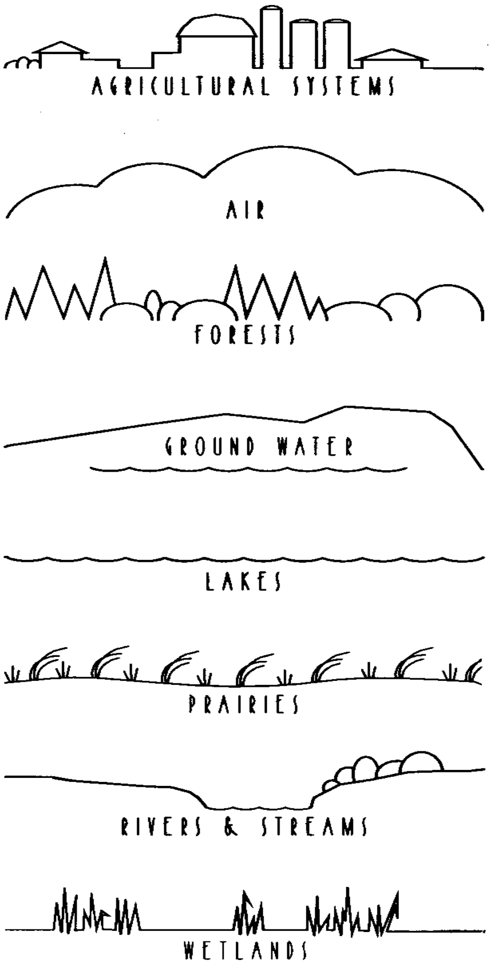
DEVELOPING ENVIRONMENTAL INDICATORS FOR MINNESOTA



Groundwater

The Environmental Indicators Initiative

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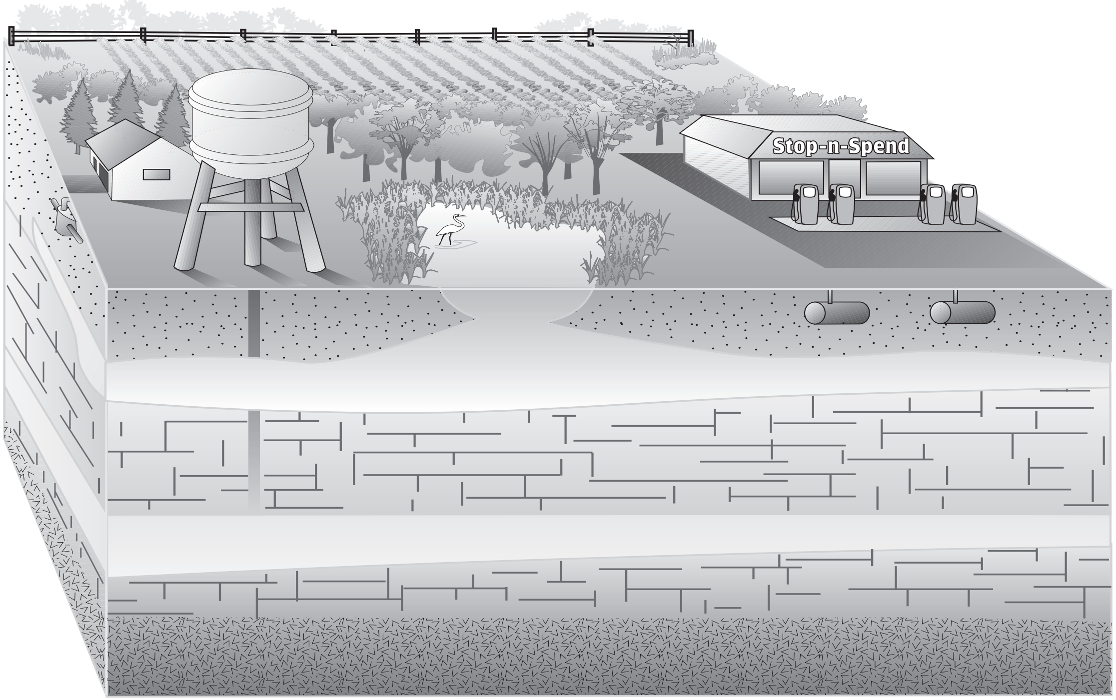
GROUNDWATER



Citizens and decision makers use environmental indicators to help effectively manage and protect Minnesota's groundwater. Environmental indicators answer four questions.

What is happening to our groundwater?

Groundwater *condition* can be assessed by determining key hydrological features and tracking indicators of water quantity and quality. Important hydrogeologic features include **groundwater distribution, flow and connectivity**. Changes in water quantity can be assessed using **water-level** indicators in observation wells. Water quality is measured with contaminant indicators such as **nitrate concentration**.

Why is it happening?

Indicators of *human activities* that affect groundwater quantity and quality include **water use (irrigation, public supply), factors influencing recharge rates (impervious surface)**, and **sources of contamination (septic tanks, storage tanks, landfills, fertilizers, animal waste**, etc.)

How does it affect us?

Changes in groundwater quantity and quality may diminish the flow of *benefits*. Indicators of how we are affected include **incidences of water restrictions based on diminished water availability, number of drinking water well advisories** and **drinking water treatment costs**.

What are we doing about it?

Societal strategies to maintain or restore healthy groundwater systems include **groundwater protection and management, development of local water management plans**, and **ongoing research** to learn more about Minnesota's hidden water resources.

In this chapter we outline important benefits from groundwater systems, the key ecological characteristics that determine groundwater conditions, the pressures affecting groundwater today, the current status and trends relating to groundwater, and the most significant policies and programs that affect Minnesota groundwater. In this chapter we give examples of indicators that provide important information about Minnesota groundwater.

GROUNDWATER

HIGHLIGHTS

Benefits of Groundwater

- Supplies drinking water to 70% of Minnesotans
- Used for irrigation of croplands
- Supports industrial and commercial activities, e.g., mining, paper production, food processing
- Provides base water flow to surface waters and unique ecosystems, e.g., fens
- Helps maintain water flows of rivers and streams during drought

Important Ecological Characteristics

- Minnesota has 14 principal aquifers. Regional differences have implications for their use and susceptibility to contamination.
- Geology and climate determine complex linkages between surface water and groundwater aquifers. Not all these relationships are well understood.
- Some aquifers have natural contaminants from surrounding rocks and sediments. Introduced contaminants can leach through soils and surface waters to reach groundwater aquifers.
- Once depleted or contaminated, aquifers can require extremely long time periods to undergo regeneration or self-purification.

Pressures

- Consumptive uses (e.g., irrigation and lawn watering) may diminish groundwater availability, especially during periods of drought.
- Leaching of contaminants from landfills, toxic waste sites, storage tanks, and accidental spills can diminish groundwater quality. Problems are associated with improper storage, use, or disposal of industrial, agricultural, business, and residential chemicals.
- Urban and lakeshore development and agricultural activities are primary sources of non-point source pollution. Fertilizers, animal waste, and leaky septic systems can introduce nitrate into groundwater systems.

Status and Trends

- Overall, Minnesota has large volumes of good quality water, but human activities have already caused some aquifer depletion and contamination in localized areas.
- The majority of groundwater use is for public water supplies and irrigation.
- Use for public water supplies increased from 53 billion gallons (34% from groundwater) in 1950 to 174 billion gallons (66% from groundwater) in 1995.
- Use of groundwater for irrigation increased from near zero levels in the 1960s to 46 billion gallons in 1995.
- Nitrate is the most widespread contaminant associated with human activities.
- 32,000 underground storage tanks (gas/fuel oil for schools, homes, industry) and 500,000 residential septic systems occur across the state.
- By 1995 all landfills were lined or covered, reducing leachate entering groundwater by 73%.

Existing Policies and Programs

- Federal laws (e.g., Clean Water Act, Safe Drinking Water Act) set groundwater quality and drinking water standards.
- The Minnesota Groundwater Protection Act (1989) aims to maintain groundwater that is free of human-induced pollutants.
- State and local agencies have complementary programs to manage Minnesota's groundwater. For example, the Minnesota Pollution Control Agency and the Minnesota Department of Agriculture focus on protecting groundwater quality. The Minnesota Department of Health works to protect wells and drinking water safety. The Minnesota Department of Natural Resources focuses on water use and groundwater quantity.
- County governments develop and implement comprehensive Local Water Management Plans.

