plate 3), and Quaternary Stratigraphy (Plate 4). The well information for each cross section was projected onto the trace of the cross section from distances no greater than one-half kilometer.

Relative hydraulic conductivity

Hydraulic conductivity is a function of the porosity (volume of pores) and permeability (connectedness of pores) of a sediment or rock layer. Percent sand content in the glacial sediment matrix is a proxy for permeability because coarse grains typically add permeability to sediment. Glacial aquitards with higher sand content are assumed to have higher hydraulic conductivity. This assumption does not account for the occurrence of larger clasts (pebbles, cobble, and boulders), the potential for fine sediment to fill pore spaces, or fractures in the shallow till units.

Glacial sediment layers that act as aquitards (till units) are shown in shades of gray on Plates 7 and 8. Lighter shades indicate aquitards with higher relative hydraulic conductivity. The percent sand in each of the aquitards is based on the average matrix texture of each glacial aquitard or till (Part A, Plate 4, Table 1).

Groundwater flow direction

Groundwater moves from areas with higher potential energy to areas with lower potential energy. The direction of groundwater movement is interpreted from the equipotential contours constructed from measured water levels in wells. These contours can be used to identify the groundwater flow direction, recharge zones, and discharge zones (Plates 7 and 8).

Groundwater recharge and discharge

Precipitation is the source of recharge to the glacial sediment covering the county, which then provide recharge to deep aquifers. Groundwater recharge preferentially occurs where sandy surficial sediment allows for higher rates of infiltration. In other areas with less permeable surficial material the recharge is limited because the materials have higher clay and silt content. Pollution sensitivity can be used as a proxy for potential recharge rates. Where pollution sensitivity is high, recharge rates are expected to be greater.

Recharge to the surficial aquifers ranges from 1.5 to 10.6 inches per year (Smith and Westenbroek, 2015). Recharge to the buried sand aquifers and bedrock aquifers is generally less than 1 percent of average precipitation, or roughly 0.3 inches per year (Delin and Falteisek, 2007). This estimate is dependent upon the matrix texture and thickness of the glacial sediment. Recharge rates are influenced by high-volume groundwater pumping, which has the potential to locally steepen groundwater gradients and increase recharge.

Groundwater is discharged to surface-water bodies, such as the Clearwater, North Fork Crow, Middle Fork Crow, and South Fork Crow rivers, and some wetlands and lakes. Stable isotopic data collected for this atlas demonstrate that lakes serve an important recharge function in the south-central portion of the county.

Aquifer characteristics and groundwater use

Aquifer specific capacity and transmissivity

Aquifer characteristics such as specific capacity and transmissivity are used to describe how water is transmitted by an aquifer. Larger specific capacity and transmissivity values indicate more productive aquifers.

Specific capacity is the pumping rate per unit depth of drawdown. It is typically expressed in gallons per minute per foot (gpm/ft) and is determined from short-term pumping or well-development tests performed after a well is drilled.

To ensure that the specific-capacity values reflect actual pumping (not air-lifting), the pumping-test data were obtained from CWI for wells with the following conditions:

- The casing diameter was at least 12 inches.
- The well was pumped for at least 4 hours.
- The pumping-water level was inside the well casing, at least 2 feet above the well screen or open hole.

In Meeker County, 37 wells met these conditions: 4 wells in unconfined aquifers, and 33 wells in confined aquifers. The unconfined aquifers had the highest mean specific capacities of over 40 gpm/ft, whereas buried sand aquifers ranged from less than 5 to just under 40 gpm/ft (Table 2 and Figure 36).

Transmissivity is an aquifer's capacity to transmit water. It is determined by multiplying the thickness of the aquifer by the hydraulic conductivity of the aquifer material (the rate groundwater flows through a unit cross section). It provides a more accurate representation of the aquifer properties than specific capacity because it is from longer-term and larger-scale aquifer tests.

Transmissivity values for 12 aquifer tests in Meeker County are also included in Table 2. These tests include one water-table well and 11 buried sand wells. The transmissivity value for the single water-table aquifer test (14,100 ft^2/day) is higher than the mean transmissivity values for the buried sand aquifers that range from 6,300 to 13,700 ft^2/day. However, the highest transmissivities of 21,600 and 24,000 ft^2/day are in buried sand aquifers. Transmissivity values are summarized from a variety of reports and evaluation approaches.

Table 2. Specific capacity and transmissivity of selected wells

Aquifer	Specific capacity (gpm/ft)					Transmissivity (ft^2/day)				
	Casing diam. (in.)	Mean	Min	Max	No. of tests	Casing diam. (in.)	Mean	Min	Max	No. of tests
Water table										
ss	12–14	41.3	35.0	53.8	3	12	14,100	--	--	1
scs	12	42.6	--	--	1	--	--	--	--	--
Confined										
hs	12–16	38.3	8.9	66.7	10	12	6,300	2,900	9,000	5
scs	12	21.7	18.0	25.0	3	--	--	--	--	--
mls	12	10.3	0.8	20.8	5	12	13,700	3,300	24,000	2
mls_wrs	12	29.9	--	--	1	--	--	--	--	--
gs4	12–16	9.8	5.8	19.3	8	8–16	9,400	1,700	21,600	3
gs5	12	3.9	3.3	4.5	2	--	--	--	--	--
wrs	12	8.4	6.7	11.6	3	--	--	--	--	--
wes	16	24.4	--	--	1	--	--	--	--	--
pu	--	--	--	--	--	12	8,800	--	--	1

Specific capacity data are adapted from the CWI.

Transmissivity data are from aquifer test data compiled by the DNR.

Dash marks (--) indicate no data in those categories.

