Geology and Ground Water in Door County, Wisconsin, with Emphasis on Contamination Potential in the Silurian Dolomite

GEOLOGICAL SURVEY WATER-SUPPLY PAPER 2047

Prepared in cooperation with the Wisconsin Department of Natural Resources

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By M. G. SHERRILL

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UNITED STATES GOVERNMENT PRINTING OFFICE, WASHINGTON : 1978

UNITED STATES DEPARTMENT OF THE INTERIOR

CECIL D. ANDRUS, *Secretary*

GEOLOGICAL SURVEY

H. William Menard, *Director*

Library of Congress Cataloging in Publication Data
Sherrill, M. G.
Geology and ground water in Door County, Wisconsin.
(Geological Survey Water-Supply Paper 2047)
Bibliography: p. 39
1. Water, Underground—Wisconsin—Door Co.
2. Geology—Wisconsin—Door Co.
3. Geology, Stratigraphic—Silurian.
4. Water, Underground—Pollution—Wisconsin—Door Co.
I. Wisconsin. Dept. of Natural Resources. II. Title. III. Series:
United States Geological Survey Water-Supply Paper 2047.
GB1025.W6W48 553′.79′0977563 77-608089

For sale by the Superintendent of Documents, U.S. Government Printing Office
Washington, D.C. 20402
Stock No. 024-001-03073-0

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Multiply English units	*By*	*To obtain SI units*
Feet (ft)	0.3048	Meters (m).
Square miles (mi^2)	2.590	Square kilometers (km^2).
Gallons per minute (gal/min)	.06309	Liters per second (L/s).
Million gallons per day (Mgal/d)	.04381	Cubic meters per second (m^3/s).
Feet squared per day (ft^2/d)	.0929	Meters squared per day (m^2/d).
Miles (mi)	1.609	Kilometers (km).
Gallons (gal)	3.78541	Liters (L).
Feet per mile (ft/mi)	.1894	Meters per kilometer (m/km).
Gallons per minute per foot [(gal/min)/ft]	.2070	Liters per second per meter](L/s)/m)].
°F (degrees Fahrenheit)	(F--32)5/9	°C (degrees Celsius).

GEOLOGY AND GROUND WATER IN DOOR COUNTY, WISCONSIN, WITH EMPHASIS ON CONTAMINATION POTENTIAL IN THE SILURIAN DOLOMITE

By M. G. Sherrill

ABSTRACT

Door County is in northeastern Wisconsin and is an area of 491 square miles. The county forms the main body of the peninsula between Green Bay and Lake Michigan. The land surface is an upland ridge controlled by the underlying bedrock. The west edge of the ridge forms an escarpment facing Green Bay.

Silurian dolomite is the upper bedrock unit throughout most of the county and is the most important aquifer. This bedrock is exposed in much of the county, particularly north of Sturgeon Bay; elsewhere, it is covered by a generally thin mantle of soil or drift.

The bedrock units are divided into two major aquifer systems in Door County; the Silurian dolomite aquifer system and the sandstone aquifer system, consisting of Ordovician and Cambrian bedrock units. These two major systems are separated by the Maquoketa Shale of Ordovician age, a nearly impermeable, generally nonproductive unit. The Silurian dolomite aquifer system is itself divided into the Niagaran aquifer and the underlying Alexandrian aquifer.

Water occurs in the Silurian dolomite aquifer system in two types of openings— nearly vertical joints (fractures) and horizontal to slightly dipping bedding-plane joints. Vertical joints are more common in the upper part of the Niagaran aquifer. These yield small amounts of water to wells. Bedding-plane joints transmit most of the water in the lower part of the Niagaran aquifer and in the Alexandrian aquifer. The bedding-plane joints, because they are poorly interconnected, act as semiartesian conduits separated by impermeable rock. Eight water-bearing zones in generally continuous bedding-plane joints have been mapped.

The dolomite is recharged from direct precipitation and snowmelt. It discharges water to pumping wells and by natural springs discharge to Lake Michigan and Green Bay and to interior lakes and streams.

Wells in the Silurian dolomite aquifer system have adequate yields to meet most needs, except in the southwest corner of the county, where the dolomite is thin or absent. Transmissivity values range from a low of 4.0 feet squared per day in the Niagaran aquifer near Sturgeon Bay to more than 13 000 feet squared per day for the Alexandrian aquifer near Fish Creek.

Water from Silurian dolomite is a very hard calcium magnesium bicarbonate type, with objectionable concentrations of iron and nitrate in water from some wells. Sanitary quality, as indicated by tests for total coliform bacteria, has been a chronic problem in certain areas. Concentrations of indicator organisms are greatest during or immediately after rapid ground-water recharge, with concentrations rapidly decreasing after periods of recharge. Wells close to septic systems and in areas underlain by

fractured near-surface bedrock have the greatest incidence of contamination. The type and thickness of unconsolidated material has a direct effect on the entry of bacteria into the ground-water system. Bacterial attenuation increases with increasing soil depth and reduction in soil permeability. After bacterial contaminants reach the water table within fractured bedrock, little attenuation occurs, and the contaminants can travel long distances in a short time.

Ground water of good sanitary quality but exceeding recommended limits of the U.S. Public Health Service for sulfate and chloride is probably available from the sandstone aquifer by drilling wells 700 to 1300 feet deep.

To minimize the possibility of obtaining contaminated ground water, well construction should include properly locating the wells upgradient and as far as practical from contamination sources, setting and pressure grouting well casings to an adequate depth into firm bedrock, and casing the well into the zone of saturation.

INTRODUCTION

Door County has a long history of ground-water contamination. The problem is most severe in late summer, when tourists and fruit-canning operations generate additional contaminants. Fecal organisms from ineffective waste-disposal systems are the major ground-water contaminants. Contaminants also enter the ground-water system from agricultural, industrial, and municipal sources.

Most contaminated ground water is in populous areas that lack sewage-treatment facilities and that are underlain by fractured bedrock at or near the surface.

PURPOSE AND SCOPE

The purpose of this report is to describe the geology, ground water, hydrology, and ground-water quality in Door County to provide a better basis for planning future wells.

Several geologic and hydrologic factors were considered and studied. Ten bedrock wells, ranging in depth from 47 to 1845 ft were drilled and tested by the U.S. Geological Survey. The thicknesses of unconsolidated deposits and Silurian rocks were determined, and the areal extent of the Silurian dolomite aquifer system was outlined. Chemical and bacterial ground-water quality was determined and monitored. Ground-water and contaminant movement were determined in selected areas, and this information was used to define areas of potential ground-water contamination.

This report separates Silurian rocks into the Niagaran Series and the Alexandrian Series. The two series were separated on the basis of hydrologic differences, lithology, fossils, and borehole geophysics, particularly gamma-ray logs.

DESCRIPTION OF AREA

Door County is located in northeastern Wisconsin and is an area of 491 mi^2 (fig. 1). The permanent population is about 20,000, but it triples during the summer. There are few perennial streams in the county and only three major lakes.

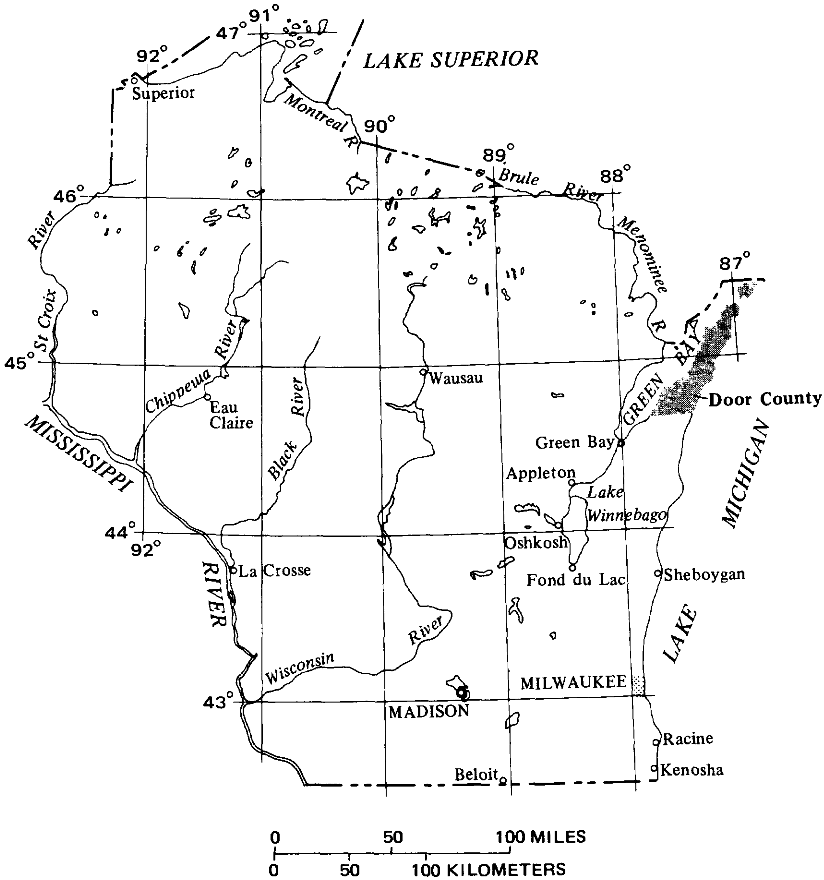


FIGURE 1. — Location of Door County, Wisconsin.

The county is located on a peninsula composed of resistant Silurian rocks, which crop out between the less resistant rock units underlying Green Bay and Lake Michigan. The land surface slopes gently to the southeast from a ridge that parallels the Green Bay shore and is as high as 260 ft above lake level. The ridge is a steep dolomite face that lines the Green Bay shore and is broken at intervals by bays and coves.

Glaciation has removed much of the soil, leaving the dolomite exposed in many places or covered by only thin soil or drift.

ACKNOWLEDGMENTS

Appreciation is expressed to the many State, county, and city officials, drilling contractors, and well owners, who provided information needed for this report. Special acknowledgments are given Mr. Thomas A. Calabresa, Wisconsin Department of Natural Resources, for his technical contributions; Dr. M. E. Ostrom and the staff of the University of Wisconsin-Extension, Geological and Natural History Survey, for their assistance and field equipment; and the Wisconsin State Laboratory of Hygiene for analyses of water samples.

This investigation is part of a cooperative program of the U.S. Geological Survey and the Wisconsin Department of Natural Resources.

GEOLOGIC ENVIRONMENT

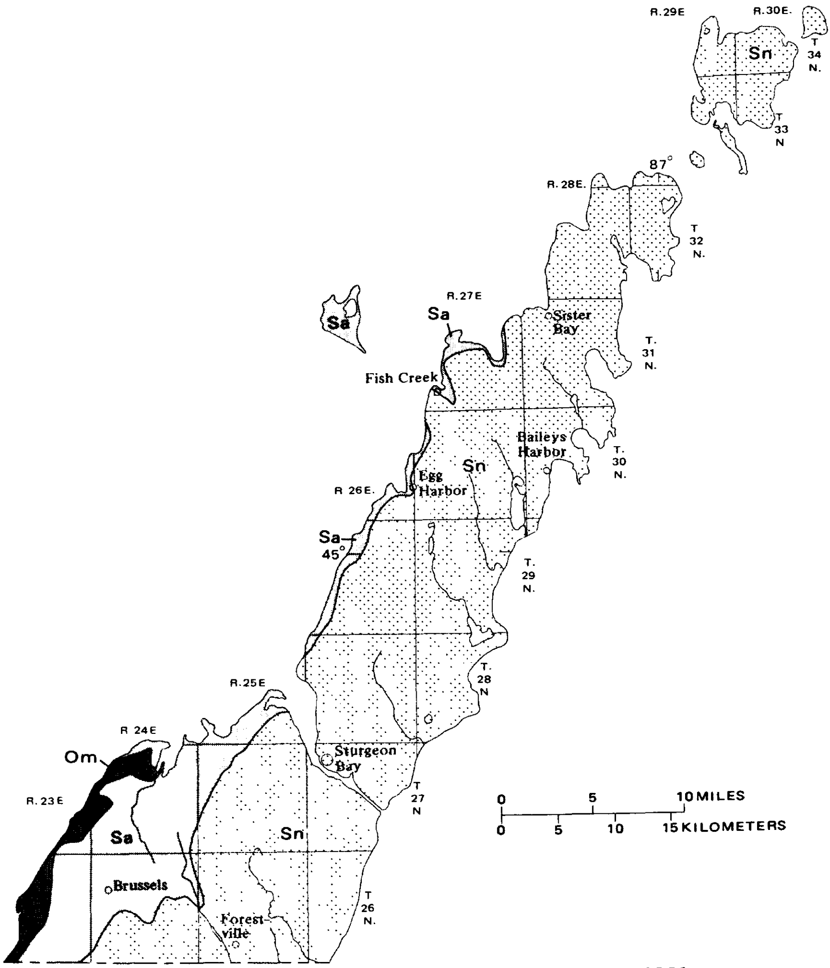
Rock units in Door County range in age from Precambrian to Holocene. The oldest are impermeable crystalline rocks of Precambrian age at depths that average more than 1500 ft below land surface. These are overlain by consolidated sedimentary rocks of Cambrian, Ordovician, and Silurian ages. Generally, thin unconsolidated deposits of Quaternary age overlie older rocks in most of the county.

The topography of the bedrock surface closely resembles the present land surface in much of northern and southwestern Door County (pl. 1). Altitudes on the bedrock surface range from about 580 ft at lake level to about 840 ft in the central and southern parts of the county. Four major bedrock valleys traverse the county from northwest to southeast. These valleys probably were cut by preglacial streams that flowed toward Lake Michigan (Martin, 1932, p. 289). The bedrock valleys are (1) near the city of Sturgeon Bay, (2) between the villages of Ephraim and Baileys Harbor, (3) between the villages of Ellison Bay and Rowleys Bay, and (4) between the northern tip of the peninsula and Washington Island.

Pleistocene glaciation modified the bedrock surface in Door County by scouring highlands and depositing drift in the lowlands. The general character and dominant features of the buried surface are as shown in plate 1. Test drilling, well logs, field mapping, soils maps, and topographic maps were used to compile the map.

Silurian dolomite is the uppermost bedrock unit over most of the county. In the southwest corner, west of the escarpment, however, the dolomite is absent, and Maquoketa Shale is the uppermost unit (fig. 2).

The consolidated rocks dip to the southeast at about 45 ft/mi, so that formations deepen toward the southeast. The sequence and maximum thicknesses of rock units are shown in table 1.



Base from U.S. Geological Survey
1:500,000, 1968

EXPLANATION

Sn	NIAGARAN SERIES – Dolomite, buff- gray, medium- to coarse-grained, thin-bedded to massive	SILURIAN
Sa	ALEXANDRIAN SERIES – Dolomite, gray, medium- to coarse-grained, thick-bedded to massive. Cherty with gypsum near base	SILURIAN
(black)	MAQUOKETA SHALE – Shale and shaly dolomite	ORDOVICIAN

FIGURE 2. — Bedrock geology.