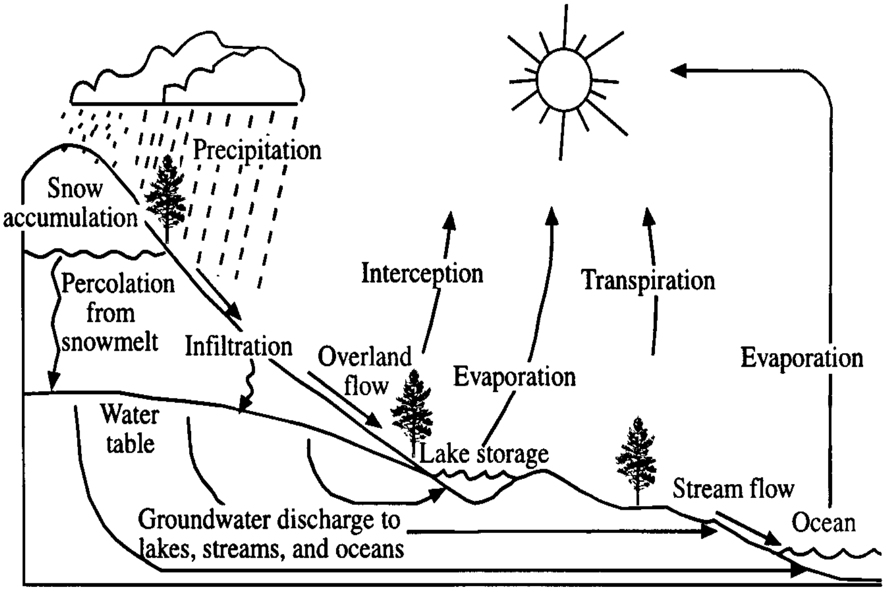
BENEFITS OF GROUNDWATER

Minnesota's aquifers provide large volumes of good-quality groundwater. While rivers and lakes are also important sources of water, about 70% of Minnesotans depend on groundwater as their primary water supply (MPCA 1995a). Groundwater supports Minnesota's agriculture and industry as well; it is the major source of water for crop irrigation, food processing, and other industrial uses (MDNR 1997). In recent years Minnesota has used more than 200 billion gallons of groundwater annually for agricultural, industrial, commercial, and domestic uses, thus highlighting the importance of this resource (MDNR 1997, 1995).

Groundwater also provides important ecological benefits through its interactions with streams, lakes, and wetlands. Groundwater contributes 40% of the annual flow in streams across the United States (US EPA 1996). This contribution can improve the quality and quantity of stream water. For example, groundwater aquifers provide clean water to tributaries along the Minnesota River, which may improve its water quality (IGWMCG 1995). And during the drought of 1988, groundwater discharge maintained much of the flow of the Mississippi River and its tributaries, allowing barge and recreational traffic to continue to navigate during dry periods (Job and Simons 1994). Groundwater aquifers also help sustain other ecosystems by recharging wetlands and unique systems such as fens and cold-water trout streams. Thus groundwater has an important, but sometimes hidden, relationship with other valued ecosystems.

Figure 1

Hydrologic Cycle



Source: Margat 1994

THE GROUNDWATER SYSTEM

While it is easy to think about groundwater as a physically isolated resource, surface waters and groundwaters together form the indivisible water resource system, as illustrated by the hydrologic cycle (Margat 1994) (Figure 1). Water that falls as rain and snow accumulates in soils and surface water bodies, but some of it percolates into groundwater aquifers. Water remains in sediments, fractures, and pore spaces of rocks, and more rarely in underground caves, for days to thousands of years, but eventually it makes its way back to the earth's surface, where it flows in streams and rivers, collects in wetlands and lakes, and is used by plants. With evaporation of water back into the atmosphere, the hydrologic cycle begins again. In this process aquifers serve as both reservoirs and conductors; they not only store water but also allow water to flow through interconnections among surface and groundwater systems, thus sustaining the water cycle (Margat 1994).

The groundwater system is dynamic and can exhibit seasonal and yearly cycles of recharge and drawdown, or renewal and depletion. Groundwater aquifers, particularly those that are closely connected to the surface, typically recharge during

Aquifer Types Found in Minnesota

Unconfined surficial drift aquifers, of water-table aquifers (Figure 2), exist mainly in sand and gravel and are widespread across much of Minnesota, especially the central and western regions. They are good sources of water and are widely used for agriculture and domestic purposes (Clark et al. 1995). These unconfined aquifers are closely connected to the surface; they recharge from rainfall that seeps through the topsoil, and from streams, lakes, and wetlands where water filters into from above. They can also be recharged through inflow from other aquifers (MDNR 1997). Because water-table aquifers are not confined by impermeable materials, they are often susceptible to contamination from land-surface sources, especially in Minnesota's central sand plains (Albin and Breummer 1986). Water-table aquifers are also highly susceptible to changes in climate patterns; while they are able to recharge relatively quickly from seasonal rainfall and snowmelt, they also experience rapidly declining water levels during times of drought and heavy use (MDNR 1997).

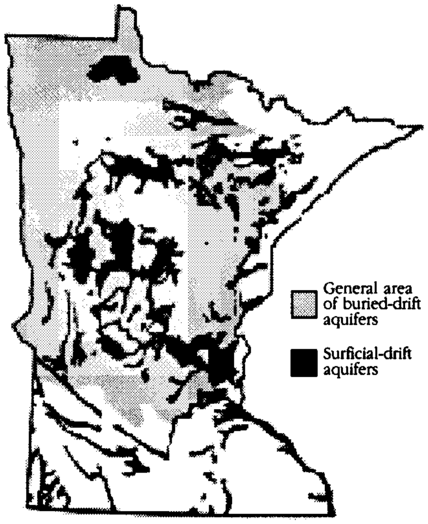
Buried drift aquifers, or buried artesian aquifers, are sand and gravel aquifers that are generally confined by a clay till overlay. Confined aquifers are pressurized and connected to the surface only through interactions with other groundwater aquifers or drilled wells. Buried artesian aquifers occur throughout much of Minnesota and are a principal source of good-quality drinking water. In some areas, however, natural contaminants (such as sulfates and chlorides) from surrounding rocks may inhibit their usefulness for drinking water (Albin and Breummer 1986). Their geochemistry and interconnections are variable and not always well understood (MDNR 1997).

Bedrock aquifers are characterized by different rock types. Sedimentary bedrock aquifers, consisting largely of sandstone, dolomite, and limestone, are widely used in southeastern and southwestern Minnesota for public and commercial water supplies. These confined aquifers are generally well defined in their extent and connection (MDNR 1997), with the important exception of karst areas where fractured limestone creates unknown interconnections among aquifers and surface waters. Such karst areas are of concern because contaminants from surface waters may flow quickly through fractured rocks in local groundwater aquifers. The Prairie du Chien-Jordan, St. Peter, and Mount Siman-Hinckley aquifers are important sedimentary bedrock aquifers that serve the Twin Cities metropolitan area (Albin and Breummer 1996).

Crystalline bedrock aquifers, such as igneous and metamorphic rocks, form the basement complex of Minnesota's aquifers. These confined aquifers generally do not provide large yields but are important in areas where there are no other aquifers, such as parts of northern Minnesota. For example, the Biwabik-Iron Formation aquifer is the only source of groundwater for many towns in northeastern Minnesota (Albin and Breummer 1986).

Figure 2

Surficial and Buried Drift Aquifers



Source: Minnesota Geologic Survey, U.S. Geologic Survey

spring snowmelt and autumn rainfall. Drawdown generally occurs during summer months when groundwater aquifers provide water to growing plants and surface water bodies and for various uses by people (e.g., irrigation, lawn watering, MDNR 1997). Aquifers also respond to yearly cycles of flooding and drought, experiencing higher and lower levels during wet and dry years. This fluctuation occurred in Minnesota during the wetter years of the early 1980s and the drought years of 1987-88 (MDNR 1989). In general, however, large and deep aquifers require extremely long time periods, perhaps centuries, to renew themselves and do not respond rapidly to short-term changes on the surface. Thus, groundwater is not necessarily a 'renewable resource'; depletion rates can exceed renewal rates when society's water needs surpass an aquifer's natural ability to regenerate.