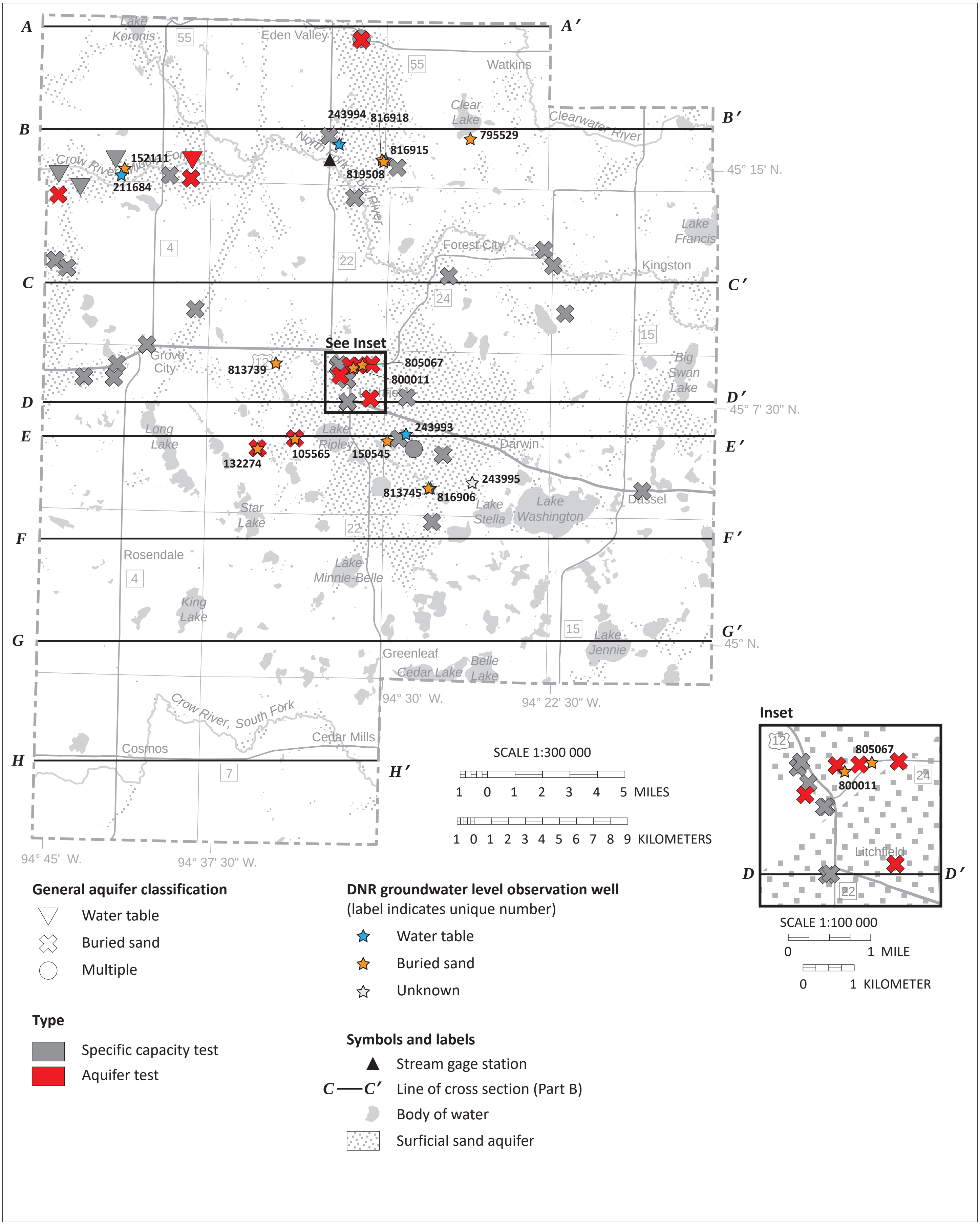


Figure 36. Well locations for DNR observation wells, specific capacity tests, and aquifer tests

Groundwater level monitoring

The DNR maintains a statewide groundwater level monitoring program for assessing groundwater resources, determining long-term trends, interpreting impacts of pumping and climate, planning for water conservation, evaluating water conflicts, and managing water resources.

Well nests consist of closely spaced wells that are constructed in different aquifers. Long periods of record from multiple aquifers are useful for determining trends and provide insight into how aquifers respond to recharge events, climatic conditions, and pumping stresses. The hydrographs shown in Figures 37–40 were produced from data retrieved from the DNR Cooperative Groundwater Monitoring program (DNR, 2017a). Until recent years, water levels in the observation wells were typically collected on a monthly or longer-term basis using steel tape or other labor-intensive means. In recent years some observation wells have been outfitted with data loggers that collect multiple water level readings per day.

