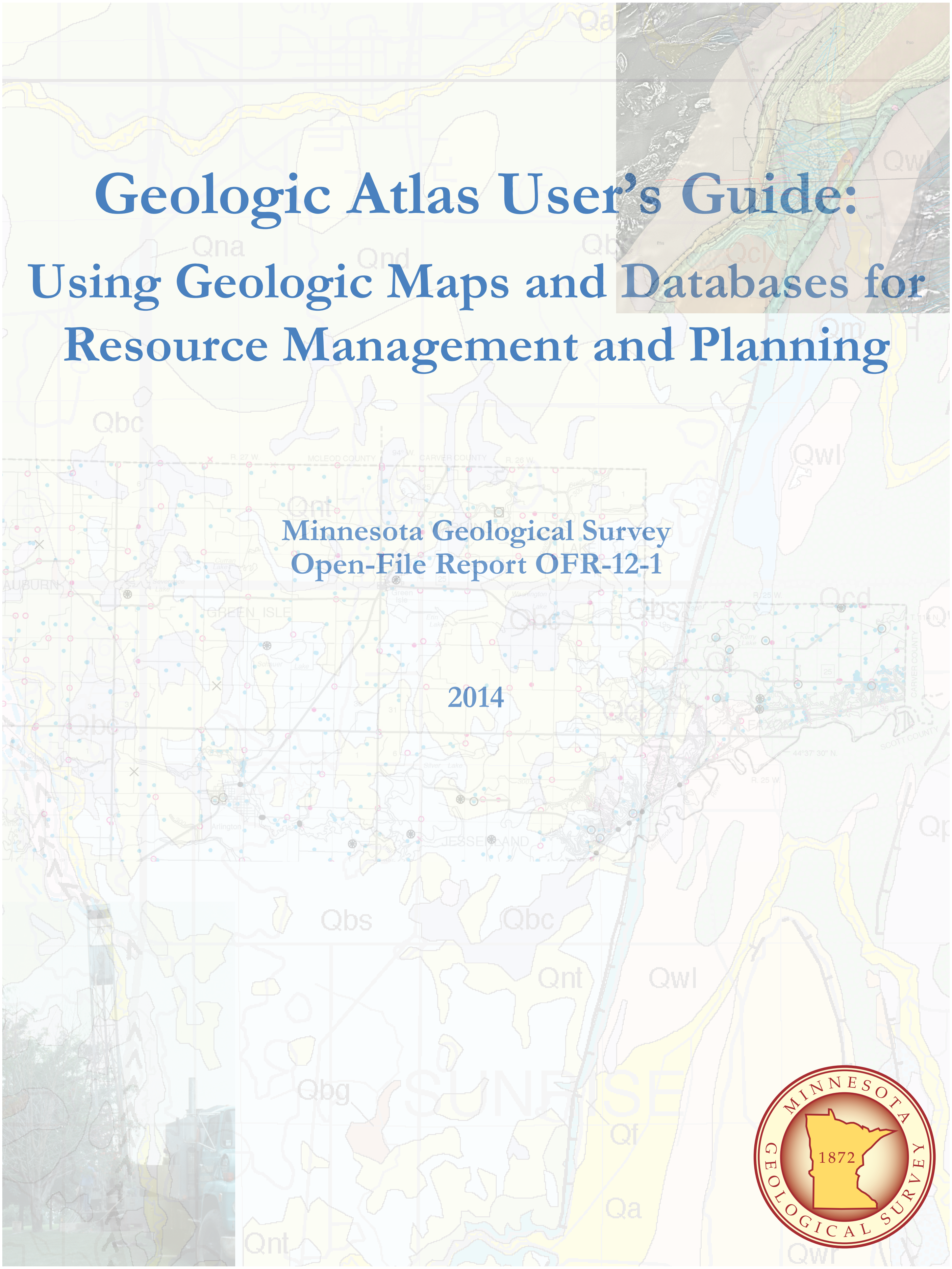

Geologic Atlas User's Guide:

Using Geologic Maps and Databases for Resource Management and Planning

Minnesota Geological Survey
Open-File Report OFR-12-1

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Using Geologic Maps and Databases for Resource Management and Planning

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Part 1: Purpose , History, and Ground Water Basics

Introduction

If you think of earth as our home, we spend almost all of our time on the main floor, and very little in the basement. We travel the land surface, interact with its features, and learn about it through our senses of sight, sound, and touch.

However, some of the things we depend on the most come from beneath the land surface. We need energy, building materials, shelter, waste disposal, and most importantly, water.

Many of us have had little opportunity or need to learn about those aspects of the earth. As our population grows and our material requirements increase human impact on energy and water resources also increases, and we need to understand the workings of our home more fully for it to provide what we need now and into the future.

We wouldn't try to manage our road network without maps to record where the roads are, what their characteristics are (number of lanes, pavement type, speed limits, etc.), and how they connect to each other. Similarly, to manage resources such as our water supply we need maps that indicate where water is stored (aquifers), and how those aquifers are connected to the land surface, to surface waters, to wells, and to each other.

A geologic atlas is intended to describe the geologic framework of our home and how the subsurface environment provides the resources we need. It describes the materials and features that begin just beneath the soil and it continues down to the bedrock surface and beyond.

The atlases provide information useful for resource management and land use planning. Sometimes they utilize terminology and concepts familiar to geologists and hydrologists that may be challenging to non-specialists. This guide is intended to overcome that gap and explain how an atlas is created, and more importantly how it can be used to support decisions that affect these essential resources.

Each atlas typically requires more than 7,000 person-hours of work. Some of that work is in the field: drilling test borings, examining, sampling, and describing outcrops where the rock or sediment beneath the soil becomes visible at the land's surface, and conducting seismic tests to measure the depth to bedrock, [sending tiny shock waves into the earth and measuring how long it takes them to rebound]. One of the most important parts of the field work, and a part often performed by county staff as a contribution to the overall effort, is establishing the exact location and land surface elevation of hundreds of wells. Much of the work that goes into preparing the atlases follows after: interpreting the field measurements, recognizing and formally naming geologic units described in well records, and making maps.

The result is a detailed account, mostly in the form of maps, of the distribution and properties of the rock and sediment that lie below the land surface. These materials, and their ability to store or transmit water, determine where we can find water, and how we can protect and make wise use of that water. This includes our lakes and rivers as well as ground water.

The introduction of computer-based methods of managing information about places, called geographic information systems, has enhanced the usability of geologic information by making it relatively easy to create maps customized for specific uses. Traditional geologic maps required far more interpretation by the user to be applied to specific management issues. The atlases are delivered in both traditional and geographic information system (GIS) formats.

This User's Guide is intended for people that don't have training in geology or hydrology- most people. Every Minnesotan uses water, and every Minnesotan has an effect on water, so we all have a role and a stake in how that resource is distributed, how it is used, and how we affect its quality and availability. The purpose of the Guide is to explain in simple terms where our water comes from, how geology and climate control its distribution, and how we can manage water to maximize the availability of high quality water for ourselves and the habitat we live in. The atlases can provide very practical information such as what aquifers are available to a homeowner that needs to drill a well. The atlases also work at larger scales answering questions such as "where is the largest or most productive aquifer in this county", or conversely, "where is the best place in this county to isolate potential contaminants from our water system?". The atlases document existing hydrologic conditions, such as water levels in aquifers, so that we can recognize and respond to changes in those levels if necessary.

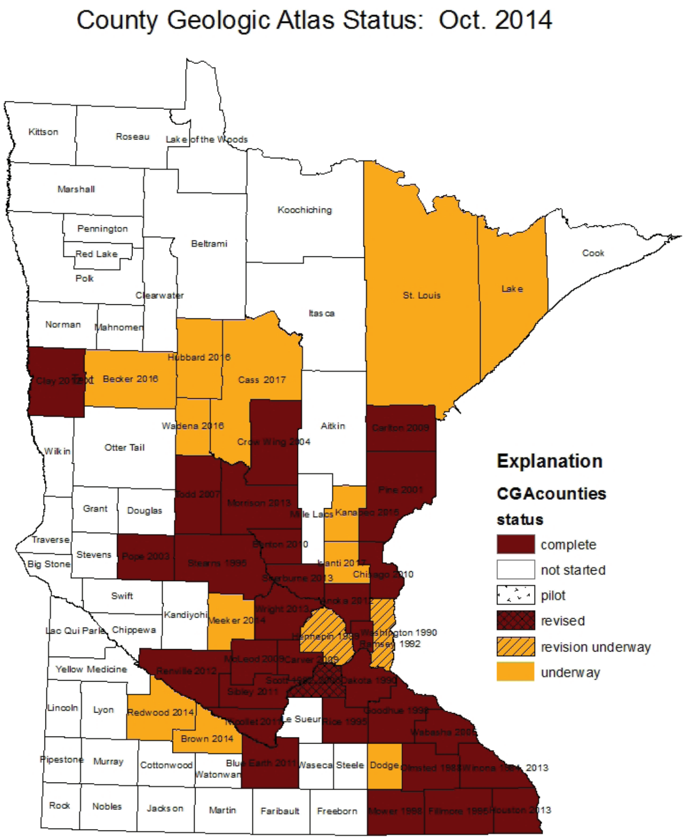


Figure 1. Status of County Geologic Atlas Program-2014

History

The Minnesota Geological Survey (MGS) produced the Scott County Geologic Atlas in 1982. In the more than 30 years since, the MGS has completed atlases for 28 more counties and projects are under way in 12 more counties (Figure 1). Funding has always been a limiting factor in accomplishing this work. The Division of Ecological and Water Resources at the Department of Natural Resources (DNR) has provided funding for many years, and the counties themselves have provided funding or in-kind service. However, in recent years the Environment and Natural Resources Trust Fund, as managed by the Legislative and Citizen's Commission on Minnesota Resources, has been the most important single source of funding to the program.

The atlases are generally highly valued by the counties, and also by consultants, state agencies, federal agencies, educators, researchers, well contractors, and citizens. The selection of counties has been influenced by population (an attempt to serve as many people as possible), by ground water sensitivity (providing guidance where resources are most threatened) and by the interest of local decision-makers (providing atlases where there is local interest in utilizing them for sound resource management).

Most atlas maps are published at 1:100,000 scale [one inch on the map = 1.6 miles on the ground]. This is detailed enough to depict features that significantly influence ground water flow, and yet doesn't require data density that would be too costly to be practical. The early atlas map plates were hand drafted, turned into color separate negatives and offset printed. Recent atlases are still printed (although fewer copies are made) to serve users who prefer that format, but all of the information on the plates and much more is also compiled in digital format, primarily as geographic information system (GIS) files, that allow users to combine the information with additional non-geologic data, create custom maps, and if desired, three-dimensional images.

The first atlases were created solely at the MGS, but starting with publication of the Fillmore County Atlas in 1995 atlases have been produced in two parts. The MGS describes the geologic framework, and the Department of Natural Resources, Division of Ecological and Water Resources describes ground water conditions and sensitivity. The MGS created a Regional Hydrogeologic Assessment (RHA) of the Anoka Sand Plain area in 1993. Between 1995 and 2008, the MGS and the DNR also produced RHAs of multi-county areas in western Minnesota. These studies are not as comprehensive as county atlases, but there is some commonality in products, and this guide is also pertinent to those products.

Organization and Formats

All atlases include a series of maps in printed form. Those maps are supported by associated databases, but it was not feasible to deliver all the data in the early years of the program. Modern atlases provide the printed maps, digital reproductions of the maps in portable document files (pdfs), and maps with associated data tables in GIS formats that can be used with free GIS software, or with fully-functioned commercial GIS software. The digital products are available from the MGS and DNR web sites, or on a DVD. The printed materials and DVDs can be purchased at the MGS Map Sales Office, and digital files can be downloaded without charge (http://www.mngs.umn.edu/). If the home page has changed, do a web search for Minnesota Geological Survey to find the current link.

The geologic components of an atlas are referred to as Part A, and the hydrologic components as Part B. This document focuses mainly on the products of Part A; a companion document describing Part B products may follow.

Minnesota Geology and Water Basics

This section provides an overview of water distribution, and the implications for a long term supply of high quality water. It describes the hydrologic system in general, and specifically in Minnesota. Some guidelines on water management techniques follow. This section should be helpful to anyone interested in understanding water, and water management, in Minnesota.

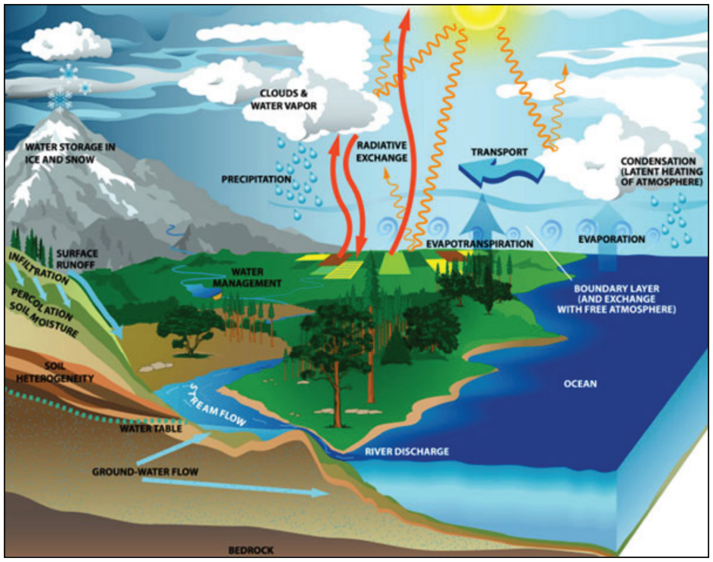


Figure 2. The hydrologic cycle moves water from the atmosphere to the land and eventually to the ocean. There are long and short paths, but the cycle is continuous.

The Hydrologic Cycle in Minnesota

Water is a transient resource, always moving in a cyclic manner, although often by pathways and at rates imperceptible to our senses.

The classic illustrations of the hydrologic cycle are drawn at a continental scale (Figure 2) and show water evaporating from the oceans, raining down on mountains, and working its way back to the oceans as surface or ground water.

Minnesota is a headwaters state (Figure 3). If you view a map of our state that shows the major rivers, you'll recognize that water mostly flows out of Minnesota, not into it. Rain and snow falling directly on our state are our main source of water, and any water that doesn't go back into the atmosphere via evaporation or transpiration leaves Minnesota as ground water, or by rivers.

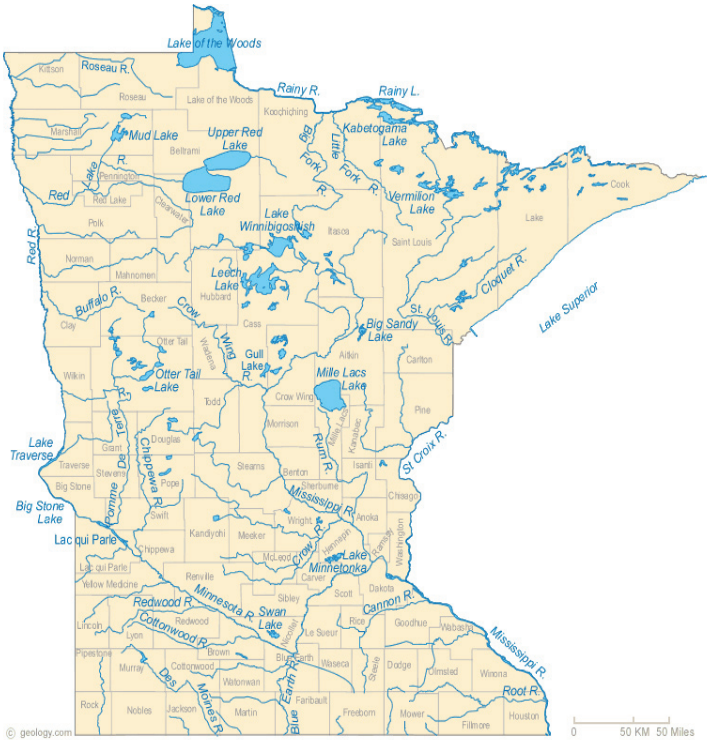


Figure 3. Minnesota is a headwaters state. Virtually all of our water arrives as precipitation that falls on our land and eventually leaves via rivers.

