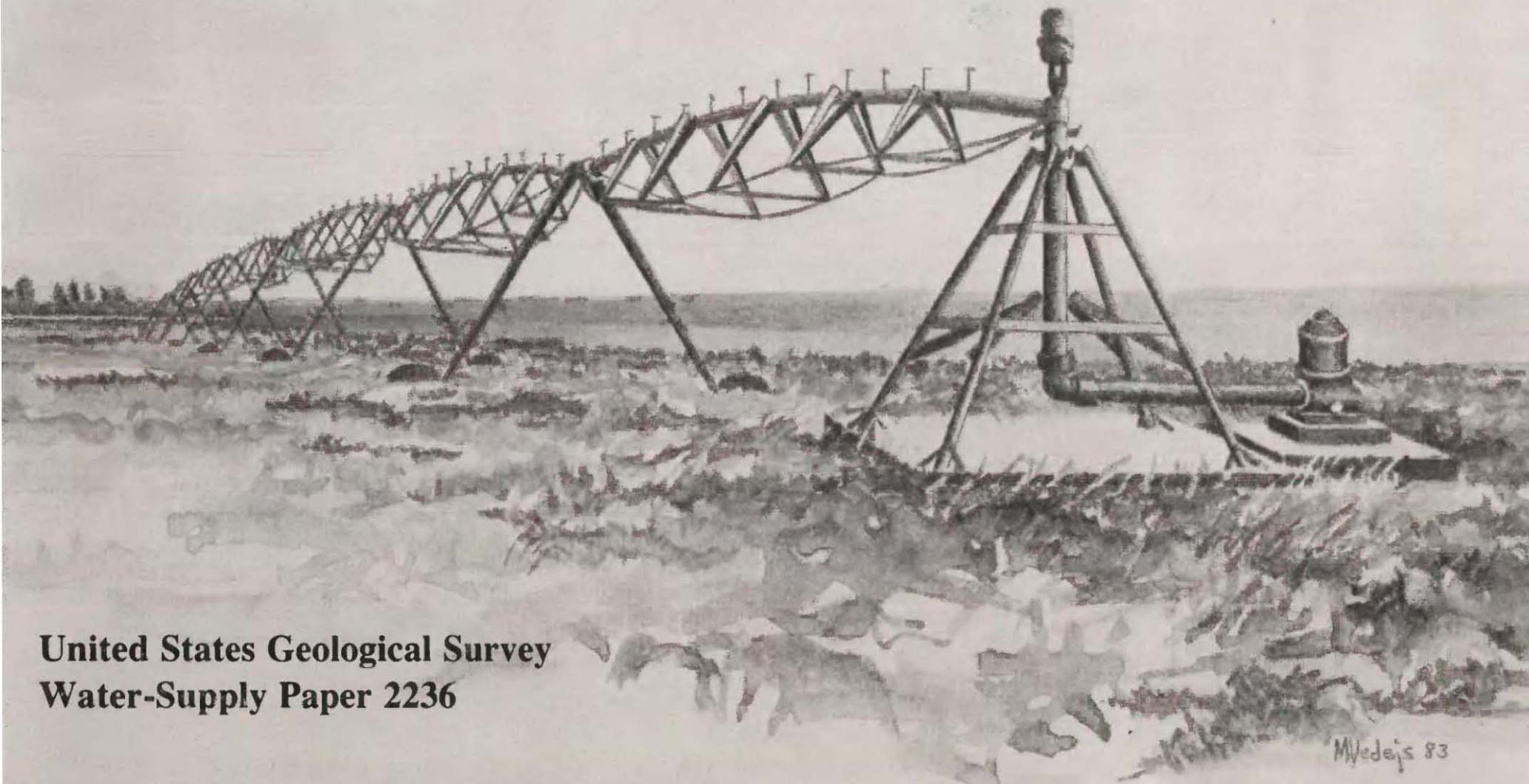


Guide to North Dakota's Ground-Water Resources



**United States Geological Survey
Water-Supply Paper 2236**

M. Vedejs 83



Ground water discharging at rate of 1,500 gallons a minute during 100-hour pumping test of well tapping Spiritwood aquifer in Griggs County, eastern North Dakota. Photograph courtesy of North Dakota State Water Commission.

Guide to North Dakota's Ground-Water Resources

By Q. F. Paulson

U.S. GEOLOGICAL SURVEY WATER-SUPPLY PAPER 2236

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GUIDE TO NORTH DAKOTA'S GROUND-WATER RESOURCES

By Q. F. Paulson



Figure 1. Irrigation well and Carrington irrigation experiment farm. Photograph by M. O. Lindvig.

INTRODUCTION

Ground water, the water we pump from the Earth through wells or that which flows naturally from springs, is one of North Dakota's most valuable resources. More than 60 percent of the people living in the State use ground water for one purpose or another. It is the only source of water for thousands of farm families and their livestock. Almost all smaller cities and villages depend solely on ground water as a source of supply. Increasingly, ground water is being used to irrigate crops and grasslands (fig. 1) during protracted dry spells so common in North Dakota. During recent years there has been a rapid development of rural water distribution systems in which thousands of farms and rural residences are connected via underground pipeline to a single water source, usually wells pumping ground water.

We depend on ground water for all of these needs and more, and yet, the subject of ground water is astonishingly misunderstood by many. Notions of underground lakes and rivers or water veins still are commonly held and often appear in the spoken or printed media. To some, ground water even has an aura of mystery, understandable to only a few gifted individuals.

The occurrence of ground water is not mysterious, but it can be complex and difficult to quantify. The science that deals with the principles of ground-water occurrence is called geohydrology. It is an imprecise science, still in an early stage of development compared to some of the older, further-evolved sciences. However, impressive advances in geohydrologic knowledge have been made during a relatively short time.

Statewide evaluations, on a county-by-county basis during the past 25 years, indicate a surprisingly good potential for ground-water development in North Dakota, particularly in the region north and east of the Missouri River. Large and productive aquifers (water-bearing formations that are capable of yielding water to wells) previously unidentified have been described and delineated in reports and maps, which are available to the public from the North Dakota State Water Commission and North Dakota Geological Survey. Except in a few localities, water use from most of these aquifers is minimal. As the economy and population of the State increase, increasing attention will be focused on these relatively unused sources of water.

Development of the State's ground-water resources, however, will not be without problems. Some of the difficult ones will be those dealing with salinity, uneven distribution of aquifers (as well as permeability within aquifers), and insufficient aquifer recharge (replenishment). Adequate solutions to these problems, which to some degree, at least, are common to ground-water use everywhere, will require the application of sound geohydrologic principles along with the best developmental technology available.



Figure 2. Exposure of unconsolidated rocks (sand and gravel) in Griggs County, eastern North Dakota. Where saturated, deposits such as these form some of the most productive aquifers in North Dakota. Photograph by J.P. Bluemle.

This report is a brief assessment of the state-of-the-art and knowledge of ground-water resources in North Dakota today. It is by no means intended as a major technical reference on the subject. Rather, it is directed at individuals who may at one time or another become involved in matters dealing with ground water, whether, for example, through the necessity of developing an

individual water supply or by serving on a board of officials who must make decisions of an institutional nature regarding ground water. Lists of public agencies and selected references are given at the end of this report for those who desire more detailed information, whether in regard to a specific area within the State or in regard to certain aspects of ground-water occurrence.

WHERE CAN GROUND WATER BE FOUND IN NORTH DAKOTA, AND HOW MUCH IS AVAILABLE FOR DEVELOPMENT?

Ground water underlies the land surface throughout most of North Dakota. At some depth, almost everywhere in the State, the earth is saturated with water. Why then, the problems one often hears or reads about in connection with developing ground-water supplies? The problems relate to both the quantity and quality of water needed at a particular location and for a particular purpose. Both the quantity and quality of water that can be obtained at a given location vary greatly across the State. These variations are related primarily to variations in the earth's composition and structure.

Generally ground water in North Dakota occurs in two major rock types. These are uncon-

solidated rocks and bedrock underlying the unconsolidated rocks. However, in many places the distinction is not precisely defined. Unconsolidated rocks are loose beds of gravel, sand, silt, or clay such as may be seen in commercial gravel pits and along river banks (fig. 2). Conversely, bedrock, as the term implies, generally is solid unbroken rock (fig. 3). However, it varies greatly from only slightly consolidated deposits of clay or sand to hard rock such as shale, limestone, or granite, which may contain numerous fractures.

The various rock formations that make up the Earth's crust have been classified by geologists according to rock type and have been given formal names. The name usually is in reference to a



Figure 3. Bedrock exposures in western North Dakota. These rocks are part of the Fort Union Formation. Sandstone and lignite beds in this formation yield water to wells and springs throughout most of western North Dakota. Photograph by D. G. Emerson.

geographic location where the formation is particularly well exposed, or, in the case of subsurface occurrence only, is well identified in geophysical logs. For example, the Fort Union Formation, which is referred to further on in this report, is well exposed in the vicinity of historic Fort Union near the confluence of the Missouri and Yellowstone Rivers in northwestern North Dakota.

Although the earth beneath North Dakota is saturated with water below certain depths, some rock formations yield much larger quantities than others. Those that yield sufficient quantities to wells or springs to be useful are termed aquifers. These generally consist of sand and gravel beds in the unconsolidated rocks and sandstone layers in the bedrock. For reasons relating to their origin, aquifers in the unconsolidated rocks are more productive and generally yield less mineralized water than those in the bedrock. In contrast, also because of origin, the aquifers in the bedrock tend to be more continuous and widespread than those in the unconsolidated rocks.

Aquifers generally are described as being either confined or unconfined. The two types are illustrated in the block diagram on the next page (fig. 4). A confined aquifer is overlain and underlain by beds of less permeable material. The water within this type of aquifer, which also may be termed artesian, is under pressure. If a well is drilled into the aquifer, water will rise in the well to some level higher than the top of the aquifer. If the pressure is great enough, the water will flow at land surface. An unconfined aquifer is not overlain by impermeable beds and the top of the aquifer is the land surface. The upper surface of the water within the aquifer is the water table, and such aquifers are referred to as water-table aquifers.

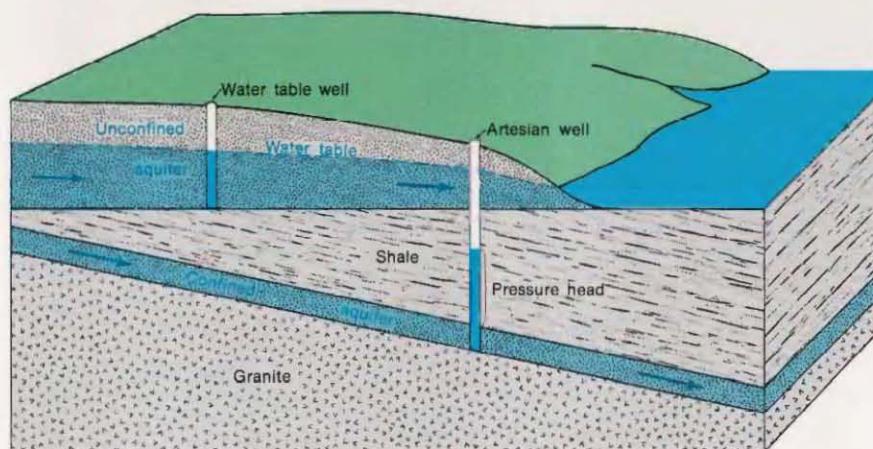


Figure 4. Confined and unconfined aquifers.

