HYDROGEOLOGIC MAP OF MINNESOTA BEDROCK HYDROGEOLOGY

A Discussion to Accompany
State Map Series
Map S-2

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HYDROGEOLOGIC MAP OF MINNESOTA

S-2 Bedrock Hydrogeology. 1978. R. Kanivetsky. Scale 1:500,000. Color. Sheet 1 (map), Sheet 2 (cross sections), with explanatory text.

S-3 Quaternary Hydrogeology. 1979. R. Kanivetsky. Scale 1:500,000. Color.

S-5 Bedrock Hydrogeology. In prep. R. Kanivetsky. Scale 1:3,168,000 (1 inch=50 miles). Color.

S-6 Quaternary Hydrogeology. In prep. R. Kanivetsky. Scale 1:3,168,000 (1 inch=50 miles). Color.

S-7 Ground-water Resources. In prep. R. Kanivetsky. Scale 1:3,168,000. Color.

S-8 Hydrogeochemistry of Quaternary Deposits. In prep. R. Kanivetsky. Scale 1:3,168,000. Color.

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HYDROGEOLOGIC MAP OF MINNESOTA

BEDROCK HYDROGEOLOGY

by

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INTRODUCTION

The Hydrogeologic Map of Minnesota is in fact a set of maps portraying different aspects of the hydrogeology of the state, which is too complex to represent on a single map. Map S-2, Bedrock Hydrogeology, portrays the water-bearing characteristics of the consolidated bedrock formations underlying the state. These formations are important aquifers in some areas and of limited value in others. Bedrock formations are covered throughout most of the state with unconsolidated sedimentary deposits of glacial and fluvial origin, which are major sources of ground water in many areas. Their water-bearing characteristics are portrayed by Map S-3, Quaternary* Hydrogeology. Both maps need to be consulted to evaluate the potential groundwater sources in a given area.

The Bedrock Hydrogeologic Map (S-2) is derived from the Geologic Map of Minnesota, Bedrock Geology, Map M-24 (33). On the Bedrock **Geologic** Map rock units or formations are defined and classified according to geologic age, mode of origin, structural continuity, and composition. On the Bedrock **Hydrogeologic** Map the same rock units or formations are grouped into aquifers according to water-bearing characteristics and hydraulic continuity. Aquifers consist of one or more geologic formations that form an hydraulically continuous unit, more or less isolated from overlying and underlying formations by confining beds or zones of rock that do not transmit water readily. Confining beds are not shown on the map separately from the aquifers for which they form a cap, but they are shown on the cross sections (sheet 2). Some aquifers, such as the Proterozoic aquifer (p-Ꞓp), are characterized by sporadic zones of water-bearing rock with little or no hydrologic continuity and uncertain boundary conditions. Large areas of the state are underlain by Precambrian crystalline igneous and metamorphic rocks (p-Ꞓim), which are generally poor in water-bearing characteristics and are not regarded as aquifers, although water is found locally, where these rocks are strongly fractured.

In using the bedrock hydrogeologic map to evaluate the occurrence of ground water it must be borne in mind that in those areas underlain by well-stratified sedimentary formations (essentially the southeastern quadrant of the state), the aquifer shown at any given place on the map is the aquifer at the bedrock surface, and it will be underlain by those aquifers in the stratigraphic succession that lie below it, as is shown on the cross sections, Sheet 2. Figure 1 is a generalized stratigraphic column for southeastern Minnesota showing how the aquifers and confining beds correlate with geologic formations and giving approximate maximum thicknesses of the rock units. For a complete evaluation of groundwater occurrence in any given area, reference should also be made to the map of Quaternary Hydrogeology (S-3).

Users should also be aware that these maps are on a scale of 1:500,000 or about 8 miles to the inch, and there are doubtless many areas where local ground-water occurrence and geology depart from information shown on this scale. For example, dashed black lines on the map show the approximate locations of known preglacial valleys in bedrock that have been filled by Quaternary deposits so that no valley appears now at the surface. In some places these valleys have cut through the bedrock aquifer shown on the map, and a narrow band of a lower aquifer that is not shown at 1:500,000 scale is present at the bedrock surface along the floor of the buried valley. Such conditions are known to exist for example in buried valleys in parts of Minneapolis and St. Paul. There are undoubtedly other buried valleys that are not known and are not represented on the map. Where specific site conditions are important, more detailed maps should be consulted if available, and test drilling should be considered.

*Quaternary: the geologic period that includes both the Pleistocene Epoch, or "Ice Age," and the Holocene Epoch, or "Recent," which spans the time from the Pleistocene to the present.