TABLE 1. — *Lithologic and water-yielding characteristics of rock units*

System	Rock units	Lithologic description	Maximum thickness (ft)	Average well yield and range (gal/min)	Hydrologic units and water-yielding characteristics		
Quaternary	Holocene and Pleistocene deposits	Unsorted mixture of clay, silt, sand, gravel, and boulders; stratified sand and gravel; lake silt and clay; organic deposits.	150 ±50	- - -	Sand and gravel aquifer system		Not evaluated because minimum casing requirements close off the entire unit except for a small area in the southeastern part of the county.
Silurian	Niagaran Series Racine Dolomite, Manistique Dolomite, and Burnt Bluff Formation undifferentiated	Dolomite and dolomitic limestone, buff-gray, medium-to coarse-grained; thin-bedded to massive in the upper part; mostly thin-bedded in the lower part.	350	15 5–60	Dolomite aquifer system	Niagaran aquifer	In the upper part, water occurs in parallel but discontinuous bedding-plane joints and nearly vertical joints; water in the lower part occurs in more prominent and continuous bedding-plane joints, particularly near the contact with the Mayville. Well yields change in relation to the number and size of joints intersected; generally, they are adequate for domestic and farm supplies.
	Alexandrian Series Dolomite	Dolomite, gray, medium- to coarse-grained, thick-bedded to massive; cherty with gypsum near base.	230	40 15–450		Alexandrian aquifer	Water occurs in bedding-plane joints or zones of joints. Bedding-plane joints are recharged into near-vertical joints where the Alexandrian Series is the uppermost bedrock unit. These conditions permit the development of large supplies of ground water with full penetration of the unit.

Ordovician	Maquoketa Shale	Shale, blue-gray, fine- to medium-grained; thin-bedded dolomite and interbedded shale common near the top.	400 ± 50	5 2–20	Confining bed		Ground water occurs in a fractured zone within the upper few feet of the unit. Remainder of the formation is nearly impermeable. Wells not obtaining water from the fractured zone usually are inadequate for domestic supplies. Unit acts as a barrier to water movement between the Alexandrian aquifer above and the sandstone aquifer below.
Ordovician	Galena Dolomite, Decorah Formation, and Platteville Formation; St. Peter Sandstone; and Prairie du Chien Group undifferentiated	Dolomite, gray, fine- to medium-grained, cherty; and fine- to coarse-grained sandstone and sandy shale.	450 ± 50	25 5–200	Sandstone aquifer system	Upper sandstone aquifer	Water occurs in crevices in the dolomite and in intergranular openings within the sandstone. These units yield small to moderate quantities of water from the sandy units where they are developed, mainly in the southwestern part of the county.
Cambrian[1]	Trempealeau Formation, Tunnel City Group, and Wonewoc Formation undifferentiated	Sandstone, dolomitic, fine- to medium-grained; fair- to good-sorting; and dolomitic shale and siltstone.	400 ± 50	(?)	Sandstone aquifer system	Lower sandstone aquifer	Not presently used as a source of water in Door County. A test well through these units near Jacksonport indicated that moderate yields of water could be obtained from the dolomitic sandstone, but only small yields could be expected from crevices, joints, and solution zones within the other units.

[1] Cambrian nomenclature follows the usage of the Wisconsin Geological and Natural History Survey (Ostrom, 1967).

CAMBRIAN ROCKS

Cambrian rocks are divided according to the usage of the Wisconsin Geological and Natural History Survey (Ostrom, 1967). From oldest to youngest, these units are the Wonewoc Formation and Tunnel City Group undifferentiated and the Trempealeau Formation. The rocks are mostly sandstone and interbedded shale, siltstone, and dolomite (table 1; fig. 3). From test-well data, the thickness of the Cambrian section is estimated to be about 400±50 ft (fig. 3).

ORDOVICIAN ROCKS

Ordovician rocks in Door County include, from oldest to youngest, the Prairie du Chien Group undifferentiated, St. Peter Sandstone, Platteville Formation, Decorah Formation, Galena Dolomite, and the Maquoketa Shale (table 1; fig 3).

The Prairie du Chien Group, St. Peter Sandstone, Platteville Formation, Decorah Formation, and Galena Dolomite were recognized in the deep test well (fig. 3) but are otherwise undifferentiated for the purposes of this report. The units consist of dolomite, fine to coarse-grained sandstone, and sandy shale. The St. Peter Sandstone is thickest where the underlying Prairie Du Chien Group has been partly eroded. The combined thickness of the St. Peter Sandstone and the Prairie du Chien Group is about 200 ft, and the Galena, Decorah, Platteville unit is about 240 ft thick.

The Maquoketa Shale averages about 400 ft. in thickness in Door County and consists of nearly impermeable, compact blue-gray shale containing some thick beds of dolomite near the top.

SILURIAN ROCKS

The Silurian rocks range from zero in the southwest to more than 500 ft thick in the eastern part of the county (fig. 4). Near-surface rock and outcrops occur over large areas, particularly along the escarpment and in the northern and southwestern parts of the county (pl. 2). Generally, the bedrock is covered elsewhere by a thin layer of unconsolidated materials.

Two types of joints, nearly vertical joints and horizontal or slightly dipping bedding-plane joints, occur in the Silurian rocks. Two joint sets are prominent (pl. 1). The azimuth of one set is about 72°; that of the other is about 155°.

ALEXANDRIAN SERIES

Rocks of the Alexandrian Series include the Mayville Dolomite (table 1). They consist of gray medium- to coarse-grained thick-bedded dolomite with uneven bedding planes. Locally, the beds contain chert,

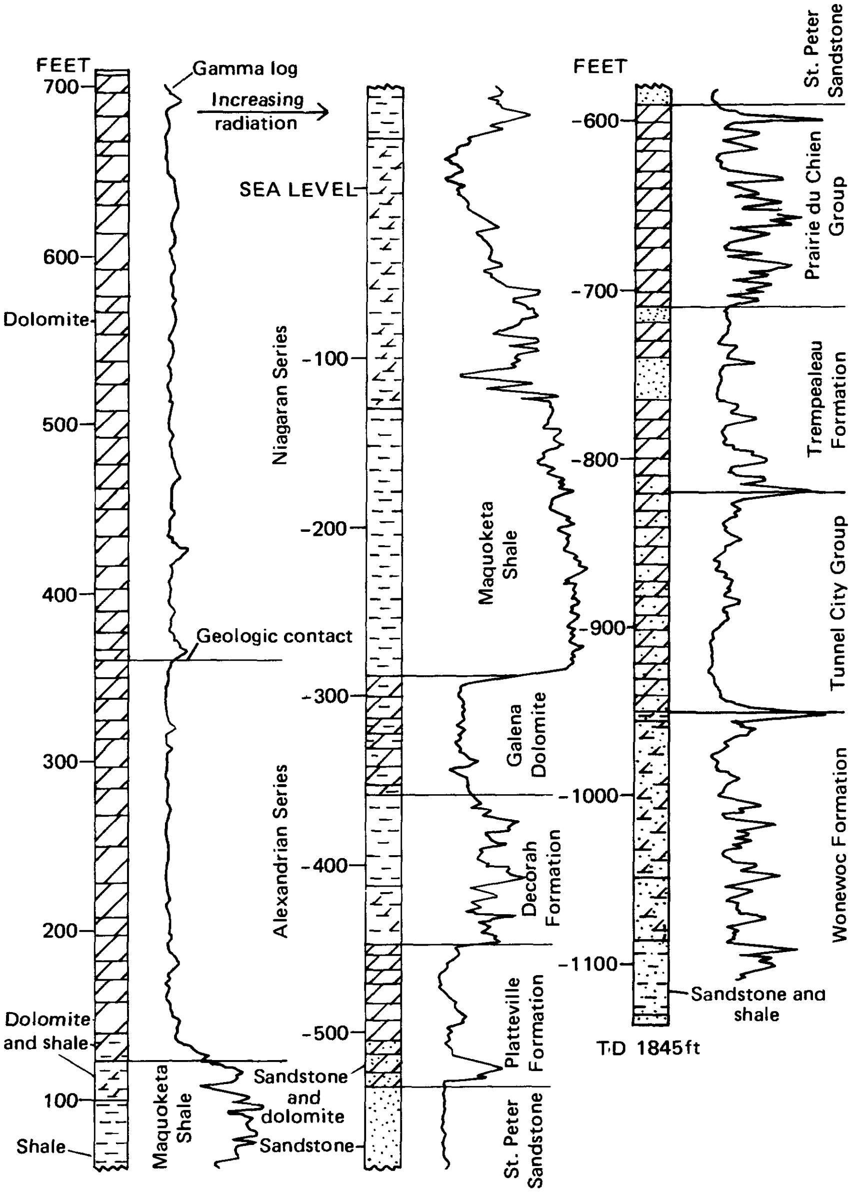


FIGURE 3. — Log of deep test well near Jacksonport, Wisconsin.

pyrite, and gypsum near the base. In outcrops these rocks weather to form a rough, coarse, craggy, and pitted surface. The maximum thickness of the unit is about 230 ft. The rocks are thinner in the southwest corner of the county and in places are absent (figs. 2, 4).

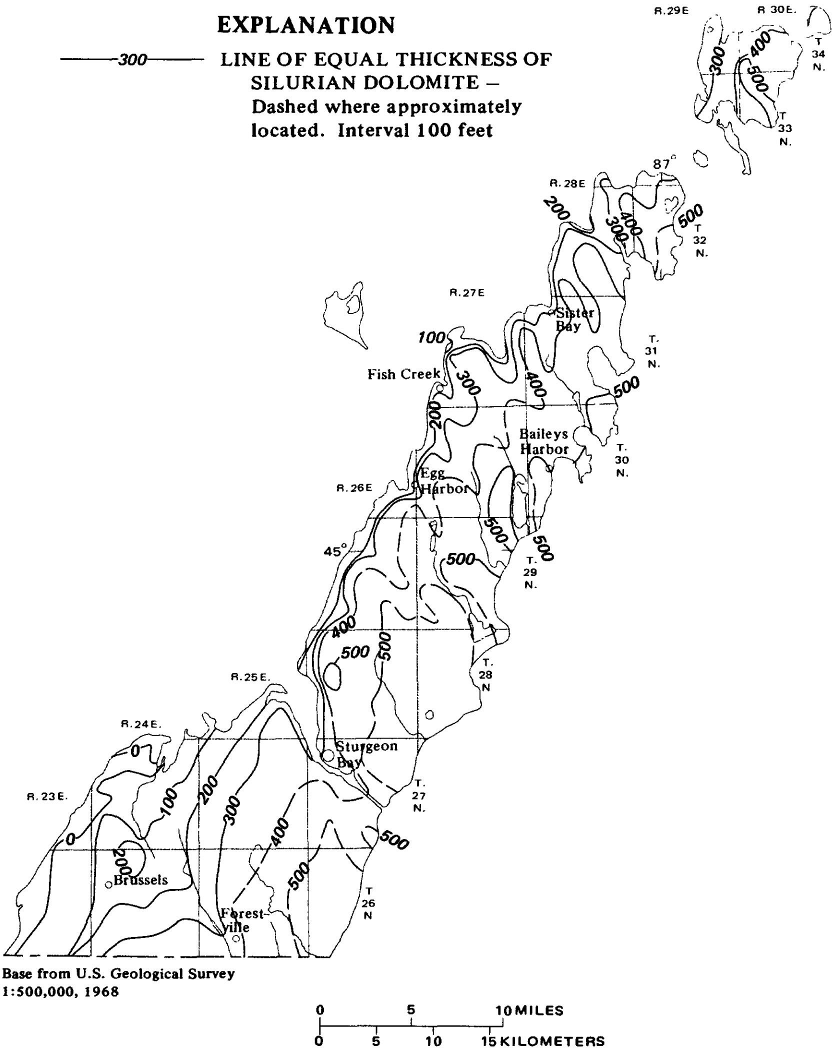


FIGURE 4. — Thickness of Silurian dolomite.

The surface of the Alexandrian unit generally forms a lowland south and west of Sturgeon Bay, and it extends along the shoreline and beneath Green Bay north of Sturgeon Bay (fig. 2).

NIAGARAN SERIES

The Niagaran Series includes, from oldest to youngest, the Burnt Bluff Formation, Manistique Dolomite, and Racine Dolomite (table 1). The rock units are mainly dolomite and range from mostly thin bedded in the lower part to thin bedded to massive in the upper part. The units are medium to coarse grained and are mostly buff gray. They reach a maximum thickness of about 350 ft on the Lake Michigan side of the county. The Niagaran Series is the most widespread areally and forms the bedrock surface everywhere except in the southwestern part of the county (fig. 2). It also forms the "Niagara escarpment," which extends the length of the county along the Green Bay shoreline north of Sturgeon Bay. Many caves, both vertical and horizontal, have been formed in these rocks (pl. 1). The caves result from solution of the dolomite along joint systems. Mapping of the caves revealed a strong similarity between their prominent joint sets and the surficial joints of the series.

Niagaran rocks yield small to moderate amounts of water to wells from both vertical and bedding-plane joints (table 1). Well yields are dependent on the number and size of joints intersected but generally are adequate for domestic and farm supplies.

QUATERNARY DEPOSITS

Unconsolidated deposits of Quaternary age overlie consolidated rocks in much of Door County. These deposits range in thickness from zero to 150±50 ft (pl. 2). In general, the unconsolidated deposits are thicker along the Lake Michigan coast and thinner on the uplands and along the escarpment on the Green Bay coast (pl. 2). Unconsolidated deposits are mostly Pleistocene in age and consist of till (an unstratified, unsorted mixture of ice-deposited sediments), lake deposits (silt and clay), and outwash (stratified gravel and sand).

The surficial materials are divided into four categories (pl. 2). Fine-grained stratified material consisting of alluvium, marsh, and lake deposits occurs mostly at lake level and in drainageways. Coarser grained stratified material, consisting of outwash, beach deposits, and sand dunes, occurs along the shorelines as beach sands and sand dunes, or with alluvial deposits in and near drainageways. Till in the form of moraines and drumlins occurs over much of the county and reaches maximum thicknesses in the southeast. The fourth category is composed of areas where the Quaternary deposits are less than 4 ft thick and is characterized by near-surface bedrock or bedrock exposures. These materials occur over large areas of the county, particularly north of Sturgeon Bay and in the southwest.

HYDROLOGIC CHARACTERISTICS OF ROCK UNITS

All or parts of three aquifer systems occur in Door County. From youngest to oldest they are the sand-and-gravel aquifer system; the Silurian dolomite aquifer system (Niagaran and Alexandrian aquifers); and the sandstone aquifer system, consisting of Ordovician and Cambrian bedrock units (upper and lower aquifers) (table 1). The sand-and-gravel aquifer system (Quaternary deposits) is commonly cased and yields little water except in the southeastern part of the county. However, the sand and gravel is hydraulically connected with the Silurian dolomite aquifer system and is an important source of recharge. Where impermeable till or residual soil overlie the bedrock, water in the bedrock may be locally under artesian pressure, especially along Sturgeon Bay and the western shoreline.

There are two bedrock aquifers. The Silurian dolomite aquifer system is the most important from the standpoint of water supply and will be discussed in greatest detail. Less is known of the sandstone aquifer system because no wells tap the lower sandstone aquifer, and only a few tap the upper sandstone aquifer.

SILURIAN DOLOMITE AQUIFER SYSTEM — NIAGARAN AND ALEXANDRIAN AQUIFERS

The Silurian dolomite aquifer system furnishes most of the water to wells in Door County. The Silurian dolomite aquifer system, as referred to in this report, includes the Niagaran aquifer, composed of the Racine Dolomite, Manistique Dolomite, and Burnt Bluff Formation; and the Alexandrian aquifer, composed of the Mayville Dolomite (table 1).

SOURCE AND OCCURRENCE OF GROUND WATER

Water occurs in the dolomite in vertical joints and bedding-plane joints. Vertical joints are commonly small and discontinuous and diminish both in size and number with depth. These joints normally yield small amounts of water. Vertical joints are only important water producers in the upper part of the Niagaran aquifer, where bedding-plane joints are scarce and less productive (table 1).

