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GEOLOGICAL SURVEY

CONFIGURATION OF THE WATER TABLE AND DISTRIBUTION OF DOWNWARD LEAKAGE TO THE PRAIRIE DU CHIEN-JORDAN AQUIFER IN THE MINNEAPOLIS-SAINT PAUL METROPOLITAN AREA, MINNESOTA

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CONVERSION FACTORS

For the convenience of those who prefer to use International System (metric) units rather than English units, the conversion factors for terms used in this report are listed below:

Multiply	By	To obtain
acres	4.047×10^{-1}	ha (hectares)
ft (feet)	3.048×10^{-1}	m (metres)
gal (gallons)	3.785	l (litres)
in (inches)	25.4	mm (millimetres)
mi^2 (square miles)	2.590	km^2 (square kilometres)

CONFIGURATION OF THE WATER TABLE AND DISTRIBUTION OF DOWNWARD LEAKAGE TO THE PRAIRIE DU CHIEN-JORDAN AQUIFER IN THE MINNEAPOLIS-SAINT PAUL METROPOLITAN AREA, MINNESOTA

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ABSTRACT

The configuration of the water table was plotted at a contour interval of 20 feet (6 metres) on quadrangle maps (scale 1:62,500) of the Minneapolis-Saint Paul metropolitan area. Control points used for mapping were water levels in wells, lakes and sloughs, and places where topographic contours cross perennial streams.

A computer program, using a variation of Darcy's law, was developed to determine distribution of 1) downward leakage to the Prairie du Chien-Jordan aquifer under steady-state conditions, using estimated vertical hydraulic conductivity values for overlying materials; 2) calculated vertical hydraulic conductivity values, assuming uniform leakage to the aquifer; and 3) additional leakage to the aquifer resulting from increased pumpage during the summer. For data determination and data input to the computer program, the area was gridded into units of 1-minute longitude by 1-minute latitude, about 600 acres (243 hectares) per unit.

Previous work estimated the increased summer pumpage (1971) of ground water to be 127 million gallons ($481x10^6$ litres) per day. Calculations, made within the limits of governing assumptions, indicate that 10 to 20 percent of increased summer pumpage is derived from increased leakage. Most of the remainder is probably from captured natural discharge and induced recharge from major streams within the influence of summer cones of depression.

Based on available data and estimates of vertical hydraulic conductivity for geologic units, major leakage to the Prairie du Chien-Jordan aquifer is indicated to occur in formation subcrop areas, especially where these areas are overlain by the most permeable glacial drift.

INTRODUCTION

This report presents maps showing the configuration of the water table and distribution of downward leakage (recharge) to the major aquifer underlying most of the Minneapolis-St. Paul area. The extent of the study area is 2,968 mi^2 (7,687 km^2), including Anoka, Carver, Dakota, Hennepin, Ramsey, Scott, and Washington Counties (fig. 1). About 2,000 mi^2 (5,180 km^2) is underlain by the Prairie du Chien-Jordan aquifer, the major source of ground-water supply in the area.

The geologic units and their water-bearing characteristics in the metropolitan area are summarized in table 1. Only that part of the geologic section above the St. Lawrence Formation is pertinent to this study.

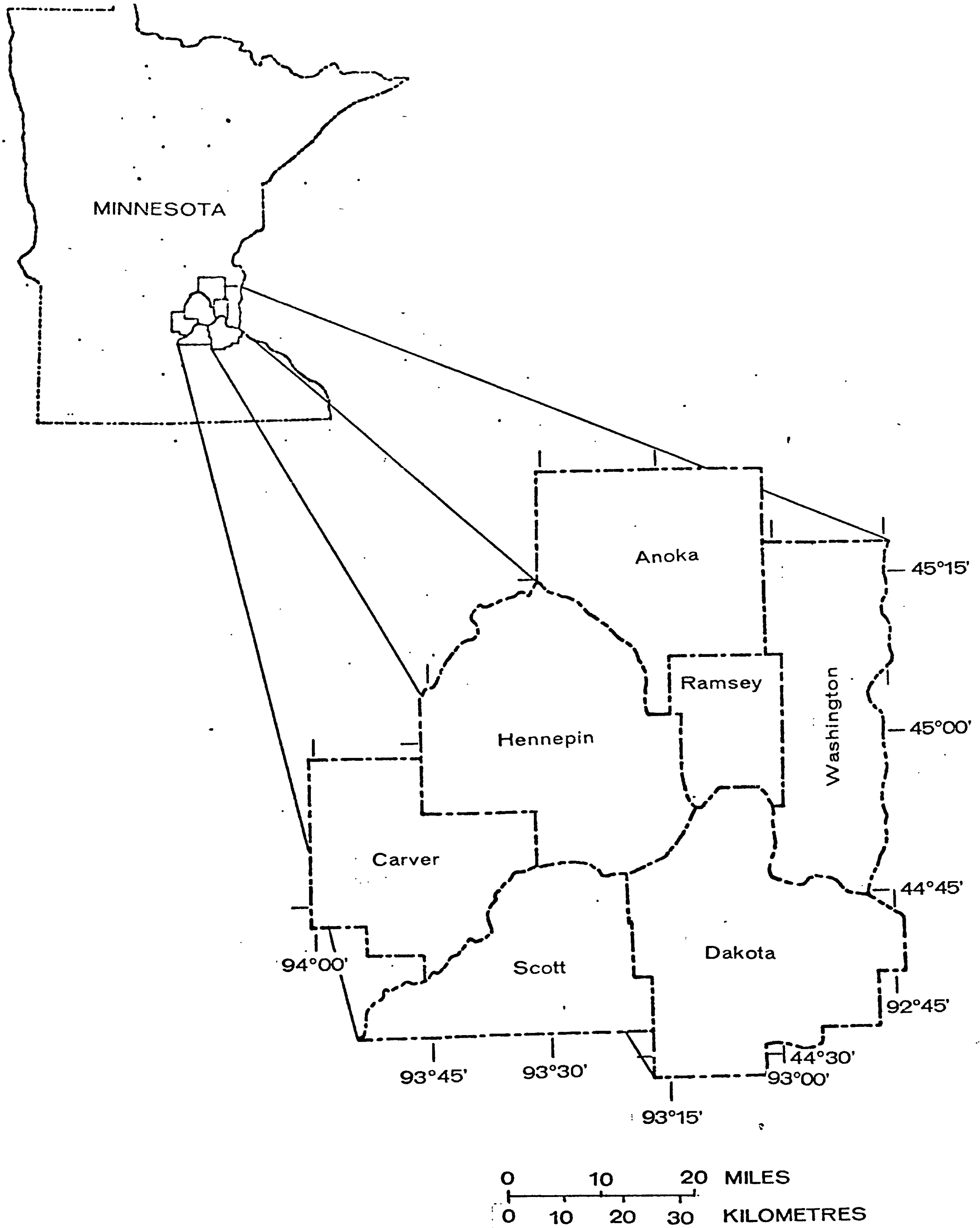

Figure 1.--Area of study described by this report.