That is good news. It means our water quality is self-determined. Unlike the situation in New Orleans or other downstream localities, our water arrives in relatively good condition as snow or rain. As it moves through the hydrologic cycle, its quality is largely determined by land use practices and other behaviors of Minnesotans. The quality of the water in our major rivers as they leave our state is affected by neighboring states that also contribute water to them, and its composition is also affected by the earth materials that

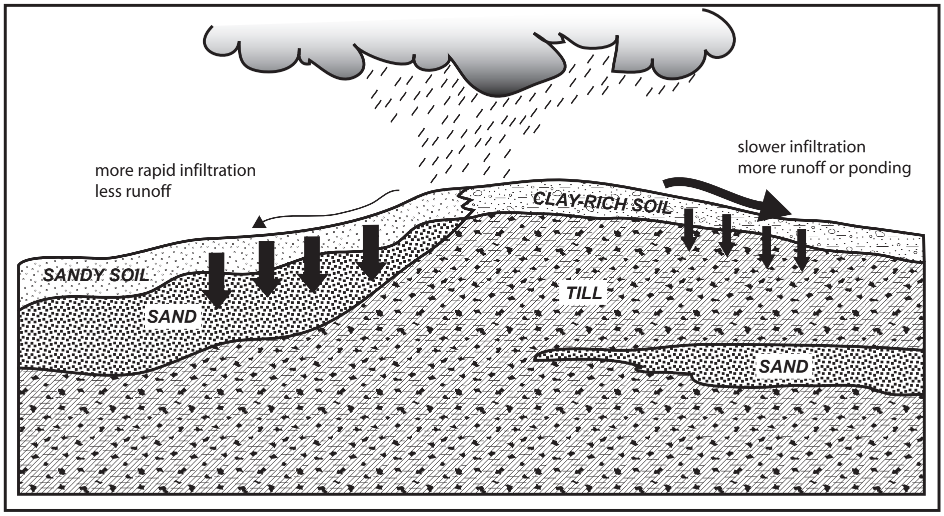


Figure 4. Infiltration as it relates to soil types.

contact it. However, the level of human-caused contaminants in that river water is a useful indicator of our collective effect on water.

As rain arrives in Minnesota it encounters the land surface- a surface with water-bearing characteristics that vary from place to place and even from season to season.

Some of the rainwater may travel across the land surface and enter streams or rivers and follow these drainages to our borders. Evaporation from lakes and rivers will return some of the water to the atmosphere. Some of the rainwater will enter the soil and either be utilized by plants (and transpired to the atmosphere) or continue to move downward and become ground water. The relative amounts of water that follow each of these paths are determined by soil type, vegetation, the presence of frost, slope, and conditions associated with our development of the landscape such as impervious surfaces, drain tile, ditching, storm water systems, and other hydrologic modifications.

One of the characteristics of soil that significantly controls infiltration (Figure 4) is its permeability. Permeability – the characteristic that allows water to soak into it and flow through it-- is determined by the presence of pore space and the connectivity of those pores. The pores may be inherent to the sediment that makes up the soil, such as sand, or pores may be created by worms or other biologic activity. Permeable soils more readily admit water into the subsurface.

We have a winter season during which precipitation is largely frozen and unable to infiltrate. Or melt water is present, but the soil is frozen and resists infiltration. In the growing season the water demands of crops or native vegetation can intercept a large proportion of available water and thereby limit deeper infiltration. The movement of available water to subsoil zones is maximized during those seasons when the soil is not frozen and vegetation is dormant.

Water that does move below the land surface is called ground water, and this movement is called recharge.

Driven largely by gravity, recharge is also affected by pressure gradients that can cause water to move laterally or even upward in the subsurface environment. Over long periods ground water moves from higher elevations toward lower elevations and may discharge back to the land surface through springs. In Minnesota, ground water discharges into stream and rivers, which eventually flow toward the oceans.

It is this continuous discharge of ground water that keeps rivers flowing even during long periods without rain and is why our rivers do not dry up in January. When water is at the land surface we call it surface water, and when it is in the ground we call it ground water. However, the hydrologic cycle shows that it is the same water, moving from the surface into the ground and then back to the surface. It is a single resource, best managed with an understanding of the path and rate at which it moves.

Beneath the soil of Minnesota there is a great variety of geologic materials, some of which can host and transmit water readily, and some of which impede the flow of water.

In some parts of Minnesota ground water can found to depths of thousands of feet, although usable ground water is more commonly found within a few hundred feet of the land's surface. In some places earth materials, such as granite or dense clay that cannot host or transmit significant amounts of water, extend to the land surface. Virtually no usable ground water exists beneath these places. A key point to keep in mind is that, in general, our water resources are usually separated from activities at the land surface by less than a few hundred feet of porous material, and often it is much less than that.

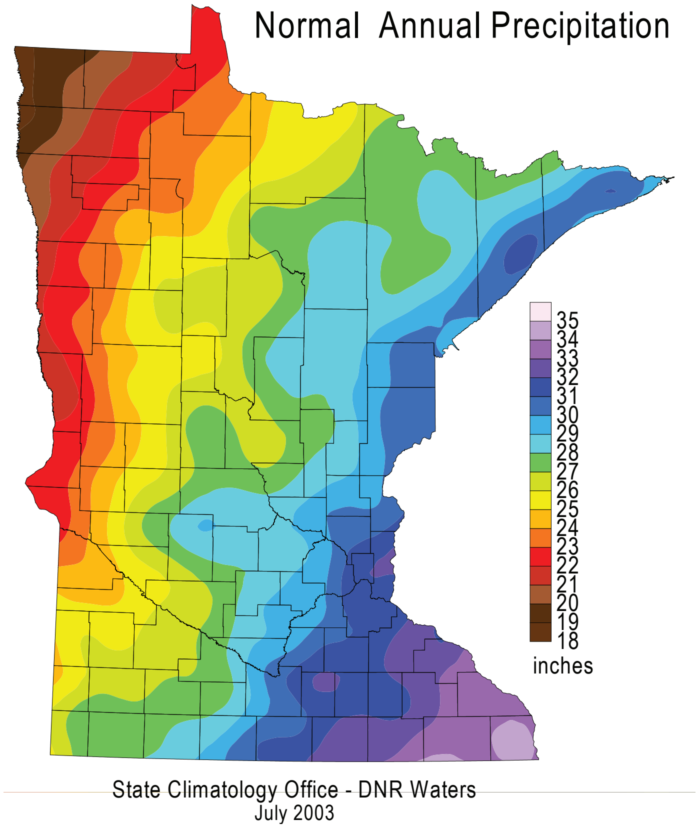
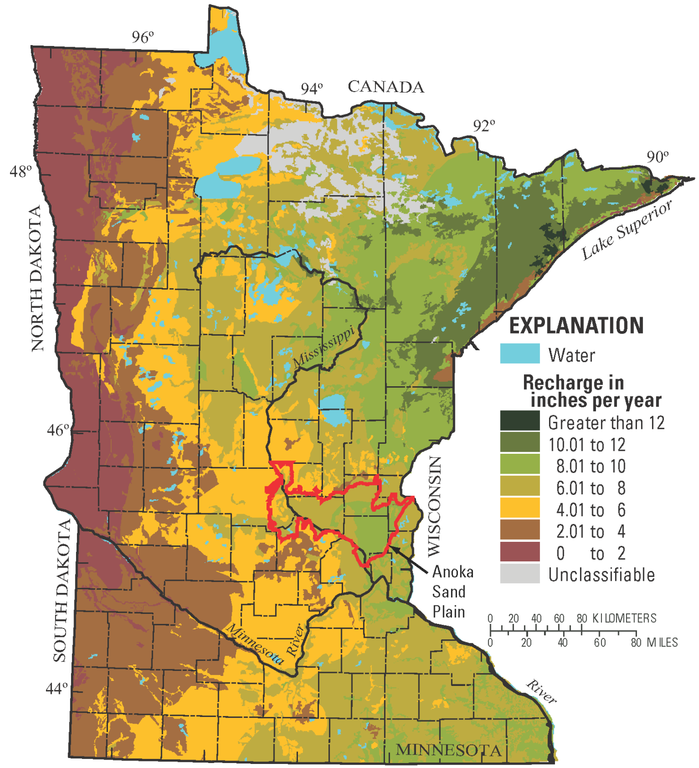


Figure 5. Distribution of annual precipitation in Minnesota

The Distribution of Precipitation and Recharge in Minnesota

Precipitation is not evenly distributed across Minnesota (Figure 5). The southeastern corner of Minnesota receives twice as much as the northwestern corner of the state.

The inequity of available potential ground water is compounded by the factors that influence infiltration rates, such as soil type, vegetation, season, and slope. Estimated recharge rates show that the clay-rich soils and geologic materials of western Minnesota tend to reduce the portion



Base from U.S. Geological Survey digital data
1:2,000,000, 1972, Universal Transverse Mercator Projection

Figure 6. Distribution of recharge to groundwater across Minnesota; from USGS Fact Sheet 2007-3002, Jan. 2007

of precipitation that becomes ground water (Figure 6). At the same time, those factors increase the amount of rain and snow melt that runs overland to streams.

Ground water in western Minnesota is relatively less abundant partly because of these phenomena, and also because of the relative scarcity there of sand and gravel or bedrock types that are capable of storing water and acting as aquifers. The amount of precipitation that becomes ground water in eastern Minnesota is estimated to be as much as six times higher than in in western Minnesota.

The Distribution of Water in Minnesota's Geologic Framework

As discussed above, ground water can only exist in the subsurface where pores provide space for it, and it can only move where those pores are effectively connected to each other.

Those pores are most common in sediment and sedimentary rocks- materials that accumulate from the breakdown of older rocks. Sand and sandstone are examples of earth materials that can have abundant pore space. The pores exist between the grains of sand. Similar to a container full of marbles, a body of sand has lots of space between the grains – spaces that water can occupy. In contrast, clay particles are shaped like plates. When packed, like sheets of paper stacked on top of each other, those clay particles have very little space that can be occupied by water. For that reason, clay-rich sediment cannot host much water, and even a relatively small amount of clay mixed with sand can impede water flow by filling the pores or clogging the connections between pores. Limestone and dolomite are sedimentary rocks that generally don't have grains surrounded by pore spaces, but they do commonly have large fractures that can host and transmit large quantities of water.

Geologic materials formed by igneous or metamorphic processes, in which the rock is formed by crystallization of minerals, generally have very little porosity or permeability. They do not host or transmit water readily.

The geology of Minnesota can be conveniently divided into bedrock and glacial sediment. Bedrock ranges from millions to billions of years old and was formed by igneous, metamorphic, or sedimentary processes. Glacial sediment, is generally less than two million years old and deposited as unconsolidated clays, sands and gravels by continental glaciers and the meltwater that flowed from them.

Geologic maps show the distribution of these earth materials. Simplified maps at statewide scale provide a sense of how ground water is distributed across the state.

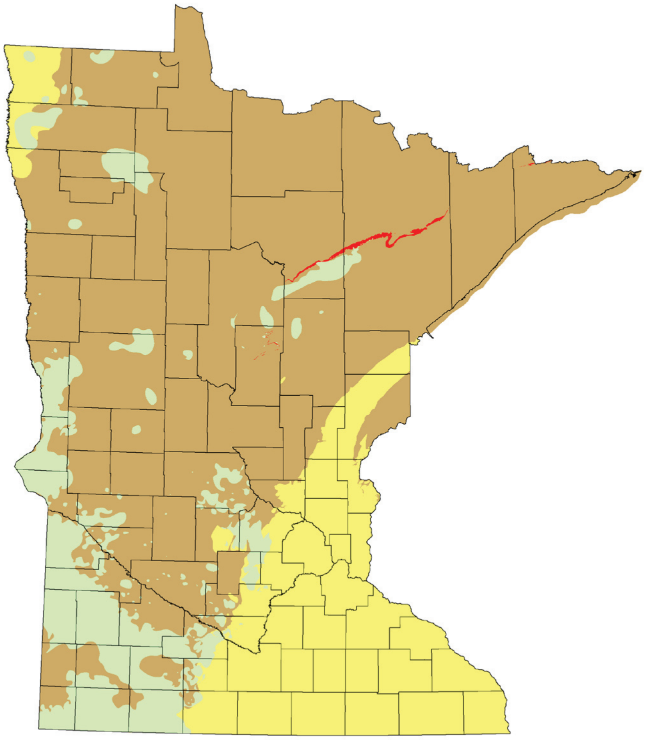


Figure 7. Bedrock units most likely to produce large quantities of water include the sedimentary rocks of northwestern and southeastern Minnesota (yellow) and the Biwabik Iron Formation (red). The sedimentary rocks of Cretaceous age (green) produce water in some areas, but in many places no suitable aquifer material is present. The igneous and metamorphic rocks (brown) typically produce small quantities of water, but only when the well intersects fractures in the rock.

In some places the bedrock contains water, in some places the glacial materials do. And in some places both, or neither, do. Similar maps can be made at scales useful for planning and management by modifying the geologic maps found in the County Geologic Atlas Series.

The statewide bedrock map shows that the sedimentary bedrock units of southeastern Minnesota are an important ground water host (Figure 7). The igneous and metamorphic rocks that underlie the remainder of the state are generally not aquifers due to their lack of porosity and permeability. In some places these rocks are fractured, especially at the surface of the rock, and these cracks can hold and supply modest amounts of ground water to wells.

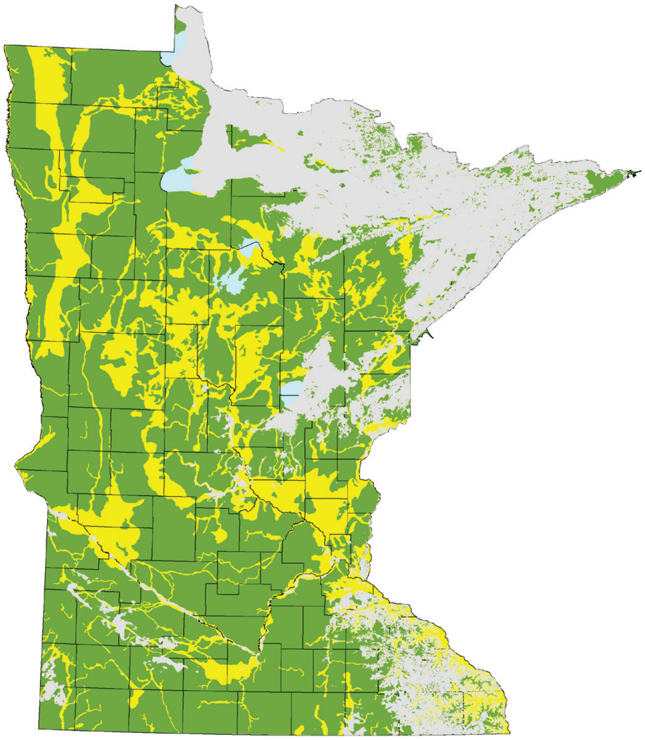


Figure 8. This map illustrates the general distribution of sandy (yellow) versus clayey (green) glacial deposits at the land surface. In the gray areas, the glacial deposits are less than 50 feet thick or absent completely. Although this map cannot illustrate the distribution of these materials in the third dimension (depth beneath the surface), they likely follow similar patterns related to equivalent processes of deposition. We know that subsurface sand bodies likely to act as aquifers are most abundant in the north-central part of the state and less abundant in the western and southern parts of the state.

On the simplified map of the glacial sediments of Minnesota it is the sand- and gravel-rich deposits that serve as aquifers. These can occur as large sheets that cover many square miles or they can occur as smaller, isolated deposits. They can occur at the land surface, or buried beneath it and contained within clay-rich units. This map only shows the deposits at the land surface.

In northeastern Minnesota, where bedrock is at or very near the land surface, both glacial and bedrock sources of water can be difficult to find.

In southeastern Minnesota there are abundant bedrock aquifers, but the glacial sediment is thin or absent.

In south-central Minnesota there are bedrock aquifers, and abundant glacial sediment, but the glacial sediment is clay-rich and aquifers are difficult to find within it.

In southwestern, far west-central, and northwestern Minnesota most of the bedrock types are not highly productive as aquifers and the glacial sediment is very clay-rich, especially in the subsurface. It can be difficult to find aquifers, and wells often do not produce ample water. Water systems that distribute water long distances by pipeline are common in these areas.

In north-central Minnesota the bedrock does not yield abundantly, but the glacial sediments are sandy and yield large volumes of water.

In east-central Minnesota including the Twin Cities metro area and extending up to Carlton County, surficial and buried sand aquifers are often available and much of the bedrock is also considered aquifer material.

The Time Factor

The rate of water movement in the hydrologic cycle varies greatly. In the atmosphere large volumes of water can move hundreds of miles in a day as clouds. Water movement in rivers can also be relatively fast. For example, rates of water movement in the Mississippi River through the Twin Cities can be as fast as 260 cm/sec (8.5 feet per second or 5.8 miles/hour) and move as much as 150,000 cubic feet per second. Rainwater runoff moving over the land surface would be somewhat slower, more episodic, and of less volume. In the ground, movement of water is much slower, but extremely variable with rates as low as 10-9 centimeter per second (about 1 centimeter in 30 years, or an inch in 75 years) and as high as 1 centimeter per second (0.03 ft/sec or 0.02 mile/hour).