Groundwater aquifers are diverse. In fact, Minnesota has 14 principal aquifers with different underlying hydrogeologic features. There are several main kinds of aquifers that are broadly characterized by their connection to the surface and surrounding rock type. Aquifers may be unconfined (water-table aquifers that are closely connected to the surface) or confined (generally deeper aquifers separated by material of low permeability such as clay; MDNR 1997). Aquifer types include glacial drift (generally consisting of sand and gravel), sedimentary rocks (such as sandstone and limestone), and crystalline rocks (such as deep igneous and granite; Albin and Breummer 1986). Aquifers are also characterized by size and volume. Aquifers have a much wider area than thickness, almost like layers of pancakes beneath the earth's surface. Aquifers can span a few square kilometers to millions of square kilometers. Thickness is generally in tens of meters to hundreds of meters, rarely occurring beyond a thousand meters. Such differences mean that aquifers vary greatly in their storage capacity, flow, and renewal rates (Margat 1994).

The geology and hydrologic features of Minnesota's aquifers have significant implications for the protection and effective management of the state's surface and groundwaters. In particular, water use in watersheds that overlay shallow, unconfined aquifers must take into consideration the close relationships that can exist between groundwater and streams, rivers, lakes, and wetlands (Margat 1994). The aquifer's connection to the surface can determine its accessibility for drilling wells. In addition, surrounding rock type can affect water chemistry. For instance, some aquifers have high concentrations of dissolved solids or natural contaminants, which may inhibit their usefulness for drinking water. Finally, knowledge of an aquifer's size, volume, and interconnections may give an indication of its ability to meet long-term water needs.

Although in recent years we have learned much more about Minnesota's principal aquifers, in many cases we still lack important information about the extent, connection, and long-term availability of groundwater (IGWMCG 1995). Indicators of hydrogeologic features provide essential background information about Minnesota's groundwater system. For example, studies that track **groundwater flow** and **recharge rates** supply information not only about an aquifer's basic characteristics but also about its potential to provide abundant clean water for the long term. Studies that identify hydrogeologic features such as **age, origin, distribution,** and the **spatial relationship of sediment and bedrock** also contribute essential geological information about Minnesota's aquifers (MGS and MDNR 1997). Identifying **hydrologic connectivity**, or interrelationships, between aquifers and surface water systems is also an important, although often difficult, task (Job and Simmons 1994; IGWMCG 1995).

PRESSURES ON GROUNDWATER RESOURCES

Groundwater resources, like surface ecosystems, may be altered by cumulative pressures. Groundwater quantity can be affected by factors that deplete groundwater (e.g., use) or diminish its recharge (e.g., changing rainfall patterns). Groundwater quality can be affected by numerous sources of contamination (e.g., spills, runoff, leakages). Because undesirable changes in aquifer quantity and quality (i.e., depletion and contamination) can be difficult or impossible to rectify, it is critical to consider how various pressures, either singly or cumulatively, might surpass the natural ability of an aquifer to sustain itself over time.

Use

Both groundwater and surface water sources provide water for Minnesota's needs. Major categories of water use include thermoelectric power generation, public water supplies, industrial processing, irrigation, and other miscellaneous uses. Groundwater is the major water source for public supplies and irrigation. Surface water is almost the sole source for power generation, and the major source for industrial processing (Figure 3). Local communities choose their water sources largely based on ease and cost of accessibility, which depend on surface and hydrogeologic features. In the Twin Cities metropolitan area, for example, where the state's most productive limestone and sandstone aquifers occur, two-thirds of public supplies are from groundwater sources. In the northeastern part of the state, where deep crystalline bedrock aquifers yield small amounts of water, most of the public supply comes from surface water (Trotta 1987).

Major Water Uses

Water users that withdraw more than 1 million gallons per year require a water appropriation permit from the Minnesota Department of Natural Resources (MDNR). The MDNR uses the following categories to track trends in Minnesota's water use:

Thermoelectric power generation–water used to cool power generating plants. This is historically the largest volume use and relies almost entirely on surface water sources. Thermoelectric power generation is primarily a nonconsumptive* use in that most of the water withdrawn is returned to its source.

Public water supply–water distributed by community suppliers for domestic, commercial, industrial, and public users. This category relies on both surface water and groundwater sources.

Industrial processing–water used in mining activities, paper mill operations, food processing, etc. Three-fourths or more of withdrawals are from surface water sources. Consumptive use varies depending on the type of industrial process.

Irrigation–water withdrawn from both surface water and groundwater sources for major crop and noncrop uses. Nearly all irrigation is considered to be consumptive use.

Other–large volumes of water withdrawn for activities including air conditioning, construction dewatering, water level maintenance, and pollution confinement.

* Note: Consumptive use is defined as water that is withdrawn from its source and is not directly returned to the source. Under this definition, all groundwater withdrawals are consumptive unless the water is returned to the same aquifer. Surface water withdrawals are considered consumptive if the water is not directly returned to the source so that it is available for immediate further use.

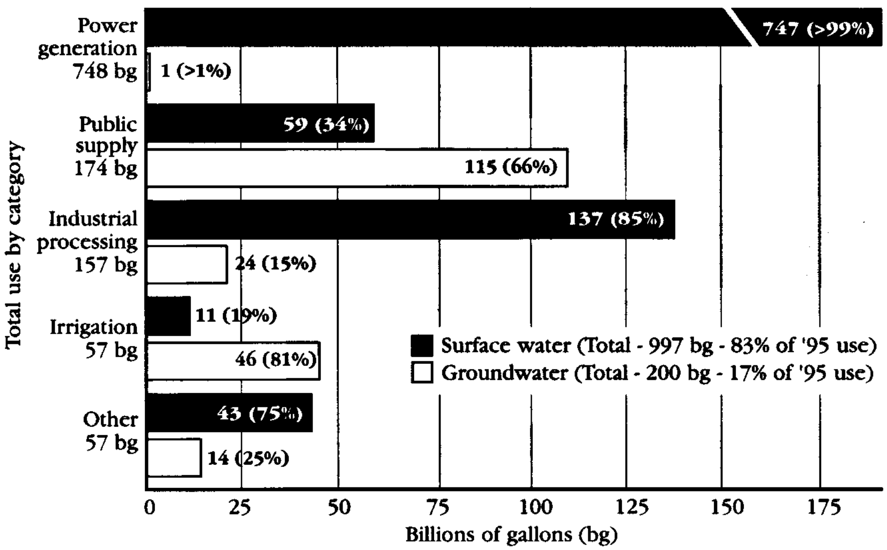
In some situations multiple uses can combine to cause groundwater depletion, especially during periods of summer drought, when groundwater levels naturally decline. This decline is compounded by peak demands for irrigation, lawn watering, air conditioning, industrial uses, and so on. Over the long term, increased population growth and development may also put added pressures on groundwater systems. A variety of conservation actions and planning efforts can help minimize pressures on Minnesota's water supplies. The most effective conservation measures are taken by individual water users at the local level (MDNR 1989).

In addition, planning for growth and development must consider the long-term availability of groundwater and its ability to sustain a variety of water uses. It is important to recognize that groundwater supplies are not uniformly distributed and that some areas may not have enough groundwater to satisfy everyone's needs (MDNR 1989). Thus, local communities can work to ensure that land-use patterns match groundwater availability.

Indicators provide necessary information for the development and implementation of water use plans. Indicators of **water use** are important to track because they identify pressures that deplete Minnesota's groundwater resources. Coupling these indicators with information about **groundwater recharge rates** gives insights into the long-term sustainability of the resource.