Table 1.--GEOLOGIC UNITS AND THEIR WATER-BEARING CHARACTERISTICS
(Modified from Stone, 1965)

[illegible]	GEOLOGIC UNIT	APPROX. RANGE IN THICKNESS (in feet)	DESCRIPTION	WATER-BEARING CHARACTERISTICS
QUATERNARY	Undifferentiated glacial drift	0-400+	Glacial till, outwash sand and gravel, valley-train sand and gravel, lake deposits, and alluvium of several ages and several provenances; vertical and horizontal distribution of units is complex.	Distribution of aquifers and relatively impermeable confining beds is poorly known, especially in subsurface. Where saturated, stratified well-sorted deposits of sand and gravel (alluvium, valley train, outwash, some lake and ice-contact deposits) yield moderate to large supplies of water to wells. Records of 24 large diameter wells completed in sand and gravel show yields ranging from 240 to 2,000 gpm (gallons per minute) with from 2 to 69 feet of drawdown. Des Moines Lobe till is non-water bearing; Superior Lobe till is sandy and may yield small supplies suitable for domestic or farm use.
ORDOVICIAN	Decorah Shale	0-95	Shale, bluish-green to bluish-gray; blocky; thin, discontinuous beds of fossiliferous limestone throughout formation.	Confining bed.
ORDOVICIAN	Platteville Limestone	0-35	Dolomitic limestone and dolomite, dark-gray, hard, thin-bedded to medium-bedded; some shale partings; can be divided into five members.	Where saturated, fractures and solution cavities in rock generally yield small supplies to wells. Records of 23 wells show an average yield of 23 gpm. Water is generally under artesian pressure where overlain by Decorah Shale. Not considered to be an important source of water in area of study.
ORDOVICIAN	Glenwood Shale	0-18	Shale, bluish-gray to bluish-green; generally soft but becomes dolomitic and harder to the east.	Confining bed; locally, some springs issue from the Glenwood-Platteville contact in the river bluffs.
ORDOVICIAN	St. Peter Sandstone	0-150+	Sandstone, white, fine- to medium-grained, well-sorted, quartzose; locally iron-stained and well cemented; rounding and frosting of grains is common; 5-50 feet of siltstone and shale near bottom of formation.	Not fully saturated throughout area. Most wells completed in the sandstone are of small diameter and used for domestic supply. They yield 9 to 100 gpm with 1 to 21 feet of drawdown. Two wells known to be used for public supply have been pumped at 600 and 1,250 gpm. Water occurs under both confined and unconfined conditions. Confining bed near bottom of formation seems extensive and hydraulically separates sandstone from underlying Prairie du Chien-Jordan aquifer. Not considered to be an important source for public supplies, but is suitable source for domestic supplies.
ORDOVICIAN	Prairie du Chien Group: Shakopee Dolomite	0-250+	Dolomite, light-brown to buff, thinly to thickly bedded, cherty; shale partings; commonly sandy and oolitic.	About 2,000 square miles in extent in metropolitan area. Together, the Prairie du Chien Group and Jordan Sandstone constitute the major aquifer unit. The two are hydraulically connected throughout most of the area, but locally some small head differences may exist owing to intervening low-permeable confining beds of limited extent. Prairie du Chien: Permeability is due to fractures, joints and solution cavities in the rock. Yields small to large supplies of water to wells. Pumping rates of up to 1,800 gpm have been obtained. Prairie du Chien-Jordan aquifer: Supplies about 75 percent of ground water pumped in the metropolitan area. Yields of 115 wells (8-24 inch diameter casings), open to both rocks, ranged from 55 to 2,765 gpm with 3 to 133 feet of drawdown. Higher obtainable yields seem to reflect closeness to the Mississippi and Minnesota Rivers or to places where the aquifer is overlain directly by glacial deposits, particularly where drift-filled valleys penetrate. Jordan: Permeability is mostly intergranular but may be due to joint partings in cemented parts. Main source of water for public supply in metropolitan area. Almost all wells completed in the sandstone are of large diameter. Recorded yields are from 66 to over 2,400 gpm with 2 to 155 feet of drawdown.
ORDOVICIAN	Prairie du Chien Group: New Richmond Sandstone		Sandstone and sandy dolomite, buff; often missing.	
ORDOVICIAN	Prairie du Chien Group: Oneota Dolomite		Dolomite, light-brownish-gray to buff; thinly to thickly bedded, vuggy.	
CAMBRIAN	Jordan Sandstone	0-100+	Sandstone, white to yellowish, fine- to coarse-grained, massive to bedded, cross-bedded in places, quartzose; commonly iron-stained; loosely to well cemented.	
CAMBRIAN	St. Lawrence Formation	0-65	Dolomitic siltstone and fine-grained dolomitic sandstone; glauconitic, in part.	Confining bed. No wells are known to obtain water from this formation.
CAMBRIAN	Franconia Formation	0-200+	Sandstone, very fine grained; moderately to highly glauconitic; worm-bored in places. Interbedded very fine grained sandstone and shale; mica flakes common. Glauconitic fine-grained sandstone and orange to buff silty fine-grained sandstone (often worm-bored).	Small amounts of water may be obtainable from the medium- to coarse-grained members of the formation, very little water from the fine-grained members. Not considered to be an important water source in the area. Records of wells completed only in the Franconia Formation are lacking.
CAMBRIAN	Ironton Sandstone	0-80+	Sandstone, white, medium- to fine-grained, poorly sorted and silty.	An important aquifer beyond the limits of the Prairie du Chien-Jordan aquifer. Yields of wells range from 40 to 400 gpm with 4 to 110 feet of drawdown.
CAMBRIAN	Galesville Sandstone		Sandstone, yellow to white, medium- to coarse-grained, poorly cemented.	
CAMBRIAN	Eau Claire Sandstone	0-150	Sandstone, siltstone, and shale, gray to reddish-brown, fossiliferous.	Confining bed. Sandstone beds may yield small quantities of water to wells for domestic use. Shale of very low permeability and apparent large areal extent constitutes the main confining bed for water in the underlying aquifer.
CAMBRIAN	Mt. Simon Sandstone	As much as 200	Sandstone, gray to pink, medium- to coarse-grained. Some pebble zones and thin, shalely beds.	Secondary major aquifer, supplies about 15 percent of ground water pumped in the metropolitan area. Recorded yields of municipal and industrial wells ranged from 125 to 2,000 gpm with 20 to 209 feet of drawdown.
PRECAMBRIAN	Hinckley Sandstone	As much as 200	Sandstone, buff to red, medium- to coarse-grained, well sorted and cemented.	
PRECAMBRIAN	Red clastics	As much as 4,000	Silty feldspathic sandstone and lithic sandstone, fine-grained; probably includes red shale.	Data are lacking in metropolitan area.
PRECAMBRIAN	Volcanic rocks	As much as 20,000	Mostly mafic lava flows, but includes thin interlayers of tuff and breccia.	Rock is at and near the surface at Taylors Falls, north of metropolitan area. Deeply buried in metropolitan area and no data available.