The rate of movement of ground water is determined by the pressure driving the water, and the ability of the host sediment to transport water. If there is little driving force,

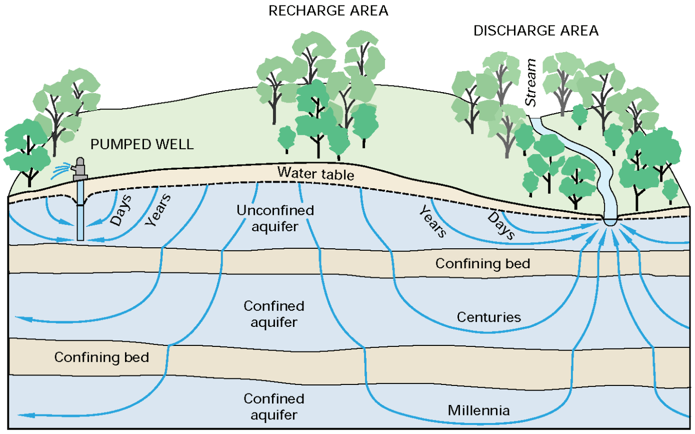


Figure 9. Ground water infiltrates and moves toward a stream where it discharges. If the water passes through materials that don't transmit water readily, the trip can take a very long time. From USGS Circular 1139, Winter and others, 1998.

water can be nearly stagnant. There are techniques available to measure how long water has been in subsurface aquifers. Some techniques work in the range of decades, while others are useful for water that entered the ground thousands of years ago. Water that has moved through materials that don't transport water readily, such as clay or shale, is often relatively old. Water that has traveled through multiple layers or great thicknesses of relatively impermeable materials may be thousands or even a few tens of thousands of years old (Figure 9.)

This slow movement of water can provide a false sense of security in our land use practices. Aquifers that are separated from the land surface by non-conductive materials may continue to pump high-quality water for a very long time regardless of how the land above them is treated.

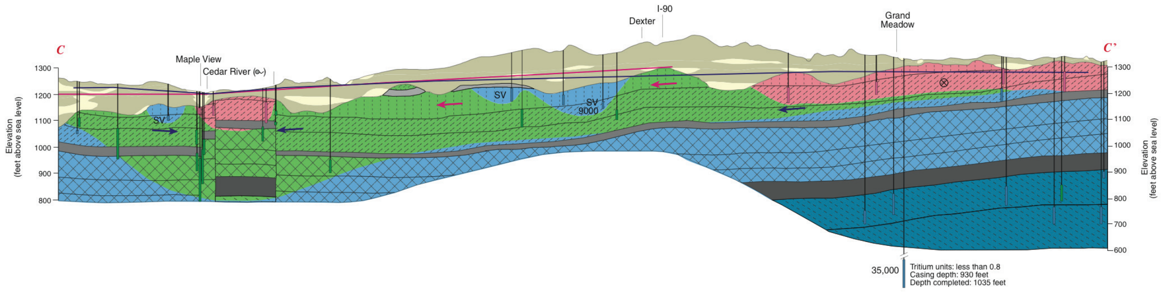


Figure 10. An example of the distribution of ground water by age. Blue is very old, green is mixed, and pink is young water. Geology and pumping can affect the rate at which water moves to depth. The gray layers are geologic materials that impede the flow of water. Where they are disrupted by faulting the young water is moving deeper more quickly. From DNR, Mower County Geologic Atlas Part B, Plate 7, Moira Campion.

The water they are providing entered the ground thousands of years ago, long before people lived here, and before the substances that typically contaminate our water even existed. This situation misleads people who believe the high quality of water from their wells shows their practices do not contaminate the ground water.

In those parts of Minnesota where aquifers receive recharge more quickly, the aquifers typically show contamination even though land use practices are no different than in places where aquifers are not yet affected. The slow movement of water delays the effects of these practices. Eventually, continued pumping of these aquifers creates a gradient that will accelerate the movement of water to replace what is pumped (Figure 10). Then the only water available to replace it will be that being generated at the land surface today.

Similarly, it is possible to significantly lower water levels in isolated aquifers by pumping and no effect may be noticeable at the land surface. However, this change in gradient will eventually cause a lowering of water levels in shallower aquifers and surface water bodies as they lose water downward toward the pumped aquifer. In some cases the rate of pumping may exceed the rate of recharge and the water level will continue to fall.

In summary, the availability and quality of water in Minnesota varies widely due to significantly different amounts of precipitation, varying rates of recharge, and different kinds and sizes and numbers of aquifers.

High quality ground water is often the result of slow water movement and the availability of slowly recharged aquifers, rather than the result of sound land use practices. Shallow ground water in areas of more rapid infiltration often is contaminated.

Determining the distribution and water-bearing characteristics of geologic materials on a scale appropriate for land use planning will help us delineate our aquifers, and to understand the connections between the land surface and aquifers and between aquifers and surface water features. With that knowledge in hand value-based judgments can be made on what land use and water use practices are appropriate for the outcomes we desire. The atlases help policy-makers and managers make informed judgments.

Managing Water Quality and Quantity Goals

Water is a vital resource and essential for a healthy economy. More water generally supports more people, or crops, or livestock, or wildlife, or businesses. However, there is a natural limit to the availability of water that is closely related to long-term precipitation levels. We act at our peril when we regularly pump ground water faster than it is being recharged.

Availability of water is also related to the quality of water. Many water uses – drinking water is the prime example -- have particular quality requirements, and water of lesser quality cannot fulfill those needs. For these reasons we wish to manage our water to maximize both its quality and quantity. If we take into account the needs of future generations, then we must manage our water in a way that doesn't limit its availability or quality in the future.

Water Budgets

The hydrologic cycle clearly shows that water moves through our landscape, with water arriving to balance that which is leaving. We also know that water can accumulate in large quantities in aquifers underground, and that it can reside there for long periods. In Minnesota, we typically choose to use aquifers as our water supply rather than collecting rain in reservoirs, because aquifers provide a more continuous supply, they are less sensitive to short-term variations in the weather, and they are protected to some degree from contamination . However, it is possible to overuse aquifers and jeopardize the continuous supply we desire for ourselves and future generations. Taking too much water from aquifers can also draw down surface waters (lakes, rivers, wetlands, springs) that provide great benefit to humans, fish and wildlife.

By measuring precipitation, discharge of ground water to rivers, and other factors, we can estimate how much water moves through an area over time, and thereby determine how much we can use without causing a deficit.

This kind of study has been performed in Minnesota and water use has been compared to the recurring availability of water on a county basis (see: Use of Minnesota's Renewable Water Resources- Moving Toward Sustainability- A report of the Environmental Quality Board and Department of Natural Resources, April 2007). It showed that over much of Minnesota human water use is only a small percentage of the estimated total water available although some of the highly populated counties used a large percentage of the available flux of water, and one county actually exceeded that amount (Figure 11).

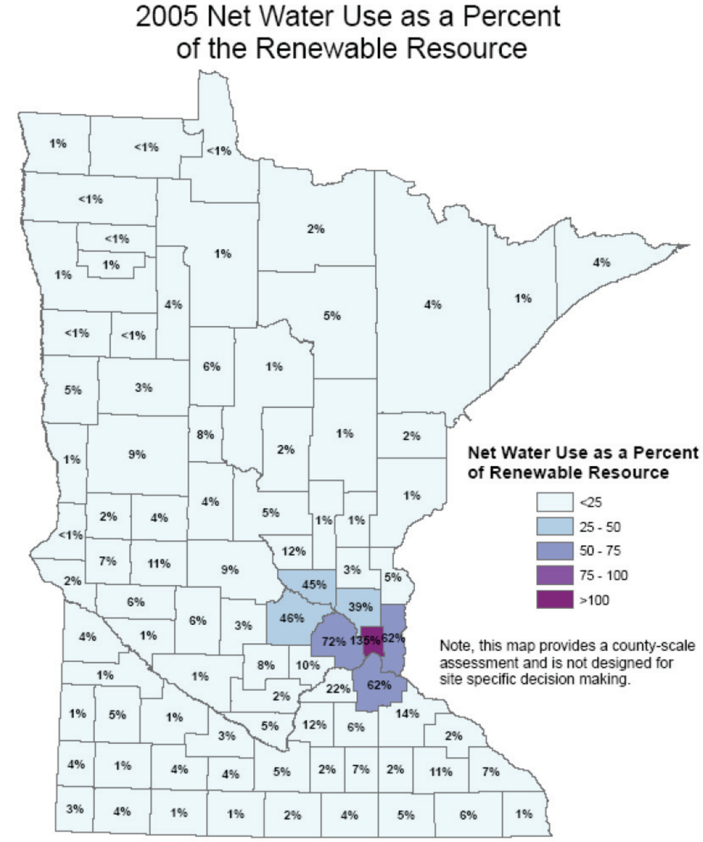


Figure 11. Water use in Minnesota by County

To make the best use of this kind of estimate of water availability it is necessary to understand the distribution and water-bearing characteristics of aquifers, recharge, surface water features, water use (wells), and the ultimate fate of the water used. A budget must be constructed that accounts for inputs and outputs of water. This is best accomplished in an area with boundaries that either do not allow the transfer of water, or where that transfer can be accurately measured or estimated. Political boundaries generally do not meet this requirement. Rivers are often used as boundaries in these exercises because they represent a measureable discharge of ground water. Factors such as precipitation, runoff, stream flow rates, evaporation, transpiration, and pumping are measured. A balance can then be determined. An outcome might be that XX gallons of water per year can be pumped within the boundaries of this area. However, more work may be necessary to determine where, and at what rate, that water can be taken without drawing down the aquifer, surface waters, or other wells beyond the capacity to recharge in a similar time frame.

The Impacts of Pumping

When we pump ground water there are three possible effects:

- Pumping lowers the water level in the vicinity of the well in the shape of a cone. The size and shape of the cone are determined by the water-bearing characteristics of the aquifer, and the rate of pumping. The resulting low spot causes water to flow toward the well. Recharge rates may increase as the cone of depression created by the pumping well captures water that would have gone somewhere else had the pumping not occurred.
- Discharge from the aquifer being pumped may decrease. For example, pumping from an aquifer feeding a spring may decrease discharge to the spring or even stop it from flowing.
- Pumping may lower the water level in the aquifer. This is a decrease in the water stored in the aquifer.

Commonly, more than one, or some combination of these effects occurs. It is important to recognize that pumping water out of the ground does have consequences and to decide which effects and outcomes are acceptable, and which are not.

Knowing where the aquifer is and what it is made of makes it possible to predict the impact of pumping on water levels and estimate the rates at which water can be withdrawn without harming other wells or surface waters.

How Much Is Too Much?

It is helpful to think of aquifers as a savings account. Precipitation and associated recharge are income, and pumping and discharge to surface waters are spending. When pumping and discharge exceed recharge, the aquifer level begins to fall. This is like spending money faster than your income provides it-- your bank account shrinks.

With aquifers, and bank accounts, we can use the resource faster than it is being replaced, but only temporarily. During a multi-year drought, recharge is negligible and we continue to pump from our aquifers. The water level will begin to fall, but hopefully rain returns before the effects on the aquifer create problems. In order for the aquifers to recover fully, there must be a period in which recharge exceeds pumping causing the water level to rise.

There are places where aquifers are being pumped at rates that exceed recharge and the water levels in the aquifers continue to fall. This is clearly not sustainable because each aquifer has a finite thickness and eventually the water level will fall to the bottom of the aquifer and water will not be available.

In the Milwaukee, Wisconsin area aquifer water levels have fallen nearly 500 feet over the last 130 years and continue to fall. When determining a sustainable water supply rate, the question is not "how much water is in this aquifer?" but rather "at what rate does this aquifer recharge, and how does that rate compare to water use and the amounts required to maintain surface water features? " In Minnesota, where we have a life style, and economy, and identity closely linked to lakes and rivers and the fish and wildlife they support, keeping aquifer levels adequately high to maintain these surface waters is a priority.

Managing Water Quality

Water is often called the universal solvent. It tends to dissolve things it comes in contact with and these things then travel with the water. This is true of both natural and man-made compounds. Water in some of the aquifers of southwestern and western Minnesota has relatively high concentrations of sulfate from the sediments of the formations the water occupies or passed through. Some aquifers on the North Shore of Lake Superior contain saline water far saltier than seawater. These are naturally poor-quality waters.

Similar effects can occur when humans introduce wastes, road salt, solvents, pesticides, fertilizers, pharmaceuticals and other commonly used products into the hydrologic cycle. If I drop food on the ground I might wash it off before I eat it. However, all of our drinking water falls on the ground and we often have no opportunity to clean that water before we drink it. Even in large municipal water supply systems, water goes through a limited process designed mostly to remove pathogens and maintain clarity. These systems are not designed to remove many of the other contaminants we introduce. Furthermore, the treatment of wastewater doesn't always return it to its original quality. For example, individual sewage treatment systems that rural and some suburban homeowners rely on do a relatively good job of removing pathogens, but they don't remove the nitrates introduced by our wastes. Nor do they effectively remove some common pharmaceuticals.

Homeowners with wells as their primary source of drinking water, rather than municipal water systems, consume "raw" untreated ground water that originally fell on fields, roads, feedlots, and all other parts of the land surface before moving underground.

Soil does have some capacity to improve water quality. In particular, soils with high organic content and thriving biologic activity are good at removing nutrients and breaking down some contaminants. However, these systems have a limited capacity that is often exceeded. Clay-rich soils and earth materials also have some capacity to bind contaminants and impede their travel. As mentioned earlier, most of us benefit from the slow movement of ground water that allows us access to water that entered the ground long before contaminants were introduced. That is not a permanent solution.

The key to managing water quality is to avoid or minimize contact of water with contaminants. When potential contaminants are introduced they should be introduced no faster than natural systems can utilize or break them down into harmless compounds or concentrations. There are also efforts under way to change the products we use every day so that they don't cause harm and can be removed or made harmless by natural systems or the treatment systems we employ.

Keeping Track- How Are We Doing?

Water supply managers track the water in wells to see if levels are being maintained and they continually analyze water samples to see if it is good enough for public use. A key to meaningful monitoring is knowing what land areas, what wells, and what activities can affect the quality or quantity of water in the monitored well. If the quality of water in a well shows a change, we need to know what land areas recharge that aquifer (via overland flow and infiltration), and what the land uses and practices on those lands are. This allows us to consider changes that will improve the water quality. If water levels show a continuous fall in a monitoring well we need to know what wells and natural discharge points utilize that aquifer so that we can change pumping practices and manage the impact on surface waters. In both cases, geologic maps at scales useful for planning and aquifer management, with associated data bases such as well information with locations and aquifers identified, are the necessary tools to understand and react to the situation. It is important to realize that monitoring is reactionary. Action is only taken after effects are seen, and the time lag common to ground water movement delays the signs of trouble, and increases the time necessary to correct problems.

Modeling- Predicting Outcomes

If a city anticipates growth, it plans for new wells to supply the necessary water. Installation of a new municipal well in the suburbs of the Metro Area can easily cost $750,000. A permit is necessary and pumping tests may be required before the permit is granted. If the tests show that the well is likely to negatively impact other wells or surface waters, the well may not be permitted, and the costs of constructing it are largely wasted. Hydrologists have mathematical means of predicting the effects of pumping if they have a good understanding of the distribution of earth materials and the water-bearing characteristics of those materials. A computer-based simulation (model) of the hydrologic system can be constructed and potential well locations can be tested before spending any funds on wells. These methods provide the means of predicting outcomes prior to expensive infrastructure investments. They can also be used to predict the spread of contaminants and to test the effectiveness of methods proposed to remove contamination.

Guidance and Best Practices for Water Management:

Choices about how we use water, and how much water we use, impact both water supply and water quality. An obvious choice is to minimize use. There is nothing to be gained from using more water than necessary, and use always comes at a cost. Minimizing transport of water and water quality degradation will also help maintain the water resources we need to maintain quality of life into the future.

Water availability and quality should be included in all planning exercises, not only plans focused on ground water. This is especially true for plans that affect the distribution of population, industrial development, and other water intensive development.

