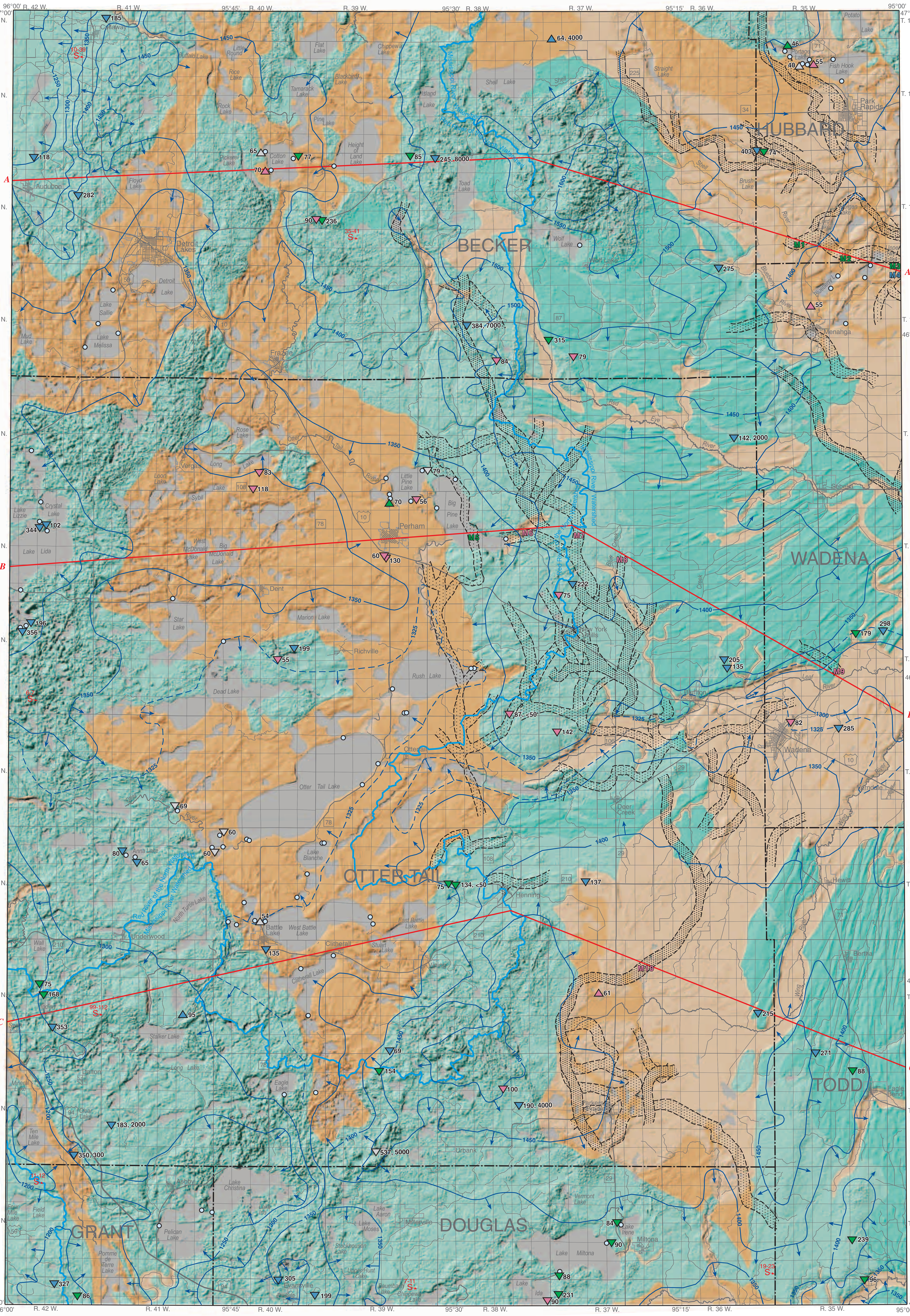


Digital base composite: Roads and county boundaries - Minnesota Department of Transportation
GIS Statewide Base Map (source scale 1:24,000)
Hydrologic features - U.S. Geological Survey Digital Line Graphs (source scale 1:100,000)
Digital base annotation - Minnesota Geological Survey
Project data compiled from 1997 to 1999 at the scale of 1:200,000. Universal Transverse Mercator projection, grid zone 15, 1983 North American datum. Vertical datum is mean sea level.
Modified from Minnesota Geological Survey RHA-5, Part A, Plate 1 (Surficial Geology).