Ground Water in the Unconsolidated Rocks

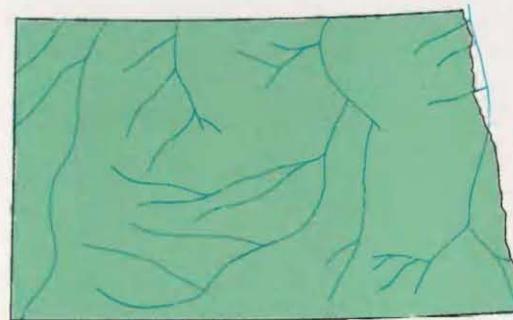
The unconsolidated rocks contain the most productive aquifers in North Dakota. The aquifers are composed of loose deposits of sand and gravel through which water readily moves. Some of these deposits are tens of square miles in area and are as much as 100 feet thick.

As shown on the accompanying map (fig. 5), the aquifers commonly are linear in shape with tributary branches and have some resemblance to surface-drainage systems. This is because the sand and gravel deposits forming the aquifers were deposited by rivers in much the same manner as our present-day drainage systems deposit sand and gravel. However, in terms of volumes of water conveyed and sediment transported, the ancestral rivers would dwarf present-day rivers in North Dakota. The sources of water for those great rivers were mainly the glaciers that had covered most of North Dakota and disrupted the preglacial drainage systems (fig. 6) some tens of thou-

sands of years ago. There is some evidence, however, that rainfall also may have contributed to the large flows.

Only the major aquifers are shown in figure 5. Test drilling and other geohydrologic data indicate that in most places within the aquifer areas, well yields ranging from 50 to as much as 500 gallons per minute can be obtained. In some parts of the aquifers, usually near their centers where the aquifers are thickest, yields larger than 500 gallons per minute may be obtainable. The indicated well yields are only approximations, to be used mainly for comparative purposes. Detailed drilling and aquifer testing are needed to determine well yields at specific locations. A cross section of typical unconsolidated aquifers is shown on the accompanying diagram (fig. 7).

Away from the major aquifer areas, water is obtainable in many places from the unconsolidated rocks, but in small quantities; well yields generally are 10 gallons per minute or less. These minor aquifers consist of thin isolated beds of sand and

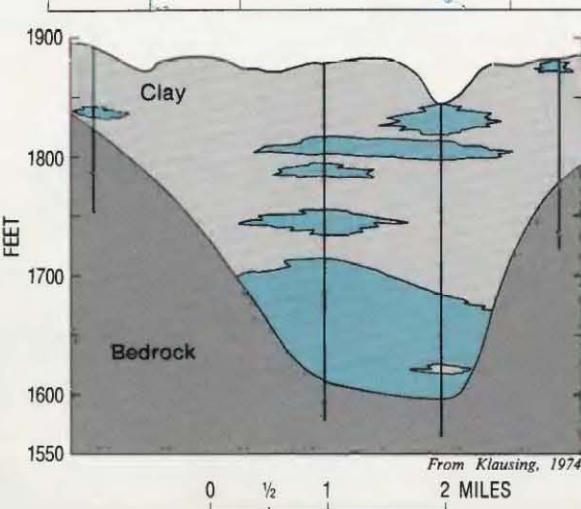
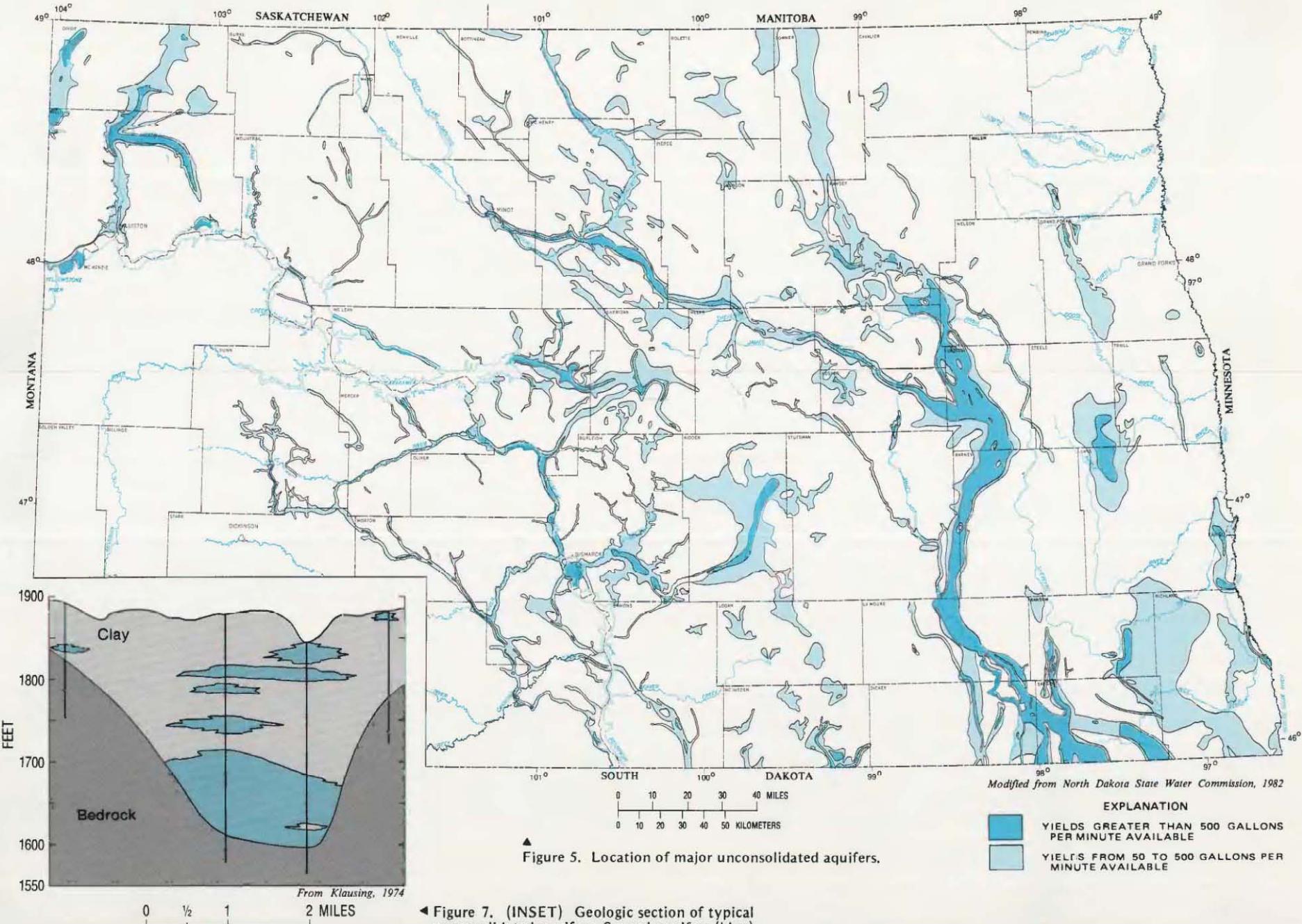


From Bluemle, 1977

◀ Figure 6. Preglacial drainage pattern in North Dakota. Before North Dakota was glaciated, drainage was mainly northward into Hudson Bay. Southward-moving glaciers blocked and diverted drainage into new channels that extended southward or southeastward along edges of the ice sheets. Many of the preglacial and glacial-diverted channels are occupied by productive aquifers, as shown in figure 5.

gravel that seem to have a random distribution, both vertically and areally. Nevertheless, the minor aquifers occur in sufficient numbers that wells of adequate yield for domestic needs generally can be drilled within the confines of a farmstead.

The North Dakota State Water Commission has estimated that the major unconsolidated aquifers contain about 60 million acre-feet of water in storage (1982). By contrast, the huge reservoir (Lake Sakakawea) on the Missouri River in west-central North Dakota has a maximum storage capacity of about 24 million acre-feet (U.S. Geological Survey, 1981, p. 328). Many of the aquifers have been little utilized. As use increases in any given aquifer, water levels will decline, and, in places, yields will be decreased. Even so, some of the aquifers constitute major sources of water, both in quantity and quality, capable of supplying much of the large-scale needs of irrigation, municipalities, and industry. However, optimum use of these aquifers will be dependent on sound management practices, as discussed in greater detail further in this report.



Vertical scale is greatly exaggerated. National Geodetic Vertical Datum of 1929.

Ground Water in the Bedrock

The accompanying map and geologic section show the distribution of bedrock formations and associated aquifers in the State (fig. 8). Although the map shows where the various formations occur (crop out or subcrop) at land surface, one needs to examine the geologic section in order to visualize their occurrence beneath the land surface. A large number of individual bedrock formations have been formally identified and described in North Dakota, but for the purpose of defining bedrock aquifers these formations can be grouped into four major units, which are labeled A-D in descending order.

The relationship of the bedrock formations to the aquifer units is given in the following table.

Bedrock formations	Thickness (feet)*	Aquifer units
Rocks of Tertiary age White River Group Golden Valley Formation Fort Union Formation	250 300 2,300	A
Rocks of Cretaceous age Hell Creek Formation Fox Hills Sandstone	600 400	B (includes lower part of Hell Creek Formation).
Undifferentiated rocks	3,000	C
Dakota Sandstone	400	
Rocks of Jurassic age	1,000	
Rocks of Triassic age	600	
Rocks of Paleozoic age	7,000	D

*Maximum known thickness, rounded to nearest 30 feet.

Unit A, the uppermost unit, includes a series of aquifers composed of sandstone and lignite beds that occur mainly in the Fort Union Formation in the western one-half of the State. Generally these aquifers are quite variable in horizontal extent and thickness. Although several may be present in vertical sequence at one location, none may be present at another. Consequently, the aquifers in unit A are less reliable sources for development than the deeper aquifers. Nevertheless, most farms and ranches and many small

communities are able to obtain sufficient quantities of water for most purposes from these aquifers. Water in unit A, although commonly more mineralized than desirable, is used for most purposes except for irrigation. Even if the quality were suitable for irrigation, quantities available in most places would be inadequate except for limited use.

Unit B is an extensive sandstone aquifer, which underlies all except the eastern one-third of the State. The sandstone beds are mainly in the Fox Hills Sandstone, but they also are in the lower part of the overlying Hell Creek Formation. The aquifer is at or near land surface near its eastern edge, from where it slopes westward to depths of about 2,000 feet below land surface.

In most places, water in unit B is under artesian pressure, but the pressure is not sufficient to produce flowing wells except in low-lying areas such as major river valleys. The aquifer is a relatively dependable source of water because of its wide extent and uniform character. It supplies water to many farms and ranches and several small cities in central and western North Dakota. Water from unit B is similar in quality to that of unit A and generally is used for the same purposes.

The undifferentiated rocks between units B and C consist mainly of shale or other fine-grained materials and are virtually non-water bearing. However, in the eastern part of North Dakota, where not covered by unit B, the upper part of the shale is locally fractured and will yield small quantities of water to wells.

Unit C, which underlies most of the State, consists of several sandstone layers that are commonly referred to as the Dakota Sandstone aquifer, or simply the Dakota aquifer. This aquifer is

well known throughout the Great Plains because of the large number of artesian wells that have been drilled into it. Most of these wells in North Dakota are in the southeastern part of the State. The first well drilled in the Dakota Sandstone is reported to have been drilled at Ellendale in 1886 to a depth of 1,087 feet (Wenzel and Sand, 1942, p. 26). The well reportedly flowed 600 to 700 gallons per minute and had a pressure variously reported between 115 and 175 pounds per square inch. Because of the expense of such deep drilling, few additional wells were drilled until about 1900 when a new and less expensive method of drilling, termed jetting, was developed. From 1900 to 1930, thousands of small-diameter wells were drilled into the Dakota Sandstone in southeastern North Dakota and in eastern South Dakota. Most of the wells were allowed to flow freely, and pressures decreased rapidly in many areas so that some wells ceased to flow, and the flows in others were decreased to a few gallons per minute. In 1921, State laws required all Dakota wells be equipped with pressure-control valves.