Bedding-plane joints, although fewer than vertical joints, are larger and more continuous and yield most of the water in the lower part of the Niagaran aquifer and in the Alexandrian aquifer. These joints are fractures along prominent bedding planes. Many of these joints have been widened by solution and can be identified and mapped over large areas in the county.

Eight water-bearing zones separated by relatively unproductive rocks have been identified in the Niagaran and Alexandrian aquifers and the Maquoketa Shale (pl. 3*A*). Water-bearing zone 1 is within the Niagaran aquifer. It divides this unit into an upper part, where most of the water is in vertical joints, and a lower part, where most of the water is in bedding-plane joints. The lower part of the Niagaran aquifer contains zones 2 and 3. Zones 4, 5, 6, and 7 are in the Alexandrian aquifer, and zone 8 is in the upper dolomitic section of the Maquoketa Shale.

Commonly, the total yield of a well is contributed by one or more of these zones. The zones may consist of a single bedding-plane joint or an interval of rock containing several joints. Certain zones, such as zone 5, consist of several very productive, laterally extensive joints; others, such as zone 6, consist of a single, less-productive joint that has less continuity. The water-bearing zones of greatest lateral extent are multiple joints located at distinctive lithologic changes.

Water in the dolomite aquifer system may be unconfined or artesian. Unconfined conditions prevail in water-table zones, such as the upper part of the Niagaran aquifer, where vertical joints predominate. Artesian conditions prevail locally, particularly in the southeast part of the county, where thick, relatively impermeable drift overlies the dolomite bedrock (pl. 2). Artesian conditions generally also prevail in the lower part of the Niagaran aquifer and the Alexandrian aquifer, where bedding-plane joints predominate, but where local unconfined conditions also may exist.

RECHARGE, MOVEMENT, AND DISCHARGE OF GROUND WATER

The Silurian dolomite aquifer system is recharged from precipitation that enters dolomite through near-vertical joints. The type and thickness of unconsolidated material overlying the bedrock affects the amount of precipitation entering the ground-water system. Near-surface rock areas and rock covered by sand and gravel are more easily recharged than areas covered by thick till and lake clays (pl. 2).

Recharge is normally greatest in the early spring of the year (fig. 5). In early spring, after the frost leaves the ground, snowmelt and spring rains enter the ground-water reservoir. During the growing season a high percentage of precipitation goes to satisfy demands of plants. After the first killing frost, but before the ground freezes, recharge again increases, if precipitation is sufficient. Recharge may again occur during warm winter periods if precipitation comes as rain or if sufficient snow cover is available over surficial fractures.

As the dolomite is recharged, water moves downward in the unsaturated zone through nearly vertical joints. When the water reaches the zone of saturation, its movement becomes nearly horizontal along bedding-plane joints. The hydraulic gradient controls the ground-water movement, but this gradient may be altered locally by pumping wells.

After a period of prolonged discharge, probably in late summer or early fall, hydraulic equilibrium develops between the vertical and horizontal joints, and the dolomite behaves as an unconfined aquifer.

The water table in the Silurian dolomite aquifer system is shown in plate 4 as it was in October 1971 after an extended period of no recharge. The map was constructed by plotting depth-to-water

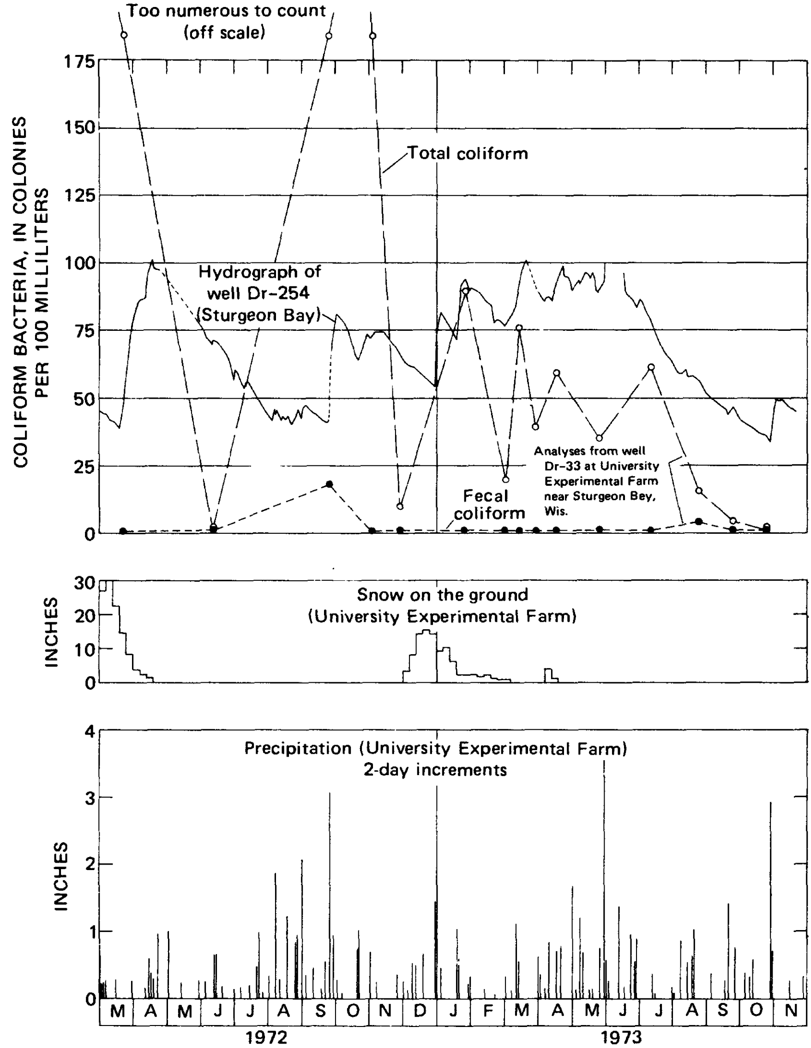


FIGURE 5. — Relationship of total and fecal coliform counts to ground-water levels, precipitation, and depth of snow on the ground.

measurements from about 200 wells. The lateral direction of ground-water movement is downgradient at right angles to the contour lines.

Lakes and streams in the county are fed by ground water. The major lakes, as well as the lower reaches of the major streams, are water-table outcrops, as shown in plate 4. North of Sturgeon Bay, the upper reaches of many streams dry up as the water table declines below the stream valley bottoms during summer and early fall.

The Silurian dolomite aquifer system discharges water into Lake Michigan, Green Bay, Sturegon Bay, some of the smaller lakes, streams, springs near the escarpment, and pumping wells.

WATER-LEVEL CHANGES AND THEIR SIGNIFICANCE

Water-level decline is slower and more constant than the rise. During periods of rapid recharge, the aquifer is under a pressure-head differential. As the ground water discharges into lakes and streams, water levels decline, and the aquifer approaches water-table conditions.

The water table for the Silurian dolomite aquifer system is delineated as it was during October 1971 (pl. 4). If this map had been constructed from measurements taken during recharge, such as during the spring of 1972 or 1973, the map would show much sharper relief.

A 24-year record (1950--73) of well Dr--7 (fig. 6), a 111-ft-deep well in dolomite shows a seasonal variability of water levels. The base water level in this well seems to be about 50 ft below land surface, the probable level of a horizontal water-bearing zone.

SPECIFIC CAPACITY AND WELL YIELDS

Specific-capacity data have proved useful in defining producing zones tapped by a given well and to estimate regional yields. The relationship between well discharge and the resultant water-level drawdown in the well is known as "specific capacity" and is expressed as yield/drawdown (gallons per minute per foot of drawdown). As an example, if a well is pumped at 20 gal/min and the water level is lowered 10 ft, the specific capacity of the well is 2.

The specific capacity and the yield of a well depend mainly on the water-bearing zones open to the well and, in the upper part of the dolomite, upon the occurrence of vertical joints.

Specific-capacity frequency curves for the Silurian units and the Maquoketa Shale are shown in figure 7. These curves indicate that the Alexandrian aquifer is the most productive, followed closely by the lower part of the Niagaran aquifer. The upper part of the Niagaran aquifer is less productive and would be dewatered with sustained pumping. The Maquoketa Shale is the least productive and probably most inconsistent of the water producers.

Well yields increase abruptly in the Silurian rocks as wells penetrate water-bearing zones. For example, the yield of Dr--265 increased by 50 gal/min as water-bearing zone 3 was penetrated (pl. 3*A*).

Well yields in the Silurian dolomite aquifer system meet most needs. A small area in the southwest corner of the county, where the dolomite is thin, is an exception (fig. 4). Wells here have to be drilled into the Maquoketa Shale or into the underlying sandstone aquifer system for adequate yields.

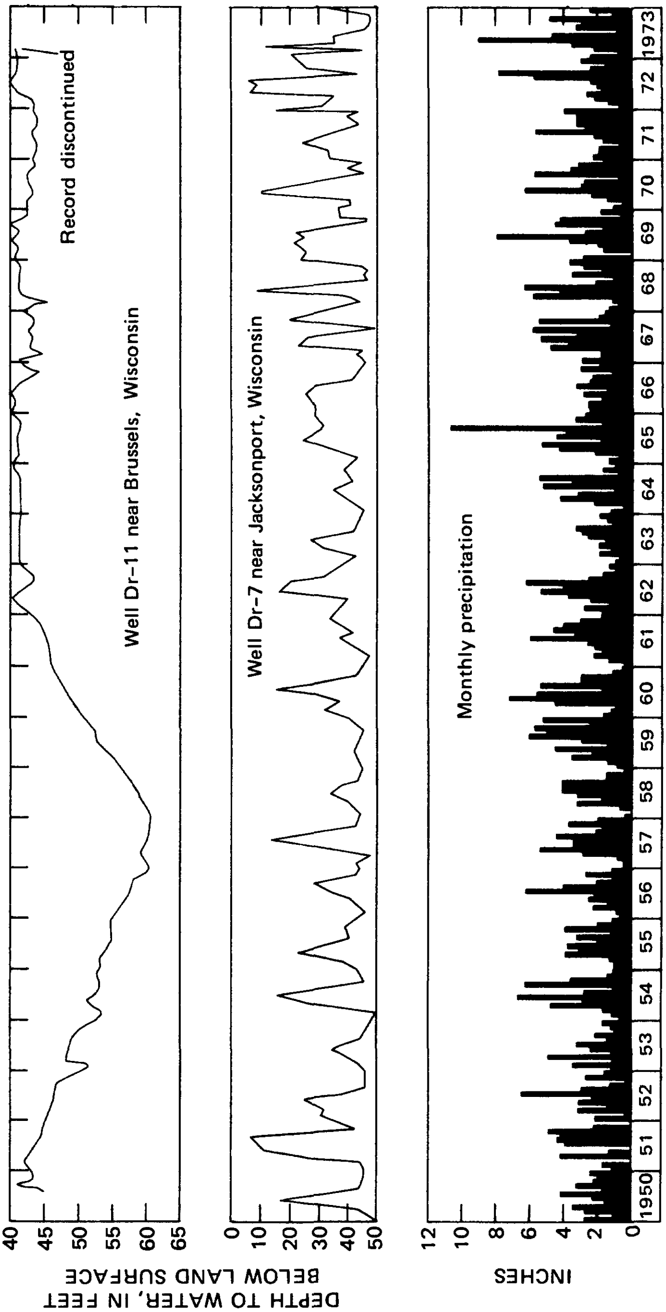


FIGURE 6.—Hydrographs of wells Dr-7 and Dr-11 and monthly precipitation.

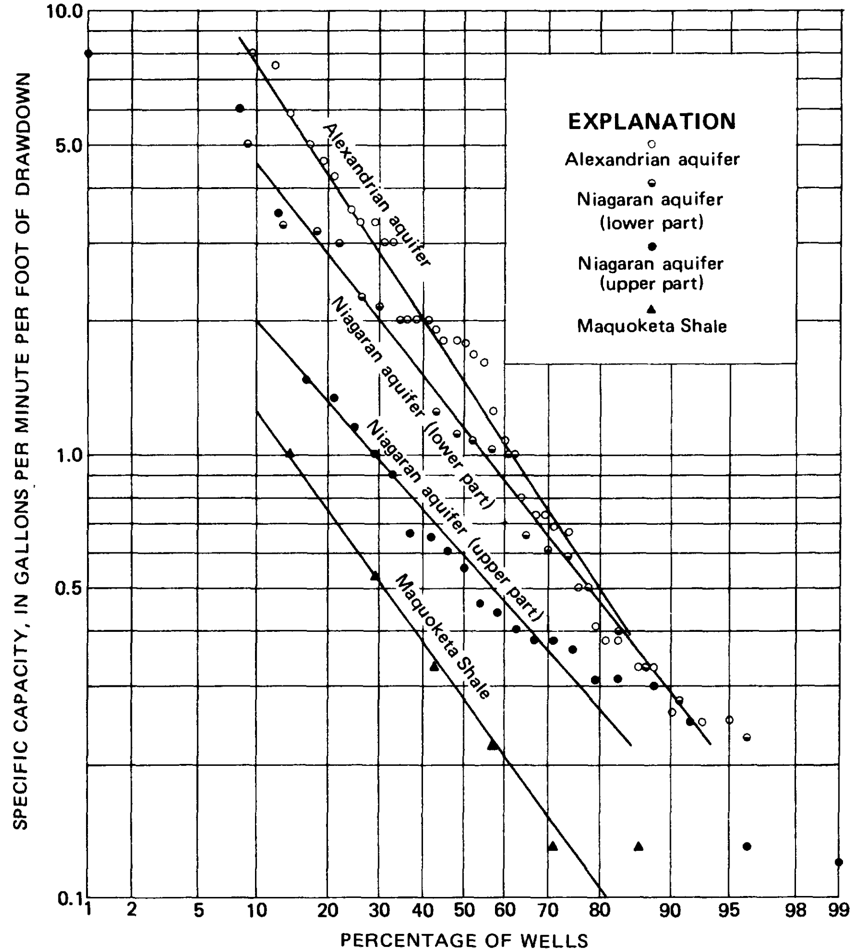


FIGURE 7.—Specific-capacity frequency curves for Alexandrian, Niagaran (lower part), and Niagaran (upper part) aquifers, and Maquoketa Shale.

Figure 8 is a water-availability map for the Silurian dolomite aquifer system in Door County. The yields assume full penetration of the dolomite and compliance with the State well-construction code (Wisconsin Department of Natural Resources, 1975, p. 26–35). Much of the county has potential well yields of 400 gal/min or more from the Silurian aquifers, although only the city wells in Sturgeon Bay and a few others are pumped at this rate. Well interference should not be a problem in the existing and anticipated areas of usage.