SCALE 1:200 000
5 0 5 10 Miles
5 0 5 10 Kilometers
Contour Interval 50 Feet
Supplementary Contours Shown in Selected Areas

MAP EXPLANATION

Hydrologic Symbols

- 1100 Water-table elevation (feet above sea level), contour interval 50 feet
- Water-table supplementary contours (25-foot interval)
- General direction of ground-water movement at the water table
- Surface watershed divide between Mississippi River and Red River of the North watersheds

Hydrogeologic Settings (map units from Part A, Plate 1)*

Outwash

- Outwash Plain—Low relief, meltwater stream deposits (cc, lgc, lgow, oc, oow, ugc, ha)
- Collapsed Outwash—Moderate to high relief, meltwater stream deposits that later collapsed (lgo, lgp, oo, op, ugo, ugp)

Moraine

- Hummocky Moraine—High relief, collapsed glacial deposits (cd, cm, cs, lgd, lgm, lgs, lgt, od, om, os, ugd, ugm, ugs)
- Ground Moraine—Low to rolling relief, eroded glacial deposits (cg, cw)

*Thin, near-shore lake sediments and Holocene bog sediments (map units lgn, cn, and ho from Plate 1 of Part A) were considered part of the surrounding geologic materials for the purposes of this assessment.

Mapped, Buried Aquifers (elevation in feet above mean sea level)

- Elevation of top of aquifer is 1340–1430
- Elevation of top of aquifer is 1260–1360
- Elevation of top of aquifer is 1240–1310
- M5 Mapped, buried aquifer where intersected with cross section (see Figure 1 explanation)

Sample Sites (number of samples)

- Quaternary water-table aquifer (11)
- Quaternary buried outwash aquifer (71)
- Lake water (82)

Tritium Age of Ground Water

- Recent—Water with tritium concentration of 10 or more tritium units (TU) entered the ground water since 1953.
- Mixed—Water with 0.8 to less than 10 TU is a mixture of recent and vintage.
- Vintage—Water with tritium concentration of less than 0.8 TU entered the ground water before 1953.
- Not tested for tritium.

Well Labels

113, 4000 — If shown, ground-water age in years, estimated by carbon-14. Samples labeled "< 50" were used to calibrate the carbon-14 model.
Well depth in feet.

Seismic Refraction

9-10 S — Numbers indicate range of depth in feet to the water table; arrow points to location of the midpoint of transect.

SURFICIAL HYDROGEOLOGY

by
Julie C. Ekman and James A. Berg
2002

INTRODUCTION

The Otter Tail Area Regional Hydrogeologic Assessment is an examination of surficial geology and near-surface stratigraphy (Part A) and hydrogeology and geologic sensitivity to pollution (Part B) for use in managing ground-water resources. The study area includes most of Becker and Otter Tail counties and parts of Douglas, Grant, Hubbard, Todd, and Wadena counties in west-central Minnesota. This plate displays a map of the major hydrologic features, including water-table elevation and general flow directions of shallow ground water.

Surficial hydrogeology in this report refers to the ground-water systems within the glacial deposits. Sediments deposited by several glacial episodes have been grouped into four hydrogeologic settings to characterize the ground water in this study area: outwash plain, collapsed outwash, hummocky moraine, and ground moraine. These four settings are identified based on the most recent glacial processes and sediment textures as described on Plate 1 of Part A.

Shallow and deeper ground water was assessed by sampling 82 wells throughout the study area that ranged from 40 feet to 537 feet deep. Eight wells with vintage water were chosen for carbon-14 age dating. Nine sites in moraine areas were chosen for geophysical testing to determine the depth to the water table. Water samples from seven lakes were compared with water from nearby shallow wells to assess lake and ground-water interactions.

SHALLOW GROUND WATER

Shallow ground water in this report is defined as that part of the ground-water system bounded above by the water table and locally interacts with lakes, wetlands, and streams. Shallow ground-water movement is influenced by topography and generally trends away from the major watershed divide.