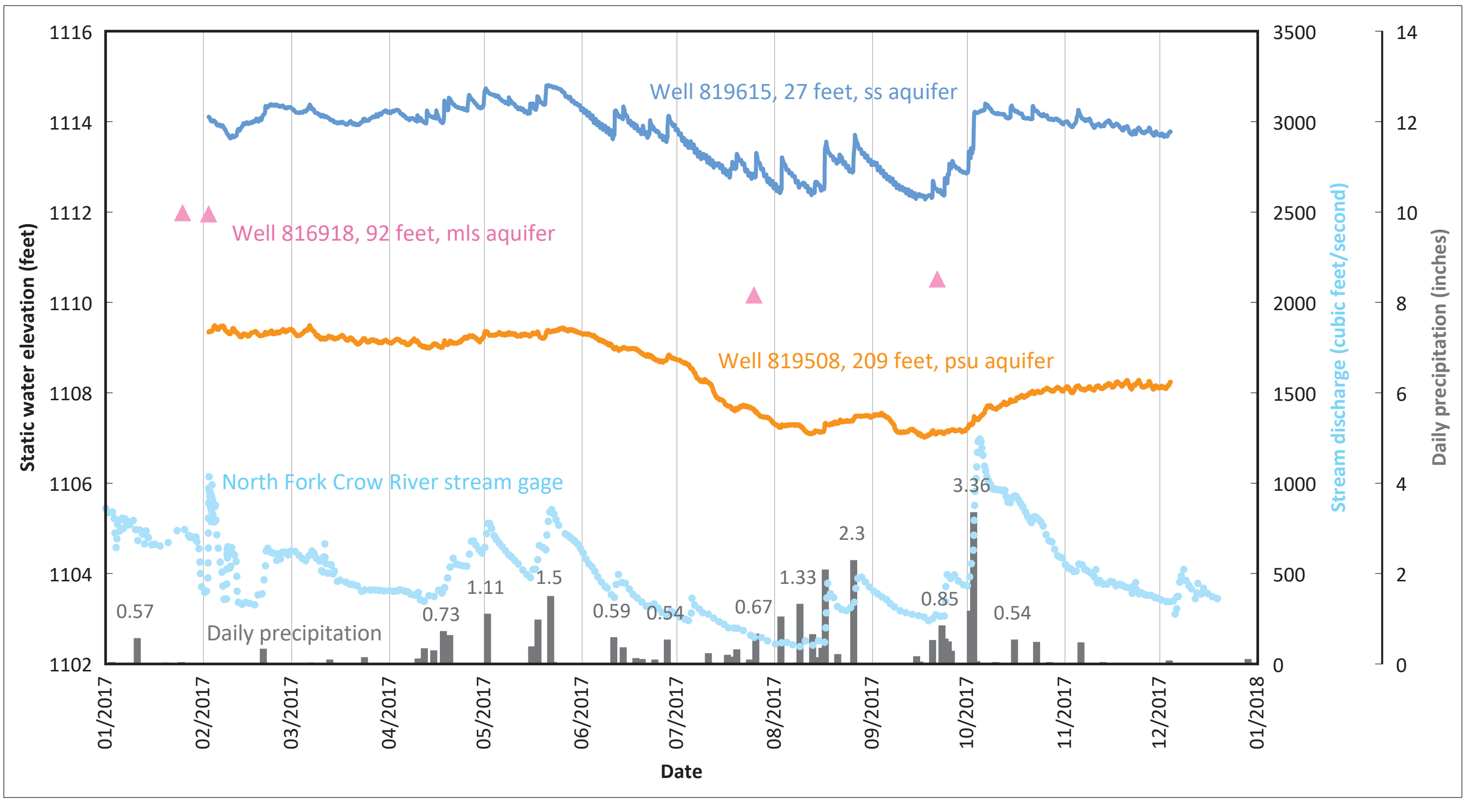


Figure 37. Surface water and groundwater responses to daily precipitation

Daily precipitation plots as vertical bars with amounts varying up to nearly 3.5 inches (DNR, 2018a).

The stream flow data are reported as discharge in cubic feet per second (DNR, 2017d) and generally show increases in response to runoff associated with substantial rainfall events. The stream gage (18063001) is on the North Fork Crow River less than 5 miles south of Eden Valley.

The groundwater data are from a nest of three closely-spaced wells of variable depths approximately 2 miles east of the stream gage. These include a 27-foot deep surficial sand well and two buried sand aquifer wells at 92 and 209 feet deep.

The shallow and deep wells have hourly water elevation readings; the intermediate-depth well has only four hand measurements collected over the nearly one year period of record.

Over time water levels in the three wells rise in response to precipitation. Fluctuations in the shallow surficial sand well are more responsive to daily precipitation, rising in direct response to water percolating below the surface to recharge the water table. Declines in the water-table elevation are the result of evaporation, transpiration, and discharge to surface-water features.

The deepest aquifers respond to changes in confining pressure, which generally corresponds to fluctuations in water-table elevations. Changes are more subdued and generally follow a more seasonal trend of precipitation cycles.

The well nest is also useful for determining vertical groundwater flow direction. Downward flow is indicated by the decline of water level elevations with increasing well depth.

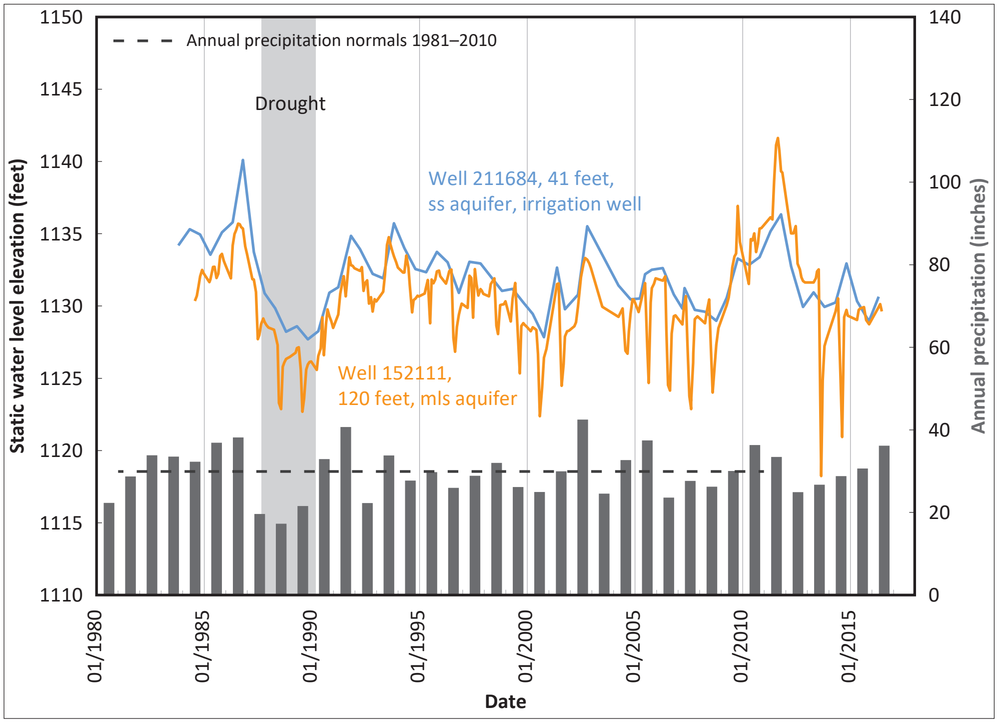


Figure 38. Similar fluctuation to long-term precipitation trends

Two wells just north of the Middle Fork Crow River in northwestern Meeker County are in an east-west band of surficial sand deposits in which many irrigation wells are constructed. The water levels have co-varied in response to long-term precipitation trends over the last 33 years (DNR, 2017c).