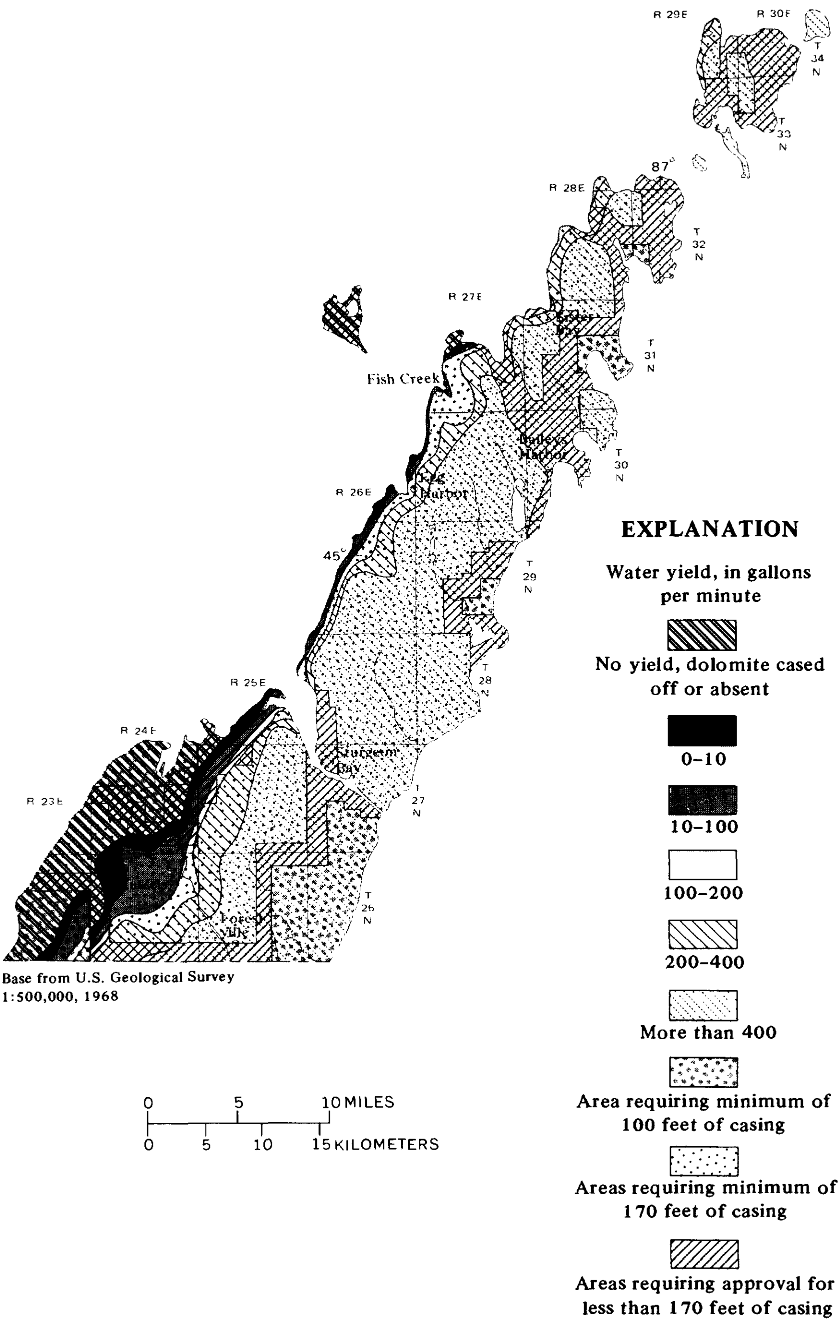


FIGURE 8. — Water availability from the Silurian dolomite aquifer system.

HYDROLOGIC ANALYSES OF STURGEON BAY, FISH CREEK, AND BAILEYS HARBOR SUBAREAS

A major concern of this study was the recharge and movement of ground water and associated contaminants. It was felt that the best approach toward this end would be to study a few subareas and to extrapolate the data thus gained to the entire county. Most of the U.S. Geological Survey drilling, aquifer tests, and other testing was concentrated in three detailed study areas; one at the north edge of the city of Sturgeon Bay, one in the Fish Creek–Peninsula Park area, and one in Baileys Harbor. In Sturgeon Bay two fully penetrating dolomite wells (Dr–254 and Dr–265) and three shallow observation wells (Dr–262, Dr–263, and Dr–264) were drilled into the dolomite (pl. 3*B*). In Fish Creek one deep well (Dr–268) was drilled through the Silurian dolomite into the Maquoketa Shale, and two observation wells (Dr–266 and Dr–267) were drilled into the dolomite. In addition to the Sturgeon Bay and Fish Creek subareas, one test well (Dr–255) was drilled through the Silurian dolomite into the Maquoketa Shale in the village of Baileys Harbor (pl. 3*A*).

The positions of water-bearing joints and individual and cumulative water yields from these joints were determined while the test wells were being drilled (pl. 3*A*, 3*B*).

GEOPHYSICAL TESTS

Borehole geophysical methods, lithologic data, and hydrolic data were used to interpret the subsurface geology and hydrology (pl. 3*A*,*B*). Caliper logs and resistivity logs were beneficial in determining the depth and character of joints. Gamma-ray logs provided a measure of the clay of shale content of rocks and helped determine the degree of clay filling in joints. Gamma-ray logs, resistivity logs, and caliper logs were used in lithologic and stratigraphic correlation.

Flow-meter, fluid-conductivity, and temperature logs provided information for subsurface interpretations. A flow-meter log for well Dr–268 (pl. 3*B*), which was flowing 50 gal/min, indicated that 30 gal/min was entering the well from zone 7, and 20 gal/min was coming from zones 6 and 7. The fluid-conductivity logs (pl. 3*B*) are measures of the dissolved solids of the water in the rock penetrated by the borehole. They are more fully discussed in the water-quality section. Temperature logs (not shown) indicate that temperature increased with depth. The temperature near the Silurian dolomite–Maquoketa Shale contact was about 2°C warmer than in the upper part of the dolomite. Only slight temperature shifts occurred in the water-bearing zones in the well when they were logged in June. Temperature logs may be useful for identifying recharge water at certain times of the year, such as when cold water from melting snow is entering the relatively warm ground-water reservoir.

AQUIFER TESTS

Aquifer tests were made to help identify the hydrologic characteristics in the Silurian dolomite aquifer system. Aquifer tests are used to determine hydraulic properties —transmissivity and storage coefficient —of an aquifer or group of aquifers. Transmissivity (*T*) is expressed as the rate at which water of the prevailing kinematic viscosity is transmitted through a unit width of the aquifer under a unit hydraulic gradient. The storage coefficient (*S*) is defined as the volume of water an aquifer releases from or takes into storage per unit surface area of the aquifer per unit change in head.

The difference between an ideal porous medium, assumed in aquifer-test analysis, and the actual anisotropic dolomite suggests that aquifer-test analyses will not completely describe local responses to pumping. However, the generally regular potentiometric surface, particularly north of Sturgeon Bay (pl. 4), and an analysis of well hydrographs, suggest an extensive degree of interconnection of water-yielding joints which might allow aquifer tests to reflect regional conditions fairly closely.

Twelve aquifer tests were made at the sites of five test wells during different stages of well completion, using techniques outlined by Lohman, 1972 (table 2).

Transmissivity in the Silurian dolomite aquifer system ranged from 4.0 ft^2/d, in a section of the upper part of the Niagaran aquifer near Sturgeon Bay penetrated by well Dr–254 (pl. 3*B*) to 13 000 ft^2/d, in the upper and middle parts of the Alexandrian aquifer penetrated by well Dr–268 near Fish Creek. Representative transmissivities for the entire saturated thickness of the dolomite system, assuming full well penetrations, are between 10 000 and 11 000 ft^2/d near Sturgeon Bay and 6900 ft^2/d in Baileys Harbor. A transmissivity of about 13 200 ft^2/d can be expected in the Fish Creek area, where several major continuous water-bearing zones are present.

Storage coefficients (*S*) listed in table 2 ranged from 0.0002 to 0.002. These values indicate water under generally artesian conditions.

An 8-hour aquifer test was made at the sit of well Dr–265 (pl. 3*A*,*B*) on September 19, 1972, when the well was 170 ft deep and before casing was installed. Dr–265 was open to zones 1, 2, and 3, all in the Niagaran aquifer. The average pumping rate was 125 gal/min. The computed transmissivity was 3200 ft^2/d for Dr–265, and the storage coefficient was 0.002 (table 2). The specific capacity was 4.3 (gal/min)/ft of drawdown. The hydrographs in figure 9 show the

TABLE 2. — *Summary of aquifer tests in the Silurian dolomite aquifer system*

[Leaders indicate no data available]

Pumping well	Location	Observation well	Date of test	Pumping rate (gal/min)	Saturated thickness (ft)	Well depth tested (ft)	Duration of test (hours)	Composite transmissivity (*T*) values (ft^2/d)	Composite storage coefficient values (*S*)	Aquifer
Dr–254	Sturgeon Bay	...	July 1971	13	80	20–100	1.2	4.0	...	Upper Niagaran.
		...	Aug. 1971	48	165	100–265	2.7	1 400	...	Lower Niagaran and Upper Alexandrian.
		Dr–265	June 1973	225	110	100–210	24.0	1 700	0.0002	Do.
		...	Aug. 1971	192	302	100–402	10.3	10 200	...	Lower Niagaran and Alexandrian.
Dr–255	Baileys Harbor	Dr–261	..do.	40	95	7–102	1.7	9 000	...	Upper Niagaran.
		Dr–261	..do.	43	193	102–295	2.0	900	.0002	Lower Niagaran and Upper Alexandrian.
		Dr–261	..do.	220	417	102–519	11.9	6 900	.002	Lower Niagaran, Alexandrian, and Upper Maquoketa.
Dr–265	Sturgeon Bay	Dr–254 Dr–262 Dr–263 Dr–264	Sept. 1972	125	158	12–170	8.0	3 200	.002	Niagaran.
		Dr–254 Dr–262 Dr–263 Dr–264	June 1973	290	272	170–442	24.0	10 700	...	Lower Niagaran, Alexandrian, and Upper Maquoketa.
Dr–268	Fish Creek	Dr–266 Dr–267	Sept. 1972	270	95	5–100	7.7	13 200	...	Upper Alexandrian.
		Dr–266 Dr–267	Aug. 1973	250	324	100–322	20.0	17 800	...	Lower Alexandrian.
Sister Bay	Sister Bay	Dr–273	Oct. 1972	[1]	70	138–208	24.0	6 200	...	Do.

[1] Pumping rate variable.

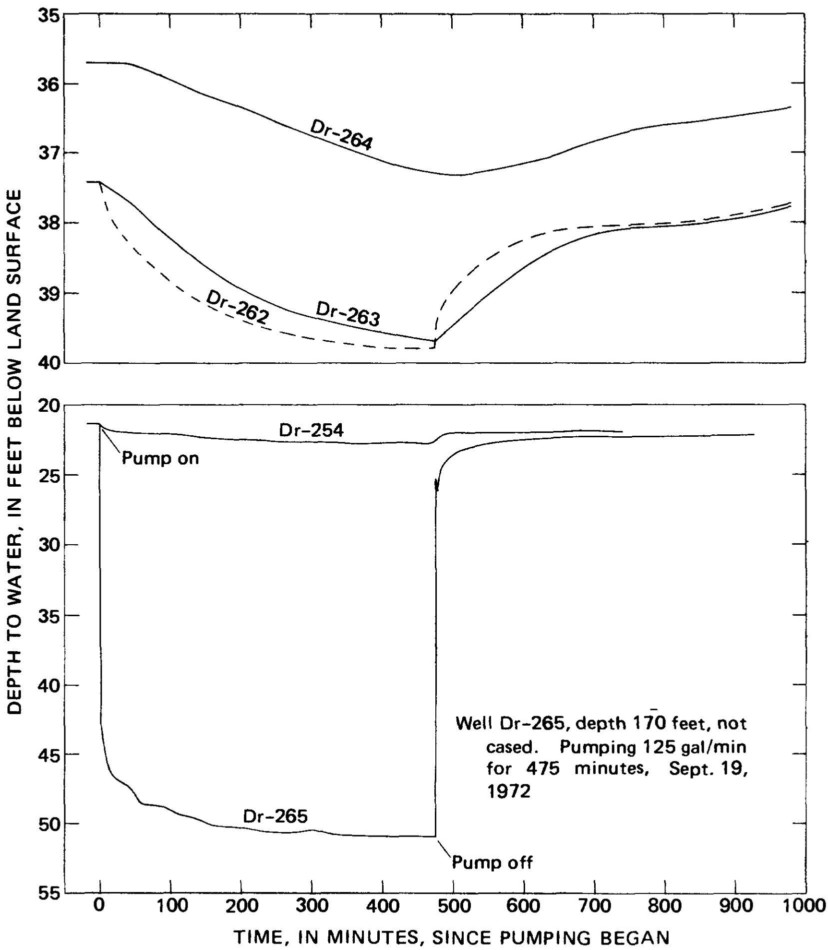


FIGURE 9. — Changes in water levels in pumping well and observation wells in Sturgeon Bay, September 1972.

decline and recovery in the four observation wells and the pumped well. The water level in Dr--254 was drawn down only 1.33 ft while pumping Dr--265, even though the wells were only 169 ft apart. This is because Dr--254 was open to deeper water-bearing zones in the Alexandrian aquifer (pl. 3*B*). A greater and more immediate effect was noted in Dr--262, which was 1000 ft from the pumped well and open only to water-bearing zone 2. Drawdown in Dr--263 was more gradual, although nearly as great as in Dr--262, indicating a good vertical connection with zone 2. Dr--264, open to zone 1, was less affected than Dr--262 and Dr--263 but more affected than Dr--254.

A second aquifer test was made in June 1973 at the site of well Dr–265, after the well was completed to a depth of 420 ft and 170 ft of casing had been installed. In this test the well was open to water-bearing zones 3, 4, 5, and 7 (pl. 3*B*) and was pumped at 290 gal/min for 24 hours. The computed transmissivity was 10 700 ft^2/d, and the specific capacity was 15.0 (gal/min)/ft of drawdown. Figure 10 shows the hydrographs of the pumped well and observation wells. The drawdowns for this test were 19.30 ft for Dr–265; 3.45 ft for Dr–254; 0.70 ft for Dr–262; 0.64 ft for Dr–263; and 0.45 ft for Dr–264. The reduced drawdowns in the shallow observation wells and the increased drawdown in Dr–254 indicated that water-bearing zones 1 and 2 had been sealed by the addition of 170 ft of casing in the pumped well and that most of the water was coming from zones 3, 4, 5, and 7.

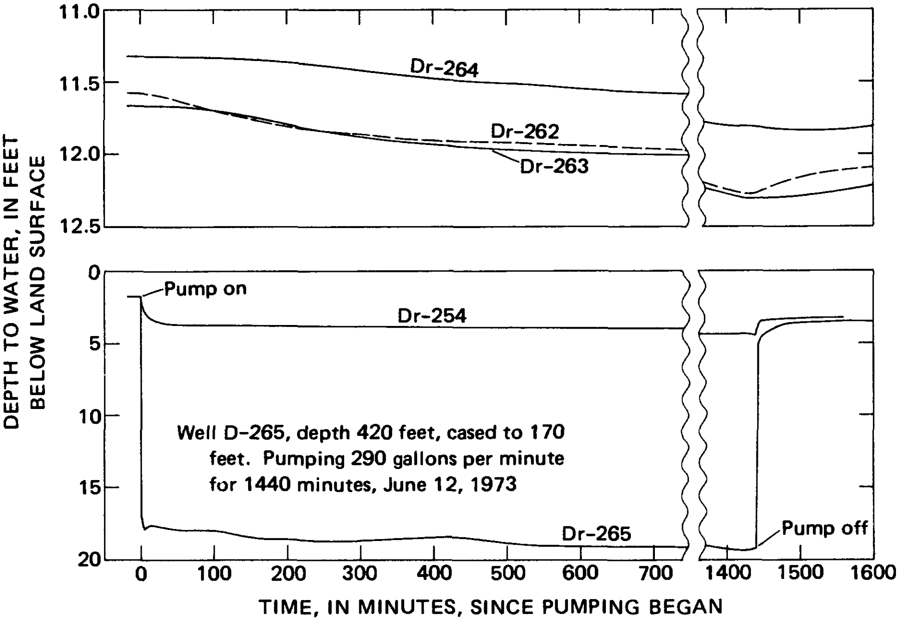


FIGURE 10.—Changes in water levels in pumping well and observation wells in Sturgeon Bay, June 1973.