Purpose and scope

The study was made by the U.S. Geological Survey in cooperation with the Metropolitan Council of the Twin Cities area. It may be considered to be an addendum to a report by Norvitch and others (1973), which describes the general geology and hydrology of the Twin Cities metropolitan area.

The primary purpose of this study was to define the hydrology of the area more clearly. The water-table maps contained herein are approximations. Within their range of accuracy, however, they should be useful to engineers, planners, water managers, and to individuals seeking water supplies for municipal, industrial, farm, and home use. Specifically, the water-table maps may provide data for a possible computer model of the local hydrologic system. The leakage maps also are approximations. Where used in proper perspective, they could help guide land development in the area as well as aid in development of a hydrologic model. In this study, the comparative leakage values obtained are more significant than the absolute values.

The scope of the project was necessarily general because of the extreme complexity of the hydrogeologic system being mapped, the large size of the area, and the relative lack of available data.

Acknowledgments

Permission was granted by officials of the Minneapolis, St. Paul, and several suburban public-school districts; city water-department and county engineers; and several private-property owners to auger test wells and install observation wells. For their cooperation and help, the authors are extremely grateful.

WATER-TABLE MAPS

The water table in the seven-county metropolitan area was plotted at a contour interval of 20 ft (6 m) on the following U.S. Geological Survey 15-minute topographic quadrangle maps (scale 1:62,500):

Anoka	Glencoe	New Richmond
Belle Plaine	Hastings	Prior Lake
Buffalo	Isanti	Red Wing
Elk River	Lake Minnetonka	Rockford
Farmington	Minneapolis	St. Francis
Forest Lake	New Brighton	St. Paul
Gaylord	New Prague	Waconia

and on the following U.S. Geological Survey 7½-minute topographic quadrangle maps (reduced to the same scale as the 15-minute quadrangles):

Dennison	Little Chicago	St. Paul Park
Hudson	Marine-on-St. Croix	Stillwater
Hugo	Northfield	White Bear Lake East
Lake Elmo	Prescott	

The locations of the above quadrangles are shown in figure 2. The water-table maps are shown in figures 3 through 20. The water-table altitudes are approximate and should not be interpreted as being precise at any particular point at any particular time.

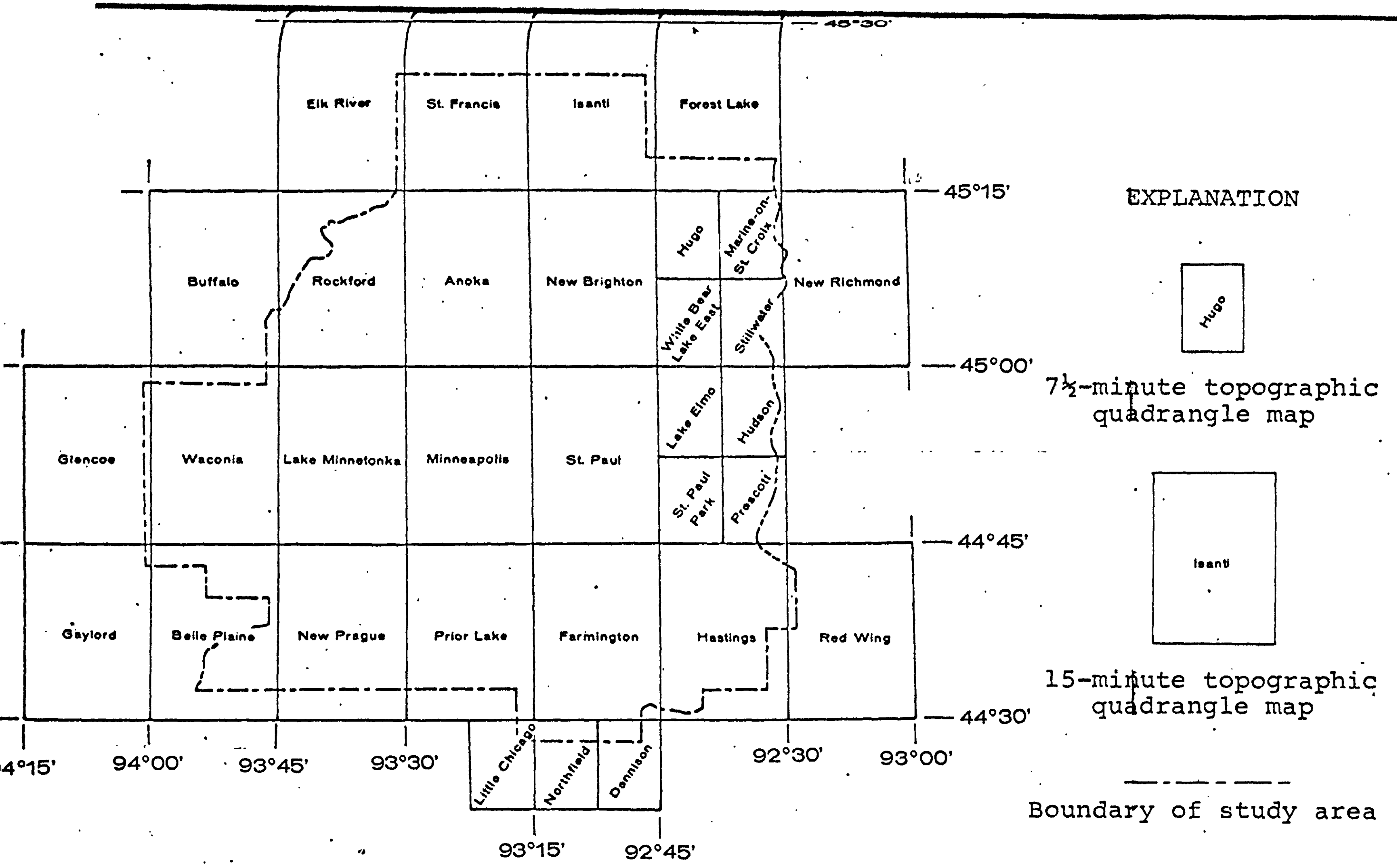

Figure 2.--U.S. Geological Survey quadrangle maps used in mapping the water table in the Minneapolis - St. Paul area.