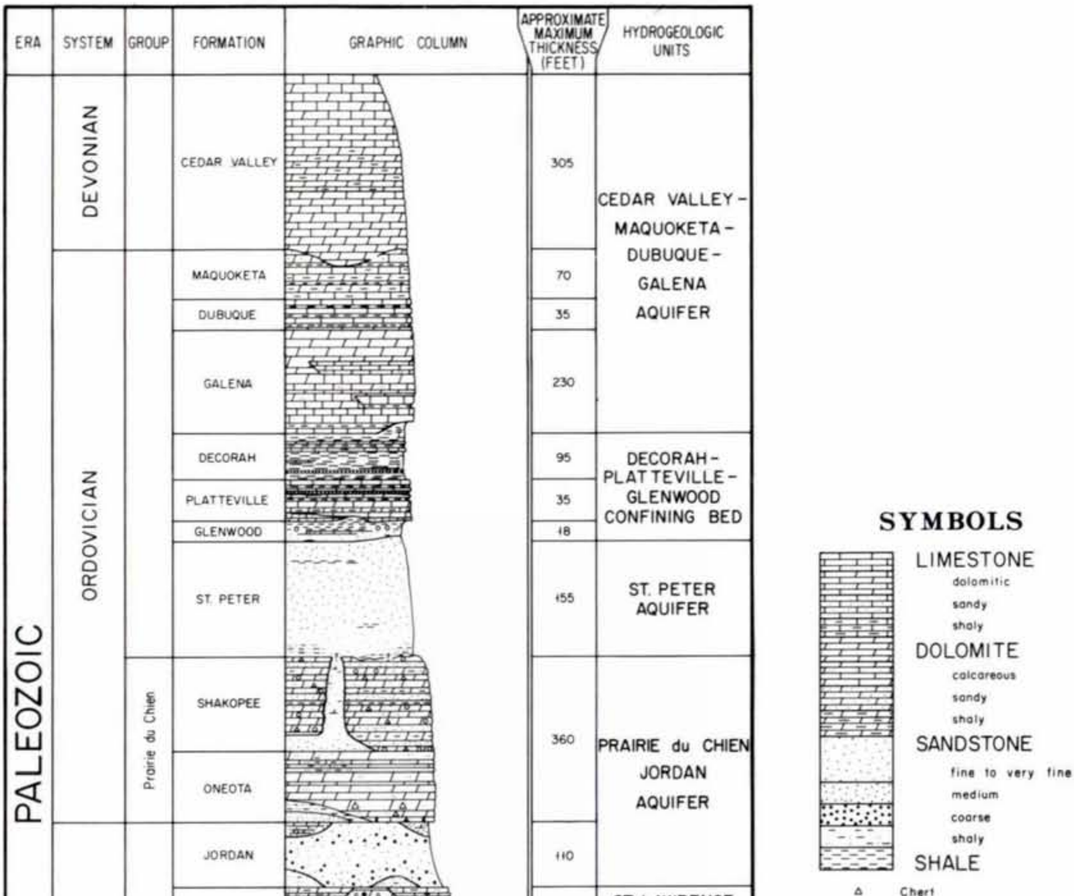

Figure 1 — Generalized stratigraphic column for southeastern Minnesota showing bedrock aquifers. Modified from Austin (6).

DESCRIPTION OF HYDROGEOLOGIC UNITS

Descriptions follow on the geology and water-bearing characteristics of each of the hydrogeologic units and other features shown on the map.

Cretaceous Aquifer (K)

The Cretaceous aquifer comprises eroded remnants of sandy, silty and shaly beds deposited in a shallow sea which spread from the west across most of Minnesota in the Cretaceous Period. Two large outliers, about 500 square miles (1,295 km^2) and 100 square miles (259 km^2) in area, occur south of the Biwabik Iron-Formation (Mesabi range). The aquifer becomes nearly continuous in large areas along the Red River and in the southwestern quadrant of the state. A dashed line up to 50 miles (80 km) east of the Red River in northwestern Minnesota encloses an additional area where there are probably numerous small outliers or patches of Cretaceous beds for which drilling data are not available.

The Cretaceous aquifer tends to thicken toward the west from a few tens of feet or less in eastern outliers to a maximum known thickness of about 600 feet (183 m) near the South Dakota border in Lincoln County. The Cretaceous beds are weakly consolidated and readily eroded and are overlain almost everywhere by glacial drift or lake sediments of Glacial Lake Agassiz (33). There are few natural exposures, and the Cretaceous is known mainly from well drilling.

Cretaceous strata were deposited on an eroded surface of much older rocks deeply weathered to form a lateritic or saprolitic regolith of decomposed rock locally more than 100 feet (30 m) thick. The contact between the clay-rich regolith and overlying Cretaceous sediments is commonly difficult to identify, especially in well cuttings. The same is true of the upper contact of the Cretaceous aquifer with clay-rich glacial till and lake sediments.