It was probably the availability of a free-flowing water supply that made the Dakota Sandstone such an attractive source. Certainly it was not the water quality, which generally is unsuitable for many uses because of salinity. However, in many areas it was the only readily available source. Water from the Dakota was particularly valued, and still is, for watering livestock during the winter because of the relatively warm temperature of the water. In western North Dakota the aquifer is used both as a source and a sink in connection with oil-field operations. Water is pumped from the aquifer for use in repressurizing depleted oil reservoirs, and waste brine from the reservoirs is injected into the aquifer.

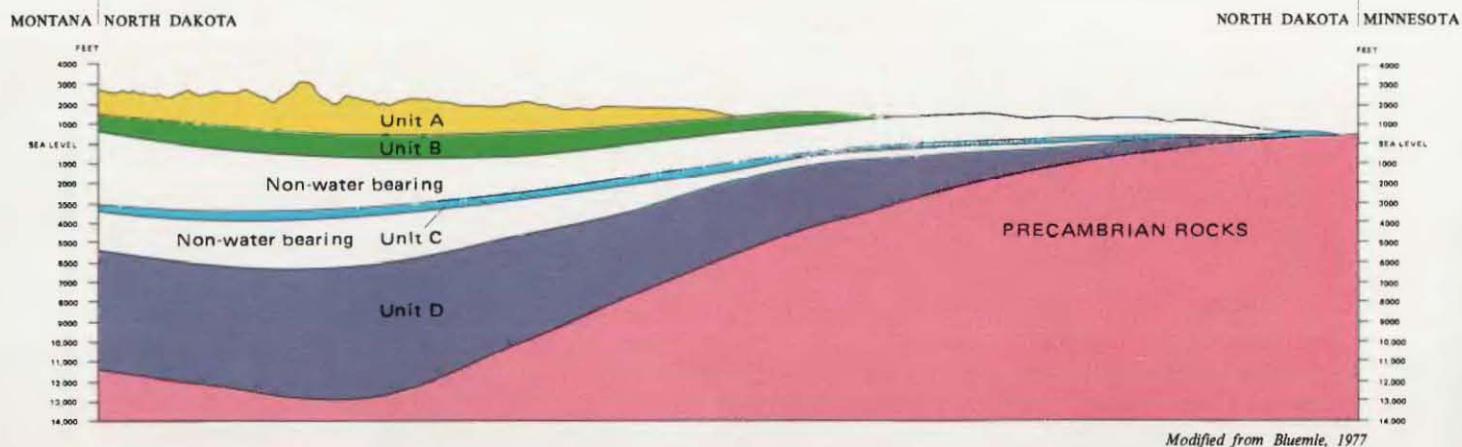
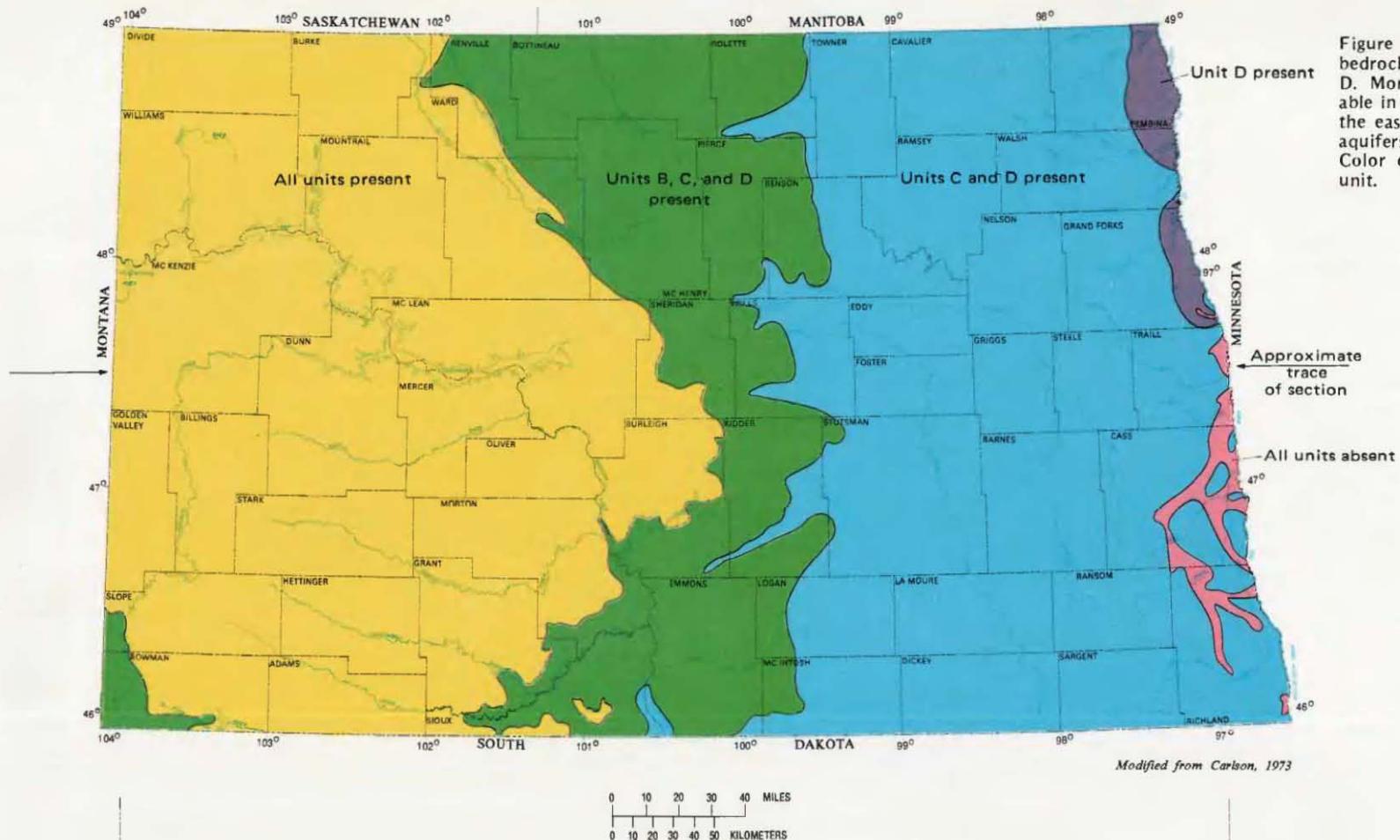


Figure 8. Location and depths of bedrock aquifer units A, B, C, and D. More bedrock aquifers are available in western North Dakota than in the eastern part. However, depth to aquifers increases towards the west. Color on map represents uppermost unit.

Unit C is separated from unit D by thick deposits of shale and other fine-grained rocks of Jurassic and Triassic age, which are virtually non-water bearing. Unit D, the deepest and thickest of the aquifer units, underlies the entire State except a small area near the North Dakota-Minnesota boundary. Comprised mostly of limestone, but also some sandstone and shale, unit D contains the oldest sedimentary rocks (Paleozoic) in North Dakota. The top of this unit is only a few hundred feet below land surface near the eastern edge of the State, from where it slopes westward to depths of about 6,000 feet. Very little is known about the water-bearing properties of the rocks in this unit. In most parts of North Dakota it would not be practical to drill wells this deep to obtain water. In addition, data from oil wells completed in rocks of this unit indicate that the water is saline and not usable for most purposes.

Table 1. Major chemical constituents in water--their sources, effects upon usability, and recommended and mandatory concentration limits.
(Modified from Durfor and Becker, 1964, table 2).

Concentrations are in milligrams per liter (mg/L), or micrograms per liter ($\mu\text{g}/\text{L}$).

Constituents	Major source	Effects upon usability	U.S. Environmental Protection Agency (1976, 1977) recommended and mandatory limits for drinking water
Silica (SiO_2)	Feldspars, quartz, and ferromagnesian and clay minerals.	In presence of calcium and magnesium, silica forms a scale in boilers and on steam turbines that retards heat transfer.	None.
Iron (Fe)	Natural sources: amphiboles, ferromagnesian minerals, ferrous and ferric sulfides, oxides, carbonates, and clay minerals. Manmade sources: well casings, pumps, and storage tanks.	If more than 100 $\mu\text{g}/\text{L}$ is present, it will precipitate when exposed to air; causes turbidity, stains plumbing fixtures, laundry, and cooking utensils, and imparts tastes and colors to food and drinks. More than 200 $\mu\text{g}/\text{L}$ is objectionable for most industrial uses.	300 $\mu\text{g}/\text{L}$ (recommended).
Manganese (Mn)	Soils, micas, amphiboles, and hornblende.	More than 200 $\mu\text{g}/\text{L}$ precipitates upon oxidation. Causes undesirable taste and dark-brown or black stains on fabrics and porcelain fixtures. Most industrial uses require water containing less than 200 $\mu\text{g}/\text{L}$.	50 $\mu\text{g}/\text{L}$ (recommended).
Calcium (Ca)	Amphiboles, feldspars, gypsum, pyroxenes, anhydrite, calcite, aragonite, limestone, dolomite and clay minerals.	Calcium and magnesium combine with bicarbonate, carbonate, sulfate, and silica to form scale in heating equipment. Calcium and magnesium retard the suds-forming action of soap and detergent. Excessive concentrations of magnesium have a laxative effect.	None.
Magnesium (Mg)	Amphiboles, olivine, pyroxenes, magnesite, dolomite, and clay minerals.		
Sodium (Na)	Feldspars, clay minerals, and evaporites.	More than 50 mg/L sodium and potassium with suspended matter causes foaming, which accelerates scale formation and corrosion in boilers.	None.
Potassium (K)	Feldspars, feldspathoids, micas, and clay minerals.		
Boron (B)	Tourmaline, biotite, and amphiboles.	Essential to plant nutrition. More than 2 mg/L may damage some plants.	None.
Bicarbonate (HCO_3^-)	Limestone and dolomite	Heating water dissociates bicarbonate to carbonate, carbon dioxide, or both. The carbonate can combine with alkaline earths (principally calcium and magnesium) to form scale.	None.
Carbonate (CO_3^-)			
Sulfate (SO_4^-)	Gypsum, anhydrite, and oxidation of sulfide minerals.	Combines with calcium to form scale. More than 500 mg/L tastes bitter and may be a laxative.	250 mg/L (recommended).
Chloride (Cl)	Halite and sylvite.	In excess of 250 mg/L may impart salty taste, greatly in excess may cause physiological distress. Food processing industries usually require less than 250 mg/L.	250 mg/L (recommended).
Fluoride (F)	Amphiboles, apatite, fluorite, and mica.	Optimum concentration in drinking water has a beneficial effect on the structure and resistance to decay of children's teeth. Concentrations in excess of optimum may cause mottling of children's teeth.	Mandatory maximum limits depend on average of maximum daily air temperatures. Maximum limits range from 1.4 mg/L at 32°C to 2.4 mg/L at 10°C.
Nitrate (NO_3^-)	Organic matter, fertilizers, and sewage.	More than 100 mg/L may cause a bitter taste and may cause physiological distress. Concentrations in excess of 45 mg/L have been reported to cause methemoglobinemia (blue-baby disease) in infants.	10 mg/L (mandatory).
Dissolved solids	Anything that is soluble.	Less than 300 mg/L is desirable for some manufacturing processes. Excessive dissolved solids restrict the use of water for irrigation.	500 mg/L (recommended).

WHAT IS THE QUALITY OF GROUND WATER IN NORTH DAKOTA, AND HOW DOES IT AFFECT INTENDED USES?