Similar aquifer tests at Fish Creek also indicated that water-bearing zones could be sealed effectively by casing.

SANDSTONE AQUIFER SYSTEM

The sandstone aquifer system includes all of the Cambrian and Ordovician rocks between the Precambrian basement and the Maquoketa Shale (table 1). It is further divided into upper and lower sandstone aquifers, however, only the upper part of the aquifer is used

(1974) for water supply in Door County. The upper sandstone aquifer consists of Ordovician units below the Maquoketa Shale and the lower sandstone aquifer consists of the Cambrian formations. The depth to the top of the aquifer ranges from about 400 to 900 ft.

Water occurs in the sandstone aquifer system in openings between sand grains and to a lesser degree along fractures and bedding planes. Permeability within the system differs according to sorting of the sand grains, the degree of cementation, and the presence or absence of less permeable strata, such as shale and dolomite.

The sandstone aquifer system is recharged by precipitation and lake-water infiltration in the outcrop area northwest of Door County and under Green Bay. The Silurian dolomite aquifer system also contributes some recharge by downward leakage through the imperfect confining layers of the Maquoketa Shale. Water in the sandstone aquifer system is under artesian conditions throughout Door County.

The water moves downgradient from areas of recharge to areas of discharge. The regional hydraulic gradient is to the southeast and parallel to the regional dip of the rocks.

A few wells in Door County obtain part or all of their water from the upper sandstone aquifer. Most of these wells are in the southwestern part of the county, where the dolomite aquifer is absent or thin (figs. 4, 8). The St. Peter Sandstone is the main source of water within the upper part of the sandstone aquifer. The quantity of water available from the St. Peter Sandstone is related directly to its thickness, which ranges from less than 1 ft to 90 ft.

The specific capacities of wells finished or tested in the upper sandstone aquifer range from 0.03 to 1.5 (gal/min)/ft of drawdown (table 3).

TABLE 3. — *Specific capacities of wells in the upper sandstone aquifer system*

Well	Pumping rate (gal/min)	Drawdown (ft)	Specific capacity [(gal/min)/ft]	Length of test (h)	Thickness of St. Peter Sandstone (ft)
Dr--274	20	90	0.22	3	15
Dr--275	15	100	.15	2	10
Dr--276	15	155	.10	2	3
Dr--277	20	75	.27	1	10
Dr--278	25	110	.23	1.5	10
Dr--281	3	90	.03	4	10
Dr--282	15	110	.13	3	15
Dr--283	15	125	.12	3	15
Dr--284	15	50	.30	4	15
Dr--285	6	210	.03	4	1
Dr--289	15	10	1.50	2	66

A test well (Dr--289), penetrating most of the sandstone aquifer system, was drilled 3.5 mi southwest of Jacksonport (sec. 32, T. 29 N.,

R. 27 E.). Specific capacities of the units penetrated in this well were 1.50 (gal/min)/ft for the upper part of the aquifer (table 3) and 0.69 (gal/min)/ft for the lower part.

Pumping of the sandstone aquifer system affects the potentiometric surface over large lateral distances. Well Dr–11 (fig. 6), in southwestern Door County, 22 mi northwest of the city of Green Bay, shows the effect of Green Bay's pumping.

The sandstone aquifer system is a potential source of additional water in Door County, although the quality of the water is generally poor. Wells that will yield 250 to 400 gal/min can be developed in the aquifer. Municipalities and other large users of ground water might investigate the sandstone aquifers as a supplement to or a replacement for water presently derived from the Silurian dolomite aquifer system.

TABLE 4. — *Use of ground water in 1972*

Use of water	Pumpage (million gallons per year)	Percent of total usage
Municipal (residential and city-serviced industrial and commercial)	500	35.7
Industrial	105	7.5
Private (permanent residents)	330	23.5
Recreational (including parks, resorts, and summer homes)	200	14.3
Livestock	260	18.6
Irrigation	5	.4
Total used	1400	100.0

USE OF WATER

Water supplies in Door County come from both ground-water and surface-water sources. Ground water is used mostly. Surface water is used mainly for recreation, wildlife, and for about 20 percent of the water used by livestock. Small amounts of surface water also are used for irrigation.

Ground-water withdrawal for all purposes in Door County in 1972 was 1400 million gallons (table 4).

Door County has approximately 6200 households, of which 2270, or 37 percent, were served by community water facilities in May 1973. The remaining households obtained their water from private wells.

Sturgeon Bay (population 7500) was the only community in 1972 that had a public water system. The city receives its supply from six wells ranging in depth from 298 to 1178 ft. Average pumpage from these wells is about 1.4 Mgal/d. Sister Bay, with a population of about 700, has installed a community water system and began pumping water from two wells in 1973. The villages of Ephraim, Fish Creek, and Baileys Harbor and possibly others may develop community water systems in the future.

NATURAL CHEMICAL QUALITY

The chemical character of water may restrict its use. Although use requirements are not uniform, the chemical character of water for public supplies is commonly judged by U.S. Public Health Service (1962) recommended standards. These standards recommend an upper limit of: Iron, 0.3 mg/L (milligrams per liter); magnesium, 250 mg/L; chloride, 250 mg/L; sulfate, 250 mg/L; nitrate, 45 mg/L; and dissolved solids preferably not exceeding 500 mg/L, but as much as 1000 mg/L may be permitted.

Chemical analyses were made of water from 52 wells (table 5). Analyses are grouped as to their geologic source.

Streams, lakes, and springs in Door County are all associated with the Silurian dolomite, and their natural water quality is similar. The water in streams and lakes has somewhat less dissolved solids than ground water, owing to the diluting effect of rain and surface runoff.

NIAGARAN AND ALEXANDRIAN AQUIFERS

Water in the Silurian dolomite aquifer system is a very hard calcium magnesium bicarbonate type. It is generally uniform in chemical character down to water-bearing zone 7, where dissolved solids increase considerably (pl. 3*B*). This characteristic is significant in some parts of southwestern Door County, where water supplies are obtained from the lower part of the Alexandrian aquifer or the upper part of the Maquoketa Shale. In the southwestern part of the county and the area near the village of Fish Creek, much of the water is obtained from the lower part of the dolomite or the Maquoketa Shale and dissolved solids exceed 500 mg/L (fig. 11).

Chemical analyses of water from 33 wells in the dolomite aquifer are included in table 5. Water from almost 25 percent of the sampled wells had excessive iron. None of the samples exceeded 45 mg/L of nitrate, the upper limit of this constituent. The temperature of the water is near the mean annual air temperature. Temperature logs from test wells showed temperatures ranging from 9.5° to 11.0°C, with a gradual increase from the top of the dolomite to the bottom and a sharper increase closer to the Maquoketa Shale below zone 7.

MAQUOKETA SHALE

Although the Maquoketa Shale is not regarded as an aquifer, several low-capacity wells obtain all or most of their water from its upper dolomitic beds. The water ranges from a calcium magnesium sulfate type to a sodium sulfate type and has very high dissolved solids.

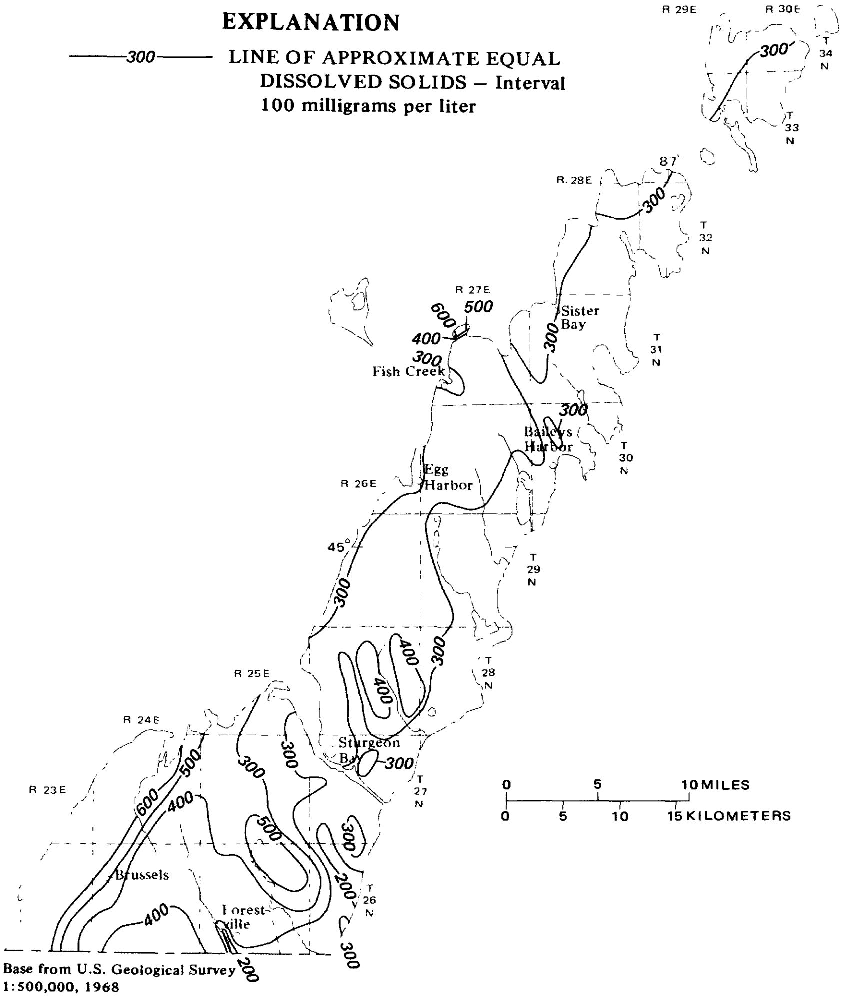


FIGURE 11. — General distribution of dissolved solids from the Silurian dolomite aquifer system.

All six samples of water from the Maquoketa Shale greatly exceeded the recommended values for sulfate and dissolved solids (table 5). Two of the six samples also exceeded the recommended standards for chloride and iron.

UPPER AND LOWER SANDSTONE AQUIFERS

Most of the wells penetrating the upper sandstone aquifer are also open to the Maquoketa Shale. Water samples include contributions from both units. Water quality in the upper sandstone aquifer is simi-

TABLE 5. — *Selected chemical analyses of ground water*

[Sample source: Sn, Niagaran aquifer; Sa, Alexandrian aquifer; Om, Maquoketa Shale; Ous, upper sandstone aquifer; and Cls, lower sandstone aquifer. Analysis by: G, U.S. Geological Survey; L, Wisconsin State Laboratory of Hygiene. All results in milligrams per liter except temperature, specific conductance and pH. Leaders indicate no data available]

Well (Dr–1)	Date of collection	Sample source	Analysis by	Temperature °C	Total iron (Fe)	Calcium (Ca)	Magnesium (Mg)	Sodium (Na) and potassium (K)	Bicarbonate (HCO_3)	Sulfate (SO_4)	Chloride (Cl)	Nitrate (NO_3)	Dissolved solids	Hardness (as $CaCO_3$)	Specific conductance (micromhos per cm at 25° C)	pH	Remarks
28	Nov. 10, 1972	Sn	G	11.0	.06	62	33	1.6	326	13	1.1	0.4	274	290	500	7.9	
55	May 29, 1968	Sn	G	9.0	.78	51	39	1.9	318	18	1.0	.2	263	288	500	7.7	
57	June 12, 1968	Sn	G	11.0	.08	20	18	15	160	13	8.0	.6	158	124	280	8.2	Possibly softened.
58	Oct. 12, 1971	Sn	G	9.0	.08	62	29	1.5	302	24	4.0	7.8	276	270	480	7.4	
68	Oct. 26, 1971	Sn	G	12.0	.08	110	43	8.5	426	38	2.6	38	500	450	790	7.3	
128	Sept. 8, 1972	Sn	G	18.0	3.8	66	25	3.4	316	6.0	1.0	.0	250	270	470	7.5	
151	...do	Sn	G	11.0	.04	60	30	8.7	300	16	16	4.1	273	280	510	7.4	
185	Oct. 26, 1971	Sn	G	11.5	.05	46	42	38.2	375	37	12	16	370	290	610	7.3	
187	Sept. 8, 1972	Sn	G	13.0	.06	54	28	6.7	288	14	3.6	.7	250	250	440	7.7	
212	...do	Sn	G	13.0	.06	64	26	2.8	286	22	3.0	1.5	264	260	460	8.0	
215	Nov. 10, 1972	Sn	G	11.5	.03	65	27	4.9	294	16	6.0	13	277	270	490	7.8	
244	Sept. 8, 1972	Sn	G	11.0	.04	70	32	3.5	332	18	8.0	8.3	276	310	510	8.0	
254	July 11, 1971	Sn	L	10.5	3.2	87	36	28	383	29	54	20	438	368	850	8.2	Sample taken when well was 100 feet deep, with no casing. From water-bearing zone 1.
255	Aug. 6, 1971	Sn	L	11.0	.30	69	33	5.5	358	12	9.0	4.4	366	308	330	7.8	Sample taken when well was 102 feet deep, with no casing. From water-bearing zone 1
2	June 30, 1966	Sn, Sa	G	...	1.9	74	32	...	337	24	9.0	1.8	348	320	...	7.8	
13	...do	Sn, Sa	G	...	.03	54	31	1.0	312	6.0	3.0	.4	250	264	460	7.5	
21	...do	Sn, Sa	G	...	.49	68	34	...	320	21	8.0	14.0	362	312	...	7.4	
33	May 28, 1968	Sn, Sa	G	14.0	.14	49	56	10	310	36	24	39	410	337	580	7.7	
47	May 29, 1968	Sn, Sa	G	15.0	.03	74	37	...	372	25	3.0	.5	322	353	670	7.5	
254	Aug. 3, 1971	Sn, Sa	L	8.3	.10	88	41	55	393	29	100	23	614	388	1000	7.9	Sample taken when well was 265 feet deep, with 100 feet of casing. From water-bearing zones 2, 3, 4, and 5.
254	Aug. 13, 1971	Sn, Sa	L	...	.40	60	43	15	349	20	30	...	422	328	680	8.0	Sample taken when well was completed to 402 feet, with 100 feet of casing. From water-bearing zones 2, 3, 4, 5, and 7.