Ideally, in mapping a dynamic surface such as the water table, all altitudes at the control points are measured within a short time span, perhaps during the month when fluctuations in water levels are minimal. The hydrographic controls used in this study are contained on maps whose survey dates range from 1916 to 1972. Long-term hydrographs of water-table fluctuations in the study area are lacking; but in one well with an 11-year record, the range in water levels was slightly more than 10 ft (3 m). The annual range in any one well is probably no more than 5 ft (1.5 m), and no long-term trends are known to be occurring in any parts of the area. Thus, for the range of accuracy attempted in this study, the points used for control seem reasonable on a time basis.

In summer 1973, 84 test holes were augered in the study area, of which 73 were completed as water-table observation wells. Static water levels in these and other water-table wells were measured on November 27-28, 1973 (the water table is normally lowest and most stable during fall and winter). These water levels, lake and slough levels, and points where topographic contours cross perennial streams were used as control points for mapping the water table.

In this study, all ponds and lakes were considered to be expressions of the water table. It is apparent in outwash plains that lakes are generally continuations of the water table because of concordant lake levels and the small difference between altitudes of lake surfaces and water levels in adjacent shallow wells. However, in till areas, this hydraulic continuity is not so obvious, especially where the gradient of the water table near a lake may be steep due to low hydraulic conductivity of the earth materials underlying and surrounding the lake.

Some investigators may not consider lakes as satisfactory control points for contouring the water table. Manson and others (1968, p. 9) infer that many ponds and small lakes in Minnesota are perched above the main water table owing either to impervious lake-bottom sediments or to underlying impervious silt and clay. However, these natural materials are not totally impervious. In a study in North Dakota, Eisenlohr and others (1972, p. 83) considered the following as seeming evidence of perched ponds: (1) apparent dryness of test holes when augered near ponds, (2) wide variations in water level between nearby ponds, (3) wide variations in water level between ponds and nearby wells, and (4) wide variations in water level between clusters of wells finished at different depths. They conclude that if the very low hydraulic conductivity of till is considered, the above criteria are not enough proof that a relatively permanent pond is perched above the regional water table by an unsaturated zone. Thus, the water-table maps included in their report were based on data from observation wells and ponds.

It is possible that some lakes and ponds, particularly in areas underlain by clayey till, in the Twin Cities area are perched above the water table, but they are believed by the authors to be exceptions, rather than the rule.

Perennial stream levels also were used as control points on the water table because the water table is hydraulically connected to streams in most places. Water normally discharges from the ground-water system into streams, thus stream volume increases as a stream flows through the area. During times of high flow, streams may recharge the ground-water system, but this is short lived. Intermittent streams flow only during parts of the year, so points where they cross topographic contours were used as guides rather than as control points in contouring the water table.

Although the number of points used to draw the water-table maps was considerable, the maps could be refined by more water-table well data, especially where surficial expressions of the water table are lacking. The augering done for this study was limited to unconsolidated deposits and the St. Peter Sandstone; also, augering depths were limited to no more than 100 ft (30 m). As a result, observation wells could not be installed in some places.

Horizontal ground-water movement is downgradient, roughly perpendicular to the water-table contours. The water table somewhat parallels the land surface; therefore, ground water moves from relatively high areas toward low areas, where it discharges from the system. Locally, shallow ground water discharges to lakes and streams, is lost to evapotranspiration, is discharged by pumping, or percolates downward to recharge bedrock aquifers. Water from the bedrock aquifers discharges to the major streams --the Minnesota, St. Croix, and Mississippi Rivers.

The water-table maps (figs. 3 through 20), in conjunction with potentiometric surface maps of underlying bedrock aquifers, may be used to approximate the direction and amount of flow between the glacial drift and the bedrock aquifers by means of Darcy's law (Ferris and others, 1962, p. 71). As a part of this study, the water-table data were used as input to a computer program to estimate downward leakage to the Prairie du Chien-Jordan aquifer.

DOWNWARD LEAKAGE TO THE PRAIRIE DU CHIEN-JORDAN AQUIFER

Recharge rates for aquifers are determined so that ground-water resources may be evaluated and consequences of aquifer use may be predicted. Conversely, aquifer use may be influenced greatly by changes in recharge (or discharge) brought about by that use. (See Lohman, 1972, p. 62-67.)

Recharge involves vertical leakage through earth materials. The quantity of leakage is controlled by the hydraulic conductivity and thickness of the materials through which leakage occurs, the head differences between the water table and the potentiometric surface of the bedrock aquifer, and the area involved. This report considers leakage only to the Prairie du Chien-Jordan bedrock aquifer below the zone of saturation, that is, between the water table and the top of the bedrock aquifer where it is under artesian conditions. Where the water table is in the aquifer, data are not available to compute an average annual leakage rate.

Ideally, for total land-use planning, the areal distribution of recharge from the land surface to the water table should be determined. This determination was not within the scope of this study. Recharge to water-table aquifers is largely by downward percolation of precipitation. The amount of precipitation that reaches the water table depends mainly on the following: (1) depth to the water table; (2) character and thickness of materials above the water table; (3) antecedent soil-moisture conditions; (4) vegetal cover; (5) land use; (6) topography and drainage; (7) intensity, duration, and distribution of rainfall; (8) occurrence of precipitation as rain or snow; and (9) air temperature and other meteorological factors.

The Prairie du Chien-Jordan aquifer is recharged in large part by vertical leakage of water through overlying materials. The rate of vertical leakage may be expressed by the following form of Darcy's law:

$$Q_c/A_c=365(P'/m')\Delta h$$

where

Q_c=leakage through deposits, in cubic feet per year

A_c=area through which leakage occurs, in square feet

P'=vertical hydraulic conductivity (coefficient of vertical permeability) of deposits, in feet per day

m'=saturated thickness of deposits, in feet

Δh= difference between the head in the aquifer and in the source bed above the deposits through which leakage occurs, in feet

This equation was used to generate maps of the study area showing areal distribution of: (1) leakage rates to the Prairie du Chien-Jordan aquifer under steady-state conditions based on estimated P' values; (2) calculated P' values, assuming uniform leakage to the aquifer; and (3) leakage to the aquifer resulting from increased pumpage during summer.

The following assumptions were made to simplify the calculations of leakage rates and distribution of P' values: (1) The potentiometric surface of the Prairie du Chien-Jordan aquifer in winter 1970-71 (fig. 21) and the water table (fig. 3-20) represent long-term steady-state conditions.

(2) The assigned thickness of each bedrock unit, where present, is constant over the entire area. For example, the St. Peter Sandstone is assumed to average 120 ft (36.6 m) thick wherever it is present above the Prairie du Chien Group. (Any error introduced by this assumption would probably be small in comparison to that introduced in estimating the approximate vertical hydraulic conductivity for the respective geologic unit.)