Fortunately, ground water in most parts of the State, as in most other areas of the Earth, is bacteria-free and safe to use. That is to say, if wells are sited and constructed according to modern sanitation codes, the water generally does not require chlorination or other forms of purification. Nature already has purified the water for us. Also, fortunately, ground water in North Dakota has been relatively unaffected by toxic-waste disposal or other man-made actions as has been the case in some parts of the United States. But that is the bright side of the picture. Unfortunately, the ground water in parts of North Dakota is so mineralized or saline that it has only limited uses.

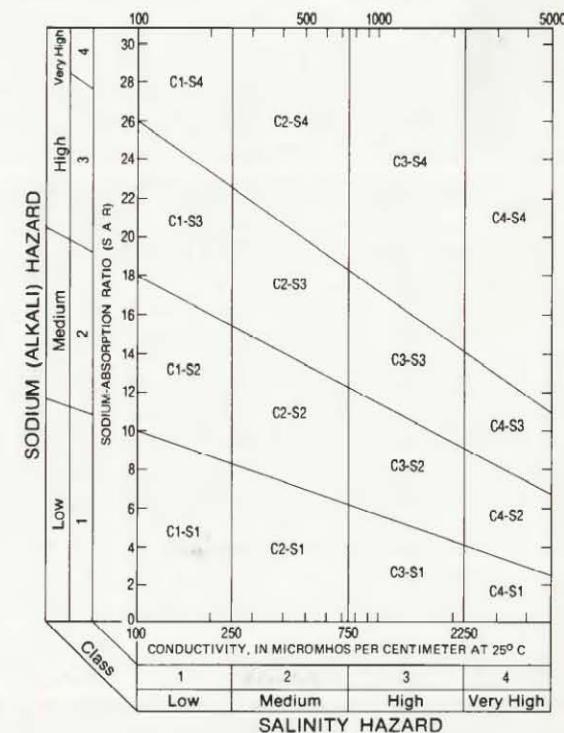
Salinity in water begins to develop almost immediately at its point of origin as rainfall. Rainfall dissolves some mineral matter from dust and other air-borne particles as it falls and continues to dissolve mineral matter as it infiltrates into and through the soil. The quantity and kind of dissolved mineral matter in water depends upon the kinds and proportions of minerals that comprise the soil and rocks through which the water moves, as well as upon temperature and pressure. As would be expected, the longer the time that the water is in contact with the rocks, the more mineralized the water becomes. Therefore, water that has moved great distances (or very slowly) through the rocks from its point of entry, or recharge, to its point of exit, or discharge, is likely to be significantly mineralized. And, of course, the converse is true. Some comparatively unmineralized ground water exists in places in North Dakota where the aquifers are shallow and are readily recharged by rainfall or melted snow.

The suitability of water for various uses is determined by the kind, as well as the quantity, of various dissolved substances it contains. The accompanying tables (tables 1 and 2) and graph (fig. 9) show some of the major chemical constituents and properties found in water--their sources, effects upon usability, and recommended and mandatory concentration limits.

Table 2. Scale of hardness used by U. S. Geological Survey.

Calcium and magnesium hardness as CaCO ₃ (milligrams per liter)	Hardness description
0- 60	Soft
61-120	Moderately hard
121-180	Hard
More than 180	Very hard

Calcium and magnesium are the principal chemicals causing water hardness.



From U.S. Salinity Laboratory Staff, 1954

Figure 9. Salinity and sodium hazard classifications. Water to be used for crop irrigation needs to be tested for salinity (dissolved-solids concentration) and sodium hazards. As these hazards increase, the usability for irrigation decreases. However, other factors such as soil drainage, climate, and type of crop also are important. Advice usually can be obtained from County Extension Agents.

Quality of Water from the Unconsolidated Rocks

The least mineralized ground water in North Dakota is obtained from aquifers in the unconsolidated rocks (fig. 10). The dissolved-solids concentration commonly is less than 1,000 mg/L. Although in most places the water is very hard, it can be successfully treated both for commercial uses and individual home use. Iron and manganese also may be problems, particularly in shallow aquifers, but these too generally are amenable

to modern treatment methods. Generally the water is suitable for irrigation use, but there are local exceptions. Potential irrigators need to compare the water quality with the crop type and soil conditions. Help usually can be obtained from State and Federal water agencies as well as the County Extension Agents in making this determination (see table at the end of this report).

Quality of Water from the Bedrock

Most ground water in the bedrock of North Dakota is more mineralized than that in the overlying unconsolidated rocks. Also, it generally is true that the deeper the source of water, the more saline the water.

The water in unit A is extremely variable in character, and the representation shown in the water-quality diagram for this unit probably is less accurate than that of the other units. In most places the water is soft but contains excessive sodium and dissolved solids. As such, it is suitable for most domestic uses, but not for irrigation because of the salinity and sodium hazards. However, aquifers at shallow depths in unit A may yield hard water with less sodium and dissolved solids. These waters may require softening for domestic use, but may be satisfactory for irrigation on a small scale.

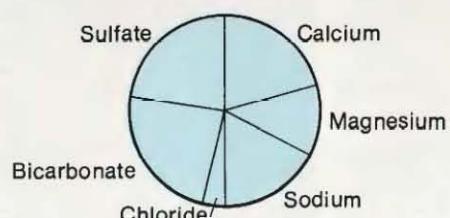
Water in unit B is soft, but contains excessive sodium. The average dissolved-solids concentra-

tion is 1,100 mg/L. Although usable for most domestic purposes, the water generally is not suitable for irrigation because of the salinity and sodium hazards.

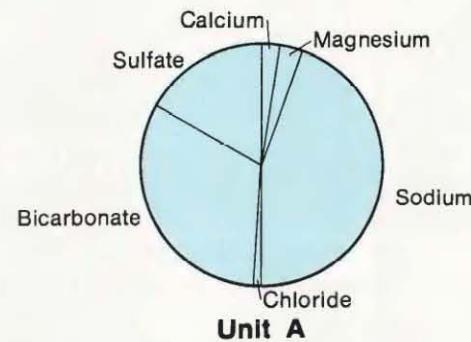
Water from unit C, the Dakota Sandstone, averages nearly 3,000 mg/L of dissolved solids, which is greater than the concentrations recommended for most uses. The dissolved solids consist mainly of sodium, sulfate, and chloride. The excessive sodium concentration along with the overall excessive mineralization of the water precludes most irrigation uses.

The most mineralized water in the State is found in unit D, the Paleozoic aquifers. Water in these aquifers generally contains more than 10,000 mg/L of dissolved solids. In the deeper parts of the Williston basin in western North Dakota the concentration is more than 200,000 mg/L. The salinity prohibits use of the water for purposes other than those in which water quality is not a factor.

Unconsolidated rocks

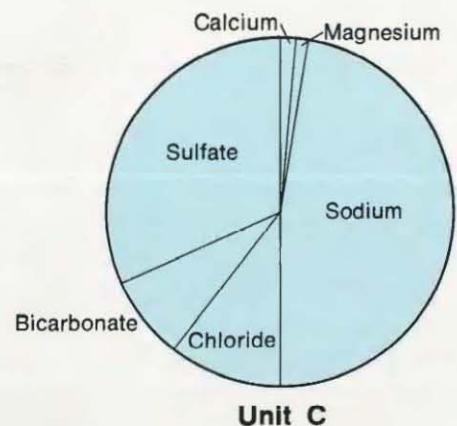
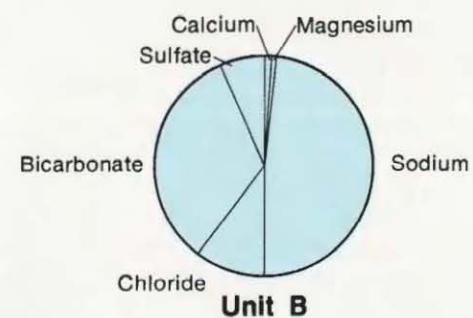


Bedrock aquifer units



▲ Figure 10. Average water quality in aquifers in unconsolidated rocks and bedrock aquifer units A, B, C, and D.

Bedrock aquifer units

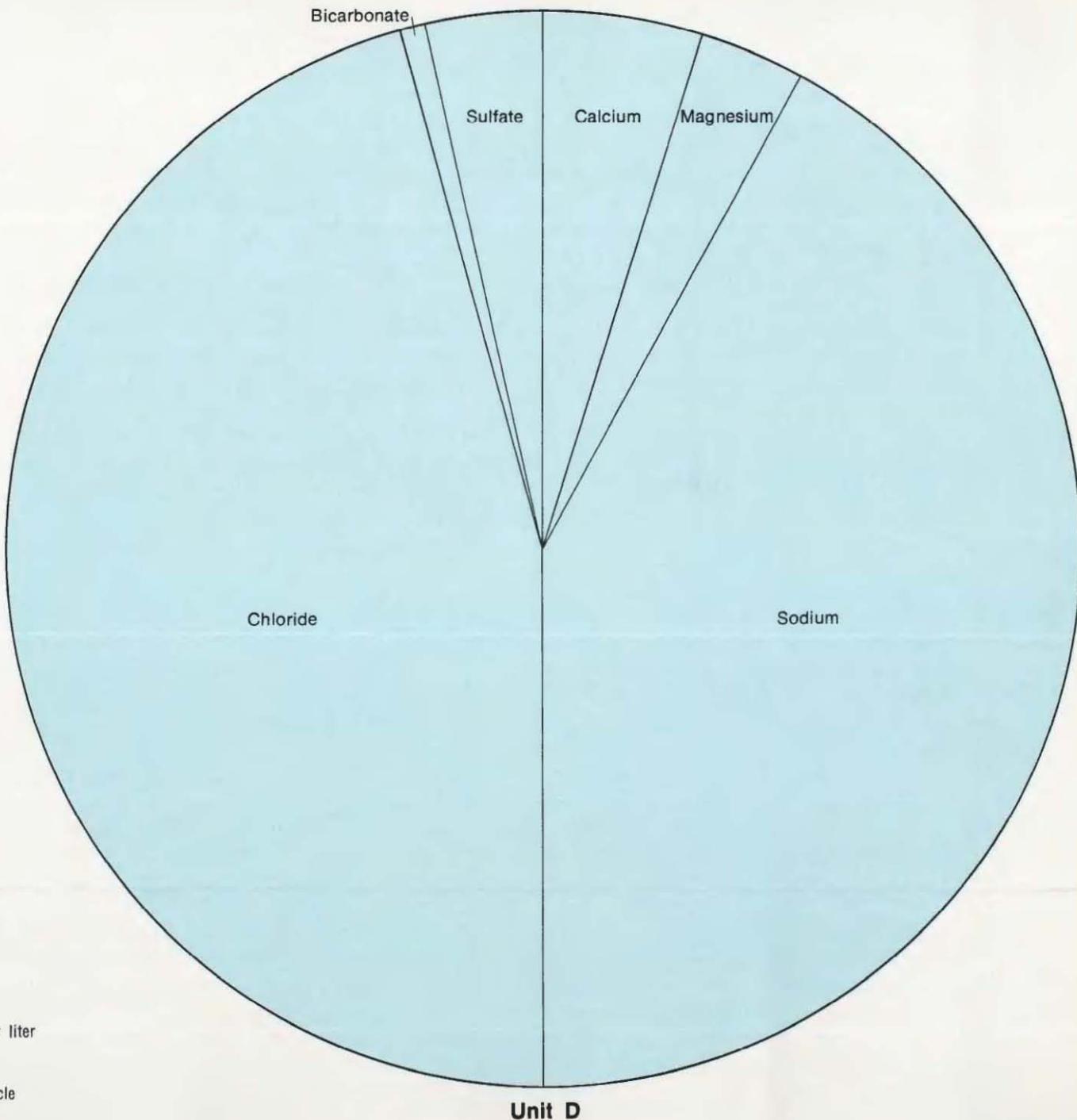


EXPLANATION

Scale of radii



Total dissolved solids are proportional to area of circle



CAN GROUND WATER BE PROTECTED? SHOULD IT BE?