Beds of fine- to coarse-grained quartzose sandstone in the lower part of the aquifer carry most of the water. The sandy section is overlain by strata that are dominantly shale or siltstone. Thin beds of lignite occur locally within the sandy section. The thickness and lateral continuity of beds within the aquifer are poorly known. The typical yield to wells ranges from 5 to 50 gallons per minute (gpm) (2, 12, 13, 14, 15, 26, 27, 29, 31, 38, 42, 45), but in the extreme southern part of the state some wells are capable of yielding about 250 gpm (1, 2). In order to produce enough water to satisfy needs, wells completed in Cretaceous beds commonly also draw water from overlying Quaternary deposits.

Total dissolved solids in the water range from 500 parts per million (ppm) to 6,000 ppm. Most of the water in the aquifer is mineralized (more than 1,000 ppm), with the most highly mineralized water concentrated in a narrow zone along the western border of the state (1, 2, 3, 10, 14, 27, 31, 38, 42, 43). Only Cretaceous beds northeast of the Minnesota River contain water with less than 1,000 ppm dissolved solids (44).

Cedar Valley-Maquoketa-Dubuque-Galena Aquifer of Middle Devonian to Late Middle Ordovician Age (Dcv+Omdg)

The Paleozoic formations of Minnesota, which include this aquifer, consist of almost horizontal beds of limestone, dolomite, sandstone and shale with very few known faults and minor local folding or warping. These formations occupy a shallow southward-plunging troughlike structure in southeastern Minnesota known as the Hollandale embayment. A test hole through the center of this structure near the Iowa border penetrated 1,619 feet (493 m) of Paleozoic sedimentary rocks overlying Late Precambrian Keweenawan sandstone (7). The Cedar Valley-Maquoketa-Dubuque-Galena aquifer comprises the four youngest formations in the sequence of Paleozoic sedimentary strata. In the area underlain by Dcv+Omdg the beds dip southward and inward at the rate of about 10 feet per mile.

The outer limit of the aquifer is where the base of the Galena Formation is exposed and all the rest of the aquifer has been eroded away (41). Successively younger formations add to the thickness of the aquifer toward the center until it reaches its full thickness in Minnesota of about 640 feet (195 m) at the Iowa border, where all four formations are present (6). Because of this structure, it is generally some distance inward from the margin of the aquifer that the thickness is sufficient to provide substantial yields of water. The full yield is obtained in the area of maximum thickness. The aquifer is not capped by a confining bed in Minnesota, although locally some confinement is provided by unconsolidated Quaternary deposits and by patches of Cretaceous shale.

The formations composing the aquifer consist mainly of grayish-yellow or olive-gray limestone, dolomite and dolomitic limestone. Beds are a few inches to a few feet in thickness and the rock is vuggy and fractured. Locally thin shale beds in the Galena, Dubuque and Maquoketa Formations somewhat confine the flow of water in separate layers, and differences in static water levels may be found in wells in the same general area. Regionally however, for all practical purposes, the four formations function as a single aquifer.

The aquifer yields water mainly from solution channels, joints and fissure systems, which tend to be more prevalent and open in the uppermost beds present at any location. Subsurface cavities of significant size encountered occasionally during well drilling indicate that some degree of karst development (drainage through sinkholes, caverns and solution channels) affects most of the aquifer, whether it is exposed at the surface or overlain by glacial drift. This markedly affects the surface drainage of the area. Sinkholes, disappearing and reappearing streams and free-flowing springs are present in many places. Caves and large underground streams have developed, especially in Fillmore and Olmsted Counties. Where this aquifer is not protected by an unbroken cover of glacial till, surface water may enter rapidly into these underground channels without filtration or retention by soil or porous rock, rendering the aquifer especially sensitive to pollution. Karst conditions are shown on the map by an overprinted pattern.

Water yields from this aquifer are typically between 200 gpm and 500 gpm (3, 4, 5, 11, 17, 31), but because solution channels and fissures are irregular in size and distribution, yields from adjacent wells can differ markedly. The natural quality of the water is good, with total dissolved solids generally less than 500 ppm (3, 4, 5, 11, 17, 31).

Red River-Winnipeg Aquifer of Middle Ordovician Age (Orw)

The Red River Formation, which is the upper member of this aquifer, is vuggy limestone and dolomitic limestone with thin shale partings. The lower part of the formation is more dolomitic than the upper (36). The Winnipeg Formation, which is the lower member, is fine- to medium-grained, quartzose sandstone, friable or moderately cemented with calcite. Some shale beds locally occur in the upper part of the sandstone (36). These rocks do not crop out at the surface anywhere in Minnesota, being covered by as much as several hundred feet of till and lake sediments of Glacial Lake Agassiz (36). On the basis of drilling, the aquifer appears to form a thin wedge in the northwestern corner of Minnesota that dips gently westward and thickens toward the Williston basin.