(3) All water is moving vertically; lateral movement is not considered. The head difference between the water table and the potentiometric surface of the aquifer is considered to be the driving force for vertical leakage. Although leakage can occur both in and out of the base of the aquifer depending on differences between heads in the aquifer and in the underlying beds, the net gain or loss at the base is assumed to be zero.

(4) The basin-storage discharge of the study area is mostly outflow from the Prairie du Chien-Jordan aquifer. According to Norvitch and others (1973, p. 68), the average basin-storage discharge in the Twin Cities area is 5.24 in (133 mm) per year. Therefore, the average leakage rate to the aquifer should be about the same. (Use of the 5.24 in or 133 mm of leakage was intended to obtain an approximate realistic distribution of unit leakage in the computations that follow. However, the comparative leakage values are more important than the absolute quantitative values. An accurate determination of total leakage only to the Prairie du Chien-Jordan aquifer is not available.)

Leakage under steady-state conditions

Darcy's law was applied to estimate the amount of leakage through overlying materials to the Prairie du Chien-Jordan aquifer under steady-state conditions. This was done by a computer program (page 30) that calculated the leakage rate, Q_c, for each 1-minute longitude by 1-minute latitude grid unit in the study area.

Procedure

Recharge to the Prairie du Chien-Jordan aquifer was calculated for that part of the study area underlain by the aquifer. Identifiers for lithology and numerical values for altitudes of the water table, top of the Prairie du Chien-Jordan aquifer, and potentiometric surface of the aquifer were coded and stored for use in the calculations. These data remained constant for every run. Estimated values of P' for each geologic unit, thickness of bedrock units, and percent sand in glacial drift were changed from run to run. Using these values, leakage was calculated and plotted for each grid unit. Finally, the total average leakage in the area was computed and compared to the basin-storage discharge value.

The following outlines of the procedure by steps:

A. Grid

1. covers that part of the seven-county area that is underlain by the Prairie du Chien-Jordan aquifer
2. units are 1-minute longitude by 1-minute latitude
3. area per grid unit is 2.62×10^7 ft^2 (2.43×10^6 m^2) or about 600 acres (243 ha)

B. Coding and storage of input data, averaged for each grid unit; these data remain constant for all runs

1. surficial geology types
    a. glacial drift (from Stone, 1965)
        1) outwash--includes outwash sand and gravel, valley-train sand and gravel, alluvium, and wind-deposited sand
        2) red till--includes red till, lake deposits, and undifferentiated glacial drift
        3) gray till
    b. bedrock
        1) Decorah Shale
        2) Platteville Limestone and Glenwood Shale
        3) St. Peter Sandstone
        4) Prairie du Chien Group and Jordan Sandstone

2. gedrock geology types

   a. Decorah Shale

   b. Platteville Limestone and Glenwood Shale

   c. St. Peter Sandstone

   d. Prairie du Chien Group and Jordan Sandstone

3. water-table altitude

4. Altitude of the top of the Prairie du Chien-Jordan aquifer (Norvitch and others, 1973, figs. 12 and 14)

5. Altitude of the potentiometric surface of the Prairie du Chien-Jordan aquifer, winter 1970-71 (fig. 21)

C. Coding and storage of input data, averaged for the entire study area; these data are adjusted from run to run

   1. estimated values of P' for the geologic units

   2. estimated values of m (thickness) for the bedrock units

   3. estimated values of percent sand in outwash, red till, and gray till

D. Solution of the leakage equation, $Q_c=365(P'/m')(\Delta h)(A_c)$, for each grid unit; storage of results

   1. calculation of m', the difference in altitude between the water table and the top of the Prairie du Chien-Jordan aquifer

   2. selection or calculation of P' according to m' and the occurrence of various geologic units; input data for the following examples are given in table 1, and geologic conditions are shown in figure 22

a. m'=175 ft (53.3 m); at the surface is outwash, which is underlain by Decorah Shale. Thus, all of the St. Peter Sandstone, Platteville Limestone and Glenwood Shale, and Decorah Shale is saturated; and none of the outwash is saturated. (See fig. 22.) The value of P' to be used is that given for St. Peter plus Platteville and Glenwood plus Decorah, 0.0000035 ft/d (0.0000011 m/d).

b. m'-160 ft (48.8 m); St. Peter Sandstone is overlain by gray till. Thus, the entire 120-ft (36.6-m) section of St. Peter Sandstone is saturated and 40 ft (12 m) of the gray till is saturated. (See fig. 22.) The composite P' is determined by the equation

$$P'=((m_1+m_2)P'_1P'_2)/P'_2m_1+P'_1m_2)$$

In this case, P'=0.00140 ft/d (0.000427 m/d)

3. calculation of Δh, the difference in altitude between the water-table and the potentiometric surface of the Prairie du Chien-Jordan aquifer
4. the value of A_c remains constant at $2.62x10^7$ ft^2 ($2.43x10^6$ m^2)
5. calculation of Q_c for each grid unit
6. leakage rate was not calculated for the following areas:
   a. valleys of the Minnesota, Mississippi, and St. Croix Rivers (considered to be areas of discharge for the Prairie du Chien-Jordan aquifer)