255	Aug. 11, 1971	Sn, Sa	L	10.0	.03	54	31	1.0	312	6.0	3.0	.4	250	264	460	7.7	Sample taken when well was 295 feet deep, with 100 feet of casing. From water-bearing zones 2, 3, and 4.
255	Aug. 19, 1971	Sn, Sa, Om	L	...	.40	42	42	1.0	310	23	2.0	.4	350	278	560	8.6	Sample taken when well was completed to 519 feet, with 100 feet of casing. From water-bearing zones 2, 3, 4, 5, 6, 7 and 8.
3	June 30, 1966	Sa	G	...	.03	70	30	...	307	23	6.0	14.0	336	300	...	8.2	
36	May 28, 1968	Sa	G	...	.10	72	32	3.0	362	15	4.0	.2	304	311	540	7.7	
37	May 29, 1968	Sa	G	8.0	.07	65	31	2.0	318	18	4.0	1.8	274	290	510	7.6	
61	Oct. 12, 1971	Sa	G	...	3.5	67	32	5.0	368	2.8	3.9	.1	307	300	530	7.7	
144	Oct. 13, 1971	Sa	G	10.5	.05	70	30	2.0	294	28	4.0	9.0	298	300	500	8.4	
197	...do	Sa	G	11.5	.21	62	28	3.0	305	22	1.0	.2	277	270	470	7.7	
268	Oct. 13, 1972	Sa	L	...	2.0	62	32	...	266	30	3.0	.5	324	288	...	...	Sample taken at start of aquifer test. Well was 102 feet deep with no casing. From water-bearing zone 5.
268	...do	Sa	L	...	.10	66	35	...	274	19	6.0	.7	404	308	...	...	Sample taken 7 hours into aquifer test. Well was 102 feet deep with no casing. From water-bearing zone 5.
54	May 30, 1968	Sa, Om	G	9.0	.22	...	...	...	396	18	5.0	2.8	332	350	610	7.4	
268	Aug. 22, 1973	Sa, Om	L	...	.10	66	26	13	260	20	3.0	.5	344	272	...	7.6	Sample taken when well was 329 feet deep, with 100 feet of casing. From water-bearing zones 6, 7 and 8.
18	July 7, 1970	Om	G	...	.16	344	107	13	245	1080	20	.1	1710	1300	1870	7.3	
18	May 20, 1968	Om	G	...	.40	286	83	11	268	776	14	.3	1430	1060	1580	7.4	
76	Sept. 7, 1972	Om	G	...	.38	250	79	320	340	1000	230	1.8	2080	950	2820	7.3	
93	Nov. 7, 1972	Om	G	...	.14	320	100	650	100	2000	320	1.6	3770	1200	4450	7.2	
97	Sept. 7, 1972	Om	G	...	.57	200	71	219	206	500	380	1.8	1460	790	260	8.2	
99	...do	Om	G	...	.04	270	52	104	294	760	18	1.7	1440	890	1700	7.3	
4	Oct. 22, 1954	Om, Ous	L	...	0	103	41	...	281	128	114	...	666	423	...	7.3	
4	Nov. 1, 1967	Om, Ous	L	...	.22	67	33	...	288	36	28	1.0	324	303	...	7.4	Part of hole in upper sandstone aquifer and Maquoketa Shale may have caved since 1954 sample.
214	Nov. 12, 1971	Om, Ous	G	9.5	1.1	100	46	155	204	330	170	0	964	440	1440	7.3	
277	April 2, 1974	Om, Ous	G	11.5	2.4	180	63	209	211	480	330	.4	1580	710	2270	7.4	
278	...do	Om, Ous	G	11.0	.68	180	68	208	205	440	380	.2	...	...	...	...	
281	...do	Om, Ous	G	9.5	3.8	150	68	292	222	560	320	.6	1640	650	2370	7.5	
283	...do	Om, Ous	G	10.0	.5	180	65	198	202	410	370	.01	1440	720	2230	7.3	
289	May 23, 1975	Ous	G	12.0	...	264	73	170	188	520	450	.2	1940	960	2400	7.5	
289	...do	Cls	G	13.5	...	268	72	170	189	526	420	.1	1950	965	2550	7.3	

lar to that in the shale, although levels of dissolved solids are generally lower. Concentrations of iron, sulfate, chloride, and dissolved solids locally exceed recommended limits.

No wells are presently developed in the lower sandstone aquifer in Door County.

In the test well drilled southwest of Jacksonport, selected samples were taken from both the upper and lower sandstone aquifers. Water samples from the two aquifers were similar. The water was slightly saline, with a dissolved solids concentration greater than 1900 mg/L. U.S. Public Health Service (1962) recommended standards also were exceeded for sulfate and chloride concentrations (table 5).

SANITARY WATER QUALITY IN THE SILURIAN DOLOMITE AQUIFER SYSTEM

Thin soil cover and fractured bedrock allow ground-water contaminants easy entry to the ground-water system in large areas of Door County. Many contaminants enter the Silurian dolomite aquifer system with recharging ground water. These contaminants include gasoline, oil, road salt, domestic and farm wastes, cannery wastes, effluent from septic tanks, and dry wells. Both chemical and bacterial contamination occur in the county. The term "contamination," as used in this report, refers to either chemical substances or bacteria in the ground water that make it unfit, or undesirable, for human consumption.

The most widespread type of ground-water contamination is bacterial. Most organisms in ground water are not harmful, but some may cause disease and sickness if ingested. Harmful organisms include pathogenic bacteria, viruses, and intestinal parasites that may be present in the feces of warm-blooded animals, including man.

Tests for specific pathogenic organisms have proved difficult to evaluate. Nonpathogenic coliform bacteria coexist with the pathogens and have been used as indicator tests. Research Report 42 by the Wisconsin Department of Natural Resources (Schuettpelz, 1969) explains coliform testing procedures and how these tests may be used to indicate the presence of pathogenic organisms.

Where total coliform counts are relatively low, pathogenic bacteria are less likely to be present (Schuettpelz, 1969, p. 3). It does not necessarily follow, however, that where total coliform counts are high, pathogenic bacteria will be present in great amounts. Tests for fecal coliforms may be more indicative or recent contamination by warm-blooded animals because fecal members are normally present only in the gut and fecal materials and are not expected to survive as long as nonfecal members in the unfavorable environment provided by the water.

Five wells and two springs, were monitored for total and fecal coliform bacteria from March 1972 through October 1973. Three of the wells showed less than two colonies of total and fecal coliform per 100 milliliters of water for all samples. In the other two wells total coliforms ranged from less than 2 to more than 200 colonies per 100 milliliters of water. Fecal coliform colonies in these two wells were two or less per 100 milliliters in all but two tests. A plot of the total and fecal coliform analyses for one of these two wells (Dr–33) is shown in figure 5. The two springs had total coliform counts ranging from less than 2 to 200 colonies per 100 milliliters and fecal coliform counts from less than 2 to 9 colonies per 100 milliliters.

Figure 5 shows the total and fecal coliform analyses from Dr–33, the hydrograph of well Dr–254, the depth of snow on the ground, and precipitation from March 1972 through November 1973. This figure shows a relationship between types, concentrations, and longevity of the coliform groups and the recharge and movement of ground water. The composite graphs indicate that the highest concentrations of total coliform occur when the water level is rising, the lowest when the level is declining. A relatively rapid die-off rate or flushing of total coliform is indicated; in one instance total coliform dropped from 600 colonies per 100 milliliters to 10 colonies per 100 milliliters (estimated) between November 3 and November 29, 1972. The fecal coliform count in the sampled well (Dr–33) rose from 2 colonies or less to 18 colonies per 100 milliliters in late August 1973. All other samples had less than two colonies per 100 milliliters. The fecal coliform group was unable to survive, or was not introduced, in the unsaturated zone through the winter. It may enter the ground-water system with recharging water during late summer and early fall, when precipitation increases.

The Silurian dolomite aquifer system is not contaminated everywhere. Ground-water contamination occurs in zones or enclaves that originate from point sources of contamination. These then elongate in the direction of ground-water flow. The contaminated zones constitute only a small percentage of the total ground-water system. Many of the zones represent manmade contamination and are located in areas with closely spaced septic systems. Drilling a new well in these areas may result in contaminated water entering the well.

Well contamination can be greatly reduced by properly casing the well, as shown in the following tests. Sanitary-quality samples were taken from well Dr–268 located at the edge of the village of Fish Creek during two different pumping tests. The first test was in September 1972, when the well was uncased and 102 ft deep. The second test was August 22–23, 1973, when the well was 329 ft deep with 100 ft of casing. Plots of these samples are shown in figure 12. The pumping rate during the first test was 270 gal/min and 250 gal/min during

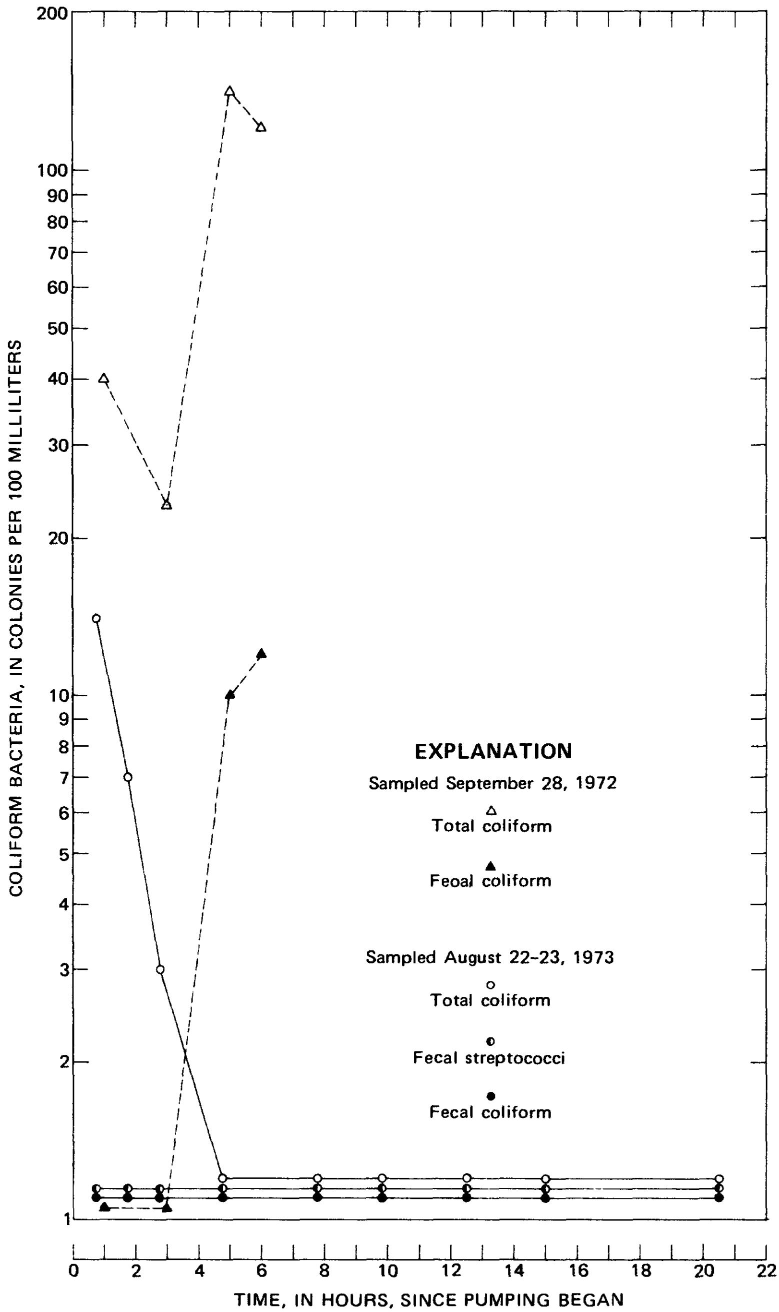


FIGURE 12. —Total and fecal coliform counts (for samples from pumped well Dr–268) against time of pumping.

second. In the 1972 test after 1 hour of pumping, the total coliform count was 40 colonies per 100 milliliters, and the fecal coliform count was less than 2 per 100 milliliters. The total coliform count dropped somewhat during the next 2 hours of pumping, and the fecal coliform remained at less than 2 colonies. Between the third and fifth hour of pumping, the counts for both coliform groups rose and were relatively high at the end of the 6-hour test. The rise in coliform counts after the third hour of pumping indicates contaminated water was being drawn into the well.

After deepening the well and casing off the shallow ground water the second test was conducted in 1973. The total coliform count was 14 colonies per 100 milliliters, and the fecal coliform and fecal streptococci counts were less than 2 colonies per 100 milliliters after 1 hour of pumping. The total coliform count gradually decreased until, at the fifth hour, it was less than two colonies per 100 milliliters. Total coliform, fecal coliform, and fecal streptococci samples remained less than two colonies throughout the test. The gradual reduction of total coliform from the initial concentrations, with sustained low counts during the remainder of the test, indicate that contaminated water was not drawn into the well.

The type and thickness of the unconsolidated material at land surface affect the entry of bacteria into the bedrock and ground-water system. Romero (1970, p. 38) showed that the attenuation of bacteria concentrations is rapid in thick soils with low permeability, but attenuation decreases with increased permeability and a reduction in soil thickness.

In Door County the probability of bacterial contamination of the ground-water system is especially great where fractured dolomite is at or near the surface. Once bacteria can reach the saturated zone in fractured dolomite they travel long distances underground with little attenuation.

In one phase of testing in Sturgeon Bay, a tracer dye was introduced into zone 3 through well Dr–265 (pl. 3*B*), while well Dr–254, 173 ft away, was being pumped at 225 gal/min. The dye moved from Dr–265 into Dr–254, up through the well to the ground surface, and through 150 ft of discharge pipe in slightly less than 2 minutes.

Many wells tapping dolomite yield turbid water shortly after heavy rain, indicating rapid movement of water and sediment from the recharge areas into the well. Turbidity indicates possible contamination, and any wells yielding such water are suspect.

Depth to water and density of septic systems are other factors that may affect entry of contaminants into the ground-water system. A septic system located near a well increases the chances of contamination, particularly where the overburden material is very thin and permeable and especially if the system is upgradient from pumping wells. In areas of great topographic relief where the ground-water level is far below the ground surface, the presence of permeable bedrock might allow easy entry and transmission of contaminants.

Physical and cultural factors that may influence contamination are shown in plate 5. Area A has little or no unconsolidated material over bedrock, so that surface water might easily enter the Silurian dolomite aquifer system. Area B has great topographic relief with a deep water table. Surface recharge would generally be through permeable unsaturated bedrock into the Silurian dolomite aquifer system, with little or no horizontal movement. Area C is overlain by thin permeable material with rapid recharge potential. Area D has concentrations of population using private septic systems. Contamination potential is greatest where areas designated A overlap those designated B, C, or D.

WELL-CONSTRUCTION CRITERIA

Several test wells were drilled during the study to evaluate the effects of casing length and grouting techniques on water quality. Increasing casing depth effectively sealed off water from upper water-bearing zones and proper grouting ensured this seal.

Setting the casing into firm rock to the minimum depth specified by the Wisconsin Department of Natural Resources (1975) greatly reduces the possibility of contamination. This requires casing at least 30 ft below the water table at the time of grouting. Fluctuating water levels may result in the casing being occasionally above the water level when precipitation is scant. These areas of the county where such conditions are most likely to occur are shown in figure 13.

Commonly, the joints and fractured zones are interconnected. By properly setting and pressure grouting the casing into firm bedrock, the well can be effectively sealed from surface and near-surface bacterial contamination. Pressure grouting from the bottom up results in a better seal of the annular space between the outside of the casing and the drill hole and insures better filling and sealing of bedding-plane joints than does gravity grouting.

A better seal also is obtained when sufficient time is allotted for the grout to harden before continuing the drill hole below the casing. In one U.S. Geological Survey test well the casing seal failed when grout was not allowed to harden for a full 24 hours.