Until recently, water-pollution-control activities have focused mainly on rivers and lakes. Ground water was considered a pristine source, protected from the effects of man's activities by virtue of burial within the Earth. We are becoming increasingly aware, however, that not only is ground water vulnerable to pollution but that serious degradation already has occurred in places, particularly in parts of the industrialized eastern United States where toxic chemicals have been detected in drinking-water supplies. It is because ground water is widely used as a source of drinking water that we need to be constantly alert to the hazards of pollution.

North Dakota is not an industrial State, and the likelihood of serious ground-water pollution resulting from industrial processes appears remote at this time. However, little is presently known concerning the long-term hydrologic effects of the State's rapidly expanding energy-related industries, such as coal and oil production and coal-fired electrical plants. Studies of the present and potential impacts due to these activities are currently underway, but few data are as yet available.

It appears that the most likely sources of ground-water contamination in North Dakota are related to agricultural activities, which is not unexpected, considering the intensity of farming within the State. Some pesticides and herbicides as well as fertilizers leave residues that can and do leach downward to shallow aquifers. To date, monitoring efforts within the State have indicated very little contamination due to these sources. Other possible sources of ground-water contamination include cattle feedlots, municipal landfills, septic tanks, sewage lagoons, oil wells, and the mud pits used for oil-well drilling operations. Even ground-water wells can be sources of contamination if they are not properly constructed.

The location, construction, or both, of potential sources of contamination need to be based on earth-science considerations. Information is available at a number of State and Federal agencies (listed at the end of this report) that would aid in the location or construction so that aquifer contamination can be avoided or minimized.

Absolute protection against ground-water contamination probably is an impractical, if not impossible, goal. The first and foremost consideration needs to be the protection of aquifers that are being used, or have the potential for being used, as sources of drinking water. In North Dakota these sources would include most aquifers in the unconsolidated rocks and in bedrock units A and B and at least part of unit C. The water in bedrock unit D generally is too saline to be used for drinking purposes, although treatment may be economically feasible in some instances if the water needs to be used for drinking-water supplies.

Although total protection against ground-water contamination may not be attainable or even desirable, measures can be taken that will minimize the hazards. A thorough knowledge of the geohydrology is necessary to determine the direction and rate of movement as well as the eventual fate of contaminants. Water beneath the Earth's surface generally moves very slowly (a few feet per year is not uncommon). This slow movement may result in optimism by some regarding the possibility of a slug of contaminants ever reaching a point of withdrawal. Added comfort may be derived from the knowledge that as the contaminant moves through the subsurface it is continually being dispersed and diluted. However, studies have shown that given enough time and driving energy, a contaminant can travel considerable distances from the point of origin. Also,

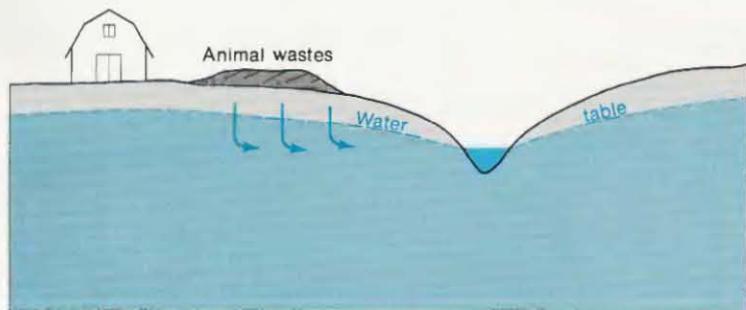
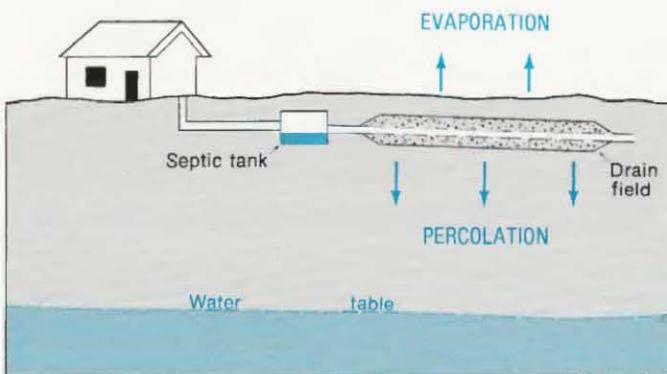
unfortunately, once the contaminant reaches a point of withdrawal, the damage may be complete and remedy impossible in terms of a lifetime or even several generations because of the slow movement.

Many inorganic and most synthetic substances that move through the subsurface remain relatively unchanged except for dilution and dispersal. Contamination associated with human and animal wastes generally is decreased to acceptable limits by bacterial processes within the soil, if the depth to the water table is sufficient. Once the contaminant reaches the water table, however, these processes are no longer effective. Thus, the depth to the water table is a critical factor in regard to contamination from such sources as septic tanks and animal feedlots, as shown in diagrams on the next page (figs. 11 and 12).

Also of importance is the texture of the materials through which the contaminant moves. Obviously coarse sand or gravel will permit a much faster rate of movement than will clay or shale. In fact, the existence of a thick continuous bed of clay or shale overlying an aquifer may, for practical purposes, be considered sufficient protection against non-point sources of contamination (fig. 13).

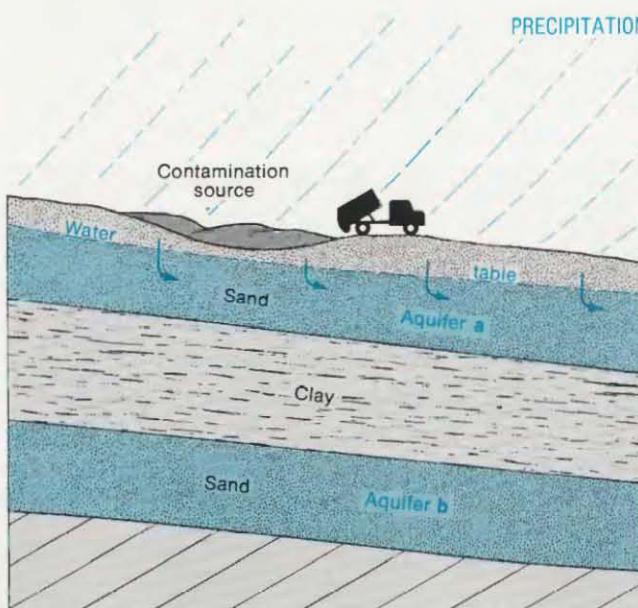
As can be seen from this brief discussion, the possible sources of ground-water contamination are many and diverse. This field of study is relatively new, and some of the findings to date have resulted in controversy. Unfortunately, there are few generally accepted standards regarding either the effects of various contaminants or the limits that should be defined for various uses.

Figure 11. Operation of a septic system.► Bacterial action and sorption by soil particles will remove bacterial contaminants, provided depth to water table is sufficient.



◀ Figure 12. Contamination of ground water from surface source. Where water table is shallow, contaminants such as feedlot wastes can move considerable distances through ground-water systems and may eventually discharge into surface-water bodies.

Figure 13. Protection against contamination provided by clay deposits. Aquifer "a" is vulnerable to contamination from surface source. Ground water carries the contaminant downward until it reaches the clay deposit and then moves laterally through aquifer "a". Aquifer "b" is protected by the clay deposit and is unaffected by the contaminant.



However, the North Dakota State Department of Health in cooperation with the U.S. Environmental Protection Agency has adopted regulations regarding maximum acceptable levels of certain contaminants in water used for public water supply systems. These are listed on the next page (table 3).

In summary, it should be stressed that the protection of ground-water quality is complex, involving all components of the terrestrial hydrologic systems. Philip Cohen, Chief Hydrologist for the U.S. Geological Survey, perhaps expressed it best while addressing the American Geophysical Union in May 1981 when he stated "...control of contaminants at their source is the most practicable means of excluding them from ground-water reservoirs [aquifers], but these sources commonly are located at the land surface, not within the underlying ground-water reservoirs. Information demands, therefore, extend beyond the internal workings of these reservoirs alone, broadening the kinds and amounts of hydrologic and geologic information needed for resource management."

Table 3. Maximum contaminant levels permitted for public supply use: Inorganic chemicals, organic chemicals, radionuclides, and microbiological. (From North Dakota State Department of Health, 1977).

Inorganic Chemicals	Contaminant	Level Milligram Per Liter
The maximum contaminant level for nitrate is applicable to both community and non-community water supply systems. The levels for other inorganic chemicals apply only to community water supply systems. The maximum contaminant levels for inorganic chemical contaminants are as follows:	Arsenic Barium Cadmium Chromium Lead Mercury Nitrate (as N) Selenium Silver Fluoride	0.05 1. 0.01 0.05 0.05 0.002 10. 0.01 0.05 2.4
Organic Chemicals	Contaminant	Level Milligram Per Liter
The maximum contaminant levels for organic chemical contaminants, applicable only to community water supply systems, are as follows:	Chlorinated Hydrocarbons: Endrin (1,2,3,4,10, 10-hexachloro-6,7-epoxy-1,4,4a,5,6,7,8,8a-octa-hydro-1,4-endo, endo-5, 8-di-methano naphthalene). Lindane (1,2,3,4,5,6-hexachloro-cyclohexane, gamma isomer). Methoxychlor (1,1,1-Trichloro-2,2-bis [p-methoxyphenyl] ethane). Toxaphene ($C_{10} H_{10} Cl_{18}$ -Technical chlorinated camphene, 67-69% chlorine).	0.0002 0.004 0.1 0.005
	Chlorophenoxy's: 2,4-D (2,4-Dichlorophenoxyacetic acid). 2,4,5-TP Silvex (2,4,5-Trichlorophenoxypropionic acid).	0.1 0.01
Radionuclides	Contaminant	Level Picocuries Per Liter
The maximum contaminant levels for radionuclides, applicable only to community water supply systems, are as follows:	(1) Combined Radium-226 and Radium-228. (2) Gross alpha particle activity, including Radium-226, but excluding radon and uranium.	5 15
Microbiological	(1) Membrane Filter Method (2) Fermentation Tube Method	
The maximum contaminant levels for coliform bacteria, applicable to both community and non-community water supply systems, are as follows:	When the membrane filter method is used, the number of coliform bacteria colonies shall not exceed: (a) One per 100 milliliters as the arithmetic mean of all routine and check samples examined per month; or (b) Four per 100 milliliters in more than one sample when less than 20 are examined per month; or (c) Four per 100 milliliters in more than five percent of the samples when 20 or more are examined per month.	When the fermentation tube method and 10 milliliter standard portions are used, coliform bacteria shall not be present in: (a) More than ten percent of the portions from both routine and check samples examined in any month; or (b) Three or more portions in more than one sample when less than 20 samples are examined during the sampling period; or (c) Three or more portions in more than five percent of the samples when 20 or more samples are examined per month.

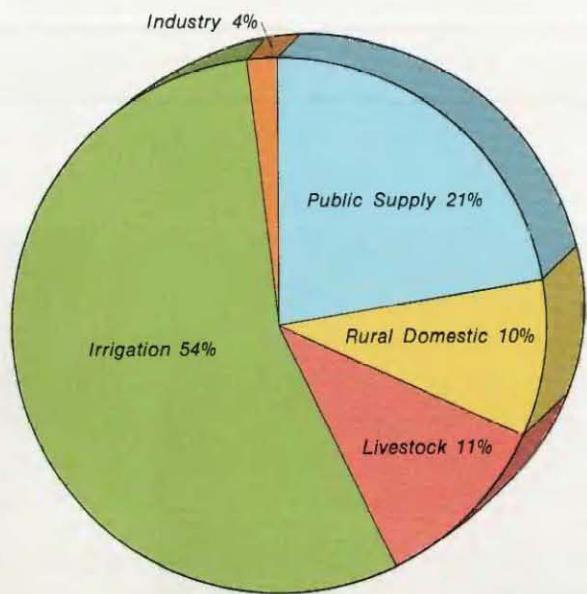
HOW MUCH GROUND WATER IS USED IN NORTH DAKOTA?