In most of the study area, the water table approximates a subdued surface topography. In the outwash settings, the elevation of the water table was established from field measurements of water in wells, information from the County Well Index (CWI), and surface-water elevations. The median depth to water measured in the outwash settings is 19 feet. In the moraine settings, the elevation of the water table was determined from information in CWI, nine seismic analyses, and surface-water elevations. Median depth to water in the ground moraine setting is less than 35 feet. Depth to water is most variable in the hummocky moraine setting where the median is less than 30 feet. Seismic refraction in the hummocky moraine (near the west end of C–C′ on the map) determined the water table to be more than 100 feet below the land surface. The water-table elevation is subject to seasonal and climatic variations.

In the outwash settings, the saturated sediments beneath the water table may be an aquifer where these sand and gravel deposits are thick. Two important aquifers are the Pineland Sands (Helgeson, 1977) aquifer in the northeast corner of this study area and the Pelican River (Miller, 1982) aquifer in the northwest corner. In moraine settings, the saturated till sediments beneath the water table do not provide a practical water supply.

Infiltration of water can be rapid through the sand and gravel sediments of the outwash but is slowed by clay minerals in the moraine sediments, which retard vertical recharge. However, fractures in sediments that extend into the water table, as well as root zones and animal burrows, provide pathways for more rapid recharge in all settings.

Throughout the study area, recharge to the water table is most likely to occur following heavy spring rains when the vadose zone is wet from snowmelt. Recharge occurs to a lesser extent during lighter autumn rains when many plants are dormant and crops have been harvested. During the peak growing season, plants intercept most precipitation before it can reach the water table.

DEEPER GROUND WATER

The deeper ground water lies beneath the shallow part of the ground-water system. The boundary between shallow and deeper ground water is indistinct. Deeper ground-water flow systems are those that generally do not interact with minor surface-water features. Movement of deeper ground water is driven by potentiometric highs that correspond to regional topographic highs in the study area, such as the major watershed divide. Directions of deeper flow are also influenced by buried sand and gravel bodies and contact zones between till units. Throughout most of the study area, deeper ground water moves downward at regional recharge zones that correspond to topographic highs. It moves laterally at depth and then moves upward at regional discharge zones that correspond to major surface-water features, such as Lake Lida and the Leaf River. The directions of deeper ground-water movement were interpreted from static water-level data in CWI and are shown on Figures 1 and 2.

In the moraine settings and in till units below the outwash settings, water can be obtained from buried aquifers created by former glacial meltwater channels and buried sand and gravel deposits of limited extent. Some of these channels have been mapped in the eastern part of the study area (see map and Figure 1). Buried aquifers occur frequently in the hummocky moraine setting where melting ice deposited pockets of sand and gravel in the till. In the ground moraine, subsequent glacial processes eroded existing sediments; consequently, buried aquifers are thinner and occur less frequently in this setting than in the hummocky moraine.

Vertical recharge to buried aquifers can occur where the overlying till is thin, locally absent, or fractured. Subsurface ground-water movement from adjacent areas recharges isolated sand and gravel bodies in till. Water in buried aquifers as shallow as 100 feet may be thousands of years old, indicating recharge by older water and little or no infiltration from the surface.

WATER CHARACTERISTICS

The chemical characteristics of shallow and deeper ground water are influenced by the hydrogeologic setting through which the water infiltrates, even though glacial material and sediment texture may be different at depth. Recharge sources and ground-water residence times can be inferred from analyses of chemistry data combined with tritium and carbon-14 age dating. These analyses determined that 51 of 72 ground-water samples from wells across the study area have chemistry indicating a wetland recharge source. Because wetlands represent the largest source of ground-water recharge, preservation of wetlands will help recharge future water supplies. Ground-water residence times within the surficial sediments of the outwash settings generally ranged from years to decades. Buried aquifers in the moraine settings had water that ranged from decades to several centuries old.

Chemistry data also provide information about the geologic source material that affects the type of ground water found in the study area. The source materials brought by several glacial episodes vary, but all contain significant amounts of carbonate rock. Consequently, nearly all samples analyzed had hard water and were the calcium-magnesium-bicarbonate type. Clay minerals in the moraine sediments slow the movement of ground water so the dissolved solids are not depleted. As a result, concentrations of total dissolved solids and alkalinity were higher in water samples from the moraine settings than they were in water samples from the outwash settings.