Figure 3

Comparison of Surface and Groundwater Use by Category, 1995



From MDNR 1997

Alteration of groundwater recharge

Altering the recharge rate of groundwater aquifers can put subtle, but long-term, pressure on our water resources. When water moves slowly across the landscape, it naturally percolates into soils and groundwater aquifers. Land-use activities that alter the natural flow of water, causing water to race across the landscape, not only can result in flooding and droughts but can also diminish the amount of water available to recharge groundwater aquifers. Removing plant cover, draining wetlands, separating rivers from floodplains, and paving land can all change the flow of water across the landscape. In the Mississippi basin, for example, changes over the past 150 years have reduced the water-holding capacity of the soils by up to 70% (Abramovitz 1997). Such land-use changes may diminish the ability of groundwater aquifers to naturally recharge over long time periods.

Drought also diminishes groundwater recharge and can lower groundwater levels. The effects of decreased water levels are widespread, as evidenced by the midwestern drought of 1988 (MDNR 1989). For example, many irrigation permits were suspended, Minneapolis implemented its first ban on outdoor water use, 40 homes in Sherburne County were left without water when wells went dry, and lakes and rivers dropped to all-time lows (MEQB 1991).

Global climate change may also affect the use and recharge rate of groundwater aquifers. While the specific effects of global climate change are not well understood, shifting rainfall patterns could alter stream flow and lake levels and affect groundwater resources (US EPA 1997).

Indicators that track the potential for changing recharge rates give researchers and managers insights into the long-term ability of an aquifer to meet society's water needs. In general, however, these kinds of indicators are not easy to interpret and need to be measured over long time periods. For example, the **distribution and amount of rainfall** over time might help determine if global climate change is affecting regional weather patterns. And tracking land-use changes, such as **percent impervious surface**, may also illustrate how water flows across the landscape are being altered.

Contamination

Groundwater contamination occurs when contaminants seep through soils or enter groundwater aquifers through connections with streams, rivers, lakes, and wetlands. In Minnesota there are over 600,000 potential sources of groundwater contamination, ranging from residential septic tanks to state and federal Superfund sites (Table 1). Potential sources of groundwater contamination are associated with many kinds of land-use activities including the following (MPCA 1994):

- Agricultural land use (fertilizers and pesticides, animal feedlots)
- Industrial and commercial land use (hazardous materials, mining wastes)
- Municipal land use (urban runoff, landfills, sewage, road salts)
- Other sources (septic systems and injection wells, underground storage tanks, accidental spills)

These activities can introduce many contaminants including nitrate, various chemicals, and pesticides. Natural contaminants (e.g., iron, manganese, and arsenic) are of concern in some parts of the state (MPCA 1994).

Groundwater contamination is often localized because some aquifers are more susceptible to contamination than others. Water-table aquifers are closely connected to the land surface and thus more likely to collect contaminants that seep through sandy soils. The central Minnesota sand plain aquifers are highly susceptible to contamination by land-use activity such as irrigated agriculture, septic systems, lakeshore development, unsewered commercial and industrial development (IGWMCG 1995). And in the northern lakes region shallow aquifers connected to wetlands can be contaminated by septic tanks and lakeshore residences (IGWMCG 1995). Bedrock aquifers, though often protected by confining layers that impede contaminant flow, may be contaminated when they occur close to the surface. They are also highly susceptible in karst areas, where fractured rocks close to the surface allow contaminants to flow quickly into confined aquifers (Albin and Breummer 1986). Karst aquifers

Table 1

Potential Sources of Groundwater Contamination

Potential source	Number of known facilities
Septic tanks	Approximately 500,000*
Permitted municipal landfills	40 active
On-site industrial landfills	20 active
Other permitted landfills	142 active
Closed landfills of all types	192
Historical "open dumps"	1,800
Scrapyards	525
Class V injection sites	At least 100,000*
State Superfund sites	184
Federal Superfund sites	41
Permitted hazardous waste facilities	38
Voluntary investigation cleanup	342
Leaky petroleum tank sites reported	6,813
Leaky petroleum tank sites cleaned up	3,230
Total reported spills	18,563
Land application of waste/sludge	Not compiled
Road salting	191,303 tons/year
Feedlots	Approximately 50,000*

*No complete survey of injection wells, septic systems, or feedlot exists.

From MDNR

in southeastern Minnesota are susceptible to contamination from industrial, municipal, and agricultural facilities (IGWMCG).

Because some groundwater aquifers are naturally susceptible to contamination, the only way to ensure high-quality drinking supplies is to limit the amount of contaminants entering the groundwater system. This does not require that all chemical use should be eliminated; many activities that use chemicals are integral parts of Minnesota's economy. For example, midwestern farmers produce about 80% of the nation's corn and soybean crops. At the same time, however, agricultural land-use practices can introduce contaminants into groundwater. Thus, programs that work with farmers to manage fertilizer and pesticide application help protect the quality of Minnesota's groundwater (USDA 1994). And many options exist for reducing or eliminating pesticides in agriculture.

Whatever the use, agricultural, industrial, or municipal, it is necessary to consider how to meet the needs of these activities while at the same time protecting groundwater resources. Efforts to reduce groundwater contamination focus in four areas (Job and Simons 1994):

- Reduce or eliminate pollution
- Recycle residuals
- Stimulate proper treatment
- Mediate safe disposal

There are many programs that work with industries, businesses, and municipalities to help implement these approaches to prevent groundwater contamination. The Minnesota Office of Environmental Assistance provides technical assistance and grants to help businesses properly manage their waste. Farm programs target efforts to better manage pesticides and fertilizers. And there are a range of actions that individual citizens can take to reduce pollution and the possibility of groundwater contamination.

All of these approaches are critical because groundwater contamination is extremely difficult to remedy. While groundwater aquifers do have self-purifying processes that can help improve water quality in some cases, these natural processes are extremely slow. Thus, once pollutants have reached aquifers, they generally have extremely long residence times, and in high enough concentrations can threaten groundwater quality (Notenboom et al. 1994).

Indicators that measure contaminants inform local communities about potential problems and highlight areas where management actions are necessary. Indicators of problem contaminants include groundwater **concentrations of nitrate, volatile organic compounds,** and **heavy metals**. And indicators of naturally occurring contaminants (e.g., **concentrations of manganese, chloride, and arsenic**) give communities baseline information about the availability of clean drinking water from area aquifers. It is also important to identify potential sources of contaminants. Indicators related to human activities include, for example, the **percentage of petroleum tanks not in compliance**, the **density of septic systems in susceptible areas**, and the **number of contaminated sites**.

GROUNDWATER RESOURCES STATUS AND TRENDS

Minnesotans are concerned about the state's water resources, especially groundwater quality. In 1996, the Minnesota Pollution Control Agency (MPCA) held a series of regional focus groups to better understand what Minnesota citizens think about key environmental issues. Groundwater contamination surfaced as the largest concern among these group participants, probably because people readily understand the link between groundwater quality and human health. People were especially concerned about practices that can introduce contaminants into groundwater, and how these contaminants might affect groundwater suitability for drinking and other uses (MPCA 1996a).

What are the actual trends in groundwater contamination? Are concerns justified? And do groundwater resources have the capacity to continue serving growing water needs? There are no simple answers because Minnesota has a complex groundwater system, and the most serious problems are usually localized (Albin and Breummer 1986). It is difficult to make generalizations when Minnesota's 14 principal aquifers vary considerably in hydrogeologic features and susceptibility to contamination or depletion. However, statewide monitoring studies give insights into trends across Minnesota's groundwater aquifers, thus providing essential baseline information for both local and statewide decision makers (MPCA 1998).