Here are some basic tenets of this conservative use philosophy:

- Utilize water in a manner that returns as much of it as possible to the location from which it was taken. Some water uses don't actually consume much water. Use within a home is a good example. Most of the water is used and then discharged to some type of wastewater treatment system. If it is an onsite wastewater treatment system (septic) the water is returned near the point it was taken, although probably not directly to the aquifer that supplied it. However, if it is discharged to a regional waste water treatment system the water may be discharged after treatment tens of miles from where it was found. In this case the use is not consumptive, but transports the water far from where it was taken. Lawn watering is a highly consumptive use. Most of the water is evaporated or transpired into the atmosphere and transported far from the location where it was obtained. Other examples of more consumptive use are bottling water or putting water into products that will be shipped away. Water use for cooling that evaporates the water is also highly consumptive.
- Surface water sources should be utilized first, and then the least confined aquifers (aquifers with the least amount of low permeability overlying material). More confined aquifers should be used only as necessary. Deeper and more confined aquifers (those that recharge slowly through overlying materials that convey water at very low rates or over long distances) contain our highest quality water and water that will take a long time to replenish. These most valuable resources might be reserved for special purposes and special circumstances. An example of this is the Minnesota Statute that reserves use of the Mt. Simon aquifer in the Metro area for drinking water purposes and prohibits use of this resource for lower priority and nonessential purposes such as lawn watering. Surface water sources and less confined aquifers are easier to monitor, and respond more quickly to our actions. With shallow systems we are more likely to see the effects of our use and take action to manage those effects as opposed to utilizing deep systems that delay and obscure the effects of our practices.
- Return water should be of similar quality to the water that is taken -- water treatment technology should be evaluated and enhancements considered. The discharge of degraded water will impact our surface or ground water resources, or those downstream. The quality of our future water supply is directly related to the quality of water we put into the system today.
- Whenever possible, high-capacity water users should be directed to those places that have more water or less dependency on water. Utilize planning to avoid stressing resources unnecessarily.
- Water availability is fixed, but more can be done with the same volume of water through conservation and reuse. Some needs could be supported with reused water, lower quality water, or wastewater. Stormwater retention and use might also be useful.

Part 2: the Elements of a Geologic Atlas - how they are made, and how they can be used

Databases

Each atlas contains a database map that conveys the distribution of data used in the construction of the atlas products. Data types common to atlases are water well construction records; geophysical surveys (downhole, seismic, gravity, magnetic); outcrops of rock or exposures of subsoil materials; engineering, scientific, and exploration borings; cores and drill cuttings; and textural or chemical analyses of samples. All maps and atlas products use multiple data sources. Most of these data represent information about the geology or hydrology at the location they were collected. It is up to the geologist or hydrologist to use their experience and knowledge to fill in the spaces between the data points to create a map. It is prudent when using the maps to look at the database map to evaluate how much, and what types, of data were available to support the map. Most of these data will be discussed in the description of the maps or atlas products they support. The County Well Index database will be discussed here in detail because of it is the most abundant data type, it is used for many applications, and it is useful as a stand-alone resource.

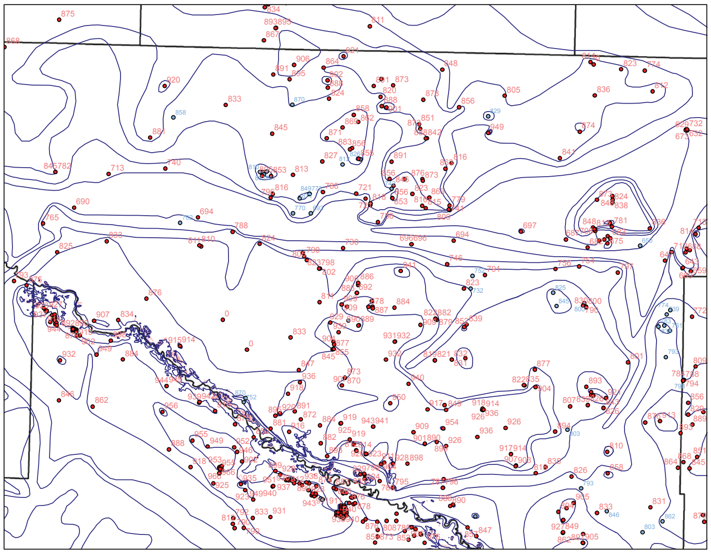


Figure 12. A plot of CWI data points labeled with the elevation of the bedrock surface. A geologist has drawn contours of the bedrock surface elevation in a geographic information system program.

County Well Index (CWI)

The County Well Index (CWI) database contains information about more than 480,000 wells drilled across Minnesota. These records include information useful to geologic mapping and hydrologic investigations such as descriptions of the sediment and rock penetrated by the well, and the water level of the aquifer that supplies water to the well. Some of these records came from the personal records of well drilling contractors who collected this information for their own use. The bulk of the records were submitted as required by law, beginning in 1974. The database is operated cooperatively by the Minnesota Geological Survey (MGS) and the Minnesota Department of Health (MDH). MGS adds value to the well information by interpreting the descriptions of the materials penetrated by the well and assigning more formal rock and sediment names and aquifer designations common to the geologic framework of Minnesota. This provides a common understanding and consistency among the many users of CWI including resource management agencies, state and local government units, consultants, engineers, drillers, citizens, and researchers.

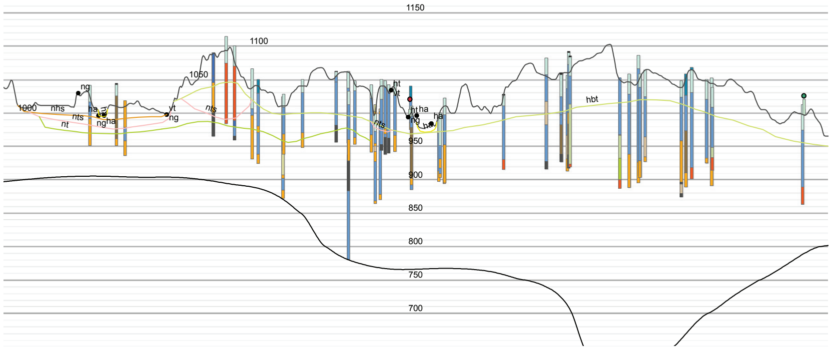


Figure 13. A plot of CWI data projected to a cross-section line. The vertical lines represent wells and the colors represent different sediment types (clay, sand,gravel, silt, till). The upper black line indicates the elevation of the land surface, the bottom black line the elevation of the bedrock surface. Colored lines between represent geologic units.

Each well record that is submitted has information about where the well is located. MGS and others have established accurate, field-checked locations for 252,000 of the wells (52%) and most of these are part of a geographic information system (GIS) file that can be used to create map products based on the well information. Users can obtain CWI information online at http://www.health.state.mn.us/divs/eh/cwi/ and it is also distributed on DVDs by the MGS Map Sales Office.

MGS uses the CWI information in creating geologic maps, including those constructed for county geologic atlases. In the process of building a geologic atlas, MGS or its local partner verifies the locations and elevations for wells of a particular county. Geologic units and aquifers are identified as part of the map-making process. That process compiles information from many wells into a geologic map and allows us to recognize and assign formal names to geologic units common to multiple well records.

CWI data is often plotted in map view with unit

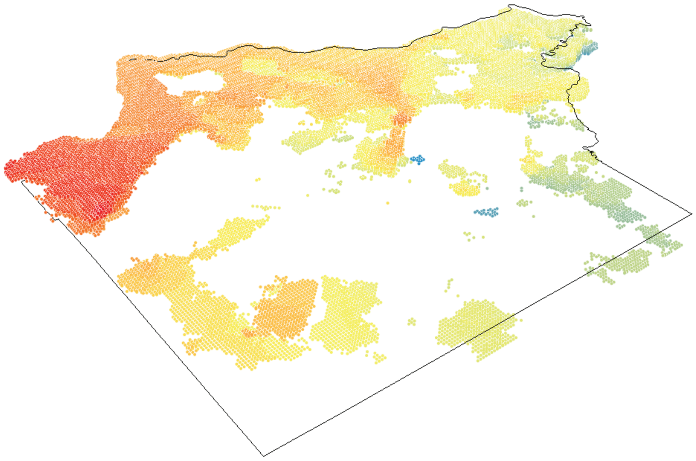


Figure 14. A depiction of sand distribution in Wright County generated by a statistical treatment of CWI data. Color indicates elevation above sea level (red-higher, blue-lower). The program can be adjusted to yield different scenarios for the geologist to consider in creating maps. The program calculates the likelihood of sand occurring in areas between known data points.

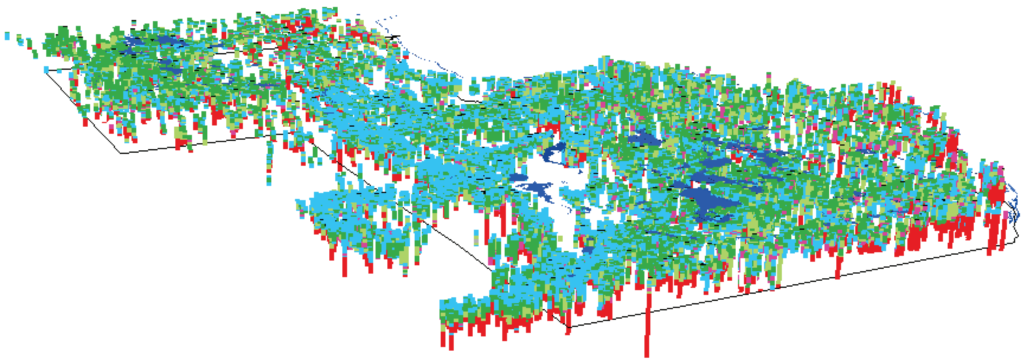


Figure 15. A three-dimensional view of CWI data for Chisago County. The wells are color-coded (red indicates bedrock, green-clay or till, and blue-sand. The dark blue bodies are surface lakes. The data can be tilted or rotated to any perspective, and the scale can be changed for added detail.

elevations or water levels or other features labeled to support mapping of those features (Figure 12). The well data is also projected to lines and color-coded by lithology (sediment type) to facilitate the drafting of cross-sectional views of geologic strata (Figure 13). We also utilize GIS programs to generate three-dimensional representations of geologic materials to assist geologists in mapping (Figure 14) and to provide a "big picture" view of large data sets (Figure 15).

Quaternary Data Index (QDI)

MGS has developed a new database called Quaternary Data Index that contains information related to unconsolidated deposits, usually at depths of less than 50 feet. The database structure is similar to the County Well Index, but has added capabilities to allow the inclusion of engineering test results, textural analyses (grain size distribution, sand lithology), outcrop descriptions, and other data.

The data come from MGS investigations and analyses, current or previous projects, and from external sources. Currently it is our intention to add data as we need it to complete current projects. It is not a comprehensive database like CWI that strives to collect all the data of a certain type, and at this time it is not a public database. It is specifically designed to support geologic mapping, and it is populated to support our current projects.

Geophysical Data

Geophysical data are measurements of the properties of earth and earth materials. Often these measurements are useful in identifying and mapping bodies of rock or sediment, and some of these techniques can "see through" overlying materials and allow us to map units that are not exposed at the land surface. There are techniques applicable to many kinds of earth materials, but in the County Geologic Atlas program geophysics is most commonly applied to mapping features of the bedrock.

The density of the bedrock beneath us causes subtle variations in the earth's gravitational field. By measuring the intensity of gravity at many places across the landscape we can infer what rock type lies below, and how deeply it is buried under unconsolidated materials left by glacial activity. Approximately 60,000 gravity measurements have been made in Minnesota and this data set is particularly useful in mapping the igneous and metamorphic rocks that occur beneath glacial materials or younger sedimentary bedrock.

The earth's magnetic field is affected by the distribution of magnetic minerals (mostly magnetite). In Minnesota these minerals are mostly found in the bedrock, but magnitite in particular can be concentrated in glacial stream sediments as well. The magnetic field variations across Minnesota has been well-documented by an airborne survey of the entire state (Figure 16). An airplane towed a magnetometer across the state in a grid pattern and recorded magnetic intensity. That information can be manipulated mathematically to discern the spatial geometry of bodies of rock and the presence of faults. This method is particularly useful in Minnesota where the bedrock is mostly buried and therefore not visible. Minnesota has a particularly high quality set of magnetic data and it is used

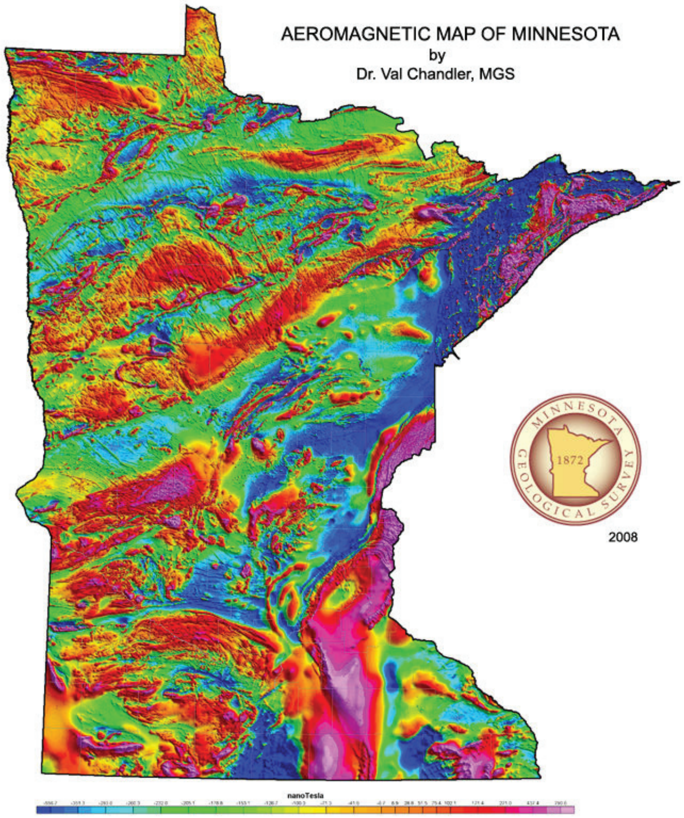


Figure 16. Aeromatnetic anomaly map of Minnesota showing variations of the ambient magnetic field as a function of bedrock geology.

in the construction of virtually all maps of igneous and metamorphic bedrock.

Geologic interpretation of gravity and magnetic anomaly data is greatly enhanced if density, magnetic susceptibility and natural remnant magnetization (NRM) data are measured on representative rock-type samples. Rock property data help relate the patterns seen in gravity and magnetic field maps to the rock types that are likely causing those patterns. The patterns are also compared to the rocks found in outcrops and drill core samples to verify correlations. MGS maintains a database of rock property data acquired over the last two decades. Additional data have been gleaned from studies done elsewhere on rocks similar to, or identical to those found in Minnesota.

Our understanding of subsurface conditions can also be improved with seismic geophysical investigations. Traditional seismic studies use an energy source to send mechanical waves into the ground. The location and timing of the "echo" of these waves enables us to estimate the thickness of the glacial sediments that overlie the bedrock, and to infer the kind of rock. For this application a relatively small source of energy is used, for example, a sledge hammer and metal plate, or a five foot steel piston driven by a very large rubber band. In oil fields this technology is used to understand the arrangement of multiple layers of sedimentary rock. In Minnesota we are mostly applying it to measure the depth to bedrock, or the thickness of glacial material covering the bedrock.

In recent years the MGS has deployed a relatively new seismic method known as horizontal to vertical spectral ratio (HVSR) or more commonly passive seismic. This method relies on ambient energy in the subsurface (passive) rather than creating energy waves with an active source such as swinging a hammer onto a metal plate. Ambient sources include vehicle traffic, wind, tides, and low-frequency waves ubiquitous to the earth's crust. A very small and portable instrument is used to collect data for 16 to 20 minutes and the data is processed to identify reflectors, such as the bedrock surface. Again, our focus is on identifying the position of the bedrock surface and how deeply it is buried. As we gain experience with this method we are developing better mathematical solutions that are calibrated to Minnesota geology and well-established well data.

The MGS also deploys geophysical instruments in boreholes, usually water wells or holes drilled for scientific purposes. Downhole geophysics is a technique developed in the oil fields that uses a variety of probes to measure properties of the rocks and sediment exposed in the borehole wall, and the water within those materials. The probe used most often in Minnesota measures natural gamma radiation. This is a naturally occurring phenomenon and the intensity of the radiation is generally related to the concentration of uranium, thorium, and potassium in the materials penetrated by the borehole. As the probe is raised from the borehole bottom a recorder notes the depth and the gamma radiation level continuously. The gamma radiation levels help us identify the rock types penetrated by the borehole or well.