REFERENCES CITED

Helgeson, John O., 1977, Ground-water appraisal of the Pineland Sands area, central Minnesota: U.S. Geological Survey Water-Resources Investigations 77-102, 49 p., 3 pl.
Miller, R. T., 1982, Appraisal of the Pelican River sand-plain aquifer, western Minnesota: U.S. Geological Survey Open-File Report 82-347, 44 p., 3 pl.

FIGURE 1. *Hydrogeologic cross-sections A–A′, B–B′, and C–C′. These cross sections show glacial stratigraphy to as deep as 500 feet; the general directions of shallow and deeper ground-water flow; and an interpretation of recent, mixed, and vintage ground water based on tritium concentrations of ground-water samples. Locations of selected sampled wells have been projected onto the cross sections, and well screens are exaggerated for clarity.*

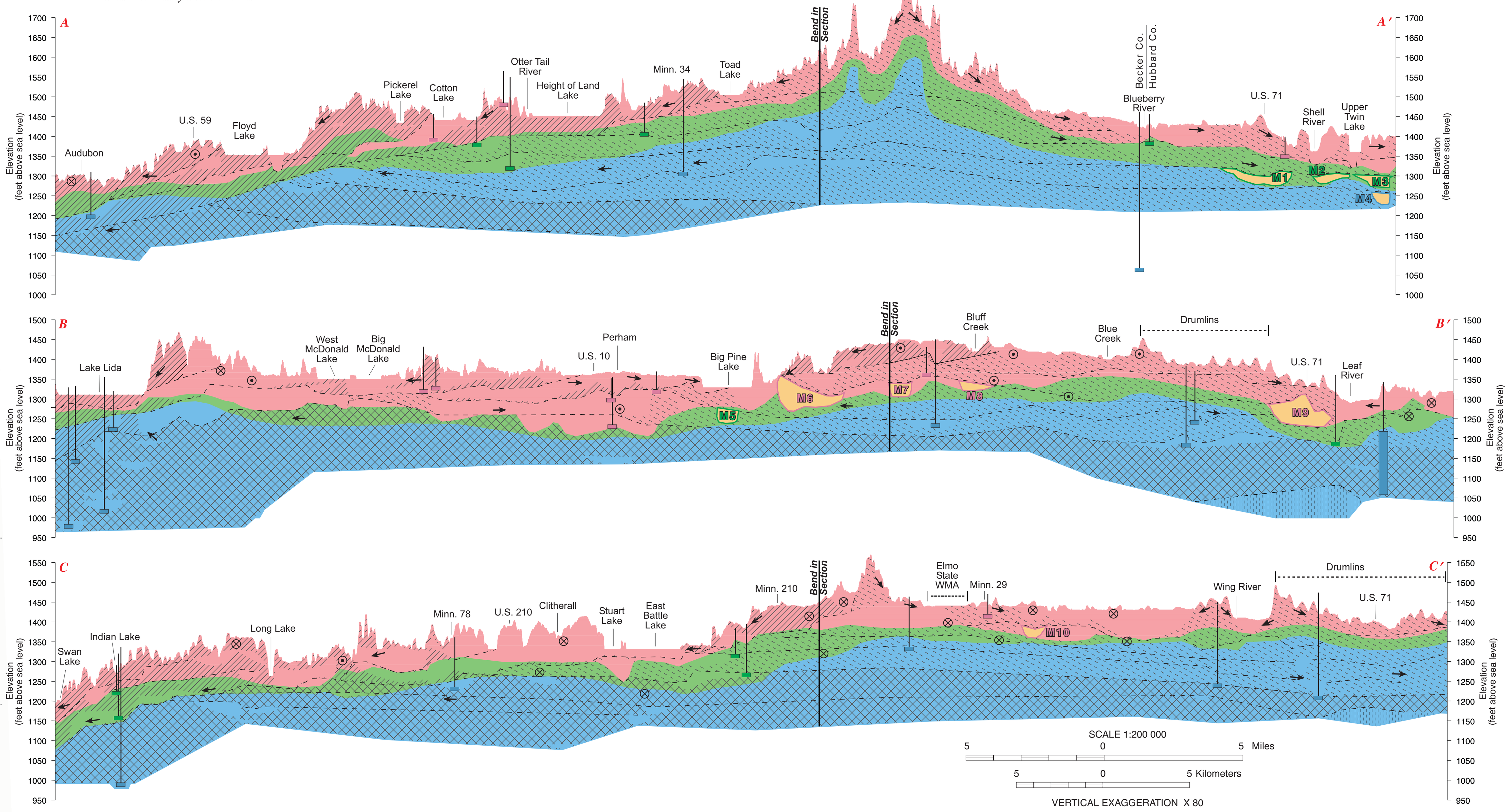
The cross sections show the sequence of sediments deposited by glacial advances and retreats. Outwash sand and gravel deposited by one glacial event were often covered by the next glacial advance, creating buried aquifers (e.g., buried aquifers at M1–M10). Outwash deposits left by the last glacial event that blanket much of the central and eastern part of the study area (in some places as much as 100 feet thick) created surficial aquifers.