The wells include a shallow 41-foot-deep irrigation well (211684) constructed in the surficial sand (ss) aquifer and a 120-foot-deep observation well (152111) completed in the mls aquifer (located approximately 1,400 feet to the northeast).

The vertical bars at the bottom represent annual precipitation; the horizontal dashed line represents the 30-year normal.

Water levels in both wells follow annual rainfall trends and fluctuate with dry and wet periods. Note the decline in water levels for the drought years 1987–1989 (MRCC, 2019).

One outstanding difference is the downward annual spikes in the deeper well. These coincide with the summer months and are likely associated with pumping of nearby irrigation wells in the mls or similar depth aquifer.

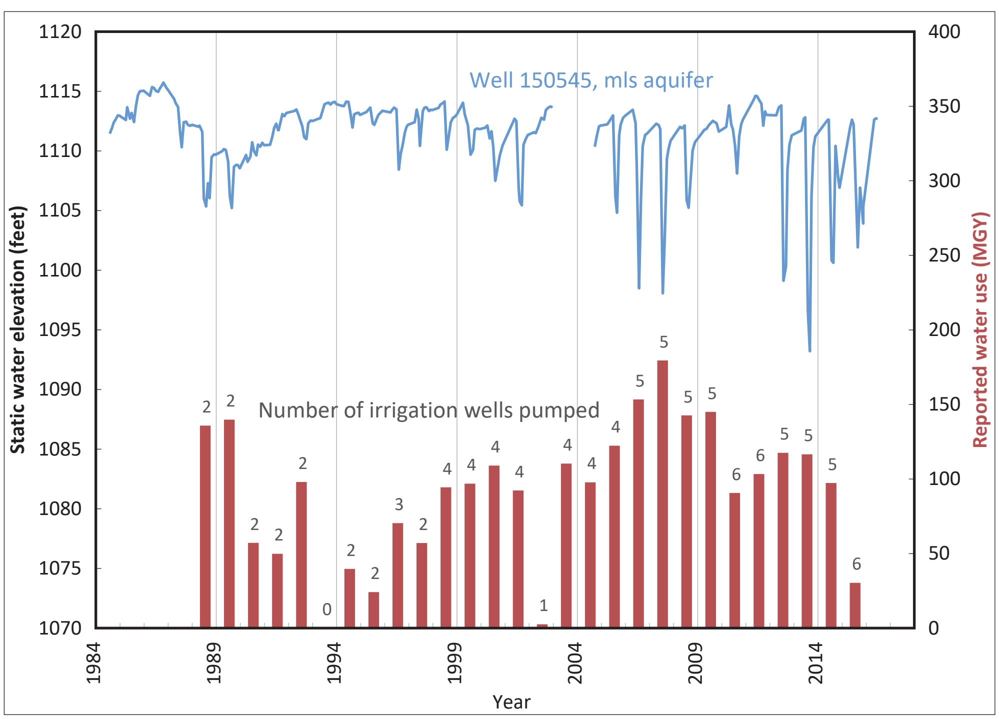
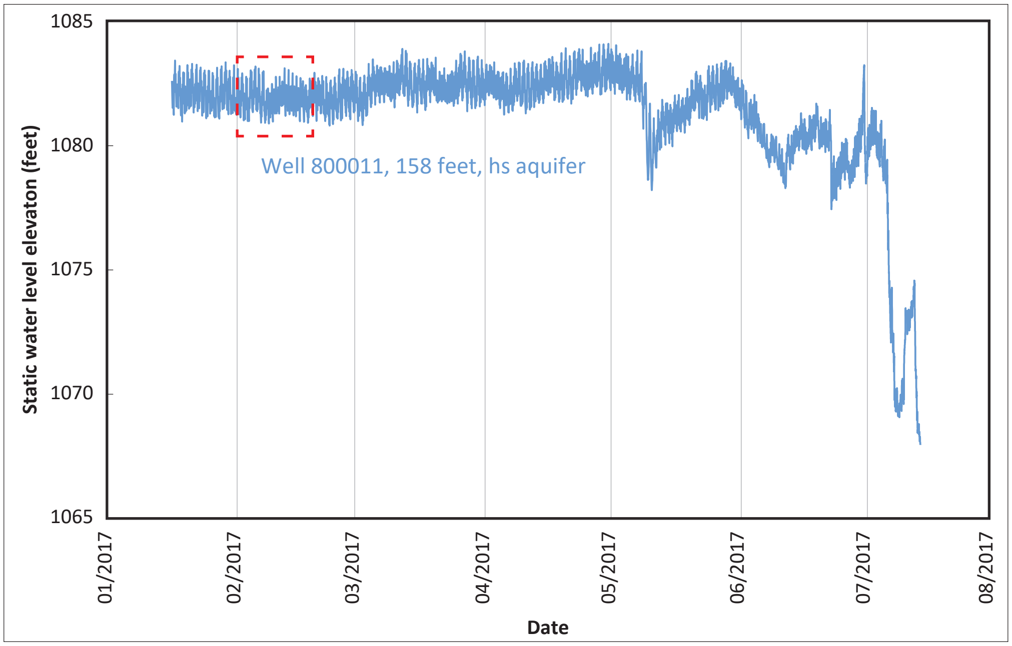


Figure 39. Drawdown effect of high-capacity wells

The groundwater elevation hydrograph shows greater drawdowns over time related to an increasing number of high-capacity wells and total combined pumping volumes within 2 miles of the monitored observation well (150545). This observation well is 180 feet deep, completed in the mls aquifer, and located just southeast of Litchfield.

The vertical bars represent combined annual pumping volumes for high-capacity wells of similar depths and within a two-mile radius of the observation well. The number at the top of each bar represents the number of high-capacity wells with reported water use for that calendar year.