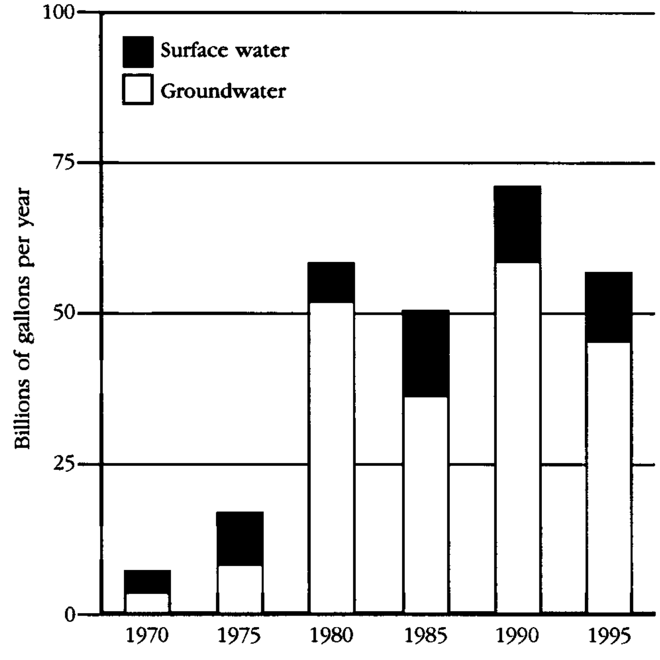
Groundwater quantity: trends in water use

Abundant surface and groundwater supplies fueled Minnesota's early commerce and settlement. Water resources supported the logging industry, railroad transportation, mining, and agriculture in the late 1800s. Groundwater use expanded throughout the 1900s for industry, urban domestic uses, and agriculture. For example, agricultural irrigation began in Minnesota in the 1920s and expanded gradually until the 1970s, when a combination of drought, grain prices, and government policies encouraged farmers to obtain permits for on-farm wells. Irrigation expanded dramatically between 1975 to 1980 (Trotta 1987). Groundwater use for irrigation (Figure 4) has been more stable since then, although there were increases during the drought in the late 1980s and decreases during wetter years in the early 1990s (MDNR 1989, 1991, 1993, 1995, 1997).

Groundwater also provided water for basic needs (e.g., drinking water) of Minnesota's growing population. By the turn of the century thousands of wells were being drilled to supply the largely rural population. Since then, population growth, especially in the seven-county metropolitan area, has continued to place demands on Minnesota's water resources (Trotta 1987). Use of groundwater has

Figure 4

Irrigation 1970-1990



Source: MDNR 1997, 1993

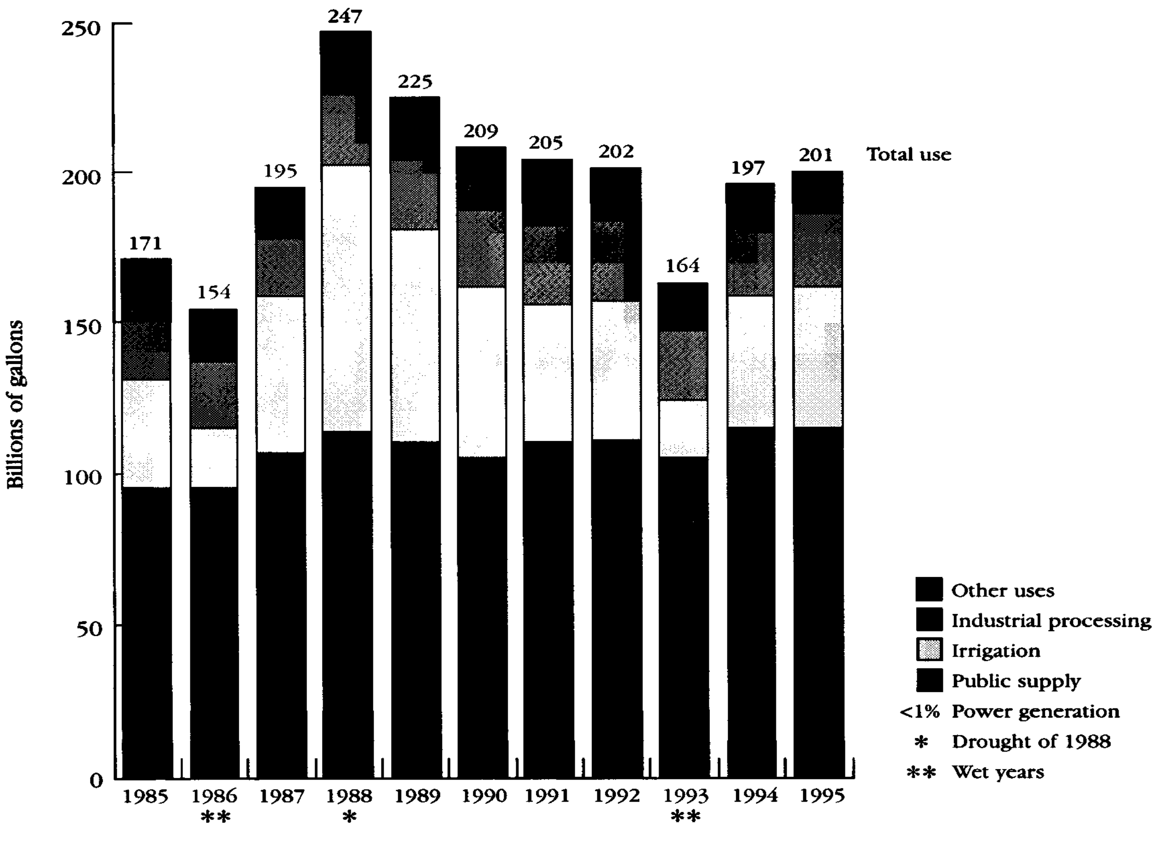
dramatically increased. When monitoring of this resource began in 1950, about 100 billion gallons of groundwater were used annually. During the past decade, around 200 billion gallons of groundwater have been used each year. This amount has fluctuated during wet and dry years; for instance, 247 billion gallons were extracted during the drought of 1988 (Figure 5). There are concerns that increased demands may strain available groundwater resources. Groundwater does not adhere to political boundaries, and as a result, competition for groundwater in the absence of cooperative planning, especially in growing urban areas, may put a strain on this resource (MEQB 1991).

Groundwater quantity: trends in water levels

Monitoring groundwater levels ensures that current uses are not depleting Minnesota's aquifers. The U.S. Geological Survey and the MDNR have cooperated on monitoring groundwater levels since 1947. The earliest groundwater level information dates from 1942. Baseline levels before settlement are unknown. Currently, water levels are measured in aquifers across the state. These data are compared to data taken during the past 15 to 30 years. Groundwater levels are naturally dynamic over time and reflect yearly changes in climate patterns, such as drought and flood years; for example, in Minnesota groundwater levels were low during the drought of 1988, and above average for the flood years of 1986 and 1993 (MDNR 1989, 1995).

Figure 5

Groundwater Use by Category



Source: MDNR 1997, 1995, 1993, 1991, 1989

In general, groundwater has remained fairly stable across the state, although some areas in western Minnesota and in the Twin Cities metropolitan area have shown declines. A Minnesota Water Year Data Summary reports that, in general, water levels were above average for 1995 and 1996 due to above-average levels of precipitation. However, specific wells showed water level declines, suggesting that large amounts of water use may be affecting area aquifers (MDNR 1997). Two of four wells that measure water levels in buried artesian aquifers in the Twin Cities metropolitan area were below average for both 1995 and 1996, and one of six wells measuring water levels in the Mount Simon aquifer has been experiencing declines since 1980. It is possible that large amounts of use from bedrock aquifers may be having an impact on local buried artesian wells; interconnections among these aquifers are poorly defined, and thus recharge rates are difficult to predict (MDNR 1997). Use for irrigation may also have localized impacts on water levels (MDNR 1997). While underlying bedrock aquifers have large supplies of water, the long-term impact of urban water use on water levels in the Prairie du Chien-Jordan and Mount Simon aquifers is not known (IGWMCG 1995).

Water quality: trends in output sources

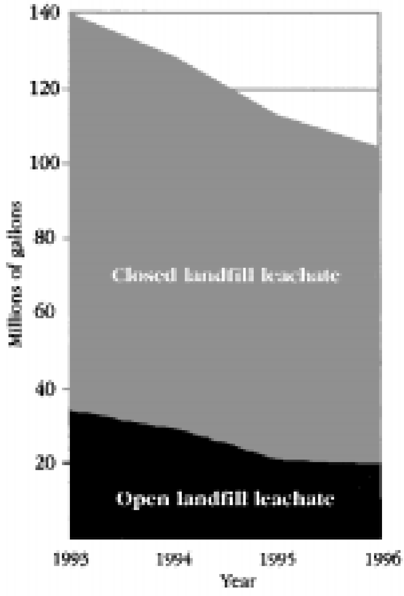
Many sources contribute to groundwater and surface water contamination, including landfills, hazardous waste, Superfund sites, underground storage tanks, septic systems, feedlots, and other land-use activities which are non-point sources of pollution (MPCA 1994). Minnesota has made significant gains in reducing point-source pollution for both groundwater and surface water. And while much progress has been made in addressing the problem of nonpoint sources of pollution (such as runoff from farm fields, urban areas, golf courses), it remains a challenge.