Shallow ground-water movement in the vicinity of cross-sections B–B′ and C–C′ is dominated by localized flow to surface waters. Deeper ground-water flow in these areas responds to the influence of major surface water features, such as Lake Lida on the western portion of cross-section B–B′.

Recent water has been found as deep as 130 feet near Perham (B–B′) where sand and gravel deposits are thick. Lateral flow in sand and gravel can move recent water beneath thick till (on A–A′ west of Cotton Lake). Where recent water penetration is shallow, sand and gravel deposits are thin and underlain by till, the clay in till is retarding infiltration, or there is an upward gradient resulting in vintage water mixing with shallower, recent water (on B–B′ near Lake Lida). The relationship between water age and geologic sensitivity is described on Plate 4.

EXPLANATION

- Recent—Water entered the ground water since 1953 (10 or more tritium units). Well screen color shows recent water.
- Mixed—Water is a mixture of recent and vintage waters (0.8 to less than 10 tritium units). Well screen color shows mixed water.
- Vintage—Water entered the ground water before 1953 (less than 0.8 tritium units). Well screen color shows vintage water.
- General direction of shallow and deeper ground-water flow
- Ground-water flow into the plane of the cross section
- Ground-water flow out of the plane of the cross section
- Uncertain boundary between till units
- Sand and gravel
- M5 Mapped, buried aquifer; text color is tritium age
- Tills of the Goose and Otter Tail River Groups
- Tills of the Crow Wing River Group
- Undifferentiated till
- Bedrock