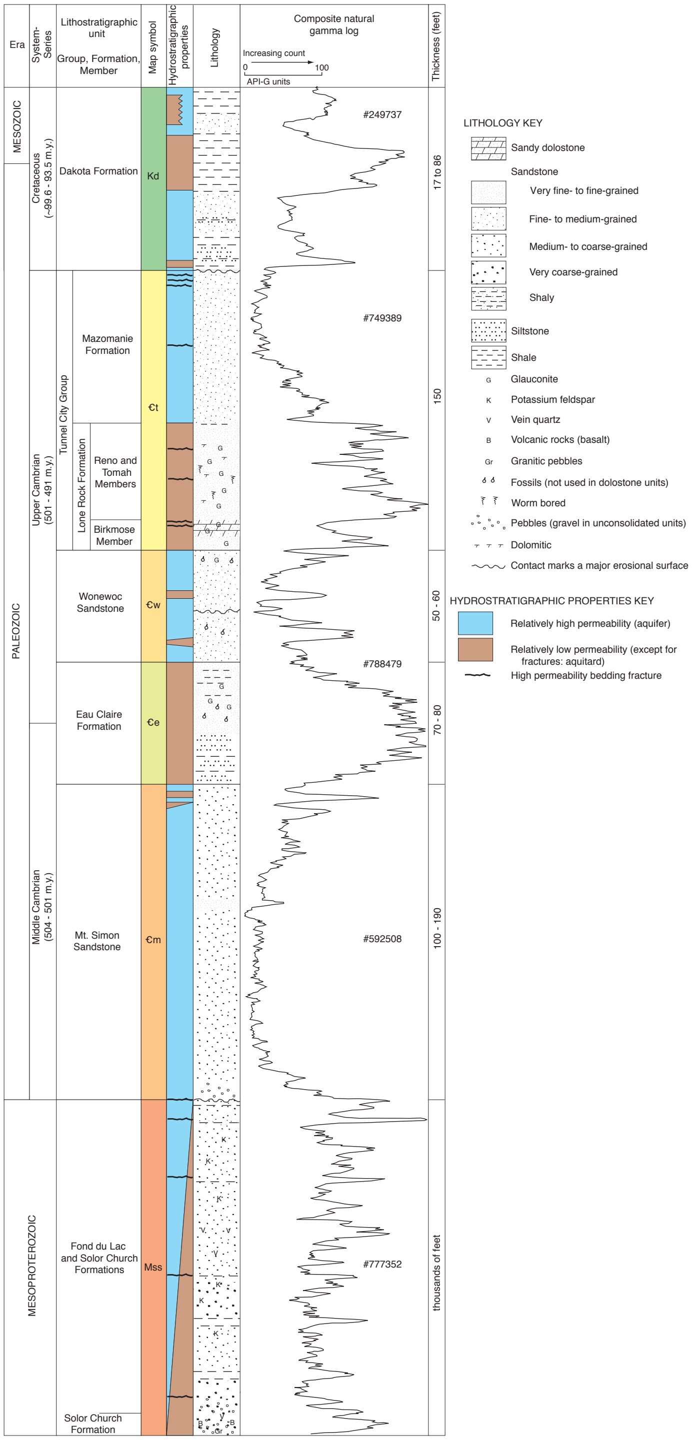


Figure 17. The line on the right is a measurement of the amount of natural gamma radiation emitted from rock in the subsurface as a function of depth in a well. On the left is the interpretation of the major rock units. In sedimentary sequences, the gamma plot is distinctive and consistent, making formations easier to recognize.

When a number of surveys have been made in the same sequence of sedimentary rocks the graph of depth versus gamma radiation becomes like a signature, and the formations in the sequence can be readily recognized (Figure 17).

This technique is especially useful because it works even in boreholes with steel or plastic casing. We often conduct these surveys in water wells, either before a pump is installed, or when the pump is pulled for maintenance or abandonment. This allows us to acquire very reliable interpretations of the subsurface geology at very low cost. Other methods measure electrical properties, the shape of the borehole, or even the movement of water in the borehole. All of these can be interpreted to help us understand subsurface geology and hydrology. MGS has geophysical logs for more than 6,000 wells in Minnesota and we collect about 200 more each year.

Surficial Geologic Maps

A surficial geologic map depicts the properties of the geologic materials that exist at the land surface. In most parts of Minnesota the surficial geology map shows units associated with glaciation over the last 2 million years, and some more modern processes.

A surficial geologic map represents geologic (and related hydrologic) conditions at that important interface where precipitation either infiltrates and becomes ground water, or runs over the land surface and drains to a surface water feature. It is the same surface where almost all human activity takes place and potentially introduces contaminants into the hydrologic cycle.

The glacial materials can be divided into two major groups: unsorted materials (a mixture of grain sizes like gravel, sand, silt, and clay) deposited directly by ice, and sediment that has been sorted (separated by grain size) by water or wind. The sorted materials vary in their ability to convey water, with larger grain sizes (gravel and sand) generally being effective at hosting and transmitting water. Silt would be less effective, and clay generally impedes water movement. In the unsorted materials (called till or diamicton) the presence of clay, even in small amounts, greatly reduces the connectivity of pores and the resulting ability to convey water.

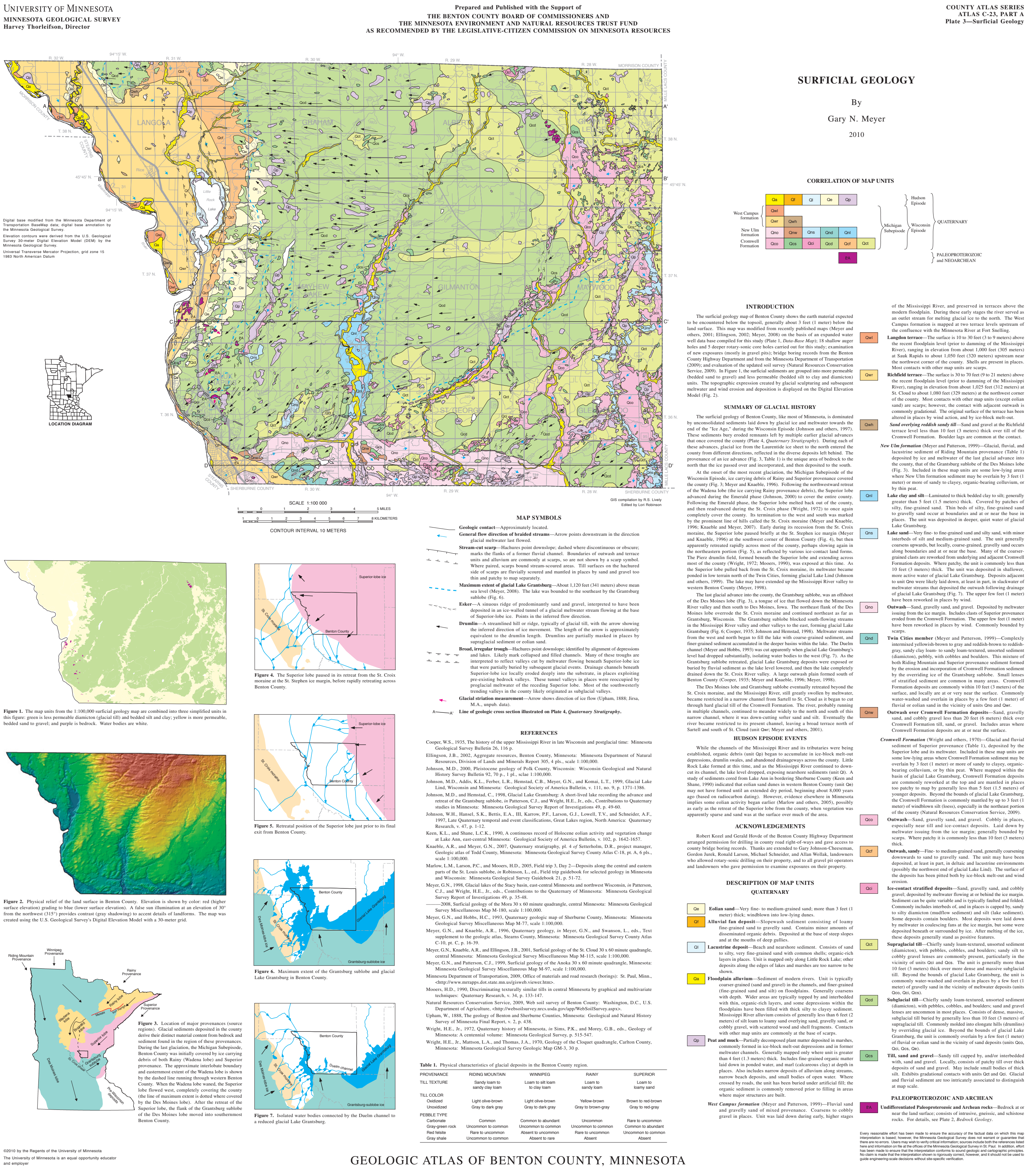
Both direct and indirect data types support surficial geologic mapping. Direct evidence includes examination and description of materials exposed at the land surface (unvegetated), descriptions of materials obtained from shallow borings, and descriptions of materials from the construction records of water wells. The geologic materials might also be inferred from landforms seen and described in the field, or recognized from topographic maps, stereo pair air photos that show relief, or LIDAR, a high-resolution measurement of the shape of the land surface. When landforms can be recognized as the product of certain glacial environments, their material composition can be ascribed with reasonable accuracy.

As a glacier advances, there is always meltwater issuing from the front. That water transports sediment from the glacier and sorts the sediment and then deposits various size components as the velocity of the water changes. Coarse materials (cobbles and gravel) will only be carried by high energy water, intermediate materials (sand) require less energy, and clay will only be deposited when the energy of the water wanes and allows it to fall from suspension.

Traditionally, the geologist has been given a two-dimensional sheet of paper to record everything they know about the geologic units present in a map form. This may include the color and texture of the sediment, an interpretation of the geologic process responsible for its deposition, its relative thickness, which episode of glaciation deposited it, and to what degree erosion has affected it. This results in a relatively complex map, with many units, each representing a unique combination of these attributes, and each unit potentially present in multiple places on the map. This was the only way to convey all that information on a single map. Today we have the ability to record all that information in a computer-based geographic information system (GIS) and then create maps based on any one of the attributes, or any combination of the attributes that best serves our purpose. For example, if we were mostly interested in seeing where sand occurs at the land surface vs. clay, we could make a map based solely on that attribute with just a few key strokes (Figure 18). That map would be much simpler than the traditional geologic map, and it might be more meaningful and easier to use for certain purposes. The GIS also allows us to work with the combinations of geologic information and any other data with geographic (location) information. We could make a map to highlight where wetlands exist over sand, or to correlate vegetation patterns with geologic features. The traditional geologic map is still the most comprehensive method of conveying all the attributes of the surficial geology, and for that reason it is the style of map printed for the atlas. However, the digital version of the map provides the opportunity to create customized maps better suited to particular uses.

In addition to the geologic map, the atlases provide a detailed description of each map unit, map symbols that indicate the location of glacial landforms, a description of the physical characteristics of the deposits of each glacial advance, and a summary of the glacial history of the county (Figure 18).

The surficial geologic map is the precursor to some important resource management maps. Pollution sensitivity maps, as created by the DNR for Part B of geologic atlases, rely on the surficial geologic map to indicate areas where focused recharge is likely. This would correspond to areas where sorted deposits of sand and gravel occur at the land surface. Because these materials are capable of transmitting water relatively quickly, there is the potential for water-borne contaminants to enter the ground water system rapidly. This information can be helpful in deciding where activities that involve hazardous materials should take place, and in determining the appropriate response to spills of potential



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COUNTY ATLAS SERIES
ATLAS C-23, PART A
Plate 3—Surficial Geology

SURFICIAL GEOLOGY

By

Gary N. Meyer

2010

Digital base modified from the Minnesota Department of Transportation BaseMap data; digital base annotation by the Minnesota Geological Survey.

Elevation contours were derived from the U.S. Geological Survey 30-meter Digital Elevation Model (DEM) by the Minnesota Geological Survey.

Universal Transverse Mercator Projection, grid zone 15
1983 North American Datum

GIS compilation by R.S. Lively
Edited by Lori Robinson

CORRELATION OF MAP UNITS

	Qa	Qf	Ql	Qe	Qp		Hudson Episode
West Campus formation	Qwl						Michigan Subepisode, Wisconsin Episode
	Qwr	Qwh					
New Ulm formation	Qno	Qnw	Qns	Qnd	Qnl		
Cromwell Formation	Qco	Qcs	Qci	Qcd	Qcf	Qct	
					PA		PALEOPROTEROZOIC and NEOARCHEAN

QUATERNARY

INTRODUCTION

The surficial geology map of Benton County shows the earth material expected to be encountered below the topsoil, generally about 3 feet (1 meter) below the land surface. This map was modified from recently published maps (Meyer and others, 2001; Ellingson, 2002; Meyer, 2008) on the basis of an expanded water well data base compiled for this study (Plate 1, *Data-Base Map*); 18 shallow auger holes and 5 deeper rotary-sonic core holes carried out for this study; examination of new exposures (mostly in gravel pits); bridge boring records from the Benton County Highway Department and from the Minnesota Department of Transportation (2009); and evaluation of the updated soil survey (Natural Resources Conservation Service, 2009). In Figure 1, the surficial sediments are grouped into more permeable (bedded sand to gravel) and less permeable (bedded silt to clay and diamicton) units. The topographic expression created by glacial sculpturing and subsequent meltwater and wind erosion and deposition is displayed on the Digital Elevation Model (Fig. 2).

SUMMARY OF GLACIAL HISTORY

The surficial geology of Benton County, like most of Minnesota, is dominated by unconsolidated sediments laid down by glacial ice and meltwater towards the end of the "Ice Age," during the Wisconsin Episode (Johnson and others, 1997). These sediments bury eroded remnants left by multiple earlier glacial advances that once covered the county (Plate 4, *Quaternary Stratigraphy*). During each of these advances, glacial ice from the Laurentide ice sheet to the north entered the county from different directions, reflected in the diverse deposits left behind. The provenance of an ice advance (Fig. 3, Table 1) is the unique area of bedrock to the north that the ice passed over and incorporated, and then deposited to the south.

At the onset of the most recent glaciation, the Michigan Subepisode of the Wisconsin Episode, ice carrying debris of Rainy and Superior provenance covered the county (Fig. 3; Meyer and Knaeble, 1996). Following the northwestward retreat of the Wadena lobe (the ice carrying Rainy provenance debris), the Superior lobe advanced during the Emerald phase (Johnson, 2000) to cover the entire county. Following the Emerald phase, the Superior lobe melted back out of the county, and then readvanced during the St. Croix phase (Wright, 1972) to once again completely cover the county. Its termination to the west and south was marked by the prominent line of hills called the St. Croix moraine (Meyer and Knaeble, 1996; Knaeble and Meyer, 2007). Early during its recession from the St. Croix moraine, the Superior lobe paused briefly at the St. Stephen ice margin (Meyer and Knaeble, 1996) at the southwest corner of Benton County (Fig. 4), but then apparently retreated rapidly across most of the county, perhaps slowing again in the northeastern portion (Fig. 5), as reflected by various ice-contact land forms. The Pierz drumlin field, formed beneath the Superior lobe and extending across most of the county (Wright, 1972; Mooers, 1990), was exposed at this time. As the Superior lobe pulled back from the St. Croix moraine, its meltwater became ponded in low terrain north of the Twin Cities, forming glacial Lake Lind (Johnson and others, 1999). The lake may have extended up the Mississippi River valley to western Benton County (Meyer, 1998).

The last glacial advance into the county, the Grantsburg sublobe, was an offshoot of the Des Moines lobe (Fig. 3), a tongue of ice that flowed down the Minnesota River valley and then south to Des Moines, Iowa. The northeast flank of the Des Moines lobe overrode the St. Croix moraine and continued northeast as far as Grantsburg, Wisconsin. The Grantsburg sublobe blocked south-flowing streams in the Mississippi River valley and other valleys to the east, forming glacial Lake Grantsburg (Fig. 6; Cooper, 1935; Johnson and Hemstad, 1998). Meltwater streams from the west and north began to fill the lake with coarse-grained sediment, and finer-grained sediment accumulated in the deeper basins within the lake. The Duelm channel (Meyer and Hobbs, 1993) was cut apparently when glacial Lake Grantsburg's level had dropped substantially, isolating water bodies to the west (Fig. 7). As the Grantsburg sublobe retreated, glacial Lake Grantsburg deposits were exposed or buried by fluvial sediment as the lake level lowered, and then the lake completely drained down the St. Croix River valley. A large outwash plain formed south of Benton County (Cooper, 1935; Meyer and Knaeble, 1996; Meyer, 1998).