The approximate maximum thickness of this aquifer is 500 feet (152 m) (9, 28, 29). Actual recorded yields have ranged from 5 gpm to 60 gpm (31), but yields ranging from 100 gpm to 250 gpm would be possible if wells penetrated the full thickness of the aquifer. The water is typically saline, having concentrations of dissolved solids of between 5,000 ppm and 60,000 ppm (31).

Decorah-Platteville-Glenwood Confining Bed of Middle Ordovician Age (Odpg)

The three formations of this unit underlie the Cedar Valley-Maquoketa-Dubuque-Galena aquifer in southeastern Minnesota. They form a nearly impervious cap over the St. Peter Sandstone and isolate it hydrologically from the overlying aquifer. The confining beds are included as part of the St. Peter Sandstone aquifer on the map, Sheet 1, but they are shown as a separate layer on the cross sections, Sheet 2. These cap rocks, or confining beds, crop out in a narrow fringe around the base of the Cedar Valley-Maquoketa-Dubuque-Galena aquifer. The confining beds also occur in a few outlying patches, notably over the center of a shallow ground-water basin that underlies the Twin Cities (Minneapolis and St. Paul) area, where the Platteville Formation crops out in many places as a resistant ledge along the crest of the Mississippi River Valley bluffs. Elsewhere in the St. Peter aquifer area the confining beds have been eroded away (41), and the St. Peter Sandstone is exposed at the surface or overlain directly by glacial drift.

The maximum combined thickness of the three formations in the confining bed is about 150 feet (45 m) (6). The Decorah Shale is fissile to blocky and greenish gray or olive gray. It generally does not yield water. The Platteville Formation is thin- to medium-bedded, yellowish-brown dolomite and dolomitic limestone, and the Glenwood Formation is grayish-green or yellow calcareous shale. Both can yield small amounts of water, ranging from less than 1 gpm to as much as 25 gpm (37). Data on the quality of this water are lacking, but it can be expected to be about the same as that of water in the overlying aquifer. All three formations, however, generally function together as a confining bed, and they cannot be considered a regional source of water.

St. Peter Aquifer of Middle Ordovician Age (Osp)

Throughout most of its extent, the St. Peter Sandstone is capped by the Decorah-Platteville-Glenwood confining bed. Where the confining bed has been removed by erosion, the St. Peter lies directly beneath glacial drift or crops out at the surface. The sandstone is light yellow or white, massive, quartzose, fine to medium grained, well sorted and friable. Thin beds of siltstone and shale near the base of the St. Peter Sandstone serve as a lower confining layer.

The gradual southward plunge of the Paleozoic rocks in the axis of the Hollandale embayment reverses in the vicinity of the Cannon River valley, and the axis plunges northward about 10 feet per mile toward the center of the Minneapolis-St. Paul urban area to form a subsidiary structural basin under the Twin Cities, as shown on section A-A′, Sheet 2. In the northern part of the Hollandale embayment, the St. Peter Sandstone lies on an old surface of erosion developed on the Shakopee Formation, which is the uppermost unit of the Prairie du Chien-Jordan aquifer. Relief on this erosional unconformity ranges to more than 100 feet (30 m) (40).

The average thickness of the St. Peter Sandstone is about 100 feet (30 m); its maximum thickness is as much as 155 feet (47 m) in the center of the Twin Cities basin. It thins gradually southward, and in southern Goodhue County it is less than 100 feet (30 m) thick (35).

Typical yields to individual wells range from 100 gpm to 250 gpm, and total dissolved solids are generally less than 500 ppm (3, 4, 5, 11, 17, 31, 37).

Prairie du Chien-Jordan Aquifer of Early Ordovician-Late Cambrian Age (Opc+€j)

The Prairie du Chien Group and the Jordan Sandstone are a major regional aquifer underlying the St. Peter Sandstone and forming the uppermost bedrock aquifer over large areas beyond the limits of the St. Peter Sandstone. This aquifer lies beneath the St. Peter Sandstone in the center of the Twin Cities basin and continues southward beneath younger rocks in the Hollandale embayment far into Iowa (40, 41).

The Prairie du Chien Group comprises two principal formations, the Shakopee Formation and the Oneota Dolomite, both of which are predominantly light brownish-gray or buff, sandy, thin- to thick-bedded dolomite, which is vuggy and fractured and contains some thin layers of interbedded grayish-green shale. The underlying Jordan Sandstone consists of a white to yellow, quartzose, fine- to coarse-grained sandstone, which is massive or thick to thin bedded and varies from friable to well cemented.

Despite their differing lithologies, the Prairie du Chien Group and the Jordan Sandstone function as one aquifer because there is no regional confining bed between them. Locally, however, small head differences may exist due to the presence of some relatively impermeable beds of limited extent.

Karst conditions are common in the Prairie du Chien Group along the Mississippi River Valley on the east side of the Hollandale embayment where it forms the uppermost bedrock unit. This area is shown on the map by an overprinted pattern.