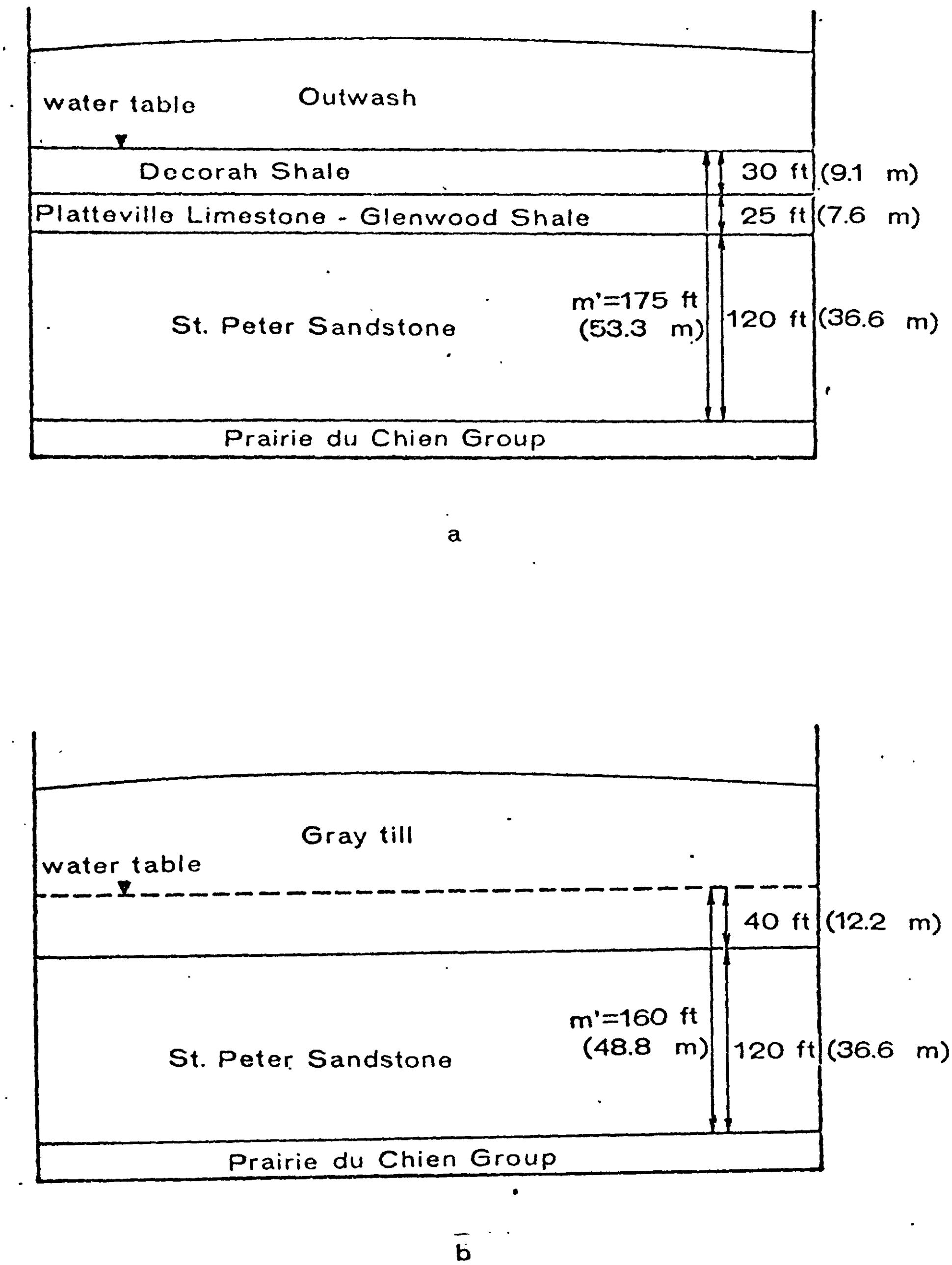

Figure 22.--Diagrammatic sections showing two possible geohydrologic combinations for calculation of P' (vertical hydraulic conductivity).

b. outcrop areas of Prairie du Chien Group or Jordan Sandstone ($\Delta h=0$)

c. areas where the water-table altitude is equal to or less than the altitude of the top of the Prairie du Chien-Jordan aquifer ($m' \leq 0$)

d. areas where the water-table altitude is equal to the altitude of the potentiometric surface in the Prairie du Chien-Jordan aquifer ($\Delta h=0$)

E. Print out of leakage values in inches per year

F. Calculation of average leakage--sum of leakage of all grid units divided by number of grid units for which leakage was computed

G. Compare average leakage rate with assumed discharge (5.24 in or 133 mm per year) of the Prairie du Chien-Jordan aquifer; if average is considered an unsatisfactory value, change values of P' (vertical hydraulic conductivity), m (bedrock unit thickness), and (or) percent sand in glacial drift and repeat steps C-G

Comments

The seventh set of input data (table 2) produced the most reasonable value for the average vertical leakage rate to the Prairie du Chien-Jordan aquifer, 5.6 in (142 mm) per year. In obtaining this value, the P' of the St. Peter Sandstone was reduced by a factor of 20 from its initial estimate. The P' of the outwash was increased by a factor of 10. Other parameter values were changed but slightly.

Geologic Unit		ft/d	m/d	feet	metres	Remarks
Outwash (at surface)	Till	0.0024	0.00073	variable		Considered to be composed of red and gray till and sand and gravel; 80 percent sand and gravel and 20 percent till
	Sand and gravel, some clay and silt	2.1	0.64			
Red drift (at surface)	Till	0.0020	0.00061	variable		Considered to be composed of red and gray till and sand and gravel; 20 percent sand and gravel and 80 percent till
	Sand and gravel, some clay and silt	2.1	0.64			
Gray drift (at surface)	Till	0.0018	0.00055	variable		Considered to be composed of 10 percent sand and gravel and 90 percent gray till
	Sand and gravel, some clay and silt	2.1	0.64			
Decorah Shale		0.0000007	0.0000002	30	9.1	Only about 25 square miles (65 square kilometres) in study area
Platteville Limestone and Glenwood Shale		0.0000035	0.0000011	25	7.6	About 220 square miles (570 square kilometres) in study area
St. Peter Sandstone		0.0013	0.00040	120	36.6	Includes a 45-foot (14-metre) thick confining silt bed at base of unit
St. Peter + Platteville and Glenwood		0.00002	0.000006	145	44.2	
St. Peter + Platteville and Glenwood + Decorah		0.0000035	0.0000011	175	53.3	

Table 2.--Input data used in program to determine areal distribution of leakage to the Prairie du Chien-Jordan aquifer under steady-state conditions.

The distribution of the leakage to the aquifer is shown in figure 23. The distribution of composite vertical hydraulic conductivities using the same input data is shown in figure 24. In comparing figure 23 with the potentiometric-surface map (fig. 21) of the Prairie du Chien-Jordan aquifer, relatively values of leakage are indicated near major potentiometric highs in the northeast and southern parts of the metropolitan area, but not near the high in the western part. Thus, it seems that potentiometric highs do not necessarily indicate areas of major leakage. Three main areas showed particularly high values of leakage, 6 in (152 mm) per year or greater: 1) from the top of T.32 N., R.20 W., to about 6 mi (9.7 km) south of Stillwater (fig. 4); 2) south and east of Anoka including most of T.31 N., R.24 W.; T.120 N., R.21 W., and T.119 N., R.21 W.; and 3) in an area from about 8 mi (12.9 km) southwest of Jordan to Shakopee. The first area closely follows the east flank of a divide in the potentiometric surface between the Mississippi and St. Croix Rivers where Superior lobe (red) drift directly overlies rock of the Prairie du Chien Group. The second is where coarse valley train deposits in the Des Moines lobe (gray) drift area directly overlie Jordan Sandstone. The third is where Des Moines lobe drift directly overlies Prairie du Chien Group or Jordan Sandstone. Other, less prominent, places of high leakage occur throughout the area--notably, one near the east end of Lake Minnetonka.

Therefore, by using the available data and estimates of vertical hydraulic conductivity for the geologic units, it seems that major leakage to the Prairie du Chien-Jordan aquifer occurs in formation subcrop areas, especially where these areas are overlain by the most permeable glacial drift. Generally, places of low leakage rates, less than 4 in (102 mm) per year, are where the aquifer is overlain by the St. Peter Sandstone and other formations.