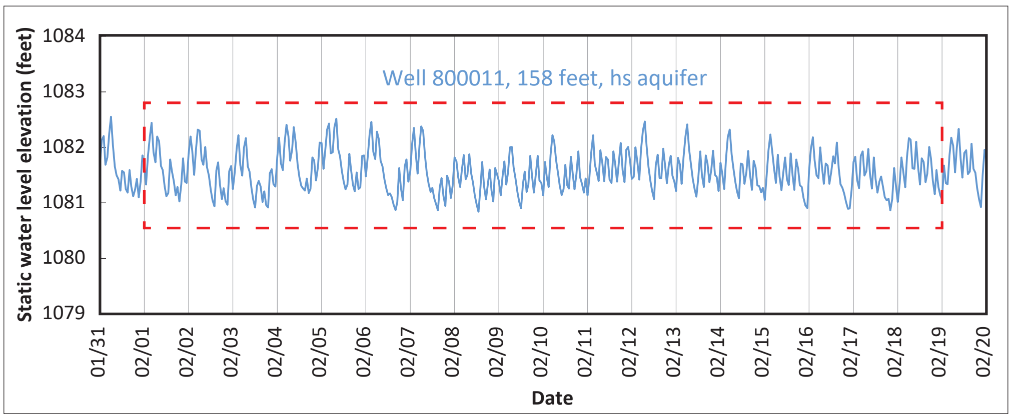


Figure 40. Pumping effects of distance

The upper hydrograph shows water levels in an observation well varying in response to pumping of an irrigation well 600 feet away in the same aquifer (hs).

Smaller drawdowns in May and June are followed by a much larger drawdown in July of up to 15 feet. Water use was reported for this irrigation well for the months of June, July, and August.

The box drawn around data represents a time period of focused interest. The lower figure expands this 20-day period in February to show the frequent smaller drawdowns of 1 to 2 feet that occur several times a day.

The city of Litchfield has four production wells in the same aquifer approximately ½ mile west of the observation well. These fluctuations likely correlate to the cyclical pumping of the city's well field.

Groundwater use

A water appropriation permit is required from the DNR for groundwater users withdrawing more than 10,000 gallons of water per day or 1 million gallons per year (high-capacity users). This provides the DNR with the ability to assess which aquifers are being used and for what purpose. Permits require annual water-use reporting. This information is recorded using Minnesota Permitting and Reporting System (MPARS), which helps the DNR track the volume, source aquifer, and type of water use.

Reported water use of high-capacity users for 2016 is categorized in Table 3 and as a graphical representation in Figure 41 by water use category and in Figure 42 by general aquifer classification (DNR, 2017b). The water-use summary uses data collected for 176 permitted wells. Three water-use categories (agricultural crop irrigation, municipal, and livestock watering) collectively made up 96 percent of the permitted water used in 2016.

Agricultural crop irrigation dominates permitted groundwater use with approximately 54 percent of the total usage. The amount of water needed each year varies significantly. Water usage in 2013 is approximately double the amount used in 2016. Also, the demand for irrigation water is concentrated into 3 or 4 months associated with the growing season. Less than 20 percent of permitted irrigation wells are completed in the water-table aquifer and the rest are completed in buried sand aquifers. The largest concentrations of irrigation wells are southeast of Litchfield and in the northwestern portion of the county where coarse-textured soils do not readily retain moisture.

The second largest category is municipal water supplies (31 percent). The majority of municipal water is from the shallower buried aquifers, chiefly the hs aquifer used by the cities of Litchfield and Eden Valley. Water-use demand for public water supplies is more consistent throughout the year than irrigation and does not change significantly from one year to the next.

The third largest category is livestock watering (11 percent), which gets its water from various buried sand aquifers.

CWI also provides information for wells that do not require permits. There are approximately 3,800 wells in CWI for Meeker County. The majority of wells in the county are for domestic use (85 percent), followed by irrigation (4 percent), and public supply (3 percent). Of the wells with identified aquifers, most are completed in the buried sand aquifers (93 percent), followed by surficial sand (ss) aquifers (4 percent), and finally bedrock aquifers (3 percent).

Table 3. Reported 2016 water use from DNR groundwater permit holders

Aquifer	Number of wells	Agricultural crop irrigation	Municipal/public water supply	Livestock watering	Sand and gravel washing	Agricultural/food processing	Sand/gravel pit dewatering	Total (mgy)	Total (percent)[5]
CWI Aquifer[1]									
Water table (QWTA)	34	218	--	--	40	--	--	258	17
Buried sand (QBAA)	132	564	460	159	--	28	--	1,211	80
Multiple[2]	3	12	16	--	--	--	--	29	2
Other[3]	7	21	--	5	--	--	--	25	2
Stratigraphic sand unit[4]									
Shallow: ss through hs	56	264	403	48	40	--	--	755	50
Intermediate: scs through mls	59	238	38	35	--	--	--	311	20
Deep: gs4 through pu	47	236	35	55	--	28	--	355	23
Aquifer not determined: UNKN	14	77	--	25	--	--	--	103	7
Total (mgy)	--	815	476	163	40	28	0	1,523	--
Total (percent)[5]	--	54	31	11	3	2	0	--	--
Highest annual use by permit 2012–2016	--	1,679	509	163	50	32	--	--	--

1. Total 2016 reported water use by CWI Aquifer code.
2. Multiple aquifer wells extract water from more than one aquifer.
3. Aquifers include Quaternary Undifferentiated (QUUU), Quaternary Buried Unconfined (QBUA), and Unknown (UNKN) for those wells where information was insufficient to identify an aquifer.
4. Total 2016 reported water use by Quaternary stratigraphic sand unit mapped for this atlas. The stratigraphic units are grouped into three depth intervals to facilitate interpretation.
5. Percentage may not equal 100 due to rounding.
Dash marks (--) indicate no data in those categories.