The approximate maximum thickness of the aquifer is 470 feet (143 m) (6). Typical yields to wells range from 500 gpm to 1,000 gpm, although some recorded yields are much less than 500 gpm; total dissolved solids generally are less than 500 ppm (3, 4, 5, 11, 31, 37).

St. Lawrence Confining Bed (€sl)

The St. Lawrence confining bed underlies the Prairie du Chien-Jordan aquifer. It is composed of dolomitic shale and siltstone, interfingered with fine-grained, quartzose sandstone, some of which is dolomitic and glauconitic. The formation contains some beds of dolomite. In some localities this formation yields a small amount of water (from 1 gpm to 25 gpm), but the sandstone in the formation is very fine grained and silty, and in general it acts as a confining bed. The maximum thickness of the St. Lawrence Formation is approximately 60 feet (18 m) (6). It is shown on the cross sections, Sheet 2, but not on the map, Sheet 1, where it is grouped with the overlying aquifer.

Franconia-Ironton-Galesville Aquifer of Late Cambrian Age (€fig)

This aquifer underlies the St. Lawrence confining bed and dips southward beneath it. The extent of the aquifer as shown on the map is derived from Sloan and Austin (41) and Minnesota Geological Survey well data. The Galesville Sandstone consists of a white to light-gray, slightly glauconitic, well- to moderately well-sorted, mostly medium-grained quartzose sandstone. The Ironton Sandstone is a white, medium-grained, moderately well- to poorly sorted quartzarenite that contains a significant amount of admixed silt-size material. The Franconia Formation consists of a gray to greenish, glauconitic, very fine- to coarse-grained quartz sandstone with some interbedded greenish-gray micaceous shale and dolomitic and nonglauconitic sandstone layers (8).

The approximate maximum thickness of the aquifer is 330 feet (100 m), of which the Galesville is about 95 feet (29 m), the Ironton 45 feet (14 m), and the Franconia about 190 feet (58 m) (6).

Typical yields to individual wells range between 250 gpm and 500 gpm; total dissolved solids are generally less than 500 ppm (16, 20, 22, 31, 37).

Eau Claire Confining Bed of Late Cambrian Age (€ec)

The Eau Claire Formation, which underlies the Franconia-Ironton-Galesville aquifer, caps the Mt. Simon-Hinckley-Fond du Lac aquifer. It consists of red and grayish-green, fine-grained silty sandstone, siltstone and shale, and has a maximum thickness of about 200 feet (61 m) (6). It is shown on the cross section, Sheet 2, but not on the map, Sheet 1, where it is grouped with the overlying aquifer.

Mt. Simon-Hinckley-Fond du Lac Aquifer of Late Cambrian-Proterozoic Age (€ms+p €hfl)

This aquifer dips southward and eastward beneath the Eau Claire confining bed at the northern and western margin of the Twin Cities basin and continues beneath younger rocks southward into Iowa (8, 33).

The Mt. Simon Sandstone of Late Cambrian age is fine to coarse grained and contains some thin beds of shale; it is commonly white, gray or pink in color, locally yellow. The Upper Precambrian Hinckley Sandstone is medium to very thick bedded, fine to coarse grained, and pale red to light pinkish or brownish gray in color. The Fond du Lac Formation, also Upper Precambrian, is characterized by lenticular beds of arkosic sandstone and interbedded mudstone, and is dark red to pink in color (32). Although each formation is a discrete lithostratigraphic unit and there is a regional unconformity between the Mt. Simon and Hinckley formations, they function as a single aquifer according to Ericson and others (16) and Lindholm and others (22).

A major rift zone, which split the Midcontinent from Lake Superior southwestward during Keweenawan time (Late Precambrian), was active at times during the deposition of the clastic sediments that form this aquifer, especially the lower part. Subsidence and uplift of blocks of ground occurred along normal faults during the deposition, resulting in abrupt variations in the thickness and texture of sediments deposited on different blocks. Variations are especially common in the Hinckley and Fond du Lac formations, but details of these variations are not well known. In some graben structures (downfaulted blocks) the clastic sediments are believed to exceed 4,000 feet (1,219 m) in thickness.

Typical yields to individual wells range from 400 gpm to 700 gpm (16, 18, 20, 21, 22). Total dissolved solids range from 79 ppm (37) in the north to 2,400 ppm in the south (4).

Keweenawan Volcanic Rocks Aquifer of Proterozoic Age (p-€kv)

This aquifer consists dominantly of basaltic lava flows with interbeds of more acidic lava flows, sandy to shaly sediments, and many sills and dikes of dolerite and basalt. It forms an irregular belt along the North Shore of Lake Superior and down the St. Croix River. This volcanic sequence filled a rift zone that was later partly covered south of Lake Superior by the Mt. Simon-Hinckley-Fond du Lac sedimentary formations. South of Lake Superior the Keweenawan volcanic rocks are now in fault contact with the Mt. Simon-Hinckley-Fond du Lac aquifer (33). The Puckwunge and Nopeming formations, which are quartzose, medium-grained, cross-bedded sandstone, occur near the base of the aquifer where it is exposed west of Duluth.