Landfills

Groundwater contamination from landfills has been widespread. In 1988 at least 37 sites had inorganic or organic contaminants in excess of drinking water standards (MEQB 1988), and 19 had levels of contaminants above normal that were attributed to leachate from landfills. In recent years new measures, including liners and caps for landfills and leachate collection systems, have reduced the impacts of landfills on groundwater supplies (Figure 6). The MPCA worked to install up-to-date pollution prevention measures in old landfills by 1995, and to introduce modern disposal facilities in any new landfills. These two measures are estimated to reduce leachate entering groundwater from 56 million to 15 million gallons each year (MPCA 1995b).

Figure 6

Amount of Contaminated Water Flowing from Landfills into Groundwater



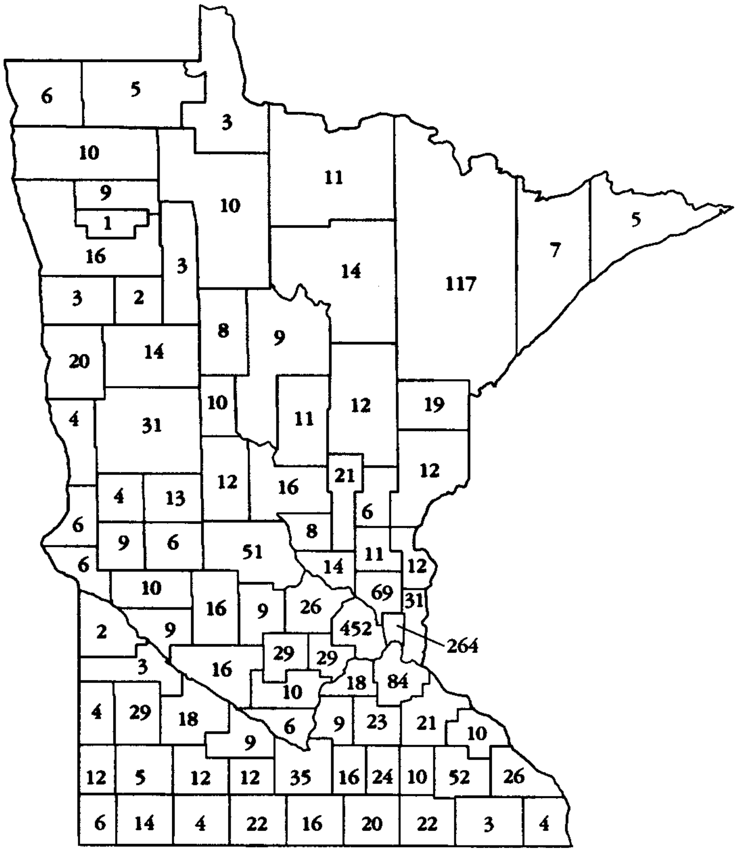
Source: PCA 1996

Hazardous waste

Inspections of hazardous waste generators in 1994 showed that about 80% were properly managed, and about 70% had proper storage. The MPCA has historically focused regulatory efforts on large producers of hazardous waste. New education efforts are being focused at very small quantity generators, often small businesses that may inadvertently mishandle their waste. The MPCA trained 4,500 individuals in hazardous waste management during 1992-94 (MPCA 1995b).

Figure 7

Known Leaking Underground Storage Tanks by County, 1990



From MEQB 1991

Superfund sites

Contaminated sites also can contribute to groundwater contamination. While cleanup is difficult and costly, progress has been made. Eighteen sites were cleaned up and removed from the list during 1991-94 (MPCA 1995b). More recently, over 140 of about 180 sites are in some stage of investigation or cleanup. The Voluntary Investigation and Cleanup Program also lists hundreds of sites, which do not necessarily legally require cleanup. In this program owners or responsible parties can clean up their property more quickly and with fewer legal costs than in the traditional Superfund program. More than 50 of these cleanups have already been completed (MPCA 1994).

Underground storage tanks

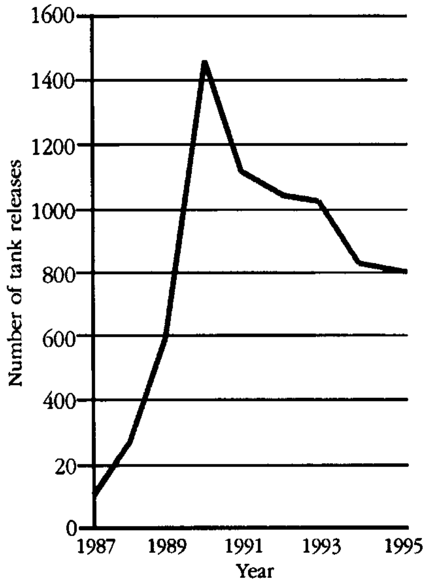
An estimated 32,000 underground storage tanks occur throughout Minnesota. Underground tanks are commonly used for storing fuel for gasoline stations, industries and schools. If not properly maintained, such tanks eventually develop leaks that may introduce benzene and other carcinogens into groundwater supplies. Leaking tanks have been reported across the state and are most common in the Twin Cities Metropolitan Area (Figure 7). Increased understanding of the problems associated with underground tanks, along with increased monitoring and repair, has resulted in rapid cleanup after a leak and more effective early detection of problems. Since 1990, the number of tank leaks reported has decreased dramatically (Figure 8). Despite improvements, however, it is still a challenge to prevent leaks in all of Minnesota's 32,000 tanks. Federal standards introduced in 1993 require that all tanks larger than 1,100 gallons have leak-detection devices. A recent inspection by the U.S. Environmental Protection Agency, which focused on larger-sized underground tanks in Minnesota, showed that about two-thirds of inspected tanks were in violation of federal requirements. This suggests that preventative measures still need to be taken to ensure that underground tanks will not leak.

Septic systems

Around 500,000 household septic systems and 100,000 nonresidential septic systems (called Class V injection wells) exist across the state of Minnesota. Household septic systems pose significant concerns

Figure 8

Number of Tank Leaks Reported



From MPCA 1996

because they are so common and are often not properly maintained; 70 percent of the household septic systems are estimated to be noncompliant with current guidelines (MPCA 1994). Regulations exist to try to bring old septic systems in critical areas up to current standards and to address other sources of non-point source pollution. But because there are so many septic systems, and the cost of repair or replacement is high, they remain a problem (Vonmeier 1996). One county water plan warns that approximately 4,000 households in the county are using septic systems that have been installed without inspection or soil investigation (MEQB 1991). Similar situations are common across the state. Currently many septic systems are being installed in unsewered developing areas and along lakeshores.

Feedlots

Across the state there are an estimated 50,000 feedlots. Traditionally many operated without permits from the MPCA. In 1988, there were about 1,200 feedlots in Olmsted County alone, and only 133 of these had MPCA permits (MEQB 1991). In recent years, however, much attention has focused on feedlots because of concerns over water and air quality. For example, spills or runoff from hog manure have been linked to stream contamination and fish kills, and have raised concerns about groundwater contamination in karst areas. Yet, people also recognize the important role that feedlots can play in local communities. Studies and forums that involve stakeholders are currently addressing environmental concerns.

Runoff from multiple sources

Most widespread, and perhaps most difficult to control, are nonpoint sources of pollution, which can readily cause low-level contamination of local aquifers. Sources include both agricultural and urban runoff containing fertilizers used in farm fields, lawns, and golf courses; road-salt runoff; and human waste leaking from residential and nonresidential septic systems. The potential for pollution from nonpoint sources is especially high in the Twin Cities metropolitan region and southern parts of the state (MEQB 1991). Urbanization has already caused widespread low-level contamination of upper aquifers (IGWMCG 1995).