In evaluation of the procedure to determine the leakage distribution, the exclusion of lateral flow was considered a potentially big factor, for which no account could be made. The assigned altitudes of contours on the water table, the potentiometric surface of the Prairie du Chien-Jordan aquifer, and structure contours on top of the aquifer were considered to be the most reliable data. However, in selecting input values to the computer programs used in this study, potentiometric-surface altitudes of the Prairie du Chien-Jordan aquifer were considered to be more reliable than water-table altitudes because of their smoothness. The water-table altitudes varied appreciably within grid units in places; thus, average values were difficult to select.

The assigned thickness and estimated P' values for each geologic unit were considered to be least reliable. Vertical hydraulic conductivity is dependent upon the properties of the water flowing through the material; the porosity of the material; the range and distribution of grain sizes; the shape, orientation, and arrangement of grains; and the mean grain size. These factors are particularly difficult to determine in glacial drift because the lithology may change markedly within short distances. For this study, only three types of drift were considered, but many types and innumerable combinations of types may exist. Bedrock units are not as variable as drift; however, one thin confining bed in a bedrock aquifer can greatly change the effective P' of the entire unit. Thus, the limitations of the leakage distribution on figure 23 must be considered for practical use. No field method is known that could be used to validate the results shown on this figure.

Vertical hydraulic conductivity assuming uniform leakage

Even if the subsurface geology were well defined, composite P' values would be difficult to approximate because actual determinations of vertical hydraulic conductivity are few. If leakage to the aquifer were known, then P' could be calculated using the following form of Darcy's law:

$$P'=(Q_c)(m')/365(\Delta h)(A_c)$$

If leakage to the aquifer were uniform (everywhere equal) at 5.6 in (142 mm) per year and values of m', Δh, and A_c were the same as those used previously, the calculated P' values would be as shown in figure 25. (See computer program, page 30.)

Leakage during summer pumping

An attempt was made to determine increased leakage to the aquifer under nonsteady-state conditions owing to increased summer pumpage in the interest of obtaining a better understanding of the workings of the ground-water system. (See computer program, page 40.) Given the composite P' values (fig. 24) and the water-level changes from winter to summer (Norvitch and others, 1973, fig. 47), the increased leakage during summer 1971 was derived as shown in figure 26. In this analysis, the water-table levels were assumed to remain fixed. Maximum values of increased leakage greater than 0.1 ft (0.03 m) per year are indicated in places where valley-train and outwash sands and gravels lay at the surface, overlying subcrop areas of the Prairie du Chien-Jordan aquifer.

An estimated 1.9 trillion gallons (7.2×10^{12} l/d) of water is in storage in sediments overlying the Prairie du Chien-Jordan aquifer. Some of this water is available for recharge to the aquifer during periods of summer pumping. The daily excess summer pumpage, that attributed to air conditioning, irrigation and other summer-only uses (Norvitch and others, 1973, p. 161), from the Prairie du Chien-Jordan aquifer in 1971 was 127 Mgal/d (million gallons per day) (4.81×10^{8} l/d). Increased leakage from overlying sediments, as calculated (computer program, page 40), was 13 Mgal/d (4.9×10^{7} l/d). An estimated 1 Mgal/d (3.8×10^{6} l/d) was removed from storage in the Prairie du Chien-Jordan aquifer. Captured natural discharge and induced recharge from the major streams within the influence of summer cones of depression probably provide most of the remainder or 113 Mgal/d (4.28×10^{8} l/d). If pumping is intensive and prolonged, water-table declines may occur and result in increased recharge from lakes, streams, or swamps, and reduced evapotranspiration or basin-storage discharge.

For comparison purposes, increased summer leakage was derived using the calculated P' values (fig. 25) and the water-level change data as used above. The resultant distribution is shown on figure 27. Maximum values of increased leakage, greater than 0.1 ft (0.03 m) per year, were in the areas of greatest water-level change from winter to summer--geologic control seemed to have little effect. Under this condition, increased leakage was 27 Mgal/d ($1.0x10^8$ l/d). The two quantitative estimates above indicate that 10 to 20 percent of increased summer pumpage is derived from increased leakage.

In evaluation of the results obtained using estimated P' values and computed P' values, lack of field data prevents the determination of which results are more correct. However, intuitively, it seems that the results derived using estimated values have more basis in fact than those determined from computed values. The intent of calculating summer leakage was not to determine which physical representation of the system was correct but rather to get an approximation of the effect of increased summer pumping on leakage. Arguments for or against the validity of either of the two methods are beyond the scope of this report.

It must be understood that quantitative estimates derived in the foregoing programs are based on the assumption that all leakage (recharge) is moving vertically downward and is equal to the basin-storage discharge. This is not entirely correct, for recharge can also occur laterally, and not all basin-storage discharge is from the Prairie du Chien-Jordan aquifer. Therefore, the comparative values of the leakage are more important than the absolute values.

SUMMARY

1. The water-table maps in this report are based on hydrographic features and water-level measurements in wells. They should be useful to engineers, planners, water managers, and individuals seeking water supplies. They do not show exactly at what depth the water table will be found at any one specific site or date.
2. In derivation of the leakage distribution shown in figure 21, the most reliable data were considered to be: a) contours of the water table, b) contours of the potentiometric surface of the Prairie du Chien-Jordan aquifer, and c) structure contours of the top of the aquifer. The least reliable data were the assigned thickness and estimated vertical conductivity values for each geologic unit. In addition, the exclusion of lateral flow, for which no accounting could be made, was considered to be a big factor.
3. Greatest leakage to the Prairie du Chien-Jordan aquifer occurs in formation subcrop areas, especially where these areas are overlain by the most permeable glacial drift. Generally, places of low leakage are where the aquifer is overlain by the St. Peter Sandstone and other formations.

4. Calculations, made within the limits of governing assumptions, indicate that 10 to 20 percent of increased summer pumpage is derived from increased leakage. Most of the remainder is probably from captured natural discharge and induced recharge from major streams within the influence of summer cones of depression.

5. The comparative values derived for leakage in this report are more important than the absolute values, for the assumptions (p. 14) that all leakage is moving vertically downward and is equal to the basin-storage discharge are not entirely correct.