Fractured and weathered zones, which occur irregularly within the upper 300 to 400 feet (91 to 122 m), and zones where flows are vesicular and brecciated constitute the aquifer. Typical yields to individual wells range from 1 gpm to 25 gpm. Total dissolved solids are highly variable, ranging from 100 ppm to 50,000 ppm, although they are generally less than 1,300 ppm (19, 23, 31, 39).

Sioux Quartzite Aquifer of Proterozoic Age (p-€sq)

The Sioux Quartzite underlies a large part of the area west of New Ulm and south of the Minnesota River. It crops out locally or is overlain directly by unconsolidated Quaternary deposits in the two areas shown on the map (33). Elsewhere it is overlain by Cretaceous beds, as well as Quaternary deposits, and its total subsurface extent and basal contacts with older rocks are not known.

The full thickness of the formation, consisting of orthoquartzite sandstone with minor interbedded quartzose conglomerates and mudstones, is at least 5,250 feet (1,600 m). The conglomerates are present in the lower two-thirds of the known section and minor thin mudstones (catlinite) in the upper third. The orthoquartzite is composed almost exclusively of well-rounded, well-sorted, monocrystalline quartz grains; it is characteristically pink, but ranges from white to deep purple (R.E. Weber, written communication).

Significant water-bearing zones occur only near the weathered and eroded upper surface of the formation, where the rock is fractured and friable because of decomposition of intergranular cement. The thickness of the water-bearing part of the Sioux Quartzite is estimated to range between 100 feet and 300 feet (30-91 m).

Recorded yields range from 1 gpm to 450 gpm, but typical yields to individual wells range from 1 gpm to 25 gpm (1, 2). Total dissolved solids are generally less than 700 ppm (31).

Proterozoic (p-Єp) and Biwabik Iron-Formation (p-Єb) Aquifers of Proterozoic Age

The middle Proterozoic rocks of the Animikie and Mille Lacs Groups (33, 34) occupy an asymmetrical basin underlying a large area of central to northeastern Minnesota. The Mesabi iron range forms the northern margin of the basin. In the Mesabi range area the Biwabik Iron-Formation contains many leached and oxidized zones which yield more ground water than is commonly found elsewhere in Animikie Group rocks. Therefore the Biwabik Iron-Formation in the Mesabi iron range area is shown as a separate aquifer.

The Biwabik Iron-Formation extends southward from the western end of the Mesabi range into Crow Wing County where it forms the Trommald Formation of the Cuyuna district (30), but here it is not notably different in water-bearing characteristics from the rest of the Animikie Group and is not shown as a separate aquifer on the map.

In the Mesabi range the Biwabik Iron-Formation is overlain by dark slaty argillites and graywackes. It is underlain by the Pokegama Quartzite, which in turn is underlain unconformably by Archean rocks. Animikie Group strata dip 10° to 15° SE. with little variation except for a structural warp in the vicinity of Virginia and Eveleth. Southward from the western end of the Mesabi range the geology becomes much more complex and rocks equivalent to the Pokegama Quartzite—Mahnomen Formation—are at least 2,000 feet (610 m) thick. Additional stratigraphic units assigned to the Mille Lacs Group (34), including lava flows, occur beneath the Mahnomen Formation. Iron-formation occurs in several units in the Cuyuna district, and the rocks are tightly folded. This complexity extends eastward across the southern margin of the Animikie basin to where the Animikie Group rocks are overlain unconformably by the Mt. Simon-Hinckley-Fond du Lac aquifer. The eastern end of the Animikie basin is cut off abruptly by an intrusive contact with gabbroic igneous rocks of the Duluth Complex. The center of the Animikie basin is completely concealed by glacial drift, and the nature of the transition from the gently dipping monoclinal structure in the Mesabi range to the strong folding in the southern part of the basin is largely conjectural.

Dark slaty argillites and graywackes with some highly graphitic and pyritiferous beds dominate the Animikie Group above the zone containing the major iron-formation. The Mille Lacs Group contains silty, sandy and conglomeratic quartzite, impure dolomitic marble and some volcanic rocks, and passes upward into argillite and graywacke. Highly carbonaceous and pyritiferous beds, pillowed basalt, and agglomerate occur in the lower part of the Mille Lacs Group.