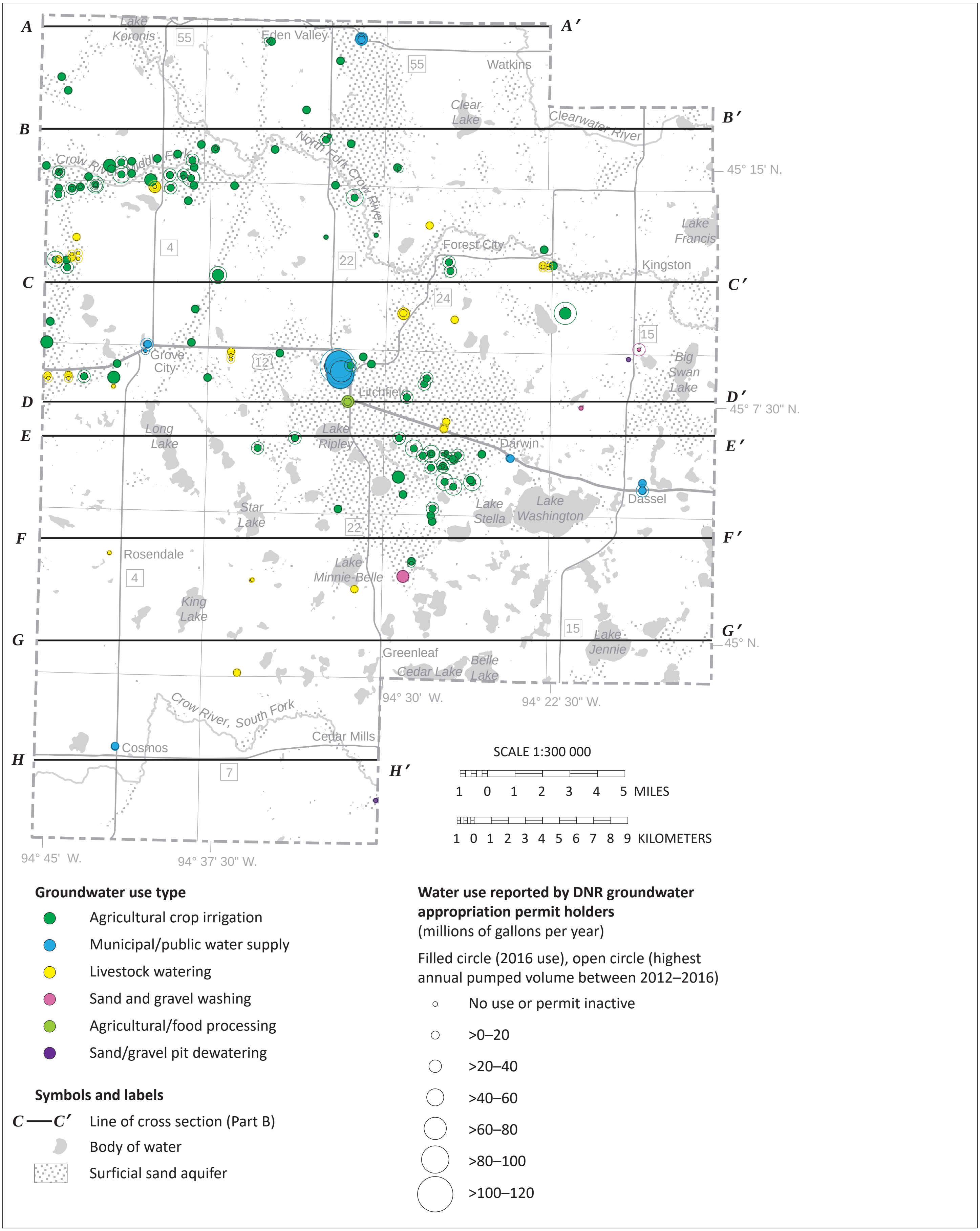
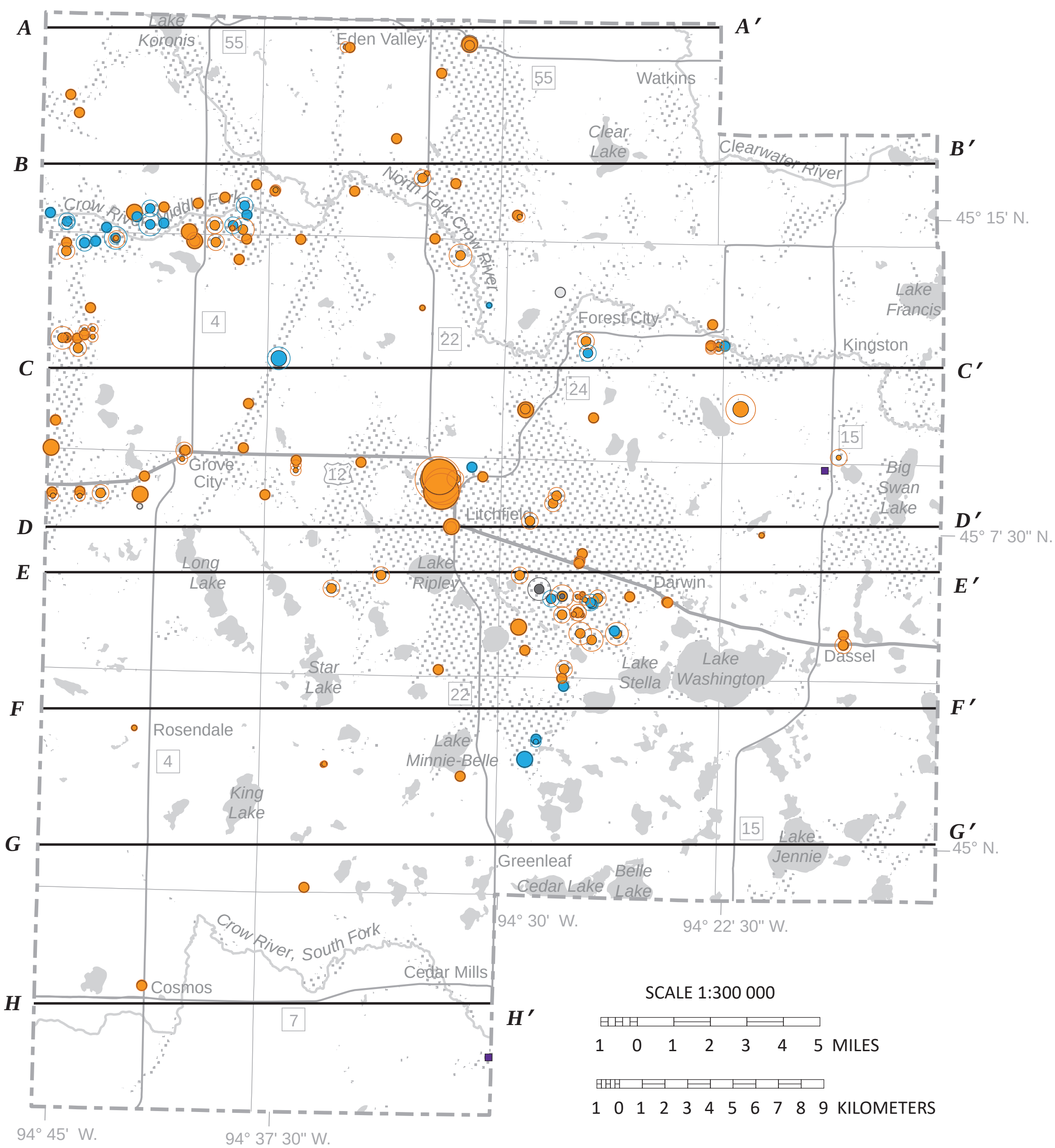