Trends in groundwater quality

Numerous studies track contaminants in Minnesota's groundwater system. Of particular concern are those substances that pose a human health threat, such as nitrate, volatile organic compounds (VOCs), and pesticides. Of these, nitrate is by far the most widely distributed chemical associated with human activity (MPCA 1998); it is also the most widespread groundwater pollution problem in the United States (US EPA 1996).

Nitrate

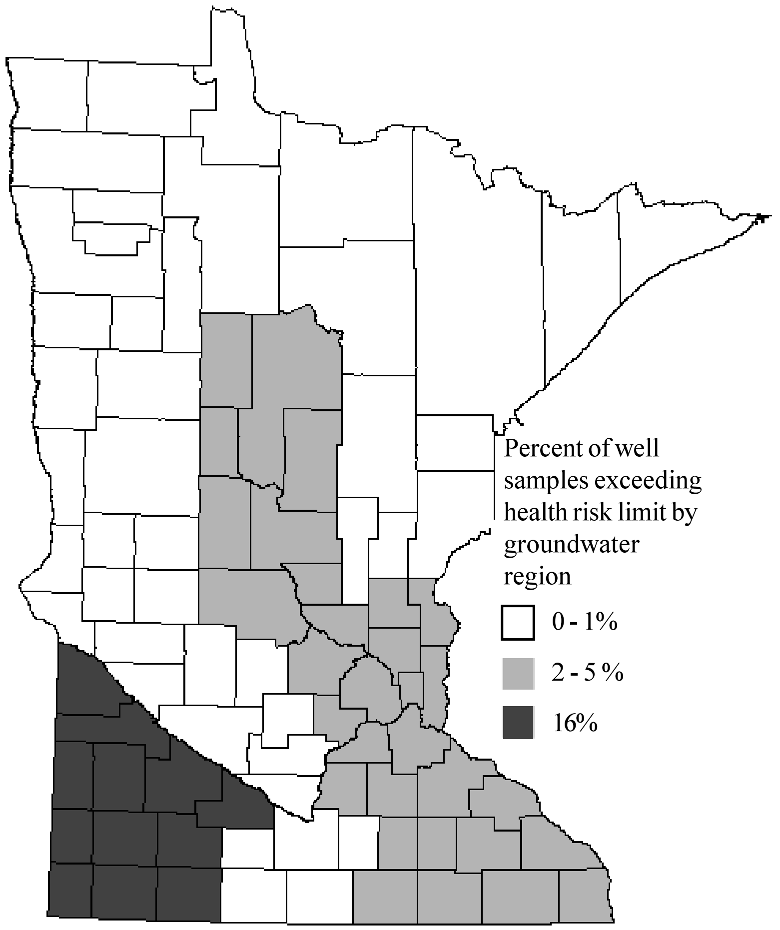
Nitrate in groundwater is a serious concern because it is dangerous to human health, causing blue baby disease in infants, and it is also the most common contaminant found in drinking water. Sources of nitrate contamination include septic systems, landfills, fertilizers, and manure from feedlots (US EPA 1996). Nitrate contamination occurs across the entire state. In general, however, elevated nitrate concentrations are most common in agricultural areas that overlay susceptible groundwater aquifers (Figure 9), such as the sand aquifers of central and southwestern Minnesota and the karst regions in southeastern Minnesota (MEQB 1991).

A Minnesota Department of Health study of nitrate showed that 7% of private water wells exceeded the nitrate Health Risk Limit (HRL) of 10 mg/l. And the MPCA's Ground Water Monitoring and Assessment

Program (GWMAP) showed that 4% of random sampling stations across Minnesota's principal aquifers exceeded the HRL criteria. It is difficult to make broad-scale generalizations, especially because nitrate contamination is not distributed equally across Minnesota's aquifers. In water-table aquifers, for example, 10% of samples exceeded Health Risk Limits. Deeper aquifers often show lower levels; none of the samples in the Saint Peter and Jordan aquifers exceeded HRL criteria in 1994. GWMAP data suggest that HRL exceedances for nitrate have not changed dramatically in the last decade; some aquifers show increases in nitrate concentrations while others show decreases in comparison to samples taken in 1985 (Clark et al. 1995). Local water-testing clinics sponsored by the Minnesota Department of Agriculture help individuals and communities identify potential problems due to nitrate contamination.

Figure 9

Nitrate Levels in Minnesota Aquifers



Source: MPCA 1996

Volatile organic compounds

Volatile organic compounds (VOCs) are potential carcinogens when they occur in high levels in groundwater. VOCs can seep into groundwater from leaking underground fuel tanks, industrial sites, and landfills. Improper disposal of industrial and household products such as paint thinners, cleaners, refrigerants, varnishes, detergents, and several other chemical compounds, can contribute to this problem (MEQB 1988). Efforts to reduce point-source pollution and improve waste disposal have likely limited recent contamination of Minnesota's groundwater. Of 356 randomly selected wells sampled in 1992-93, 41 showed VOCs present at low levels, and only two wells had VOC levels exceeding the Recommended Allowable Limit (RAL) (MPCA 1994).

Pesticides

Pesticides are widely used to improve crop production but pose concerns for drinking water safety, especially near aquifers that are naturally susceptible to contamination. Potential sources of contamination include spills and improper disposal of unused pesticides and pesticide containers (MPCA 1994). Pesticide contamination is not as widespread as nitrate contamination. In water-table aquifers where nitrate contamination occurs most frequently from agricultural activities, wells were below state health risk limits for pesticides (MPCA 1995). But pesticides remain a concern in older, shallow wells in karst areas in southeastern Minnesota (IGWMCG 1995).

Naturally occurring contaminants
Naturally occurring contaminants include sodium, chloride, arsenic, sulfate, iron, manganese, and others. While much of Minnesota's groundwater is naturally of good quality, some areas exhibit high levels of contaminants from surrounding rocks and sediments (IGWMCG 1995). For example, saline groundwater occurs in areas along Lake Superior's northern shores, in deep aquifers in southeastern Minnesota, and along the state's western border (Albin and Breummer 1986). Iron and manganese also occur in high levels throughout the state, and cause water taste problems. High levels of iron and manganese are often removed through filtration or softening devices (MPCA 1994).

Well and drinking water advisory areas
When groundwater contamination is known, the Minnesota Department of Health issues well and drinking water advisories. More stringent regulations for the construction, reconstruction, and sealing of wells apply in areas with well advisories. In 1994 six well advisory areas were due to contamination from VOCs. About 320 drinking water wells had unhealthy levels of contamination between 1989 and 1994 (MPCA 1994). Residents depending on these wells had to look elsewhere for drinking water supplies, a situation that illustrates how contamination has real-life implications for Minnesota citizens.

GROUNDWATER MONITORING

Because groundwater is such an important resource for Minnesota, many state and local agencies regularly collect and analyze data on Minnesota's groundwater. The Interagency Ground Water Monitoring Coordination Group (IGWMCG) helps coordinate monitoring efforts (MPCA 1996c). Many monitoring efforts are necessary because the state's groundwater system is complex and dynamic.

Monitoring of wells is the best way to gain information about Minnesota's groundwater system. The MDNR monitors about 700 observation wells across the state and records water-level changes due to seasonal and long-term pumping or climatic effects (MDNR 1997). In addition, stream-flow gauges help determine groundwater discharges. The MDNR and the Minnesota Geological Survey have also been working with county staff to generate detailed maps (Figure 10) that focus on important hydrogeologic features, such as groundwater flow systems and pollution sensitivity (MGS and MDNR 1997).