All these rocks are strongly indurated to weakly to moderately metamorphosed and have little primary porosity. Ground water occurs sporadically, mainly in zones of secondary porosity resulting from faulting or leaching. Typical yields to individual wells range from less than 1 gpm to 25 gpm (31) except in the Biwabik Iron-Formation aquifer of the Mesabi range. Here yields to individual wells of 250 gpm to 500 gpm have been obtained (31).

Total dissolved solids in water from both aquifers is generally less than 500 ppm (18, 31), although locally saline water has been encountered, containing as much as 2,420 ppm total dissolved solids (24).

Precambrian Igneous and Metamorphic Rocks (p-Єim)

Over a large part of central, western and northern Minnesota, Precambrian igneous and metamorphic rocks are known from drilling to lie directly beneath glacial drift. They crop out at the surface in scattered localities, especially in the Minnesota River Valley and in extensive areas of well-exposed igneous and metamorphic rocks in northeastern Minnesota. An overprinted pattern shows areas where Precambrian rocks crop out or where glacial drift overlying Precambrian rocks is believed to be thin (less than 30 feet). The drift-covered as well as the exposed Precambrian bedrock area is considered part of the Canadian Shield.

Although these rocks differ greatly among each other in origin, composition and structure and range in age from early Archean to late middle Proterozoic, they are all grouped as one hydrogeologic unit on the bedrock hydrogeologic map. This is because, with minor exceptions, these rocks all lack primary porosity and do not function as aquifers except where secondary porosity has developed by fracturing or leaching. Where geological mapping or geophysical data have indicated the presence of major fault zones, the inferred fault traces (33) are shown on the map as clues to possible locations of water-bearing fractured rock. However, it must be borne in mind that on the one hand many faults and fracture zones have not yet been located, and that on the other hand not all faults yield water. Consequently the occurrence of ground water in Precambrian igneous and metamorphic rocks is highly uncertain, and these rocks as a class are not regarded as aquifers. Ground-water supplies in these bedrock areas are generally to be sought in overlying unconsolidated Quaternary deposits of glacial drift and alluvium. (See Map S-3, Quaternary Hydrogeology.)

POTENTIOMETRIC SURFACES

Water in an aquifer enclosed by confining beds is generally under some pressure. When a well is drilled into the aquifer, the water will rise above the aquifer to a level in the well where the pressure is balanced by the column of water in the well. This is the static water level. The static water level defines a point which can be connected to every other static water level point in the aquifer by an imaginary surface which defines the head of water in the aquifer at all points. At any point where the potentiometric surface is above the ground surface, a well in the aquifer will flow freely at ground level as a flowing artesian well.

Data are sufficient to construct approximate potentiometric surfaces for the Prairie du Chien-Jordan aquifer and the Mt. Simon-Hinckley-Fond du Lac aquifer. The surfaces are represented on the map by contours showing altitude above sea level. These contours may be used to estimate static water levels or hydraulic heads for wells in these aquifers. The potentiometric surface is high where recharge or infiltration into the aquifer is taking place, and it slopes downward toward areas of discharge or water withdrawal. Water at any point in an aquifer moves down the slope of the potentiometric surface at that point, or perpendicular to the potentiometric contours.

HYDROGEOLOGIC PARAMETERS OF BEDROCK AQUIFERS IN MINNESOTA

Data are given in Table 1 for the parameters needed for calculations of the quantity and flow of ground water in the bedrock aquifers of Minnesota. These values have been estimated primarily from data in the U.S. Geological Survey Hydrologic Atlases for Minnesota, and Norvitch and others (37). The wide range of variability in most parameters for most aquifers indicates that there is considerable regional and local variation in the water-bearing characteristics of the aquifers, as well as that some data may be of doubtful accuracy. Where the data suffice, a modal value is given for each parameter as an approximation of the value most probably typical of the aquifer. In addition, the largest and the least of the reported values are also given as an indication of the range of possible variation. For evaluations of ground water in specific localities, local data should be sought or tests performed. Until additional data are available to describe variations in the hydrogeologic characteristics of the state's bedrock aquifers, quantitative evaluations based on the data in Table 1 must be regarded as approximations.

Definitions

Definitions of hydrogeologic parameters follow, abstracted from U.S. Geological Survey Water-Supply Paper 1988 (25). Values in Table 1 are given in customary American units with metric units in parentheses. These units reduce to fundamental dimensions of length, L, and time, t, also shown for each definition.