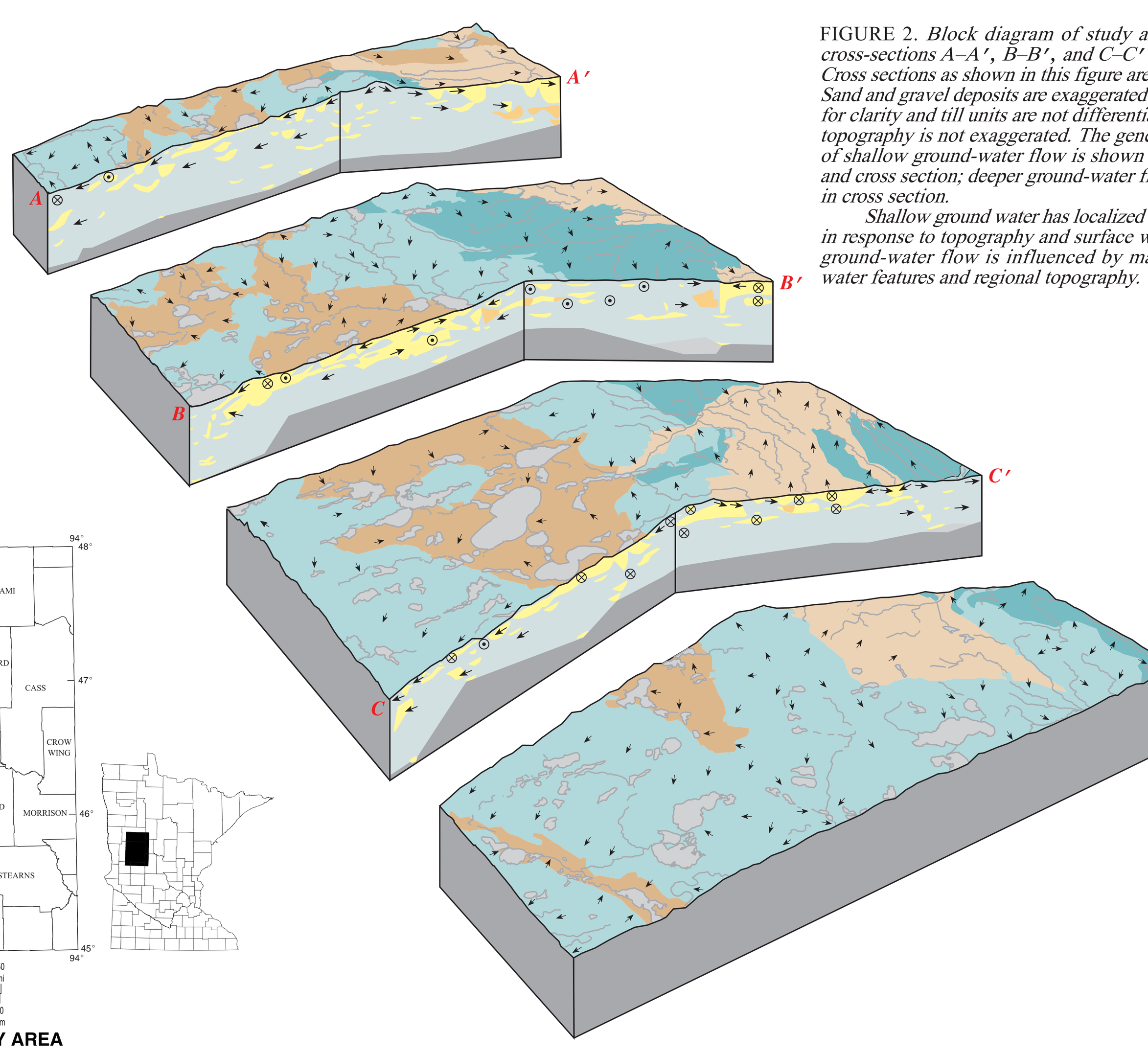


FIGURE 2. *Block diagram of study area showing cross-sections A–A′, B–B′, and C–C′ of Figure 1. Cross sections as shown in this figure are not to scale. Sand and gravel deposits are exaggerated in this figure for clarity and till units are not differentiated. Surface topography is not exaggerated. The general direction of shallow ground-water flow is shown in plan view and cross section; deeper ground-water flow is shown in cross section.*

Shallow ground water has localized flow patterns in response to topography and surface water. Deeper ground-water flow is influenced by major surface-water features and regional topography.

EXPLANATION

- Outwash
- Moraine
- General direction of shallow and deeper ground-water flow
- Ground-water flow into the plane of the cross section
- Ground-water flow out of the plane of the cross section
- Sand and gravel
- Mapped, buried aquifers
- Till
- Bedrock
- Not interpreted

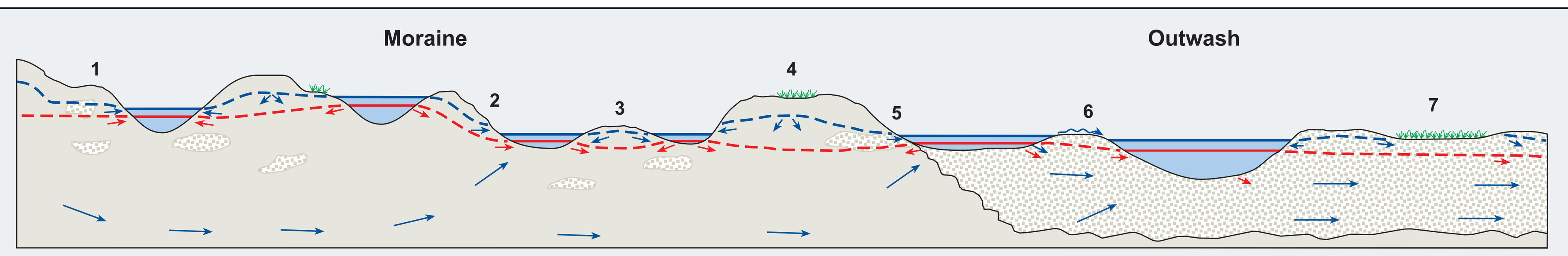


FIGURE 3. *Interactions of lakes and ground water in moraine and outwash sediments.* This schematic illustrates lake and ground-water interactions typical of the Otter Tail study area. It also shows representative changes to the hydrology when climatic or seasonal conditions shift between wet and dry.