The Des Moines lobe and Grantsburg sublobe eventually retreated beyond the St. Croix moraine, and the Mississippi River, still greatly swollen by meltwater, became restricted in a narrow channel from Sartell to St. Cloud as it began to cut through hard glacial till of the Cromwell Formation. The river, probably running in multiple channels, continued to meander widely to the north and south of this narrow channel, where it was down-cutting softer sand and silt. Eventually the river became restricted to its present channel, leaving a broad terrace north of Sartell and south of St. Cloud (unit Qwr; Meyer and others, 2001).

HUDSON EPISODE EVENTS

While the channels of the Mississippi River and its tributaries were being established, organic debris (unit Qp) began to accumulate in ice-block melt-out depressions, drumlin swales, and abandoned drainageways across the county. Little Rock Lake formed at this time, and as the Mississippi River continued to downcut its channel, the lake level dropped, exposing nearshore sediments (unit Ql). A study of sediments cored from Lake Ann in bordering Sherburne County (Keen and Shane, 1990) indicated that eolian sand dunes in western Benton County (unit Qe) may not have formed until an extended dry period, beginning about 8,000 years ago (based on radiocarbon dating). However, evidence elsewhere in Minnesota implies some eolian activity began earlier (Marlow and others, 2005), possibly as early as the retreat of the Superior lobe from the county, when vegetation was apparently sparse and sand was at the surface over much of the area.

ACKNOWLEDGEMENTS

Robert Kozel and Gerald Hovde of the Benton County Highway Department arranged permission for drilling in county road right-of-ways and gave access to county bridge boring records. Thanks are extended to Gary Johnson-Cheeseman, Gordon Jurek, Ronald Larson, Michael Schneider, and Allan Wollak, landowners who allowed rotary-sonic drilling on their property, and to all gravel pit operators and landowners who gave permission to examine exposures on their property.

DESCRIPTION OF MAP UNITS

QUATERNARY

Qe **Eolian sand**—Very fine- to medium-grained sand; more than 3 feet (1 meter) thick; windblown into low-lying dunes.

Qf **Alluvial fan deposit**—Slopewash sediment consisting of loamy fine-grained sand to gravelly sand. Contains minor amounts of disseminated organic debris. Deposited at the base of steep slopes and at the mouths of deep gullies.

Ql **Lacustrine deposit**—Beach and nearshore sediment. Consists of sand to silty, very fine-grained sand with common shells; organic-rich layers in places. Unit is mapped only along Little Rock Lake; other deposits along the edges of lakes and marshes are too narrow to be shown.

Qa **Floodplain alluvium**—Sediment of modern rivers. Unit is typically coarser-grained (sand and gravel) in the channels, and finer-grained (fine-grained sand and silt) on floodplains. Generally coarsens with depth. Wider areas are typically topped by and interbedded with thin, organic-rich layers, and some depressions within the floodplains have been filled with thick silty to clayey sediment. Mississippi River alluvium consists of generally less than 6 feet (2 meters) of silt loam to loamy sand overlying sand, gravelly sand, or cobbly gravel, with scattered wood and shell fragments. Contacts with other map units are commonly at the base of scarps.

Qp **Peat and muck**—Partially decomposed plant matter deposited in marshes, commonly formed in ice-block melt-out depressions and in former meltwater channels. Generally mapped only where unit is greater than 4 feet (1.3 meters) thick. Includes fine-grained organic matter laid down in ponded water, and marl (calcareous clay) at depth in places. Also includes narrow deposits of alluvium along streams, narrow beach deposits, and small bodies of open water. Where crossed by roads, the unit has been buried under artificial fill; the organic sediment is commonly removed prior to filling in areas where major structures are built.

West Campus formation (Meyer and Patterson, 1999)—Fluvial sand and gravelly sand of mixed provenance. Coarsens to cobbly gravel in places. Unit was laid down during early, higher stages of the Mississippi River, and preserved in terraces above the modern floodplain. During these early stages the river served as an outlet stream for melting glacial ice to the north. The West Campus formation is mapped at two terrace levels upstream of the confluence with the Minnesota River at Fort Snelling.

Qwl **Langdon terrace**—The surface is 10 to 30 feet (3 to 9 meters) above the recent floodplain level (prior to damming of the Mississippi River), ranging in elevation from about 1,000 feet (305 meters) at Sauk Rapids to about 1,050 feet (320 meters) upstream near the northwest corner of the county. Shells are present in places. Most contacts with other map units are scarps.

Qwr **Richfield terrace**—The surface is 30 to 70 feet (9 to 21 meters) above the recent floodplain level (prior to damming of the Mississippi River), ranging in elevation from about 1,025 feet (312 meters) at St. Cloud to about 1,080 feet (329 meters) at the northwest corner of the county. Most contacts with other map units (except eolian sand) are scarps; however, the contact with adjacent outwash is commonly gradational. The original surface of the terrace has been altered in places by wind action, and by ice-block melt-out.

Qwh ***Sand overlying reddish sandy till***—Sand and gravel at the Richfield terrace level less than 10 feet (3 meters) thick over till of the Cromwell Formation. Boulder lags are common at the contact.

New Ulm formation (Meyer and Patterson, 1999)—Glacial, fluvial, and lacustrine sediment of Riding Mountain provenance (Table 1) deposited by ice and meltwater of the last glacial advance into the county, that of the Grantsburg sublobe of the Des Moines lobe (Fig. 3). Included in these map units are some low-lying areas where New Ulm formation sediment may be overlain by 3 feet (1 meter) or more of sandy to clayey, organic-bearing colluvium, or by thin peat.

Qnl **Lake clay and silt**—Laminated to thick bedded clay to silt; generally greater than 5 feet (1.5 meters) thick. Covered by patches of silty, fine-grained sand. Thin beds of silty, fine-grained sand to gravelly sand occur at boundaries and at or near the base in places. The unit was deposited in deeper, quiet water of glacial Lake Grantsburg.

Qns **Lake sand**—Very fine- to fine-grained sand and silty sand, with minor interbeds of silt and medium-grained sand. The unit generally coarsens upwards, but locally, coarse-grained, gravelly sand occurs along boundaries and at or near the base. Many of the coarser-grained clasts are reworked from underlying and adjacent Cromwell Formation deposits. Where patchy, the unit is commonly less than 10 feet (3 meters) thick. The unit was deposited in shallower, more active water of glacial Lake Grantsburg. Deposits adjacent to unit Qno were likely laid down, at least in part, in slackwater of meltwater streams that deposited the outwash following drainage of glacial Lake Grantsburg (Fig. 7). The upper few feet (1 meter) have been reworked in places by wind.

Qno **Outwash**—Sand, gravelly sand, and gravel. Deposited by meltwater issuing from the ice margin. Includes clasts of Superior provenance eroded from the Cromwell Formation. The upper few feet (1 meter) have been reworked in places by wind. Commonly bounded by scarps.

Qnd **Twin Cities member** (Meyer and Patterson, 1999)—Complexly intermixed yellowish-brown to gray and reddish-brown to reddish-gray, sandy clay loam- to sandy loam-textured, unsorted sediment (diamicton), pebbly, with cobbles and boulders. This mixture of both Riding Mountain and Superior provenance sediment formed by the erosion and incorporation of Cromwell Formation sediment by the overriding ice of the Grantsburg sublobe. Small lenses of stratified sediment are common in many areas. Cromwell Formation deposits are commonly within 10 feet (3 meters) of the surface, and locally are at or very near the surface. Commonly water-washed and overlain in places by a few feet (1 meter) of fluvial or eolian sand in the vicinity of units Qno and Qwr.

Qnw **Outwash over Cromwell Formation deposits**—Sand, gravelly sand, and cobbly gravel less than 20 feet (6 meters) thick over Cromwell Formation till, sand, or gravel. Includes areas where Cromwell Formation deposits are at or near the surface.

Cromwell Formation (Wright and others, 1970)—Glacial and fluvial sediment of Superior provenance (Table 1), deposited by the Superior lobe and its meltwater. Included in these map units are some low-lying areas where Cromwell Formation sediment may be overlain by 3 feet (1 meter) or more of sandy to clayey, organic-bearing colluvium, or by thin peat. Where mapped within the basin of glacial Lake Grantsburg, Cromwell Formation deposits are commonly reworked at the top and are mantled in places too patchy to map by generally less than 5 feet (1.5 meters) of younger deposits. Beyond the bounds of glacial Lake Grantsburg, the Cromwell Formation is commonly mantled by up to 3 feet (1 meter) of windblown silt (loess), especially in the northeast portion of the county (Natural Resources Conservation Service, 2009).

Qco **Outwash**—Sand, gravelly sand, and gravel. Cobbly in places, especially near till and ice-contact deposits. Laid down by meltwater issuing from the ice margin; generally bounded by scarps. Where patchy it is commonly less than 10 feet (3 meters) thick.

Qcf **Outwash, sandy**—Fine- to medium-grained sand, generally coarsening downwards to sand to gravelly sand. The unit may have been deposited, at least in part, in deltaic and lacustrine environments (possibly the northwest end of glacial Lake Lind). The surface of the deposits has been pitted both by ice-block melt-out and wind erosion.

Qci **Ice-contact stratified deposits**—Sand, gravelly sand, and cobbly gravel; deposited by meltwater flowing at or behind the ice margin. Sediment can be quite variable and is typically faulted and folded. Commonly includes interbeds of, and in places is capped by, sandy to silty diamicton (mudflow sediment) and silt (lake sediment). Some deposits contain boulders. Most deposits were laid down by meltwater in coalescing fans at the ice margin, but some were deposited beneath or surrounded by ice. After melting of the ice, these deposits generally stand as positive features.

Qct **Supraglacial till**—Chiefly sandy loam-textured, unsorted sediment (diamicton), with pebbles, cobbles, and boulders; sandy silt to cobbly gravel lenses are commonly present, particularly in the vicinity of units Qci and Qcs. The unit is generally more than 10 feet (3 meters) thick over more dense and massive subglacial till. Beyond the bounds of glacial Lake Grantsburg, the unit is commonly water-washed and overlain in places by a few feet (1 meter) of gravelly sand in the vicinity of meltwater deposits (units Qco, Qci, Qcs).

Qcd **Subglacial till**—Chiefly sandy loam-textured, unsorted sediment (diamicton), with pebbles, cobbles, and boulders; sand and gravel lenses are uncommon in most places. Consists of dense, massive, subglacial till buried by generally less than 10 feet (3 meters) of supraglacial till. Commonly molded into elongate hills (drumlins) by overriding glacial ice. Beyond the bounds of glacial Lake Grantsburg, the unit is commonly overlain by a few feet (1 meter) of fluvial or eolian sand in the vicinity of sand deposits (units Qco, Qci, Qcs, Qe).

Qcs **Till, sand and gravel**—Sandy till capped by, and/or interbedded with, sand and gravel. Locally, consists of patchy till over thick deposits of sand and gravel. May include small bodies of thick silt. Exhibits gradational contacts with units Qct and Qci. Glacial and fluvial sediment are too intricately associated to distinguish at map scale.

PALEOPROTEROZOIC AND ARCHEAN

PA **Undifferentiated Paleoproterozoic and Archean rocks**—Bedrock at or near the land surface; consists of intrusive, gneissic, and schistose rocks. For details, see Plate 2, *Bedrock Geology*.

MAP SYMBOLS

Geologic contact—Approximately located.

General flow direction of braided streams—Arrow points downstream in the direction glacial meltwater last flowed.

Stream-cut scarp—Hachures point downslope; dashed where discontinuous or obscure; marks the flanks of a former fluvial channel. Boundaries of outwash and terrace units and alluvium are commonly at scarps, so are not shown by a scarp symbol. Where paired, scarps bound stream-scoured areas. Till surfaces on the hachured side of scarps are fluvially scoured and mantled in places by sand and gravel too thin and patchy to map separately.

Maximum extent of glacial Lake Grantsburg—About 1,120 feet (341 meters) above mean sea level (Meyer, 2008). The lake was bounded to the southeast by the Grantsburg sublobe (Fig. 6).

Esker—A sinuous ridge of predominantly sand and gravel, interpreted to have been deposited in an ice-walled tunnel of a glacial meltwater stream flowing at the base of Superior-lobe ice. Points in the inferred flow direction.

Drumlin—A streamlined hill or ridge, typically of glacial till, with the arrow showing the inferred direction of ice movement. The length of the arrow is approximately equivalent to the drumlin length. Drumlins are partially masked in places by supraglacial sediment or eolian sand.

Broad, irregular trough—Hachures point downslope; identified by alignment of depressions and lakes. Likely mark collapsed and filled channels. Many of these troughs are interpreted to reflect valleys cut by meltwater flowing beneath Superior-lobe ice that were partially buried by subsequent glacial events. Drainage channels beneath Superior-lobe ice locally eroded deeply into the substrate, in places exploiting pre-existing bedrock valleys. These tunnel valleys in places were reoccupied by proglacial meltwater of the receding Superior lobe. Most of the southwesterly trending valleys in the county likely originated as subglacial valleys.

Glacial striation measurement—Arrow shows direction of ice flow (Upham, 1888; Jirsa, M.A., unpub. data).

A——A' **Line of geologic cross section illustrated on Plate 4, *Quaternary Stratigraphy*.**

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Table 1. Physical characteristics of glacial deposits in the Benton County region.

PROVENANCE	RIDING MOUNTAIN	WINNIPEG	RAINY	SUPERIOR
TILL TEXTURE	Sandy loam to sandy clay loam	Loam to silt loam to clay loam	Loam to sandy loam	Loam to loamy sand
TILL COLOR				
Oxidized	Light olive-brown	Light olive-brown	Yellow-brown	Brown to red-brown
Unoxidized	Gray to dark gray	Gray to dark gray	Gray to brown-gray	Gray to red-gray
PEBBLE TYPE				
Carbonate	Common	Common to abundant	Uncommon	Rare to uncommon
Gray-green rock	Uncommon to common	Uncommon to common	Uncommon to common	Common to abundant
Red felsite	Rare to uncommon	Absent to uncommon	Rare to uncommon	Uncommon to common
Gray shale	Uncommon to common	Absent to rare	Absent	Absent

Figure 1. The map units from the 1:100,000 surficial geology map are combined into three simplified units in this figure: green is less permeable diamicton (glacial till) and bedded silt and clay; yellow is more permeable, bedded sand to gravel; and purple is bedrock. Water bodies are white.

Figure 2. Physical relief of the land surface in Benton County. Elevation is shown by color: red (higher surface elevation) grading to blue (lower surface elevation). A false sun illumination at an elevation of 30° from the northwest (315°) provides contrast (gray shadowing) to accent details of landforms. The map was created using the U.S. Geological Survey's Digital Elevation Model with a 30-meter grid.

Figure 3. Location of major provenances (source regions). Glacial sediments deposited in the county derive their distinct material content from bedrock and sediment found in the region of these provenances. During the last glaciation, the Michigan Subepisode, Benton County was initially covered by ice carrying debris of both Rainy (Wadena lobe) and Superior provenance. The approximate interlobate boundary and easternmost extent of the Wadena lobe is shown by the dashed line running through western Benton County. When the Wadena lobe waned, the Superior lobe flowed west, completely covering the county (the line of maximum extent is dotted where covered by the Des Moines lobe). After the retreat of the Superior lobe, the flank of the Grantsburg sublobe of the Des Moines lobe moved into southernmost Benton County.

Figure 4. The Superior lobe paused in its retreat from the St. Croix moraine at the St. Stephen ice margin, before rapidly retreating across Benton County.

Figure 5. Retreatal position of the Superior lobe just prior to its final exit from Benton County.

Figure 6. Maximum extent of the Grantsburg sublobe and glacial Lake Grantsburg in Benton County.

Figure 7. Isolated water bodies connected by the Duelm channel to a reduced glacial Lake Grantsburg.

GEOLOGIC ATLAS OF BENTON COUNTY, MINNESOTA

contaminants.

Surficial maps are also a starting point for mapping deposits that might be useful as aggregate for road building and other construction purposes. The surficial map indicates where these kinds of materials occur at the land surface and further work to evaluate their thickness and quality is expedited.

Surficial maps are often consulted in the planning stages for road building, on-site sewage treatment system design and construction, drainage work, and excavations of all types. Knowing the kind of material that will be encountered is useful to these activities. The maps of the county geologic atlas series are not intended for site specific or engineering use. They should be augmented by data from the area of interest.

Quaternary Stratigraphy, and Sand Distribution Models

Stratigraphy is a geologic practice in which bodies of earth materials are classified by their characteristics, and their significance in geologic history. The goal is to use the characteristics of each unit to understand the event that created it, where it fits in the sequence of events that created the units around it, and to recognize units from different locations that represent the same event, or the same period of time. Geologic units record earth history, but due to erosion (the destruction and removal of material) there are often large gaps in time for which no geologic units remain.