Specific capacity: The rate of discharge of water from a well, divided by the drawdown of the water level of the well below the static water level.

customary: gpm/ft=gallons per minute per foot
metric: l/sec/m=liters per second per meter
dimensions: $L^3t^{-1}L^{-1}=L^2t^{-1}$

Hydrologic conductivity: The volume of water at prevailing kinematic viscosity that will move in unit time under unit hydraulic gradient through a unit area measured normal to the direction of flow.

customary: gpd/ft^2=gallons per day per square foot
metric: m/day=meters per day
dimensions: $L^3t^{-1}L^{-2}=Lt^{-1}$

Transmissivity: The rate at which water at prevailing kinematic viscosity is transmitted through a unit width of an aquifer under unit hydraulic gradient.

customary: gpd/ft=gallons per day per foot
metric: m^2/day=square meters per day
dimensions: $L^3t^{-1}L=L^2t^{-1}$

Storage coefficient: The volume of water an aquifer releases from or takes into storage per unit surface area of the aquifer per unit change in head.

customary: dimensionless
metric: dimensionless
dimensions: $L^3L^{-2}L^{-1}$=dimensionless

Hydraulic diffusivity: The transmissivity of an aquifer relative to its storage coefficient, which is a value that characterizes the rate of propagation of head in an aquifer.

customary: gpd/ft=gallons per day per foot
metric: m^2/day=square meters per day
dimensions: $L^3t^{-1}L^{-1}=L^2t^{-1}$

Table 1. Hydrogeologic parameters of aquifers in Minnesota.

Aquifer	Specific Capacity		Hydraulic Conductivity		Transmissivity		Storage Coefficient	Hydraulic Diffusivity	
	gpm/ft	l/sec/m	gpd/ft²	m/day	gpd/ft	m²/day		gpd/ft	m²/day
1 Cretaceous									
Mode	1.5	0.3	150	6	3,000	40			
Range of values (low)	0.1	0.02	10	0.4	200	2.5	10^{-3}	2×10^{5}	2.5×10^{3}
(high)	17	3.5	300	12	30,000	370	10^{-5}	3×10^{8}	4×10^{6}
2 Cedar Valley-Maquoketa-Dubuque-Galena									
Mode	32	7	200	8	60,000	750			
Range of values (low)	4	0.8	25	1	8,000	100	10^{-2}	8×10^{5}	1×10^{4}
(high)	89	18	300	12	175,000	2,170	10^{-5}	2×10^{9}	2.5×10^{7}
3 Red River-Winnipeg									
Mode	10	2	50	2	20,000	250			
Range of values (low)	3	0.6	20	1	6,000	70	10^{-4}	6×10^{7}	7×10^{5}
(high)	15	3	60	2.5	30,000	370	10^{-6}	3×10^{9}	4×10^{7}
4 St. Peter									
Mode	4	0.8	80	3	8,000	100			
Range of values (low)	1	0.2	25	1	2,500	30	10^{-3}	2.5×10^{6}	3×10^{4}
(high)	10	2	250	10	37,000	450	10^{-5}	3×10^{9}	4×10^{7}
5 Prairie du Chien									
Mode	34	7	350	14	70,000	870			
Range of values (low)	3	0.7	40	1.5	7,000	90	10^{-3}	7.6×10^{6}	9×10^{4}
(high)	118	24	500	20	250,000	3,100	10^{-6}	2×10^{9}	2.5×10^{7}
6 Franconia-Ironton-Galesville									
Mode	15	3	200	8	30,000	370			
Range of values (low)	2	0.4	30	1	4,000	50	10^{-4}	4×10^{6}	5×10^{4}
(high)	37	8	250	10	80,000	1,000	10^{-6}	8×10^{9}	1×10^{8}
7 Mt. Simon-Hinckley-Fond du Lac									
Mode	15	3	200	8	30,000	370			
Range of values (low)	1	0.2	15	0.6	2,000	25	10^{-2}	2×10^{4}	2.5×10^{2}
(high)	33	7	175	7	70,000	870	10^{-6}	7×10^{9}	9×10^{7}
8 Keweenawan Volcanic Rocks									
Mode	no data		0.1	0.004	40	0.5			
Range of values (low)	0.01	0.002	0.05	0.002	20	0.25	10^{-3}	2×10^{4}	2.5×10^{2}
(high)	0.05	0.01	0.25	0.01	100	1	10^{-5}	1×10^{7}	1×10^{5}
9 Sioux Quartzite									
Mode	0.7	0.15	5	0.2	1,000	10			
Range of values (low)	0.09	0.02	1.5	0.06	150	2	10^{-3}	1.5×10^{5}	2×10^{3}
(high)	4	0.8	25	1	7,000	90	10^{-5}	7×10^{8}	9×10^{6}
10 Proterozoic									
Mode	no data		0.5	0.02	no data				
Range of values (low)	0.05	0.01	0.25	0.01	100	1	10^{-4}	1×10^{6}	1×10^{4}
(high)	0.25	0.05	1.5	0.06	500	6	10^{-6}	5×10^{8}	6×10^{6}
11 Biwabik Iron-Formation									
Mode	no data		no data		no data				
Range of values (low)	0.55	0.1	2.5	0.1	1,000	10	10^{-3}	1×10^{6}	1×10^{4}
(high)	9	2	50	2	20,000	250	10^{-5}	1×10^{9}	1×10^{7}

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