Figure 41. Distribution of groundwater appropriation permits by volume reported and use category

Agricultural crop irrigation accounts for the largest permitted groundwater use in Meeker County.



General aquifer classification

- Water table
- Buried sand
- Multiple
- Unknown

Symbols and labels

- C——C′ Line of cross section (Part B)
- Body of water
- Surficial sand aquifer

Water use reported by DNR groundwater appropriation permit holders
(millions of gallons per year)

Filled circle (2016 use), open circle (highest annual pumped volume between 2012–2016)

- No use or permit inactive
- >0–20
- >20–40
- >40–60
- >60–80
- >80–100
- >100–120

Maximum water use reported by DNR groundwater appropriation permit holders 2012–2016 for sand/gravel pit dewatering
(millions of gallons per year)

- No use or permit inactive

Figure 42. Distribution of groundwater appropriation permits by general aquifer classification
The majority of water used in the county is from buried sand aquifers.

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Glossary

anion—a negatively charged ion in which the total number of electrons is greater than the total number of protons, resulting in a net negative electrical charge.

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

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

aquitard (or confining layers)—layers made up of materials with low permeability, such as clay and shale, which prevent rapid or significant movement of water.

arsenic (As)—a chemical element that is sometimes dissolved in groundwater and is toxic to humans. Natural arsenic contamination of groundwater is a problem that affects millions of people across the world, including over 100,000 people served by domestic wells in Minnesota.

bedrock—the consolidated rock underlying unconsolidated surface materials such as soil or glacial sediment.

buried aquifer—a body of porous and permeable sediment or bedrock which is separated from the land surface by low permeability layer(s).

carbon-14 (^{14}C)—a radioactive isotope of carbon that has a half-life of 5,730 years. It is used to identify groundwater that entered the ground from 100 to greater than 40,000 years before present.

cation—a positively charged ion in which the total number of electrons is less than the total number of protons, resulting in a net positive electrical charge.

County Well Index (CWI)—a database developed and maintained by the Minnesota Geological Survey and the Minnesota Department of Health containing basic information for wells drilled in Minnesota. Information includes location, depth, static water level, construction, and geological information. The database and other features are available through the Minnesota Well Index online mapping application.

dolostone, or dolomite rock—a sedimentary carbonate rock that contains a high percentage of the mineral dolomite. Most dolostone formed as a magnesium replacement of limestone or lime mud prior to lithification. It is resistant to erosion and can either contain bedded layers or be unbedded. It is less soluble than limestone, but it can still develop solution features over time.

equipotential contour—a line along which the pressure head of groundwater is the same. Groundwater flow (shown on cross sections) is perpendicular to these lines in the direction of decreasing pressure.

formation—a fundamental unit of lithostratigraphy. A formation consists of a certain number of rock strata that have a comparable lithology, facies, or other similar properties.

fractionation—a separation process in which a mixture (solid, liquid, solute, suspension, or isotope) is divided based on the difference of a specific property of the components. Stable isotopes are fractionated by mass.

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

half-life—the time required for one half of a given mass of a radioactive element to decay.

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

hydraulic—relating to water movement.

hydraulic conductivity—the rate at which groundwater flows through a unit cross section of an aquifer.

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

isotope—variants of a particular chemical element. All isotopes of an element share the same number of protons but a different number of neutrons.

lacustrine—relating to or formed in a lake.

meteoric—relating to or derived from the earth's atmosphere.

nitrate (nitrate-N, NO_3^-)—humans are subject to nitrate toxicity, with infants being especially vulnerable to methemoglobinemia, also known as blue baby syndrome. Elevated nitrate (≥1 ppm) is primarily from fertilizer sources.

observation well—a well that is used to monitor the water level of groundwater. It is usually not used as a water source.

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

provenance—the place of origin of a glacier.

Quaternary—geologic time period that began 2.588 million years ago and continues to today. The Quaternary Period comprises the Pleistocene and Holocene epochs.

radioactive—a property of an element that spontaneously decays or changes to a different element through the emission of radioactive particles.

recharge—the process by which water enters the groundwater system.

residence-time indicators—chemical and/or isotope used to interpret groundwater residence time.

specific capacity—the discharge of a well divided by the drawdown in the well.

stable isotope—chemical isotopes that are not radioactive.

static water level—the level of water in a well that is not affected by pumping.

stratigraphy—a branch of geology that studies rock layers and layering (stratification). It is primarily used in the study of sedimentary and layered volcanic rocks.

till—unsorted glacial sediment deposited directly by ice. It is derived from the erosion and entrainment of rock and sediment.

tritium (^3H)— a radioactive isotope of hydrogen that has a half-life of 12.32 years. The nucleus of tritium contains one proton and two neutrons. It is used to identify groundwater that entered the ground since the 1950s.

tritium unit (TU)—one tritium unit represents the presence of one tritium atom for every 10^{18} hydrogen atoms.