Quaternary is a formal geologic time period thought to cover the last two or three million years. In Minnesota this period of time includes multiple advances (and retreats) of continental-scale glaciers. The atlas products included on the Quaternary stratigraphy plate attempt to define geologic units at the land surface and in the subsurface that represent distinct events in this glacial history, and to combine them to an account of earth history in Minnesota for this time period.

Glacial till, also called diamicton, is a mixture of clay, silt, sand, and larger materials deposited directly by glacial ice. These materials are incorporated into the ice as it moves over bedrock or the deposits of previous glaciations. Therefore, the path of the glacier is reflected in the materials it deposits. Those materials were eroded from the substrate as the glacier advanced. If we know where those materials came from we can discern the path of the glacier. For example, an ice lobe that advanced into Minnesota from the northeast will likely contain fragments of the rock types commonly seen today along the North Shore of Lake Superior including agates. With each subsequent glaciation the evidence becomes weaker, more mixed, and less direct as each glacier incorporates material from the deposits of the glacier that preceded it.

Characteristics that help define unique glacial tills include color; the relative percentages of clay, silt, and sand in the matrix; and the rock types represented in pebbles or coarse sand grains. Often the differences are subtle enough that a mathematical analysis and graphic plot of many textural analyses is necessary to recognize and define groups of similar samples that represent depositional events.

The reason we strive to define these units and their sequence is to understand the earth history they represent, and to create a common framework and set of names that earth scientists can use to communicate. The units also make it possible to infer some common properties of each unit everywhere that it is encountered. For example, till deposits of the Des Moines Lobe are known to impede water flow, to impart relatively high sulfate content to water that has spent time in contact with them, and to be dense and sticky when excavating. Wherever these deposits are seen on a geologic map you can expect these characteristics.

Finally, there is a focused effort to map all geologic units that may be aquifers. Water management is one of the most important uses of the geologic atlases, and if we want to protect and make wise use of our aquifers we need to understand where they are, and how they are connected to the land surface, to surface water features, to each other, and to wells. For about two-thirds of Minnesota, glacial aquifers are the predominant source of ground water. Aquifers at the land surface often host lakes or rivers, and these aquifers may be partially exposed (occurring at the land surface) and partially buried (covered by younger, non-aquifer

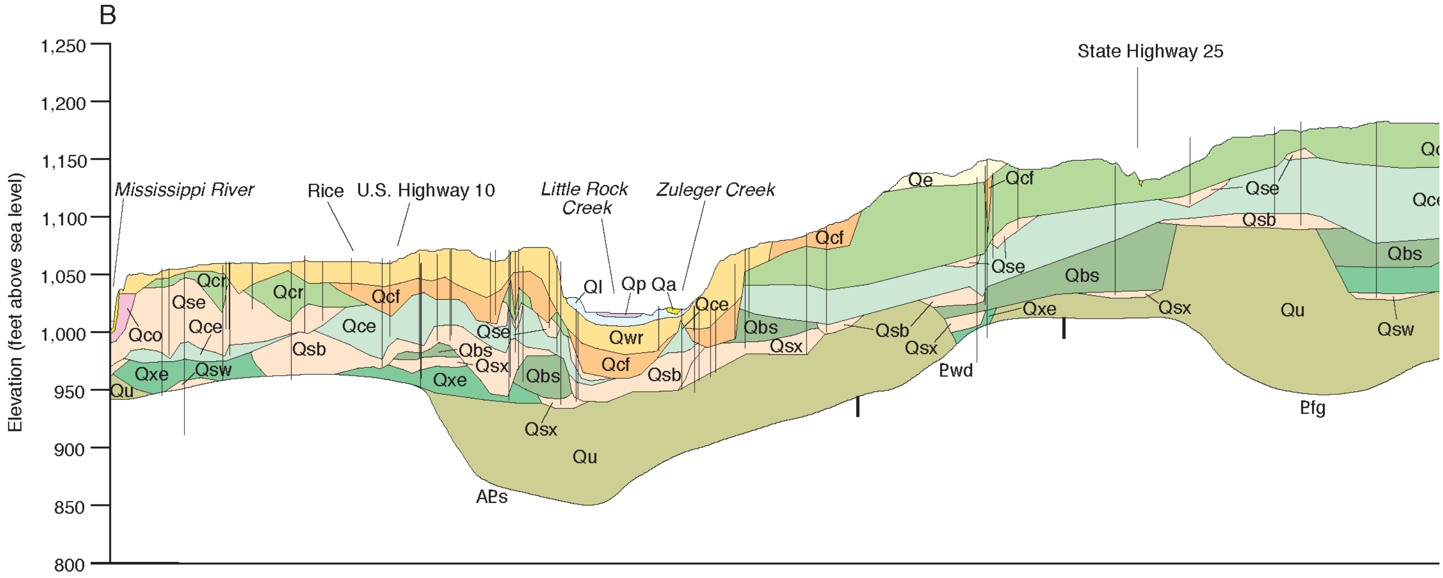
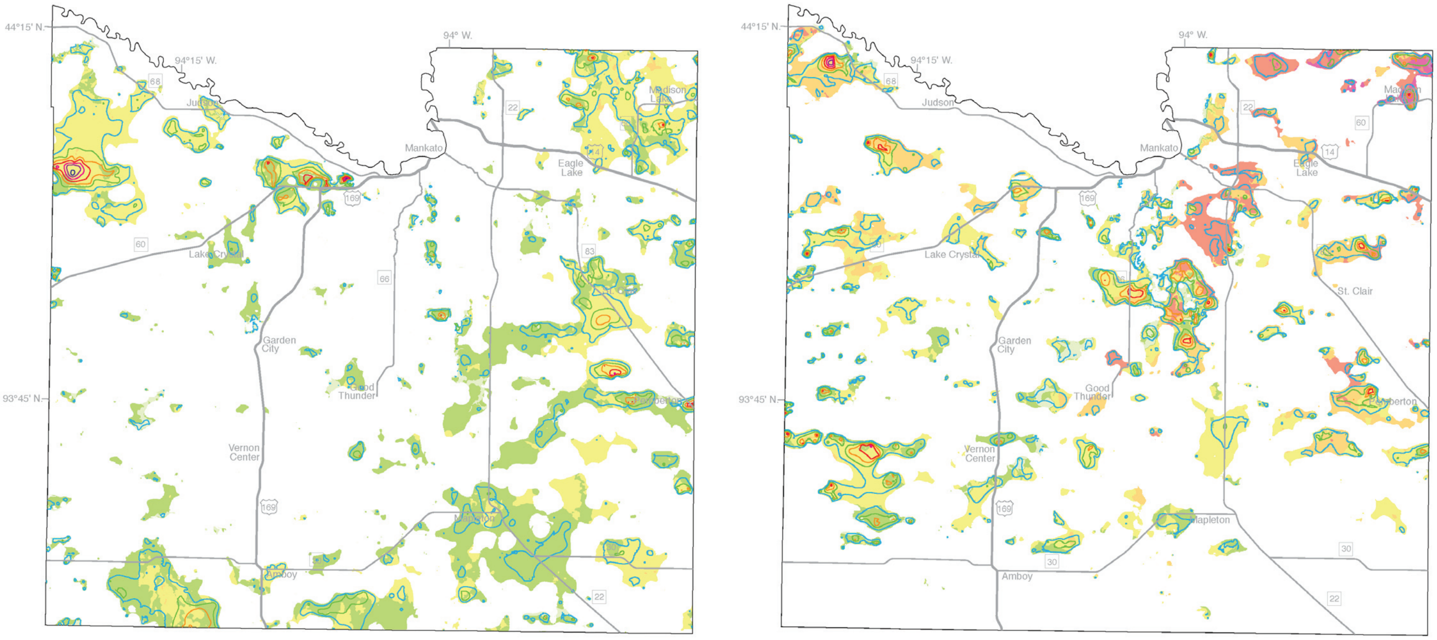


Figure 19. This partial cross-section is a geologist's interpretation of the distribution of materials in the glacial sediment of Benton county. The wells used to guide the interpretation are shown. Note that there are areas where sufficient data are not available and the material is called Quaternary undifferentiated.



Figures 20 and 21. These are two of eight maps used to depict the distribution of sand at different stratigraphic intervals in Blue Earth County. At the same geographic location there may be an aquifer at one stratigraphic interval, and not at the other. The color indicates aerial distribution and depth from the land surface and the color contour lines indicate thickness of the sand bodies

sediments) in other places. Understanding and mapping these arrangements makes it possible to understand connections between wells, aquifers, and surface water features.

The Quaternary Stratigraphy products of an atlas include geologic cross-sections. A cross-section is a drawing that shows the vertical sequence of earth materials. The printed version of the atlas usually contains three to five cross-sections drawn across the county. These illustrations are based mostly on water well construction records (shown on the illustration), with additional information from a few scientific drillholes. The scientific holes produce core samples that are described and analyzed for grain size distribution. Occasionally samples of wood are found in the core and used to establish an age of the sediment that contained it. This is very helpful in establishing the sequence of events and their deposits. The cross-sections are based on the geologist's interpretation of glacial history and the units associated with these events (Figure 19).

The boundaries between till deposition events are the places where sorted deposits (sand and gravel) are most likely to be found. The boundaries mostly represent the land surface as it existed before the next ice lobe arrived, and that surface is where glacial meltwater would have deposited sorted sediment.

A unit called "Quaternary undifferentiated" is designated in those places where we have no well records or scientific drillholes to indicate the type of glacial material present.

In addition to cross-sections, the atlases provide a description of any units that are found only in the subsurface (and therefore are not described on the surficial geology map), and a diagram showing the relative age, distribution, and provenance of the deposits of each ice lobe that traversed the county. Provenance is a term that describes the area or place from which the constituent materials of deposits were derived. The atlases also provide maps of the pathways of these lobes and their margins, and a model of the elevation of the land surface that is useful in recognizing the major drainageways, moraines, and other large landforms of the surface of the county.

Sand Distribution Models

The printed plate shows three to five cross-sections, but the geologists actually draw many more, usually spaced 1 kilometer (0.6 mile) apart. These sections are used to map continuous surfaces that form the boundaries between tills and between till and sand units. The contacts between geologic units in the cross-sections are connected laterally utilizing GIS methods. The surfaces that surround the sand and gravel bodies are then displayed as a series of maps, each describing the distribution of sand at a particular stratigraphic boundary with depths and thickness. The work of the DNR then confirms if these sands are aquifers, and creates maps of the water levels, water composition, and sensitivity of the aquifers to contamination.

The maps of the potential aquifers can be used to find a place where water is available, or to see what aquifers exist at a particular place (Figures 20 and 21).

A homeowner or drilling contractor might look at a specific location and see if one or more aquifers exist there and how deep and how thick they are. An industry looking to build a facility might look at all the aquifers across the county and then choose a place to build where the maps indicate a large and productive aquifer. As with all geologic atlas maps it is best to confirm the map findings with on-site investigations. Planners might look at the map and use the information to protect the land area where a municipal well receives its recharge. Hydrologists evaluating a permit request for a high-capacity well might use the maps as part of an effort to determine if the well will affect a surface water body (lake, river, spring). This information is also useful in constructing hydrologic models. These models are computer-based numerical simulations of real geologic settings that are useful in predicting the effects of pumping.

Bedrock Topography and Depth to Bedrock Maps

Topography means the shape of a surface, and thus bedrock topography means the shape of the bedrock surface. Glacial sediment covers the bedrock surface over most of Minnesota, with the northeastern and southeastern parts of the state being significant exceptions. In southeastern Minnesota bedrock can often be seen exposed at the land surface, mostly in the valleys of modern rivers. In northeastern Minnesota there are areas where the bedrock is largely exposed, mostly in wilderness areas.

The shape of the bedrock surface, and its elevation, are mapped mostly with data from the records of wells and scientific and exploration drill holes. If the elevation of the land surface is known, and the depth at which bedrock was encountered is recorded, an elevation of the bedrock surface can be calculated at that place. Deep wells that don't hit bedrock also provide significant data because they are evidence that the bedrock surface is somewhat lower than the elevation of the bottom of the well. If data are closely-spaced it is possible to draw elevation contours that will reveal the highs and lows of the bedrock surface and possibly changes in relief related to changes in bedrock type. Some rock types are more resistant to erosion than others and therefore stand higher on the bedrock surface. With enough data it may be possible to recognize channels associated with drainage systems developed on the bedrock surface prior to burial. Geophysical data is used to augment the well data, especially in areas where wells are not common.

Geologists at MGS draw the contours representing the elevation the bedrock surface manually rather than using automated, computer-driven routines. The ability of the geologist to incorporate knowledge of the bedrock types and the history of the terrain is deemed worthy of the extra investment of time. We generally contour the data as though an integrated drainage pattern existed, even though glacial erosion may create closed basins in some places. The geologist usually uses GIS software to display and print the available data. They may draw contours on the computer monitor, or on a paper plot to be transferred later. Paper plots have the advantage of being larger than a computer screen and therefore able to show a larger area. The geologists frequently access online databases to read the well record or otherwise increase their understanding of data points as they contour. Usually the geologist creating the bedrock topography works independently of the geologist mapping the bedrock. Then when both maps are in draft form they are compared and revisions made to increase correlation where appropriate.

The contour interval is chosen to be appropriate to the data density. Over much of Minnesota this is a 50-foot interval, although in some areas with many wells it may be possible to increase the level of detail and map at a 25- or even 20-foot interval. The accuracy of the elevations from the well records is about 5 feet because many of them are read from topographic maps of the land surface with 10-foot contours.

Depth to bedrock can be mapped in a similar manner by plotting depths as recorded in well records. However, a better map can be created by gridding the bedrock topography map and subtracting the elevation of each grid cell from a grid of land surface elevations. Gridding means dividing the map area into cells and assigning an elevation to each cell. This method is better at including the interpretive detail of the contours created by a geologist. MGS generally uses a 30-meter cell size. Usually the bedrock topography surface we draw is much smoother than the land surface topography. This smoothness is only an artifact of the relative lack of density of data used to describe the shape of the surface. The land surface topography is much more detailed and accurate than the bedrock surface because much more data is available to map it. When the values from the smoother bedrock surface are subtracted from the values from the detailed land surface the result is a grid that appears as detailed as the land surface. However, these values cannot be more accurate than the least-detailed of the two surfaces used to create it, and this must be understood by users.

In the southeastern third of Minnesota where sedimentary rocks occur the bedrock topography shows an integrated drainage pattern with relatively deep and narrow channels similar to those of the present day Mississippi River valley from St. Paul to Winona, or the present day St. Croix River valley from Osceola to Prescott. There are many valleys of similar size that are completely filled with glacial sediment, and therefore undetectable from the land surface. These are easily seen in the bedrock topography maps of that area.

Over the remainder of Minnesota, the bedrock surface character reflects the more resistant nature of igneous and metamorphic rocks, sometimes overlain by a thin cover of sedimentary rocks, and sometimes deeply weathered. The deep weathering was caused by tropical conditions about 100 million years ago, and perhaps by other episodes of similar conditions prior to that time. The heat, moisture, and acidic soil water related to rotting vegetation broke down the feldspars and other minerals common to these rocks and replaced them with clay minerals. Subsequent erosion resulted in the relatively smooth bedrock topography typical

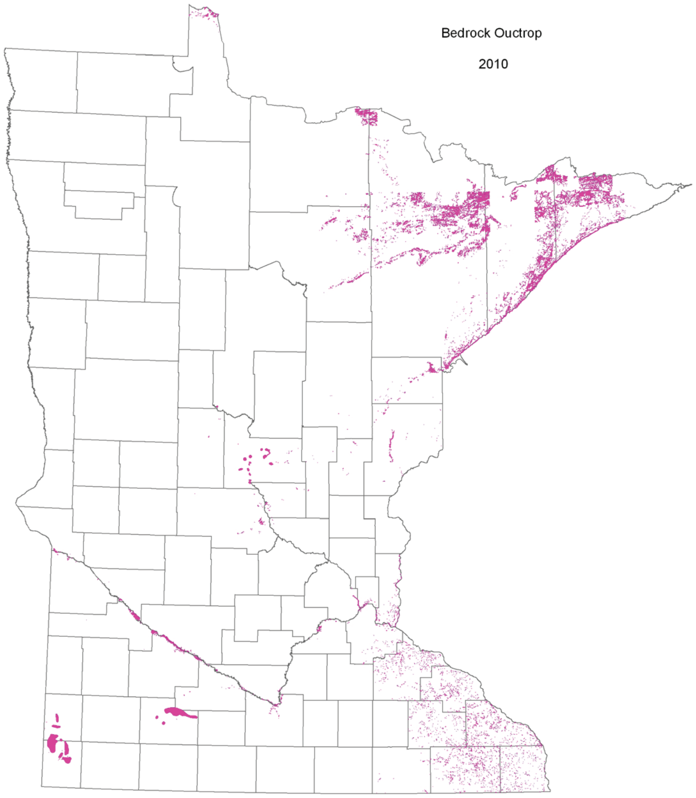


Figure 22. The distribution of bedrock outcrops in Minnesota. Many are too small to be seen at this scale. The major areas of outcrop are the Arrowhead region including the North Shore, Carlton, Pine, Morrison, Stearns, Pipestone, Rock, Cottonwood counties, the valleys of the Minnesota, Mississippi, and St. Croix Rivers, and many smaller valleys and bluffs in southeastern Minnesota.

of western Minnesota where the weathering residuum is still present in many areas.