SUMMARY AND CONCLUSIONS

Door County has a thin and discontinuous unconsolidated soil cover over dolomitic bedrock. The rock has well-developed vertical and horizontal joints, some enlarged by solution. The combination of little

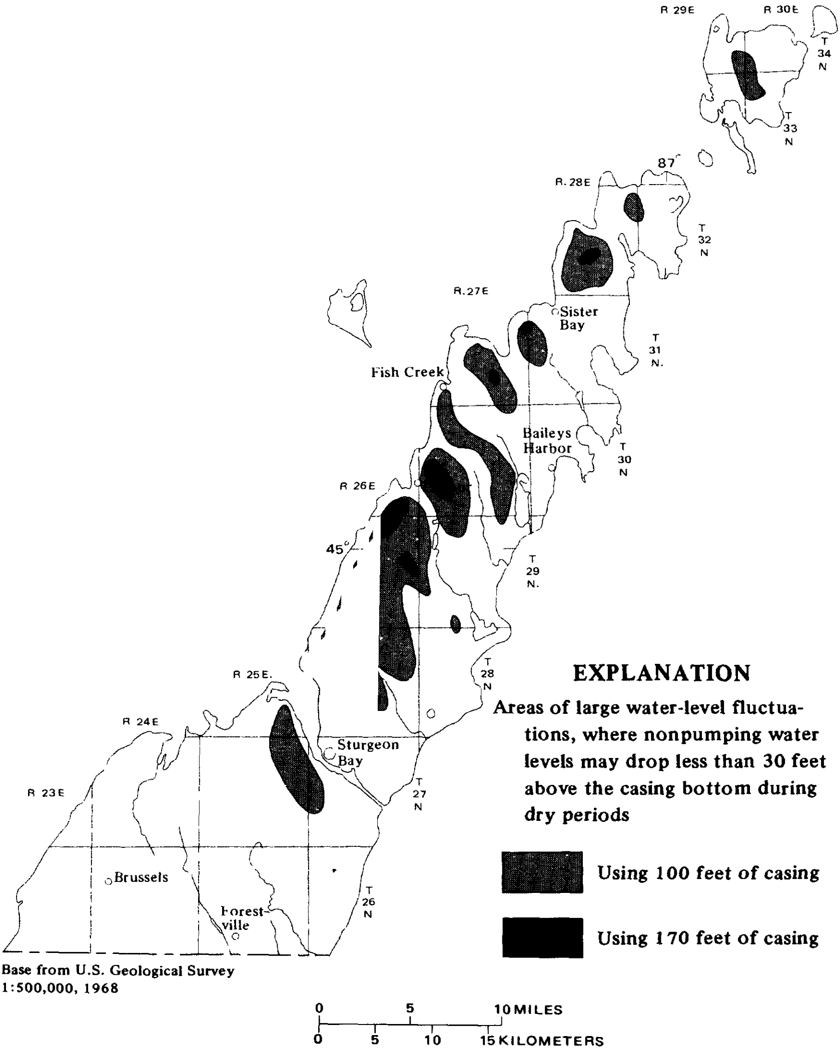


FIGURE 13. — Areas in Door County where large natural water-level fluctuations occur.

or no soil filter and the well-developed fracture system allows free entry of contaminants into the aquifers.

Water in the Silurian dolomite aquifer system occurs in nearly vertical joints and horizontal bedding-plane joints. The recharging water moves vertically through the unsaturated zone until it reaches the water table, where its movement becomes nearly horizontal through bedding-plane joints. Vertical joints are most common in the upper part of the dolomite. They are sources of water for many low-capacity wells but are unreliable for large sustained yields. Their most important function is to conduct recharging water through the unsaturated zone. Bedding-plane joints are most prevalent in the middle and lower parts of the Silurian dolomite aquifer system. These joints, although fewer in number than the vertical joints, are larger and yield greater quantities of water. Some of these water-bearing zones have good lateral continuity and yield relatively consistent amounts of water to wells.

Eight continuous water-bearing zones were identified, mostly in the Silurian dolomite aquifer system. These water-bearing zones yield adequate quantities of water for most municipal, commercial, and private supplies, except in the southwest corner of the county, where the dolomite is thin or missing. Water yields can reasonably be predicited if the saturated thickness of the Silurian dolomite aquifer system is known. Test drilling and test pumping may be necessary before large-scale development is attempted.

Water in the dolomite is of the very hard calcium magnesium bicarbonate type and is generally of good quality. Water temperature ranges from 9.5° to 11°C, with a gradual increase from the top of the dolomite to the bottom.

Ground-water contamination has been a chronic problem in Door County. A ready entry to the ground-water reservoir is provided for recharging water and associated contaminants where fractured bedrock occurs at or near land surface. Based on tests and observations, it is concluded that little or no filtration occurs in those fractures, and the contaminants move along rapidly with the water. A majority of the residents and visitors to the county rely on septic tanks for waste disposal and individual wells for water supply. The combination of the large number of septic tanks and individual wells, the occurrence of soil and bedrock conducive to rapid infiltration of contaminants, and the increasing concentrations of population (doubled and sometimes tripled during the summer) increases the probability that water from some wells will be unsafe during certain periods.

Water from contaminated wells has the highest total and fecal coliform count during or immediately after rapid recharge periods. In contaminated wells fecal coliform concentrations are at a maximum during late summer and early fall recharge periods. Lower concentrations of fecal coliform bacteria during the peak spring recharge period may indicate dilution and die off of these organisms and pathogenic organisms during the winter.

Contaminants other than bacterial may be introduced easily into the Silurian dolomite aquifer system. These substances include gasoline, oil, road salt, fertilizers, and a wide variety of municipal, commercial, and domestic wastes. Proper care when using or disposing of any of these substances will reduce the possibility of potential contaminants entering the ground-water reservoir. Properly evaluated and monitored disposal sites also may minimize the risk of ground-water contamination.

The Silurian dolomite aquifer system is not contaminated everywhere. Contamination is in zones and originates primarily from point sources and moves in the direction of ground-water flow.

Recharging water can move contaminants rapidly into the local ground-water system, but the system is flushed relatively quickly if the source of contaminants is eliminated.

Well-construction practices that may increase the chances of developing contaminant-free wells include: locating the well as far upgradient from known contamination sources as practicable; setting the bottom of the well casing into firm bedrock at least 30 ft below the lowest expected water level; pressure grouting the casing from the bottom up; and allowing adequate hardening time for the grout before continuing to drill the hole. These criteria will reduce, though not eliminate, the possibility of well contamination.

Slightly saline (170 to 450 mg/L in samples) ground water of good sanitary quality is generally available in the sandstone aquifer by drilling a well 600 to 1000 ft deep.

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U.S. GOVERNMENT PRINTING OFFICE: 1978—777-373

UNITED STATES DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY

Prepared in cooperation with the
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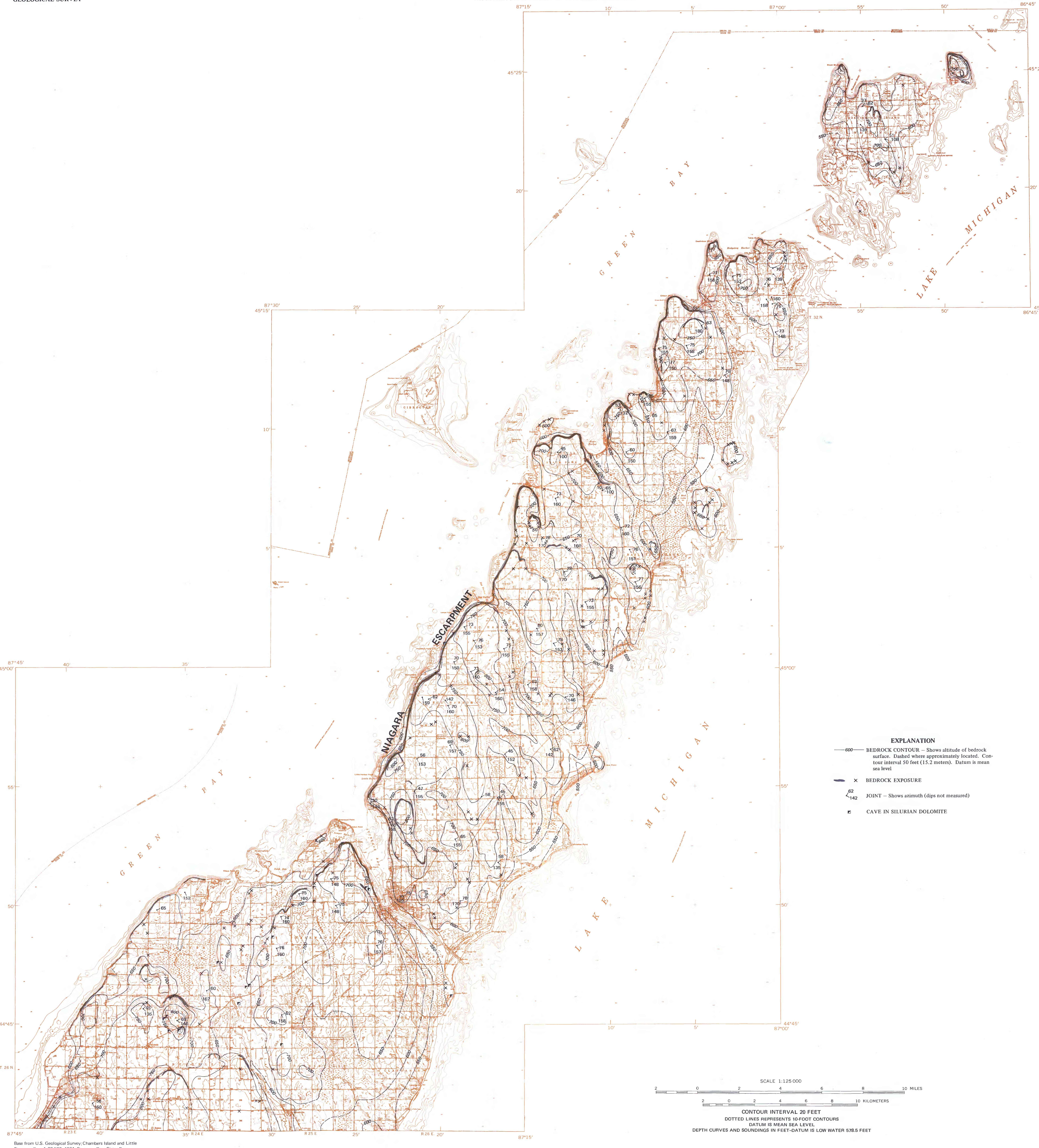
WATER-SUPPLY PAPER 2047
PLATE 1



EXPLANATION

600 — BEDROCK CONTOUR – Shows altitude of bedrock surface. Dashed where approximately located. Contour interval 50 feet (15.2 meters). Datum is mean sea level

× BEDROCK EXPOSURE

62 / 142 JOINT – Shows azimuth (dips not measured)

CAVE IN SILURIAN DOLOMITE

SCALE 1:125 000

2 0 2 4 6 8 10 MILES

2 0 2 4 6 8 10 KILOMETERS

CONTOUR INTERVAL 20 FEET
DOTTED LINES REPRESENTS 10-FOOT CONTOURS
DATUM IS MEAN SEA LEVEL
DEPTH CURVES AND SOUNDINGS IN FEET–DATUM IS LOW WATER 578.5 FEET

Base from U.S. Geological Survey; Chambers Island and Little Sturgeon Bay, 1:62,500, 1961; Sturgeon Bay, Sister Bay, Algoma, Ellison Bay, Jacksonport, and Washington Island. 1:62,500, 1960; and Casco, 1:62,500, 1952

BEDROCK TOPOGRAPHY AND LOCATIONS OF OUTCROPS, CAVES, AND JOINT-ORIENTATION MEASUREMENTS, DOOR COUNTY, WISCONSIN

Prepared in cooperation with the
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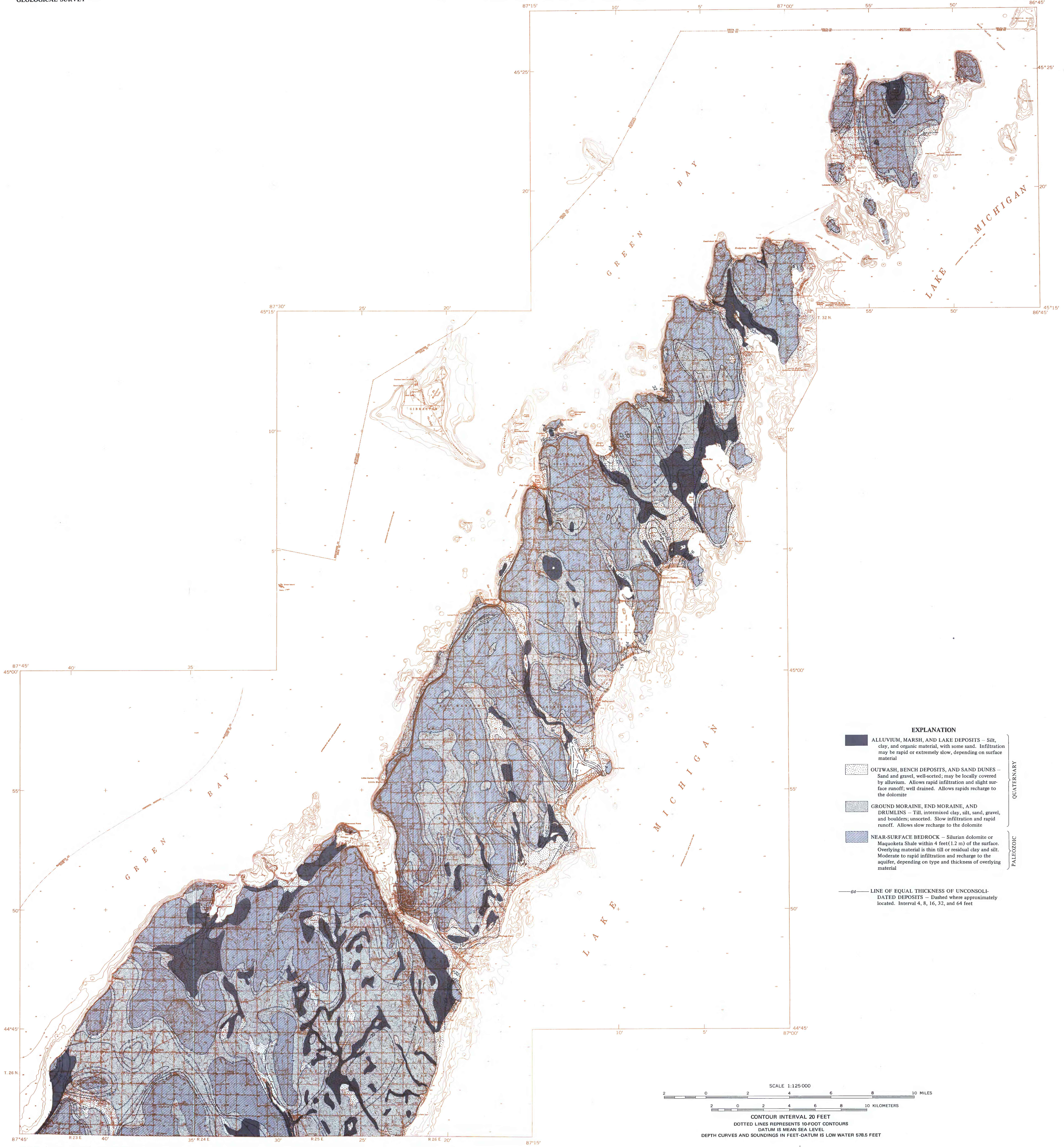

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SURFICIAL GEOLOGY, INFILTRATION AND RUNOFF POTENTIAL, AND THICKNESS OF UNCONSOLIDATED DEPOSITS, DOOR COUNTY, WISCONSIN