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

water table—the surface between the unsaturated and saturated zone where the water pressure equals the atmospheric pressure.

watershed—the area of land that drains into a specific downstream location.

well nest—two or more wells in close proximity completed in different aquifers.

Appendix A

Groundwater field sample collection protocol

Groundwater samples were collected from an outside faucet or hydrant. The wells were purged prior to sampling to remove stagnant water from the well bore and plumbing system. Samples were collected after field parameters such as temperature, dissolved oxygen, conductivity, and pH had stabilized. Each was filtered and preserved according to protocols listed below and submitted to laboratories for analysis.

Samples were analyzed by DNR staff; the Minnesota Department of Agriculture (MDA); the Minnesota Department of Health (MDH); the University of Minnesota, Department of Earth Sciences Laboratory (U of M); or the University of Waterloo Environmental Isotope Laboratory (Waterloo).

The well owners received a copy of the results including some background reference information regarding their meaning.

For additional information, contact the County Groundwater Atlas program.

Appendix Table A-1: Groundwater field sample collection and handling details

Parameter	Tritium	^{18}O Deuterium	Nitrate/ Nitrite & Total Phosphorus	F, Cl, SO_4	Metals	Bromide	Alkalinity	^{14}C
Lab	Waterloo	Waterloo	MDA	MDA	MDA	MDH	DNR	U of M
Sample container	500 ml HDPE	60 ml HDPE	250 ml plastic	250 ml plastic	250 ml plastic	125 ml plastic	500 ml plastic	30 gallon barrel
Head space	yes	yes	yes	yes	yes	yes	no	yes
Rinse	no	no	yes*	yes*	yes*	yes*	yes⁺	no
Filter (micron)	no	no	0.45	0.45	0.45	0.45	no	no
Preservative	no	no	5 ml 10% H_2SO_4 (yellow cap)	no	2.5 ml 20% HNO_3 (red cap)	no	no	NH_4OH added to adjust PH
Refrigeration	no	no	yes	yes	yes	yes	yes, if not analyzed onsite	no
Holding time	long	long	28 days	28 days	6 months	28 days	24–48 hours	years
Field duplicate	1 for every 20	1 for every 20	1 for every 20	1 for every 20	1 for every 20	1 for every 20	1 for every 20	none
Field blank	none	none	1 for every 20‡	1 for every 20‡	1 for every 20‡	1 for every 20‡	none	none
Storage duplicate	yes	yes	no	no	no	no	no	no

* Rinse the bottle three times with sample water prior to collecting the sample (FILTERED if sample is filtered). Rinsing means fill the bottle with sample water and then pour the contents out over the cap.

⁺ Rinse the bottle three times with sample water prior to collecting the sample. Fill bottle submerged with cap in hand. Seal bottle submerged ensuring no remnant bubbles.

‡ Use DI water from designated lowboy for blanks. Attach lowboy to the inline filter with a 3/8" tube and purge 1 L of water to rinse tubing and filter. Rinse and fill bottles through filter with the procedures outlined above.

Appendix B

Tritium values from precipitation and surface water

Samples were analyzed for enriched tritium by the University of Waterloo Environmental Isotope Laboratory for determining recent tritium values. Samples came from two main sources:

1. Precipitation composites were collected at the Minnesota DNR MNgage climatology monitoring station MWDM5 in Maplewood (Twin Cities metropolitan area). Samples were composited over the course of 30-day periods between spring and fall over the years 2012 through 2017.
2. A lake-water sample was collected at the surface of Lake Washington several feet from shore.

For additional information, contact the DNR Groundwater Atlas Program (mndnr.gov/groundwatermapping).

For additional weather station information, contact:

- MNgage (climateapps.dnr.state.mn.us/HIDENsityEdit/HIDENweb.htm)

Appendix Table B-1: MNgage precipitation station enriched tritium results

Sample date range	Tritium (TU)	Analytical error	Sample type
MNgage precipitation station (MWDMS)			
05/21/2012–06/20/2012	8.7	0.7	Precipitation composite
09/30/2012–10/30/2012	6.7	0.7	Precipitation composite
05/09/2014–06/09/2014	7.0	0.7	Precipitation composite
10/01/2014–10/31/2014	6.7	0.7	Precipitation composite
05/01/2015–05/31/2015	5.3	0.6	Precipitation composite
08/17/2016–09/16/2016	8.3	0.8	Precipitation composite
04/01/2017–04/30/2017	8.1	0.7	Precipitation composite
09/06/2017–10/06/2017	6.5	0.6	Precipitation composite
Lake Washington, Meeker County			
11/02/2016	6.4	0.6	Limnetic Zone

Tritium age of historic groundwater samples

The groundwater atlas uses tritium data to assess the residence time of groundwater, which is then used to evaluate atlas pollution sensitivity models and recharge conditions of the aquifer. Data from other studies prior to the DNR project sample period (historic data) are used to inform our understanding of groundwater residence time where we lack current data.

A sample's tritium age is assigned using Table B-2 based on the year that the sample was collected. Historic tritium unit values change over time because of tritium's relatively short half-life of 12.32 years (Lucas and Unterweger, 2000). For example, a sample collected in 2009 that had 9 tritium units (TU) is mixed tritium age. A sample collected in 2016 that had 9 TU is recent tritium age.

The Cold War era classification is a special case and implies that groundwater sampled for this atlas infiltrated into the ground in the 1960s. The Cold War era classification is only assigned to samples collected contemporaneously with this atlas (in 2016). Historic data (pre-2016) classified in earlier reports as Cold War era is now recent tritium age.

Appendix Table B-2: Tritium classification by date of sample collection

	Sampling periods for tritium		
Tritium age	**2016**	**2013–2015**	**2012 or before**
Cold War era	>15 TU	NA	NA
Recent	≥8 to 15 TU	≥8 TU	≥10 TU
Mixed	>1 to <8 TU	>1 to <8 TU	>1 to <10 TU
Vintage	≤1 TU	≤1 TU	≤1 TU

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