A recent survey showed that during 1980 an average of about 121 Mgal/d of ground water was withdrawn from aquifers in North Dakota. This is an increase of nearly 14 percent since a similar survey was made in 1975.

The use mainly was for the following purposes:

- Public supply
- Rural domestic
- Livestock
- Irrigation
- Industry (self supplied)

The volumes used for each purpose are shown on the accompanying diagram (fig. 14). The largest withdrawals are for irrigation use, followed by public supply, and rural domestic. Irrigation alone accounts for more than 50 percent of the ground-water withdrawals in North Dakota.



Irrigation of crops with ground water has increased steadily in North Dakota since about 1960 (figs. 15 and 16), when there were probably fewer than 6 irrigation wells in the State. By 1980 there were nearly 1,500 wells pumping a total of 65 Mgal/d during the irrigation season. Today (1982) almost 100,000 acres of land are irrigated with ground water in North Dakota.

The significant increase in irrigation use can be attributed mainly to two nearly simultaneous developments--one informational and the other technological. The first relates to the statewide program of county ground-water investigations, which began in 1955 and is now nearing completion. The reports and maps resulting from this program provided much of the decision-making information necessary for the potential irrigators. Also, during this same period, technology produced the center-pivot, sprinkler-irrigation system, which can be adapted so well for use with ground-water sources of supply.

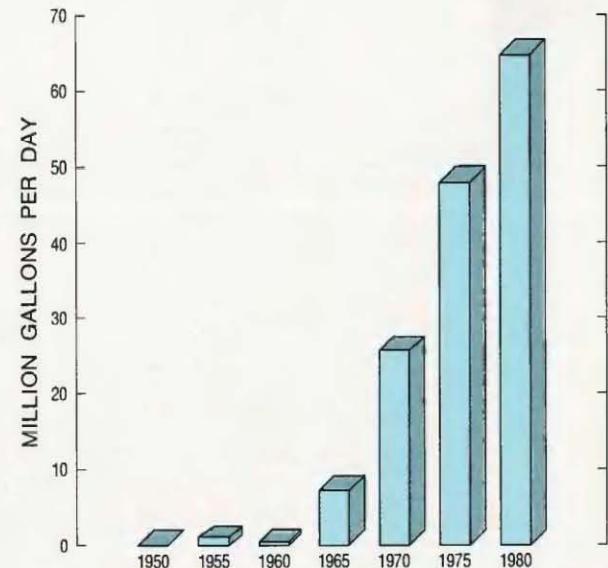


Figure 15. Increase in irrigation use from 1950 to 1980.

◀ Figure 14. Percentage of water use by category during 1980. Irrigation accounts for more than 50 percent of the ground water used in North Dakota.

Figure 16. Center-pivot sprinkler ▶ irrigating small-grain crop. Sprinkler rotates full circle and can irrigate a quarter section or more in one revolution. Photograph from North Dakota State Water Commission.



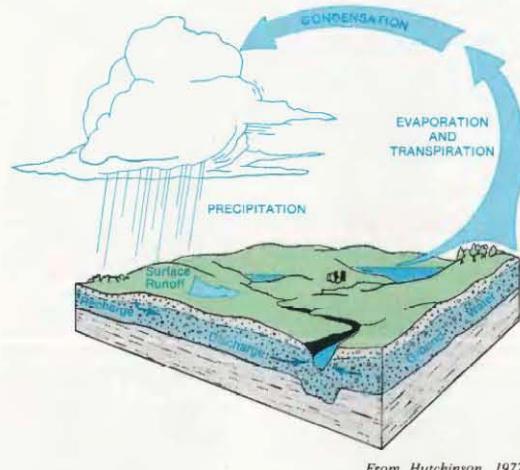
WHAT ARE THE LIMITS ON GROUND-WATER USAGE?

A Renewable Resource

Ground water is a renewable resource. The replenishment of ground water is termed recharge. The source of all recharge is precipitation from the Earth's atmosphere as shown in the accompanying diagram of the water cycle (fig. 17).

Recharge may occur as the result of rainfall or snowmelt infiltrating the Earth's surface. Infiltration is greatest in areas where the soil is sandy and where slopes are gentle so that the water does not tend to run off. However, all infiltrated water does not necessarily contribute to ground-water recharge. Other moisture needs such as soil and plant requirements must first be met. Only the water in excess of these requirements contribute to recharge.

Recharge also may occur as seepage from surface-water sources such as rivers, lakes, and



From Hutchinson, 1977

Figure 17. Water cycle. After precipitation falls to the Earth's surface, most is returned to the atmosphere by evapotranspiration, part runs off into streams, and the remainder infiltrates into the earth to recharge ground water.

wetlands. This happens when the surface water is at higher altitudes than the ground water, thus providing a downward driving force (hydraulic head). The reverse is true also, of course; when ground water is at the higher altitude it will move to the surface-water bodies. This is termed ground-water discharge. Recharge and discharge also may take place in the subsurface as leakage from one aquifer to another.

Prior to man's developmental activities, aquifers are in a state of equilibrium, and recharge is balanced by discharge. However, when a well is completed in an aquifer and water pumped from it, the balance, at least temporarily, no longer exists.

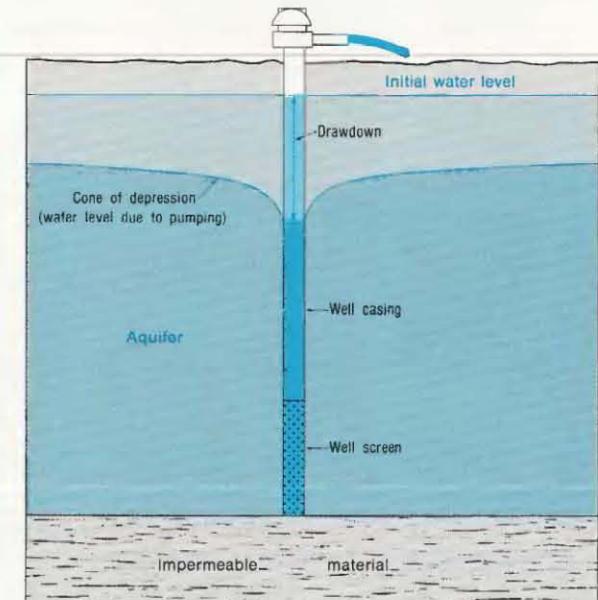
When water is withdrawn through a well, the water level in and around the well is lowered, and a cone of depression is formed, with the well at the center (fig. 18). The water level must decline in order that water may flow from the aquifer to the well. The rate and depth of decline depend upon the hydraulic characteristics of the aquifer, construction of the well, and the rate and duration of pumping.

Withdrawal of water from an aquifer will immediately result in a decrease in the volume of water stored within the aquifer. Prolonged withdrawal may result in either a decrease in the natural discharge from the aquifer or an increase in recharge, or both. However, water use may be adversely impacted long before effects on natural recharge or discharge are noted.

The "Safe Yield" Concept

One often hears the term "safe yield" used as an expression of balance between ground-water usage and recharge (fig. 19). In theory, the volume of water that can be safely withdrawn from an aquifer is dependent on the volume of water the aquifer receives as recharge. In other words, discharge must equal recharge. Most hydrologists and water managers would consider such a rigid definition of safe yield impractical, if not unworkable. If it were strictly adhered to, North Dakota's ground-water resources would receive very little development.

Over the years, numerous attempts have been made to provide a practical definition of safe



From Downey, 1973

Figure 18. Effect of pumping on water levels in an aquifer.

yield, but without much success (Kazmann, 1965, p. 158-161). Some definitions were concerned only with the quantity of water that could be withdrawn from an aquifer without producing severe water-level declines. These led to the inevitable problem of trying to define acceptable water-level declines. Other definitions included economic aspects such as energy costs. The cost of pumping water from great depths can become prohibitively expensive, as has already occurred in some parts of the United States. Still others included references to water quality. As the hydraulic head within an aquifer is decreased by withdrawals, water of a different quality may move into the aquifer from another source. This is not to say that the change in quality is always for the worse, but it commonly is.

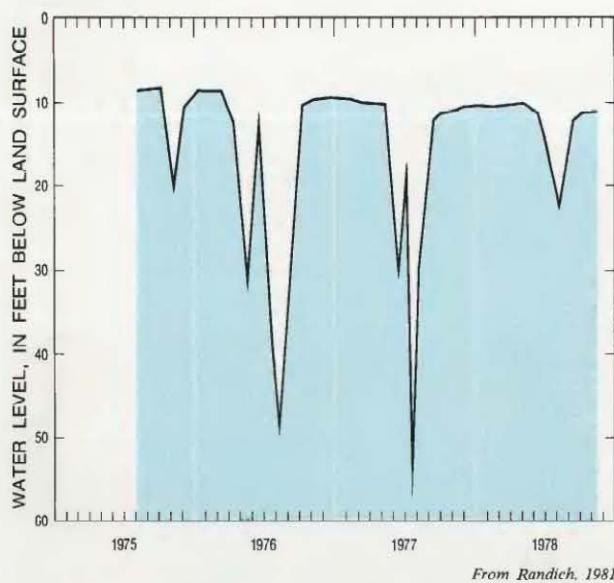


Figure 19. Annual water-level decline and rise in an observation well. Declines are caused by pumping during the irrigation season and rises are caused by recharge during the non-growing season. The concept of "safe yield" is only partly achieved because there is an overall net decline.

Ground-Water "Mining"

Another term commonly associated with ground-water use is ground-water "mining." Ground-water mining occurs when water is withdrawn at rates faster than it is replenished. The usual result is declining water levels, as illustrated in figure 20. It is unfortunate that this term ever came into use because, to many, it has an undesirable connotation and is associated with exploitation or irresponsible use of ground water. Yet, almost all aquifers are in places and at times mined. For example, the Dakota Sandstone aquifer in southeastern North Dakota and adjacent areas has been virtually mined since the first well was drilled into it in 1886.

Obviously such concepts as safe yield and ground-water mining are difficult to define and quantify. The more we learn about ground-water occurrence the more we realize that the problems of ground-water use must be dealt with on an aquifer-by-aquifer basis. This is particularly true of the unconsolidated aquifers of glacial origin in North Dakota. Instead of these terms, we probably should be thinking in terms of best management practice or optimum development. These and other aspects of aquifer management are discussed in greater detail further in this report.