Numerous lakes and wetlands are present in the western portion and northeast corner of the study area. Topography and sediments determine the nature of lake and ground-water interactions. The left portion of the diagram shows a hummocky moraine setting like that in the western part of the study area, and the right portion shows a sandy outwash setting like that of the central and northeast. Lakes rarely occur in the ground moraine setting because a well-developed stream network drains surface water from the area.

Kettle lakes dot the hummocky moraine setting. Fine-grained sediments in the till maintain steep ground-water gradients. Adjacent lakes can have quite different elevations and form local hydrologic systems with surrounding ground water. In these lakes without surface outlets, precipitation and evaporation are the primary controls on water levels. Water resides longer in these lakes, allowing more time for it to react with lake-bottom sediments. Ground water also has a longer residence time in these fine-grained sediments. Consequently, the lake water and ground water have higher specific conductance and alkalinity values than water has in outwash settings.

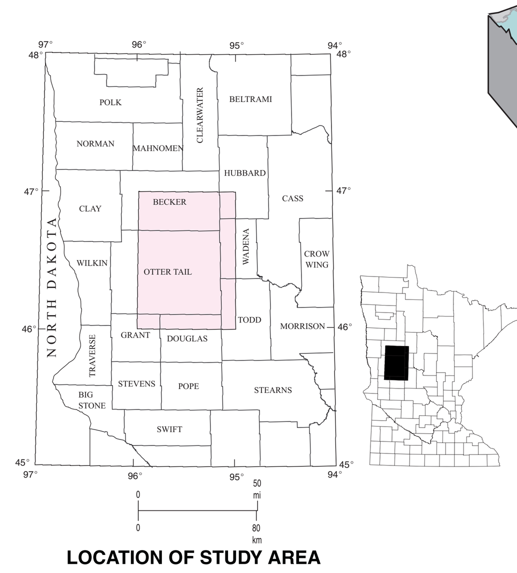
Chains of lakes in former meltwater channels are common in the outwash setting. Coarse-grained sand and gravel sediments contribute to dynamic interactions between lakes and ground water. Surface outlets (channels between lakes) control maximum lake levels. Water in the outwash settings has less time to interact with sediments, so the water has specific conductance and alkalinity values that are generally lower than water has in the hummocky moraine setting.

Variations in lake and ground-water levels result from fluctuations in precipitation and temperature. Seasonal cycles result in short-term fluctuations of water levels. After snow melt and spring rains when plants and trees are still dormant or just emerging, the levels of lakes and the water table can rise significantly. As summer progresses and plant growth is at peak levels, evapotranspiration intercepts much of the rainwater before it can reach the water table, and vegetation near a shoreline can transpire significant amounts of lake water. During fall, after plant growth slows and crops are harvested, rains may again recharge the water table and lakes. Water-level fluctuations can change the direction of shallow ground-water movement. Long-term wet or dry periods result in more persistent changes in water levels. Landscapes are altered as wetlands and streams appear or disappear and lake shorelines change.

Refer to the Technical Appendix for a description of lake and ground-water interactions as revealed by chemical data.

EXPLANATION

1 Flow direction—no change during wet or dry periods
2 Seepage face—wet conditions
3 Flow direction—changes during wet or dry periods
4, 7 Perched and water-table wetlands—evaporate during dry periods
5 Lake spring—wet conditions
6 Stream flow—ephemeral during dry periods
Stream flow
Deeper ground-water flow
Shallow ground-water flow—wet conditions
Shallow ground-water flow—dry conditions
Lake surface—wet conditions
Lake surface—dry conditions
Water table—wet conditions
Water table—dry conditions
Moraine
Outwash sand and gravel
Wetland



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