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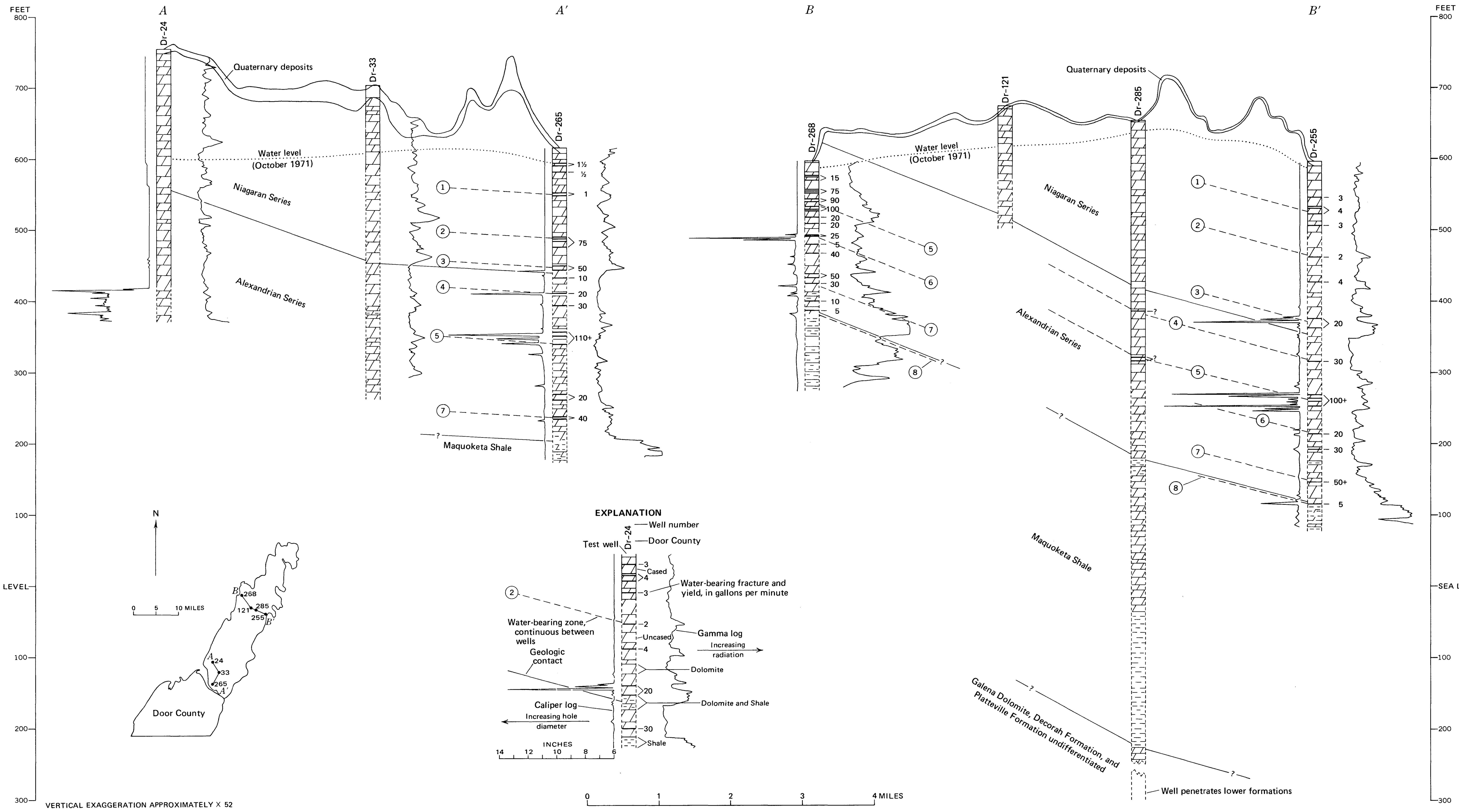
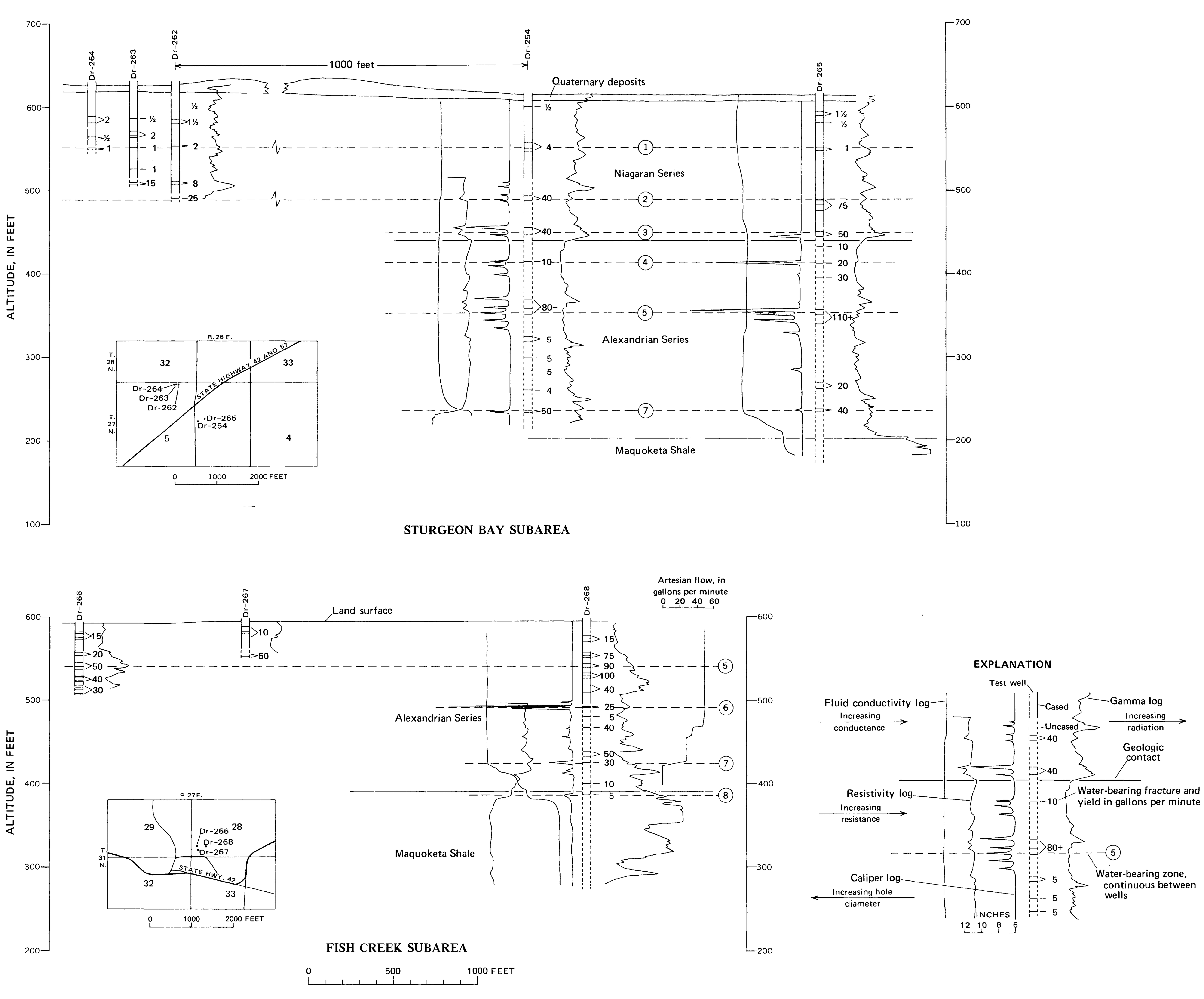


A. GEOLOGIC SECTIONS THROUGH THE SILURIAN DOLOMITE AQUIFER SYSTEM AND ASSOCIATED GEOLOGIC UNITS, DOOR COUNTY, WISCONSIN



B. GEOHYDROLOGIC SECTIONS THROUGH THE SILURIAN DOLOMITE AQUIFER SYSTEM IN STURGEON BAY AND FISH CREEK SUBAREAS, WISCONSIN

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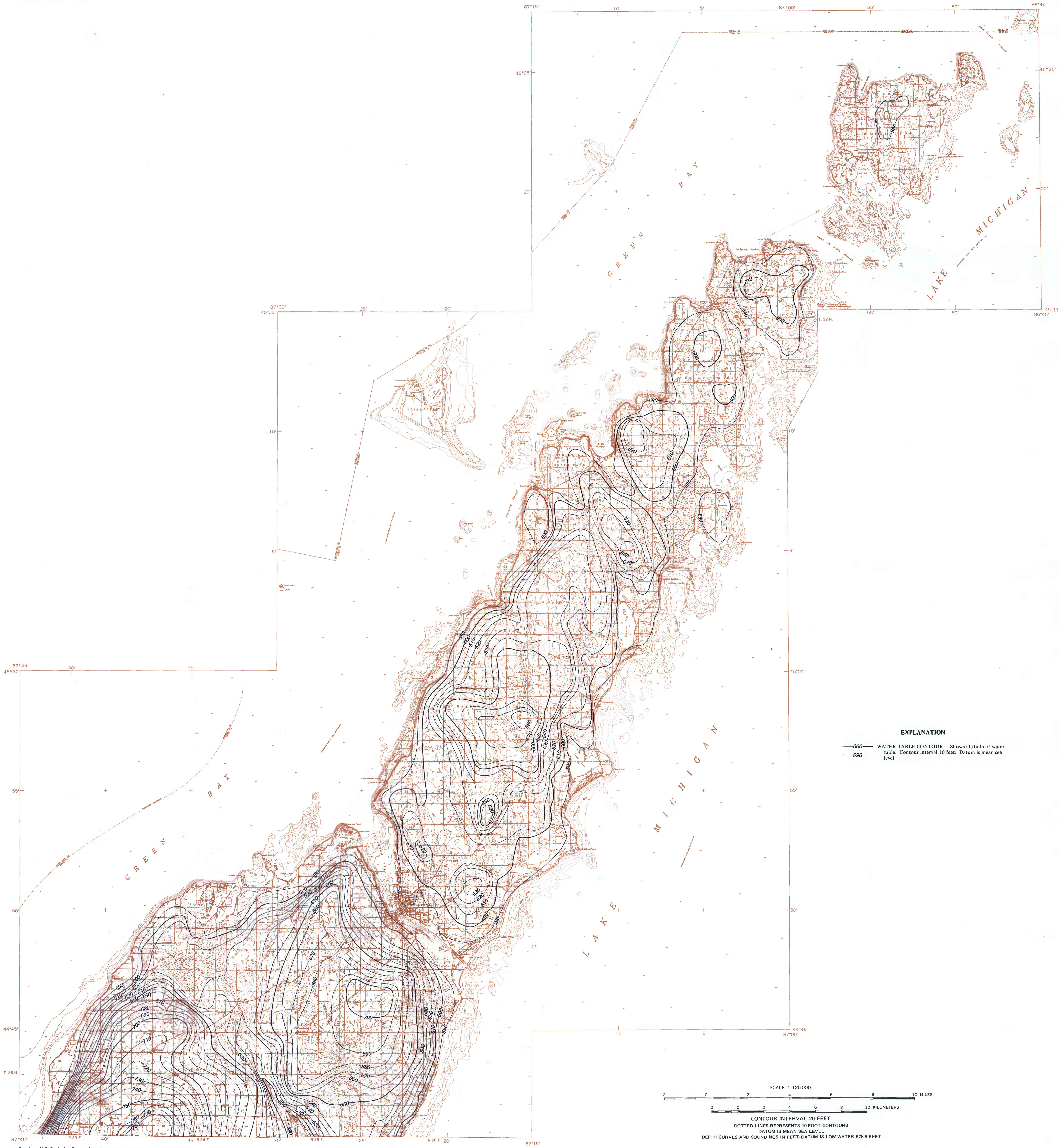

EXPLANATION

—600— / —590— WATER-TABLE CONTOUR – Shows altitude of water table. Contour interval 10 feet. Datum is mean sea level

SCALE 1:125 000

2 0 2 4 6 8 10 MILES

2 0 2 4 6 8 10 KILOMETERS

CONTOUR INTERVAL 20 FEET
DOTTED LINES REPRESENTS 10-FOOT CONTOURS
DATUM IS MEAN SEA LEVEL
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WATER TABLE OF THE SILURIAN DOLOMITE AQUIFER SYSTEM, OCTOBER 1971, DOOR COUNTY, WISCONSIN

UNITED STATES DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY

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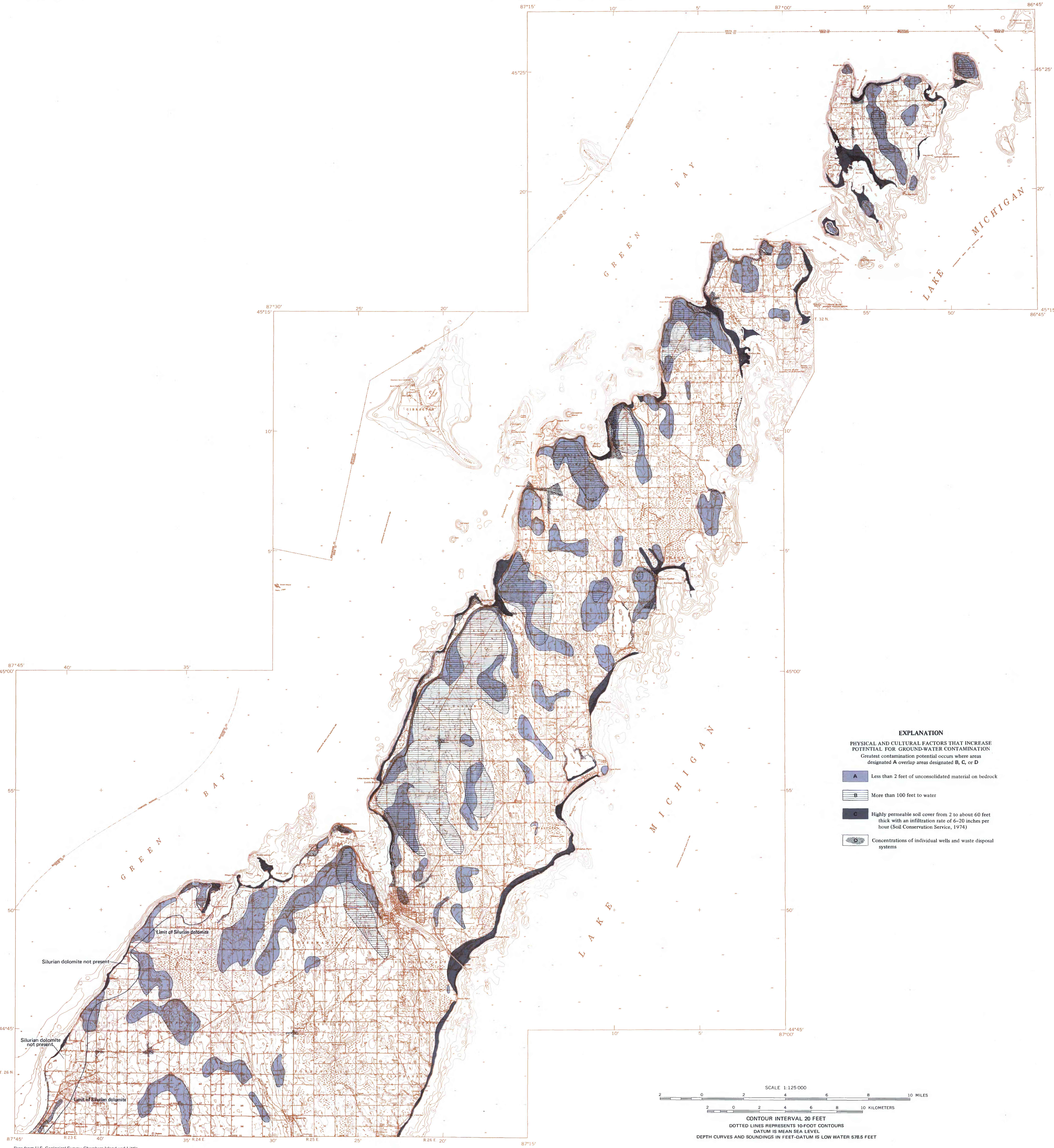
WATER-SUPPLY PAPER 2047
PLATE 5



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AREAS OF HIGH CONTAMINATION POTENTIAL IN THE SILURIAN DOLOMITE AQUIFER SYSTEM, DOOR COUNTY, WISCONSIN