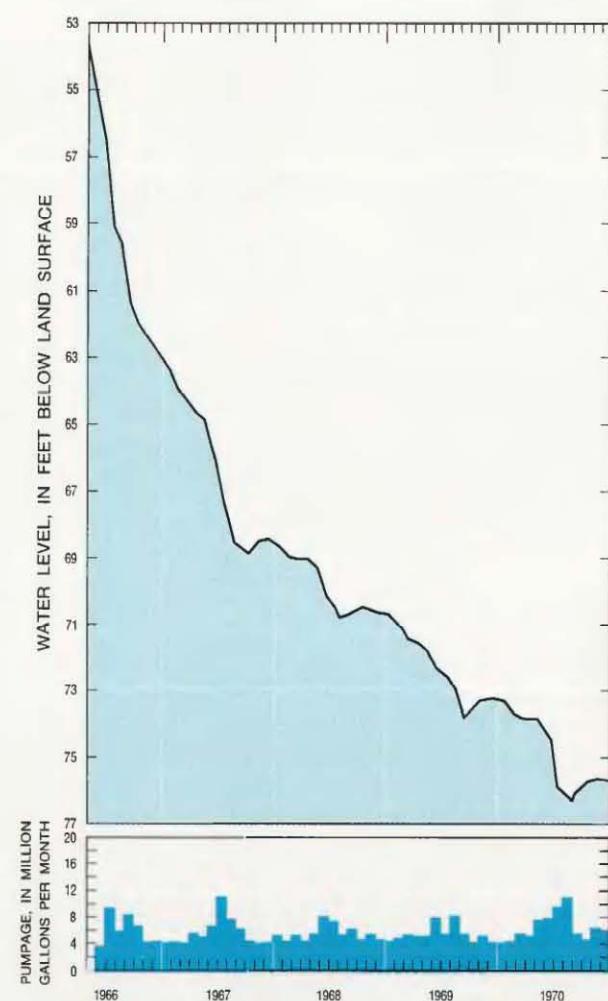


Fig. 20. *From Randich, 1977*

Figure 20. Declining water level. When aquifers are pumped at rates faster than they are receiving recharge, water levels will continue to decline. This hydrograph is for a municipal-supply well in north-central North Dakota. The well was eventually abandoned, and a new well constructed in a more favorable location.

HOW DOES GROUND WATER INTERACT WITH STREAMS, LAKES, AND WETLANDS?

Ground water is only one phase of a vast system of water transport--ocean to atmosphere to land and back to ocean again, in repeated cycles. In the process, ground water may at times and in places be discharging from aquifers to surface-water bodies, or vice versa, depending on head relationships and hydraulic connection (fig. 21). As would be expected, the importance of this interaction to the water user varies greatly from place to place.

Interaction with Streams

Probably the best example of ground-water interaction with streamflow in North Dakota is along the Sheyenne River in the southeastern part of the State (fig. 22). Studies have shown that in a 52-mile reach southwest of Kindred, where the river flows through a large, thick sand aquifer (Sheyenne delta), ground-water discharge into the river is as much as $28.8 \text{ ft}^3/\text{s}$ during the fall (Paulson, 1964, p. D181). The increase in discharge is shown on the accompanying graph on the following page (fig. 23).

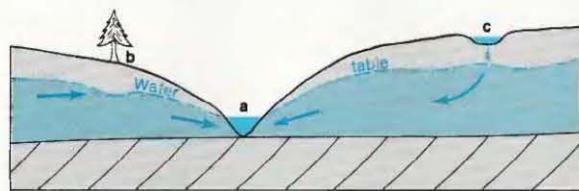


Figure 21. Interaction of ground water with stream. The water table is higher than the stream level at point a, and ground water discharges to the stream. Vegetation b, intercepts some of the ground water before it reaches the stream and discharges it into the atmosphere by a process known as transpiration. The shallow water body at point c is higher than the water table and provides recharge to the ground water.

Figure 22. Sheyenne River southwest of Kindred in August 1973. Streamflow at this time of year is derived mainly from ground-water discharge.

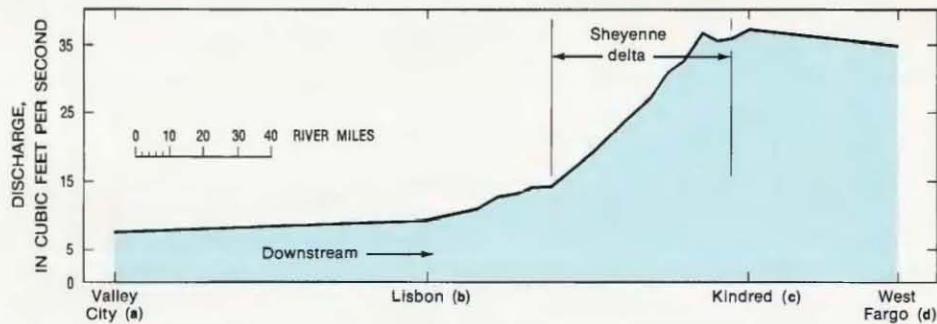
In contrast, records show that little or no ground water is discharged into the Sheyenne River in the reach from Kindred northeast to its confluence with the Red River. In fact, streamflow is decreased in this reach due to evapotranspiration losses. If it were not for the ground-water discharge, at times augmented by releases from Lake Ashtabula (a manmade reservoir north of Valley City), very little streamflow, if any, would be contributed to the Red River of the North from the Sheyenne River except during times of surface runoff.

Interaction with Lakes and Wetlands

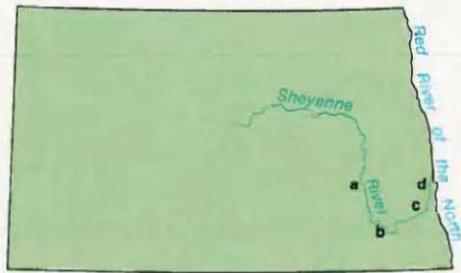
Questions often arise concerning the effects of lakes (including manmade lakes) and wetlands (locally referred to as sloughs or prairie potholes)

on ground-water levels. For example, would a significant rise in a lake level or the creation of a new lake by impoundment cause significant and possibly detrimental rises in nearby ground-water levels? Conversely, would the lowering of a lake level or the complete drainage of a lake or wetland significantly affect nearby ground-water levels? Unfortunately, the answers to questions such as these usually are not readily apparent and require rather intensive hydrologic studies. One needs to know the altitude of the lake or wetland in relation to the ground-water levels, but also other factors such as the rate and direction of ground-water movement and the rate of evapotranspiration in the area.





From Paulson, 1964



◀ Figure 23. Average discharge in Sheyenne River during fall of 1963. Measurements showed that river discharge increased significantly in 52-mile reach upstream from Kindred because of ground-water inflow.

Figure 24. Aerial view of prairie wetlands in southeastern North Dakota. Wetlands store precipitation, and, in places, provide ground-water recharge. Photograph from North Dakota Game and Fish Department.

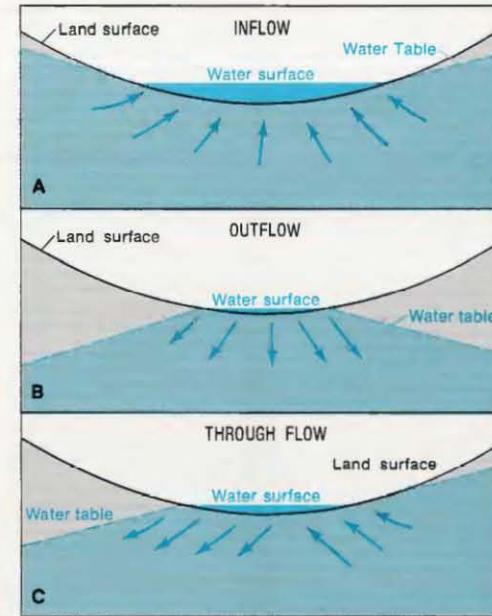


Studies to date in North Dakota have not been very conclusive, primarily because of the inability to quantify certain hydrologic characteristics needed to properly describe the ground-water flow systems. Where there is good hydraulic connection between ground-water and surface-water systems, significantly altering one obviously will alter the other.

The problems become much more difficult to resolve in areas where hydraulic connections are limited. The questions relating to the effects of wetland (fig. 24) drainage on ground-water levels and ground-water recharge are very difficult to answer, quantitatively. Winter and Carr (1980, p. 1) in a study of a wetland complex in Stutsman County, N. Dak., state, "...some wetlands appear

to recharge ground water, some wetlands are flow-through types where ground water enters one side and surface water seeps into the ground on the other side, and some wetlands are discharge points for ground water. Further, these interrelationships vary throughout the year" (fig. 25). Their study consisted of a small group of wetlands. When one considers the large area of wetlands in North Dakota and the erratic climate in the State, it is not difficult to understand why caution is needed in attempting to categorize the effect of wetlands in a given hydrologic situation.

Figure 25. Three types of ground-water-wetland relationships. Some wetlands discharge ground water to the surface where it is lost to evapotranspiration (A), some discharge water downward and provide ground-water recharge (B), and others are sources of both recharge and discharge (C).



From Sloan, 1972

WHO OWNS THE GROUND WATER?

In the United States, two main doctrines exist regarding water ownership. One is the common-law doctrine of riparian or land-ownership rights; the other is the doctrine of prior appropriation.

The land-ownership rights doctrine, simply stated, declares that the landowner owns the water on or beneath his or her land. Originally the doctrine, sometimes referred to as the English rule, implied freedom to use the water in any volume and for whatever purpose the owner wished. Since its inception, the doctrine has been modified to include concepts of reasonable use and "correlative rights" in recognition of the rights of others using water from the same source.

The doctrine of prior appropriation, in contrast, does not recognize water ownership or the right to use the water as being inherent with the land ownership. Rather, the right to use the water is based on priority in time (first in time, first in right) and has the added qualification that the use be beneficial.

The riparian or land-ownership doctrine is the basis of most water laws in the humid, generally eastern, parts of the United States; whereas, the prior appropriation doctrine is the basis for most water laws in the arid, generally western parts of the country. In the central States there is an overlap, and both doctrines are used. The accompanying map shows the water doctrines prevailing in different parts of the United States (fig. 26).

North Dakota's water laws are based on the doctrine of prior appropriation. The State Constitution, section 210, states: "All flowing streams and natural water courses shall forever remain the property of the State for mining, irrigating, and manufacturing purposes." More specifically, in

regard to ground water, chapter 61-01-01, item 2, of the North Dakota Water Laws states "Waters under the surface of the earth whether such waters flow in defined subterranean channels or are diffused percolating underground waters ... belong to the public and are subject to appropriation for beneficial use and the right to the use of these waters for such use, shall be acquired pursuant to the provisions of chapter 61-04." This chapter deals with the appropriation of water and de-

scribes the procedures for acquiring water-use permits.

At the present time, water-use permits are required only for municipal, irrigation, and industrial purposes. They are not required for domestic, livestock, or fish and wildlife purposes unless the annual appropriation exceeds 12.5 acre-feet. The permits are issued by the State Engineer.