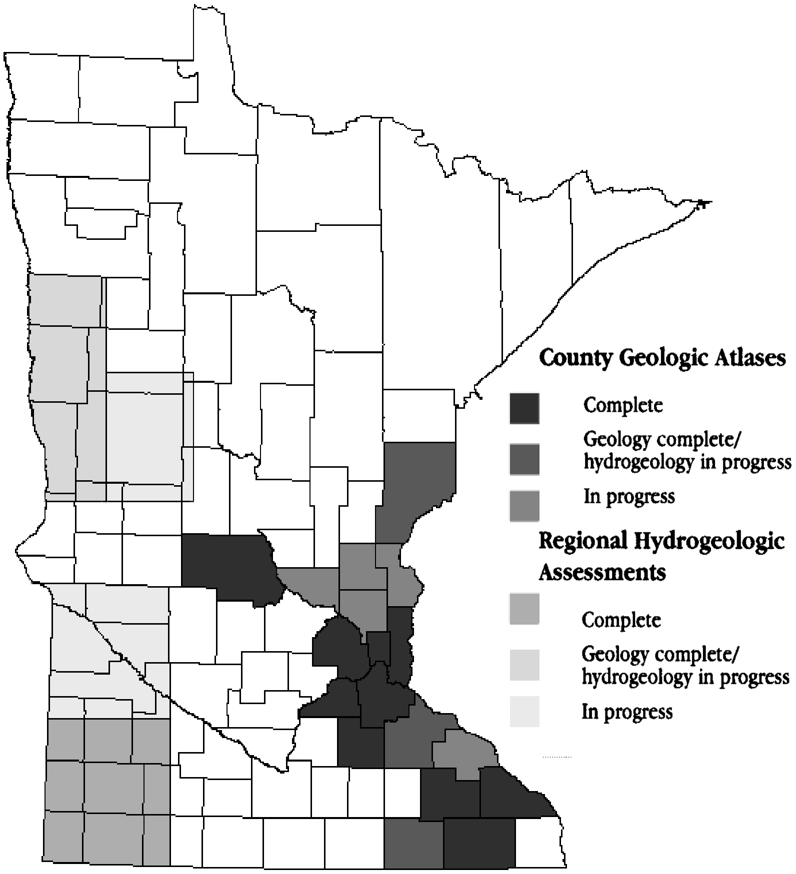
Groundwater quality is monitored primarily by the Minnesota Department of Agriculture (MDA) and the MPCA. MDA's Ground Water Monitoring Program evaluates the impact of agricultural chemicals on groundwater quality. The program utilizes geologic and hydrologic information to determine the susceptibility of regions to contamination and provides key information about the relationships between agricultural land use and groundwater quality.

The MPCA's Ground Water Monitoring and Assessment Program (GWMAP) recently completed a five-year water quality study of Minnesota's principal aquifers, using 954 wells across the state (MPCA 1998). GWMAP's approach includes several key components. A baseline assessment helps local resource managers and interested citizens interpret site-level results by comparing them to statewide trends (MPCA 1998). Ambient monitoring tracks large-scale trends (e.g., statewide trends in groundwater quality), while problem investigation focuses on specific issues of concern (e.g., problem chemicals in local areas). Effectiveness monitoring helps determine how well certain strategies are addressing specific problems (e.g., success of cleanup strategies).

All of these groundwater monitoring programs are tools that help local and statewide decision makers manage our state's water resources. It is important to note, however, that we still lack a complete picture of our groundwater resources, and many questions remain (MEQB 1991). For example, the long-term impacts of urbanization on groundwater quality and quantity in the Twin Cities, St. Cloud, and Brainerd areas are unknown. Does groundwater quality respond to best management practices and pollution control measures that have been implemented in karst regions of southeastern Minnesota? Will heavy

Figure 10

Development of County Geologic Atlases and Regional Hydrogeologic Assessments



pumping of shallow aquifers in northwestern Minnesota cause upwellings from deeper aquifers and introduce natural contaminants? How are aquifers and streams, lakes, and wetlands related? And will increased pumpage affect stream flows and stream quality across the state? Ongoing monitoring and groundwater studies will provide additional insights into these kinds of important management issues (IGWMCG 1995).

EXISTING POLICIES AND PROGRAMS

Before the 1980s, regulations pertaining to groundwater were limited and addressed groundwater issues indirectly. The impacts of aboveground activity on groundwater resources were not widely understood. Since then, many laws and policies have been developed to protect groundwater resources. Federal and state agencies focus on regulation and permitting, responses to spills, management and planning, monitoring and research, and education. And local governments develop Water Management Plans.

At the federal level, standards for safe drinking water are established by the federal Safe Drinking Water Act (US EPA 1996). The U.S. Environmental Protection Agency's Comprehensive State Ground Water Protection Programs Initiative protects the nation's groundwater resources with environmental programs and funding of state activities. The Wellhead Protection Program works with state and local governments to manage public well supplies in areas that may be susceptible to contamination. In addition, the Natural Resources Conservation Service of the U.S. Department of Agriculture focuses on conservation of natural resources on private lands, with an emphasis on protecting surface water and groundwater quality. The U.S. Geological Survey's National Water Quality Assessments (NAWQA) determines long-term trends in surface water and groundwater quality.

At the state level, the Ground Water Protection Act (1989) aims to maintain groundwater free of human-induced pollutants; the act supports projects that monitor groundwater and help control chemical inputs (MPCA 1994). Laws passed in 1990 help maintain groundwater supplies. For example, certain kinds of heating and air conditioning systems that used excessive amounts of groundwater, especially in the Twin Cities metropolitan area, must be phased out by the year 2010 (MDNR 1997).

Numerous agencies have complementary responsibilities for protecting Minnesota's groundwater resources. The MDNR administers programs related to water use and water quantity. The MPCA and the Minnesota Department of Agriculture implement programs to protect groundwater quality. The Minnesota Department of Health focuses on maintaining safe wells and drinking water (MPCA 1995a). Other programs provide assistance as well. For example, the Minnesota Office of Environmental Assistance works with small businesses to reduce pollution.

At a local level, Water Management Plans evaluate groundwater resources and improve management practices for protecting supply in nearly all counties. The Clean Water Partnership, established in 1987, provides local units of government with resources to protect waters. The project promotes data collection, diagnostic analysis, and funding for areas needing protection. And the Minnesota Geologic Survey and the MDNR provide local areas with groundwater information through the County Geologic Atlas and Regional Hydrogeologic Assessment Program (MGS and MDNR 1997).

A challenge for all these programs is maintaining a focus on hydrologic, and not political, boundaries. For groundwater, the unit is the aquifer. Without looking at all the land and water uses that affect an aquifer, it is unlikely that we will succeed in protecting it (MEQB 1991).

EXAMPLE INDICATORS

Table 2 collects the indicators used in this chapter. The indicators are organized within the EII framework to illustrate the relationships between human activities, environmental condition, the flow of benefits from the environment, and strategies for sustaining a healthy environment. The indicators used in this chapter are examples that illustrate how indicators may help assess the condition of Minnesota's groundwater resources. Many of these indicators are currently tracked by agencies that are a part of the Interagency Ground Water Monitoring Coordination Group (IGWMCG). The EII works to ensure that groundwater indicators are also related to indicators for Minnesota's ecosystems.

Table 2

Example Indicators

HUMAN ACTIVITIES	ENVIRONMENTAL CONDITION	SOCIETAL STRATEGIES
Water use • Water use by category: public supply, irrigation, industrial processing, power generation, and other • Water use by season and location **Factors that may alter groundwater recharge** • Percentage of impervious surface **Environmental contaminants** • Percentage of storage tanks not in compliance • Density of septic systems in susceptible areas • Number of known contaminated sites • Feedlot density in susceptible areas	**Hydrogeologic features** • Rock type and origin • Aquifer distribution • Groundwater flow and connectivity • Recharge rates **Water quantity** • Water levels in principal aquifers • Water levels in related surface-water systems (e.g. fens, streams, lakes) **Water quality** • Presence of human- induced contaminants in principal aquifers (e.g. nitrate, volatile organic compounds, heavy metals) • Presence of natural contaminants in principal aquifers (e.g. manganese, chloride, arsenic)	**Policy and legislation** • Clean Water Act, Federal Safe Drinking Water Act • MN Ground Water Protection Act **Management** • Local Water Management Plans—county governments • Groundwater quality—MN Pollution Control Agency and MN Department of Agriculture • Wells and drinking water safety—MN Department of Health • Water quantity—MN Department of Natural Resources **Research and Monitoring** • Interagency Ground Water Monitoring Coordination Group (IGWMCG)

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