Depth to bedrock can also be thought of, and called, glacial sediment thickness. Where the bedrock occurs at the land surface (outcrop, Figure 22) the depth to bedrock is zero, and no glacial sediment occurs. Where the depth to bedrock is 200 feet there is 200 feet of glacial sediment. When mapping the character of the glacial sediment for the Quaternary stratigraphy products, there are commonly places where one or two data points tell us that the bedrock surface is deep and the glacial sediment is thick, but we don't have sufficient data to know the character of that deep glacial sediment. Wells are drilled to access water, and if sufficient water is found at shallow depths there is no need to drill deeper. In those areas we may know that there is thick glacial sediment, but we are unable to describe or map its character.

Where the bedrock is not an aquifer, typical of igneous and metamorphic rocks, the bedrock surface represents the bottom of our hydrologic system. Water does not penetrate this surface, and no water will be found in appreciable quantities within these rocks. There are places in Minnesota (St. Cloud, the Arrowhead region, others) where igneous and metamorphic rocks are at the land surface, and are not aquifers. In these places there is no significant ground water, and alternative sources (rain, impoundments, surface water bodies, pipeline systems) must be used.

Where sedimentary bedrock occurs, there may be a succession of strata, some of which are aquifers, and some of which are not. In these places there may be several aquifers at different depths to choose from and some may supply water with significantly different composition. They may be overlain by Quaternary aquifers as well.

Depth to bedrock can be an important consideration when mining of bedrock is considered. The depth to bedrock represents "overburden", or material that must be removed to access the desired bedrock. For example, the Jordan Sandstone formation contains sand grains with the right properties for use in enhancing oil and gas recovery. The Jordan exists over large parts of southeastern Minnesota. However, it is only a realistic target for mining where depth to bedrock is relatively small, perhaps less than 25 feet. With a geographic information system and the files from county geologic atlas maps it is easy to intersect the bedrock geology map with the depth to bedrock map to find places where the Jordan is accessible. The same situation exists with mining of dimension stone.

Bedrock Geology Maps

In Minnesota, bedrock formations are at least 100 million years old, and some are more than 3 billion years old. Bedrock is generally of interest for its potential to host minerals or water. However, it can also affect how we build roads and houses, and some bedrock is useful as a building material.

The bedrock map is based on descriptions of exposures of the rock (outcrops), descriptions from water well construction records and scientific and engineering borings, drill cuttings, core samples, and geophysical data. Geophysical methods are discussed in the database section of this document. Gravity and magnetic methods are used in mapping igneous and metamorphic rocks, and borehole geophysical methods are commonly used in mapping sedimentary bedrock (Figure 23 and Figure 24).

The bedrock geology map in a county geologic atlas tells us what kind of bedrock is first encountered at, or beneath, the land surface. Over most of Minnesota glacial sediment covers the bedrock. Bedrock is often exposed in southeastern Minnesota, in northeastern Minnesota, and in a few spots in central Minnesota and southwestern Minnesota.

In those places where igneous and metamorphic rock occurs the map tells us what type of rock occurs at the bedrock surface, and not much can be said about how thick that rock unit is, or what might be beneath it. The processes that create these rocks don't typically create a predictable vertical sequence of rock types.

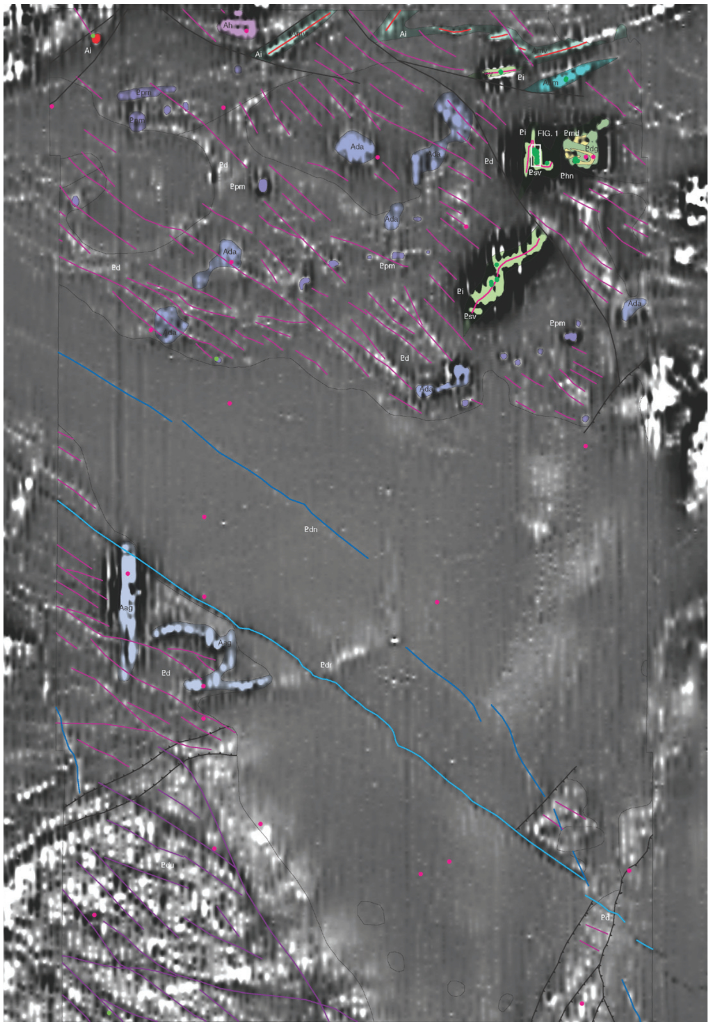


Figure 23. Variations in the intensity of the earth's magnetic field in Todd County. The magnetic data was obtained from an airborne instrument and guides mapping of rocks that are not visible at the land surface.

However, in those places where sedimentary rocks exist, there often is a vertical sequence of rock types that is consistent laterally for tens or even hundreds of miles. If we know the sequence from drillholes or outcrops, we can predict what lies beneath the first bedrock represented on the map. The bedrock sequence is typically eroded by ancient or modern rivers where we can see parts of the vertical sequence in the walls of the valleys. The thickness of each unit can be consistent, or can change laterally in a consistent fashion such that we can predict the elevation of horizontal contacts between formations. Because these layers of sedimentary rock often have unique abilities to host and transmit water, the atlases typically map the elevation of contact surfaces such that they can be used in predicting water availability and in creating numerical simulations (models) for predicting the effects of pumping. The sequence of sedimentary rocks is usually illustrated as a column near the bedrock map with unit names and characteristics.

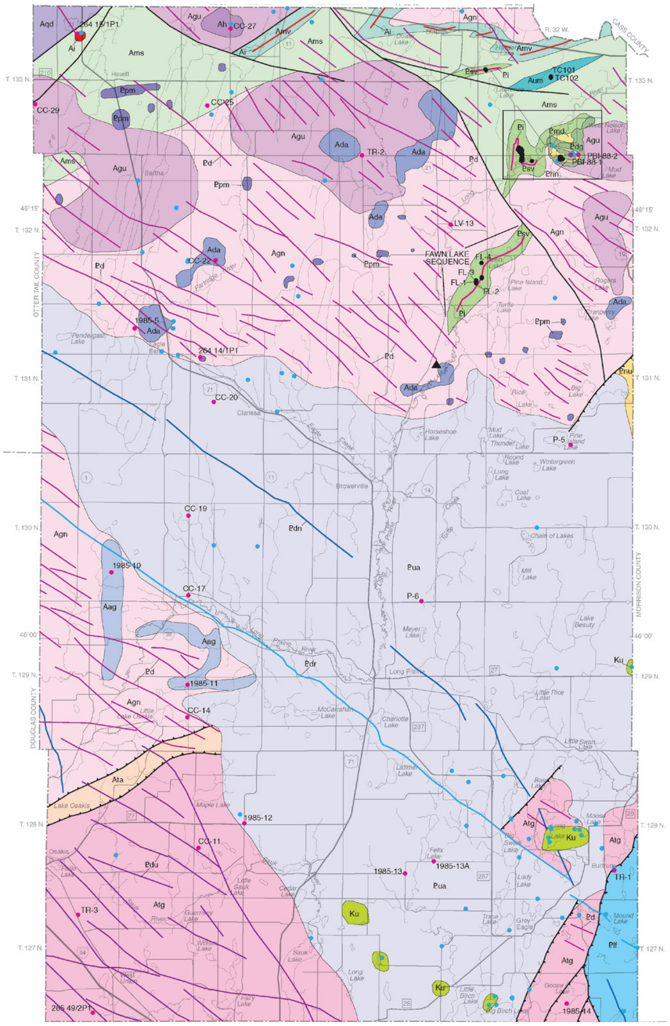


Figure 24. The bedrock geologic map of Todd County showing rock types in the same area as that shown by the magnetic anomaly map, Figure 23.

Maps of the bedrock of Minnesota show many faults. They were created at various times in the long 3 billion year history recorded in Minnesota bedrock and are not an indicator of active seismicity. Minnesota continues to experience earthquakes, but they are small and rarely cause significant damage (see Mooney, 1979). Faults in the sedimentary bedrock can affect ground water flow patterns where units that would typically impede flow are displaced from their normal position by faulting.

The type and depth of bedrock can affect construction of roads and buildings. Where igneous and metamorphic rocks lie at or near the land surface they are relatively difficult and expensive to excavate. Buildings are often constructed on top of the rock, rather than incurring the expense of excavating a basement. Similarly, road builders try to avoid excavating rock, although a drive along the North Shore of Lake Superior will illustrate this is not always possible. On the positive side, bedrock is usually very stable and not vulnerable to slumping, settling, or other movement.

The County Geologic Atlases usually assess the bedrock geology and identify the potential for mineral occurrences. This assessment is based on any resemblance between the geology as mapped, and similar geologic settings elsewhere that have hosted significant mineral deposits. The assessment does not attempt to identify grade, tonnage, value, or other economic factors.

There are many types of rock in Minnesota, and many variations in how they host and transmit ground water. We can divide the bedrock of Minnesota into two groups, one that includes igneous and metamorphic rocks and another group containing sedimentary rocks [see Figure 7].

The igneous and metamorphic rocks (granite, gabbro, basalt, schist, slate, quartzite, gneiss, greenstone, diabase, and others) form under high heat and pressure conditions and the rocks are composed of interlocking mineral grains with no pore space between them. Over time, fractures form in these rocks, most commonly near the top of the rock and less commonly at depth. Without pores, the rock itself cannot host or transmit water. However, fractures that connect to the land surface, or to overlying sand or other water bearing materials, can host and transmit water. These rocks (and the fractures within them) are the bottom of the hydrologic system in Minnesota, and water will not be found deeper than the zone of fractures within them. Wells drilled into igneous and metamorphic rocks produce water from such fractures. Where there are larger fractures and where wells are strongly connected with recharge zones the wells are most productive. Wells might also intersect a number of smaller fractures, each contributing a small amount of water, and collectively providing an adequate supply. Wells that are relatively deep provide storage capacity, and this can make a well that produces water slowly able to provide larger amounts episodically. The well fills when not in use, for example overnight, and then the water within is pumped out during daytime use. Wells are drilled vertically, and fractures are often also nearly vertical. This decreases the chance of a well intersecting a fracture. For this reason two wells drilled very near each other can have very different productivity and very different depths. Hydraulic fracturing is a technique developed in the petroleum industry to increase the productivity of wells in fractured rock. It utilizes high pressure to force open and clean the fractures, and then introduces sand grains or manufactured beads that prop open the fractures after the pressure is released. This has the effect of increasing the capacity of each fracture to conduct fluids, and also creates and connects fractures to promote flow. This technique has been adapted by the water well industry to improve the performance of water wells finished in non-porous, fractured rock. While some wells in igneous and metamorphic rocks will hit large fracture networks and produce lots of water, others will not, and some may be effectively dry holes, unsuitable for even a domestic supply.

In areas of igneous and metamorphic rocks the atlas products generally include a geologic map with unit descriptions, a correlation chart to show the relative age of the units, an aeromagnetic image, rock composition diagrams, a regional geologic map for context, and a summary of the geologic history represented by the bedrock. Igneous and metamorphic rocks underlie all of Minnesota, but are overlain by sedimentary rocks, with the thickest and most continuous sequences occurring in southeastern Minnesota and northwestern Minnesota.

The sedimentary rocks (sandstone, shale, limestone, dolomite) of Minnesota formed as an accumulation of particles of rock or minerals eroded from pre-existing rocks, or shells and other parts of plants and animals, or accumulations of materials from chemical or biochemical processes. These rocks can have primary porosity (spaces between grains) or secondary porosity (fractures and dissolution features). The cement that binds particles together (such as in sandstone) can fully or partially fill the pores and reduce the ability of the rock to transmit water. The sandstones of Minnesota commonly transmit water via primary or secondary porosity, or both. The limestone and more common dolomite units transmit water mostly by secondary porosity, utilizing horizontal and vertical fractures that in many cases have been enlarged by dissolution of the material around them. Shale is an example of a sedimentary rock that, due to its lack of porosity, does not usually transmit water readily. This rock type is also less likely to host fractures, probably due to its ability to relieve stress by bending rather than breaking. These major sedimentary rock types are typically found in layers, and while they sometimes have thicknesses of hundreds of feet, there are also many places where thin layers of various rock types occur in close vertical proximity. Formation names have often been assigned on the basis of time boundaries rather than rock type, and more than one rock type can be included in a formation.

In areas of sedimentary rocks the products generally include a geologic map with unit descriptions, a correlation chart to show the relative age of the units, cross-sections to show the vertical sequence of units, digital surfaces (topographies) on some of the unit tops, and a geologic column with ages, names, rock types, sedimentary structures, and a composite gamma log, and a summary of geologic history represented by those rocks.

Geologic Atlas Uses

The sections above have described some uses of individual atlas components. Many uses require information from more than one component.

Ground water modeling provides a numerical simulation of water movement by assigning hydrologic properties to earth materials and utilizing mathematical equations to predict how water will move through those materials. The atlases provide an account of the distribution of earth materials and in many cases their hydrologic properties. The database of well records provides information on where water is being pumped, which affects the simulation. Ground water models are typically calibrated against known water levels, and the water levels reported in Part B of the atlases provide this type of information.

The quality and quantity of water in an aquifer can be monitored by measuring the water level on a regular schedule, and analyzing the composition of the water to detect changes over time. However, this information is of limited value if we don't understand what is causing the changes we observe. We need to know what land areas contribute water to that aquifer, where the boundaries of the aquifer are located, and how other wells and surface water features utilize water from that same aquifer. All of this information is needed to make effective use of monitoring data, and the maps and databases of the atlases provide much of this information.

Public water supply wells serve many people and therefore the quality of water they produce is very important. The information in the atlases is used to create plans that protect those wells (called wellhead protection plans). These plans use geologic and hydrologic information to identify where the water supply to these wells is coming from, and how long it takes to travel there. Those calculations are used to delineate the land area that most immediately affects the quality of the water produced by the well. Special land use regulations are typically applied to that land area to protect the water supply.

To protect and make wise use of the water resource we need to focus water use on those aquifers and places that won't be negatively impacted, and we need to isolate contaminants, or activities with high potential to cause contamination where water is not present or there is a higher level of natural protection of the resource. The atlases tell us where the largest and most productive aquifers are and how they are (or aren't) connected to surface water. Conversely, the atlases can also direct us to those areas where aquifers don't exist or are separated from the land surface by thick deposits of material that impede the flow of water. These places are more appropriate sites for activities that involve materials we would like to isolate from the water resource.

Summary

This tour of the "basement" of our earthly house has described some of its most important systems and how they must be maintained to support us. The geology of our state controls where water can be stored, where it can move, and how readily the quality and quantity of water can be affected by our activities. Water is the most essential natural resource and the County Geologic Atlases provide information that is fundamental to effective management of that resource. They compile and present factual observations that will be useful forever, and interpretations that may be improved upon when more information and technology are available.