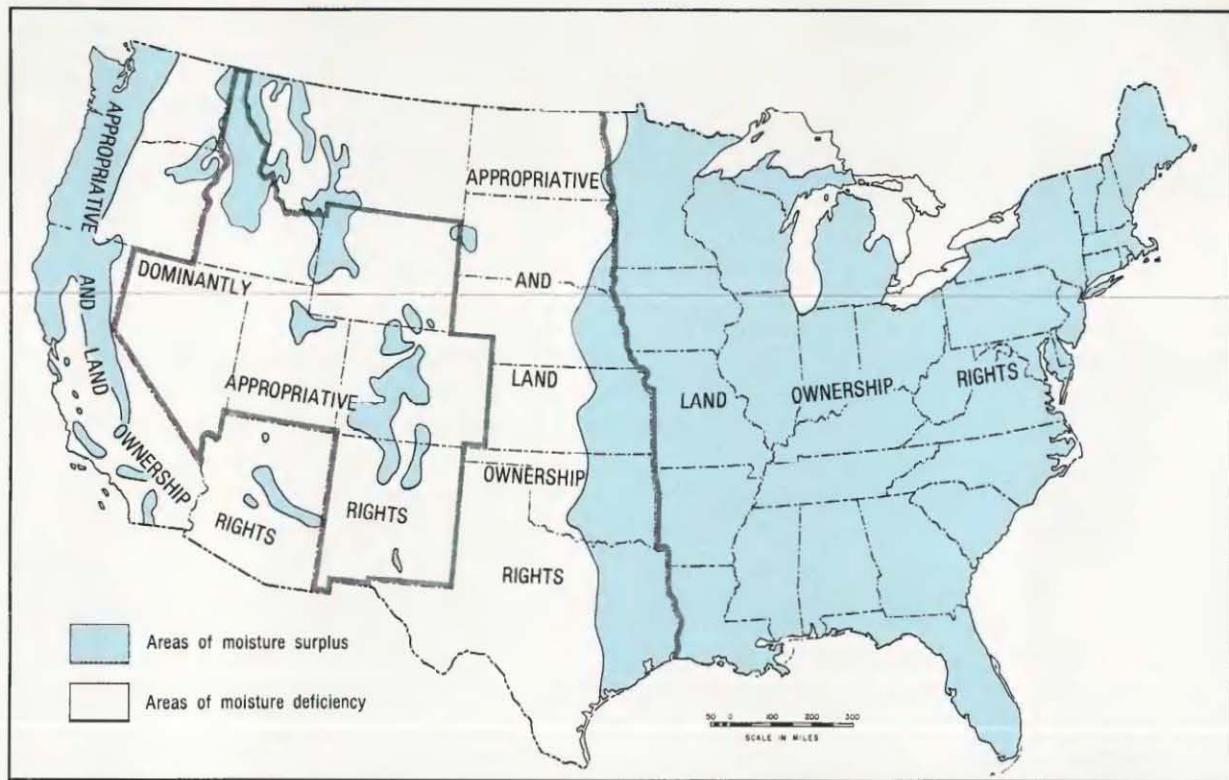


Figure 26. Water doctrines used in different parts of the conterminous United States.

HOW CAN WE BEST USE THE GROUND-WATER RESOURCES IN NORTH DAKOTA?

Most people probably would agree to the need for a planned and orderly development of the State's ground-water resources. Haphazard or piecemeal development generally leads to detrimental results; economically, environmentally, or both.

Not many years ago, the effects of a given plan of ground-water development could be assessed only in very qualitative terms. Today, thanks mainly to computer technology, more quantitative assessments can be made. It is possible to simulate or model large complex ground-water flow systems with the aid of computers so that the effects of various forms of stress on the systems may be reasonably understood. The stresses may be the result of climate, such as prolonged drought conditions, or the result of man's activities, such as pumping water from wells.

However, even the most sophisticated computer technology cannot provide the correct answers unless the "real-world" system to be simulated in the computer model is thoroughly understood. For example, if we wish to know how many productive wells a given aquifer can support with minimum interference with each other (fig. 27), we must know the physical dimensions of the aquifer, its capacity to transmit and to store water, as well as the volume of recharge it receives and the volume of water that it naturally discharges. It generally is necessary to collect a substantial quantity of geologic and hydrologic data and to carefully analyze and interpret the data to gain an understanding of how the aquifer functions. The degree to which this understanding is obtained will determine the accuracy of the predictions made by the computer.

Another example may involve the interaction between ground water and surface-water bodies. Where and when streamflow is maintained by ground-water discharge, depletion of ground-water storage (fig. 28) may result in decreased streamflow. Problems may then occur if prior appropriators, using water from the stream, find their source of supply decreasing. Again, the system may be modeled with the aid of a computer, and solutions obtained, such as how much water can be pumped from the aquifer; where, within the aquifer the pumpage should occur and at what times of the year, without detrimentally affecting the streamflow. As in the first example, a large quantity of geologic and hydrologic information is needed to design the model.

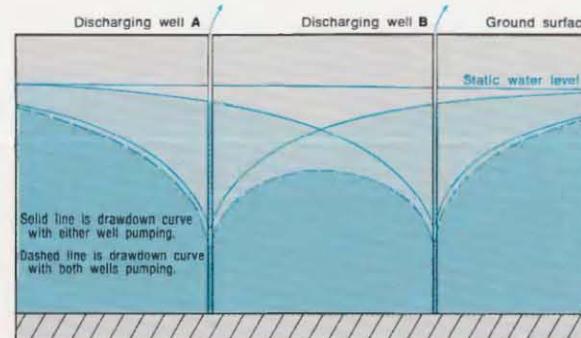


Figure 27. Overlapping pumping cones. When more than one well is constructed in the same aquifer they need to be spaced far enough apart so that interference is minimized. However, for dewatering wells such as used in construction work, interference may be desirable in order to achieve maximum drawdown.

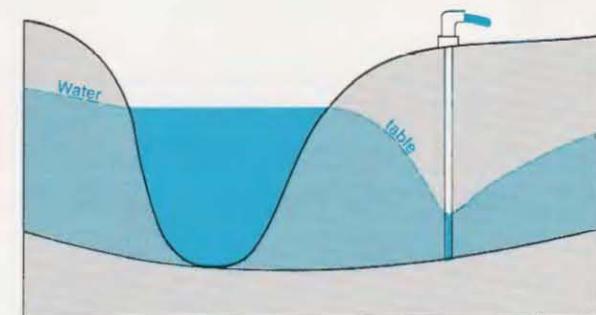


Figure 28. Well diverting water from streamflow. Where an aquifer is in hydraulic connection with a stream, water may be diverted from the stream to the aquifer and ultimately to ground-water use by means of well pumping.

These are but two examples of the many problems that may be associated with large-scale ground-water usage. The variations are almost unlimited. Fortunately, North Dakota has an excellent on-going program designed to insure the safe and orderly development of the State's ground-water resources. During the past 25 years the ground-water resources have been systematically identified and described on a county-by-county basis. The program has been a cooperative effort involving each county of the State, the North Dakota State Water Commission, the North Dakota Geological Survey, and the U.S. Geological Survey. In some counties where there are large areas of federally owned lands, other Federal agencies such as the U.S. Forest Service and U.S. Bureau of Land Management also have been involved. The last county ground-water study was begun in 1979 and will be completed in 1983.

WHERE CAN WE GET GROUND-WATER INFORMATION?

The county studies of the 1960's and 1970's provided the ground-water data base that is essential to the simulation models of the 1980's. Predictive models of some of the larger and more intensively developed aquifers in the State already have been developed by hydrologists in the North Dakota State Water Commission and the U.S. Geological Survey. The major use of water from these aquifers presently is for irrigation purposes. As noted earlier, the Water Commission is responsible for issuing permits to use water for irrigation purposes. The issuance of the permits need to be based on sound hydrologic analyses of the aquifer. New requests for ground-water permits are weighed against the effects on existing users as well as possible additional demands in the future. Thus, the balance between long-term ground-water availability and use may be thought of as a hydrologic budget, and permits for withdrawals, including specified rates and quantities, are issued after the capabilities of the aquifers have been assessed.

As an aid in determining the hydrologic budget, a statewide network of observation wells has been established and maintained by the U.S. Geological Survey and the North Dakota State Water Commission since the 1930's. Today the network consists of about 2,000 wells, which are completed in all of the major aquifers in the State. Water-level measurements made in these wells are essential in order to evaluate the effects of man's activities as well as the natural climatic variation on North Dakota's ground-water resources. Most of the data are stored in computers, and are readily available to the public, as described in the following section of this report.

Problems associated with ground-water procurement and use in North Dakota usually are in abundance, particularly during periods of drought. This is not surprising for a State that is so greatly dependent on ground water as a source of supply. Many, if not most, of the problems are handled routinely by water-well contractors who are required by law to be certified and licensed by the State Board of Water Well Contractors. The law also requires that the construction of water wells in the State must comply with prescribed standards for proper siting, well-construction materials and procedures, and well-testing and sampling procedures. A well driller's report for each well must be filed with the State Board of Water Well Contractors.

Many ground-water users, or would-be users, are not familiar with the availability of the large number of reports dealing with ground water in North Dakota (fig. 29). Prepared by local, State, and Federal agencies, the reports generally describe the ground-water conditions in selected areas of the State. In addition to the published reports, several agencies have on file large quantities of data such as well logs, water-level measurements, and water-quality analyses. Most of these data, which are in computer storage, are available to the public on request. The accompanying table (table 4) lists the public agencies in North Dakota that have a major responsibility in ground-water resources, and the types of information available at each agency as related to their primary mission.

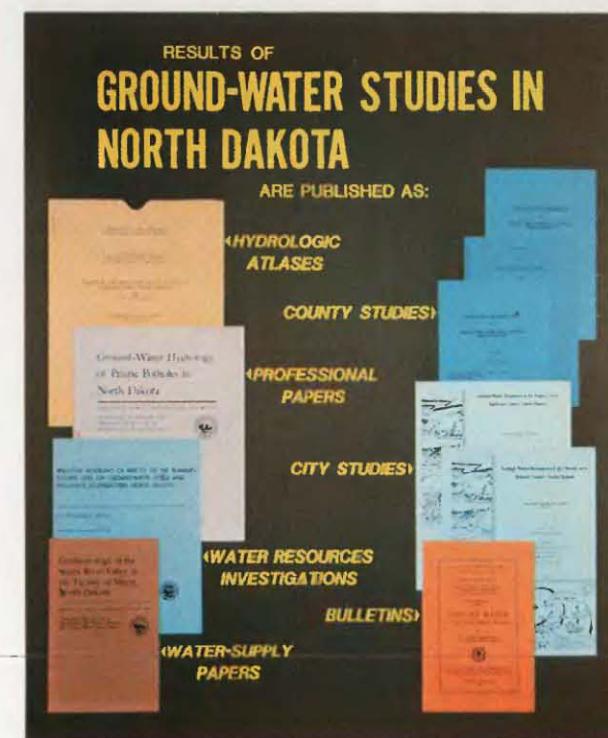


Figure 29. Samples of North Dakota ground-water publication

Table 4. Public agencies in North Dakota where ground-water information can be obtained.

<u>EXPLANATION</u>		
A - Well records.	G - Reports on ground-water availability.	M - Water-quality standards.
B - Logs of test holes and wells.	H - Engineering reports (construction problems, ground-water drainage, etc.).	N - Samples of earth materials (cores and cuttings from test holes).
C - Chemical analyses of water samples.	I - Irrigation feasibility.	O - Problems associated with land use.
D - Bacterial analyses of water samples.	J - Ground-water research.	P - Ground-water pollution, protection.
E - Water-use data (quantities pumped for irrigation, municipalities, etc.).	K - Legal aspects.	Q - Water-use permit.
F - Water-level records.	L - Well construction and siting standards.	R - Certification for well drillers.

Agency	Information	Agency	Information
North Dakota:			
Board of Water Well Contractors 900 East Boulevard Bismarck, ND 58505 224-2750	A, B, L, R	Agricultural Research Service Northern Great Plains Research Center Mandan, ND 58554 663-6445	J
Geological Survey Leonard Hall University of North Dakota Grand Forks, ND 58201 777-2231	G, J, N	Bureau of Reclamation 304 East Broadway Bismarck, ND 50501 255-4011	F, H
Health Department 1205 Avenue A West Bismarck, ND 58501 224-2384	C, D, L, M, O, P	Environmental Protection Agency 1200 Missouri Avenue Bismarck, ND 58501 255-4011	K, M, P
Laboratories Department 2635 East Main Bismarck, ND 58501 224-2854	C, D	Extension Service County Seats	I
Public Service Commission Capitol Building Bismarck, ND 58501 224-2400	O	Geological Survey 821 East Interstate Avenue Bismarck, ND 58501 255-4011	A, B, C, E, F, G, J
Water Commission 900 East Boulevard Bismarck, ND 58501 224-2750	A, B, C, E, F, G, I, K, Q	Soil Conservation Service Federal Building Bismarck, ND 58501 255-4011	H, I, N, O
United States:			
		Water Resources Research Institute North Dakota State University Fargo, ND 58102 237-7765	J

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