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      PROGRAM RECH(INPUT,OUTPUT,PUNCH)
C PROGRAM TO COMPUTE VERTICAL LEAKAGE TO PRAIRIE DU CHIEN-JORDAN AQUIFER
C PROGRAMMED BY STEVEN P. LARSON, WRD, ST. PAUL, MINN.
C INPUT VARIABLES----
C   CARD 1--FORMAT(2I10,6G10.0)
C      NR-NUMBER OF ROWS IN INPUT DATA MATRIX
C      NC-NUMBER OF COLUMNS IN INPUT DATA MATRIX
C      P-(6 VALUES)-VERTICAL HYDRAULIC CONDUCTIVITY OF LAYERS ABOVE AQUIFER,
C         FEET/DAY
C         1) ST. PETER SANDSTONE
C         2  PLATTEVILLE LIMESTONE AND GLENWOOD SHALE
C         3) DECORAH SHALE
C         4) GRAY DRIFT
C         5) RED DRIFT
C         6) OUTWASH(TILL VALUE ONLY)
C   CARD 2--FORMAT(8G10.0)
C      M-(6 VALUES)-THICKNESS OF BEDROCK LAYERS OR PERCENT SAND IN DRIFT AREAS
C         1) ST. PETER SANDSTONE, THICKNESS
C         2) PLATTEVILLE LIMESTONE AND GLENWOOD SHALE, THICKNESS
C         3) DECORAH SHALE, THICKNESS
C         4) GRAY DRIFT, PERCENT SAND
C         5) RED DRIFT, PERCENT SAND
C         6) OUTWASH, PERCENT SAND
C      SP-(3 VALUES, 2 ON THIS CARD)-EFFECTIVE HYDRAULIC CONDUCTIVITY FOR
C         AGGREGATED BEDROCK LAYERS, FEET/DAY
C         1) ST. PETER SANDSTONE ONLY
C         2) ST. PETER PLUS PLATTEVILLE AND GLENWOOD
C   CARD 3--FORMAT(8G10.0)
C      SP-(3RD VALUE)
C         3) ST. PETER PLUS PLATTEVILLE AND GLENWOOD PLUS DECORAH
C      SM-(3 VALUES)-THICKNESS OF AGGREGATED BEDROCK LAYERS, FEET
C         1) ST. PETER ONLY
C         2) ST. PETER PLUS PLATTEVILLE AND GLENWOOD
C         3) ST. PETER PLUS PLATTEVILLE AND GLENWOOD PLUS DECORAH
C      PST-VERTICAL HYDRAULIC CONDUCTIVITY OF SAND IN DRIFT AREAS, FEET/DAY
C      AREA-AREA OF INDIVIDUAL NODE ON GRID, FEET SQUARED
C   DATA SET 1-FORMAT(20F4.0)
C      WT-(NR*NC VALUES)-WATER-TABLE ALTITUDE FOR EACH NODE, FEET ABOVE MSL
C         (FOR ALL DATA SETS EACH ROW BEGINS ON A NEW CARD)
C   DATA SET 2-FORMAT(20F4.0)
C      POT-(NR*NC VALUES)-ALTITUDE OF PRAIRIE DU CHIEN-JORDAN POTENTIOMETRIC
C           SURFACE, FEET ABOVE MSL
C   DATA SET 3-FORMAT(20F4.0)
C      SPJ-(NR*NC VALUES)-ALTITUDE OF PRAIRIE DU CHIEN-JORDAN STRUCTURE CONTOUR,
C           FEET ABOVE MSL
C   DATA SET 4-FORMAT(20I4)
C      ISUR-(NR*NC VALUES)-INTEGER INDICATING SURFICIAL GEOLOGY TYPE
C            1-OUTWASH, 2-RED DRIFT, 3-GRAY DRIFT, 4-DECORAH, 5-PLATTEVILLE
C            GLENWOOD, 6-ST. PETER, 7-PRAIRIE DU CHIEN-JORDAN
C   DATA SET 5-FORMAT(20I4)
C      IRK-(NR*NC VALUES)-INTEGER INDICATING BEDROCK LAYERS PRESENT
C           4-DECORAH, PLATTEVILLE_GLENWOOD, ST. PETER AND PRAIRIE DU CHIEN-JORDAN
C           5-PLATTEVILLE-GLENWOOD, ST. PETER, AND PRAIRIE DU CHIEN-JORDAN
C           6-ST. PETER AND PRAIRIE DU CHIEN-JORDAN
C           7-PRAIRIE DU CHIEN-JORDAN ONLY
C*************************************************************************************
      DIMENSION ISUR(50,76),IRK(50,76),WT(50,76),POT(50,76),
     1 SPJ(50,76),R(50,76),P(6),M(6),SM(3),SP(3)
      REAL M
C  READ AND PRINT INPUT DATA
      READ 10,NR,NC,P,M,SP,SM,PST,AREA
   10 FORMAT(2I10,6G10.0,/,(8G10.0))
      DO 20 I=1,NR
      READ 30,(WT(I,J),J=1,NC)
   20 PRINT 40,I,(WT(I,J),J=1,NC)
   30 FORMAT(20F4.0)
   35 FORMAT(20I4)
   40 FORMAT(/,1X,I2,20(1X,F5.0),/,(3X,20(1X,F5.0)))
      DO 50 I=1,NR
      READ 30,(POT(I,J),J=1,NC)
   50 PRINT 40,I,(POT(I,J),J=1,NC)
      DO 60 I=1,NR
      READ 30,(SPJ(I,J),J=1,NC)
   60 PRINT 40,I,(SPJ(I,J),J=1,NC)
      DO 70 I=1,NR
   45 FORMAT(/,1X,I2,20(2X,I4),/,(3X,20(2X,I4)))
      READ 35,(ISUR(I,J),J=1,NC)
   70 PRINT 45,I,(ISUR(I,J),J=1,NC)
      DO 80 I=1,NR
      READ 35,(IRK(I,J),J=1,NC)
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   60 PRINT 85,I,(IRK(I,J),J=1,NC)
      PRINT 90,NR,NC,P,M,SP,SM,PST,AREA
   90 FORMAT(/,2X,I10,2X,I10,8(2X,G10.4),(/,10(2X,G10.4)))
      PUNCH 95, NR,NC,P,M,SP,SM,PST,AREA
   95 FORMAT (/,2X,I10,2X,I10,8(2X,G10.4),(/,6(2X,G10.4)))
C  CALCULATE LEAKAGE FOR EACH NODE
      DO 200 I=1,NR
      DO 200 J=1,NC
      R(I,J)=-1.
      K=ISUR(I,J)+1
C  SKIP CALCULATION FOR NODES WITH NO SURFACE GEOLOGY TYPE (R=-1) OR
C  IF PRAIRE DU CHIEN-JORDAN AT SURFACE (R=-2)
      GO TO (200,130,130,130,110,110,110,190), K
C  BEDROCK TYPE AT SURFACE
  110 L=7-IRK(I,J)
C  SKIP IF WATER-TABLE ALTITUDE BELOW PRAIRE DU CHIEN-JORDAN STRUCTURE CONTOUR
C  (R=-3)
      IF(WT(I,J).LE.SPJ(I,J)) GO TO 180
C  DETERMINE AGGREGATE HYDRAULIC CONDUCTIVITY OF SATURATED BEDROCK LAYERS AND
C  COMPUTE THICKNESS
      IF(WT(I,J).GE.(SPJ(I,J)+SM(L))) GO TO 125
  115 EM=0.
      EP=0.
      DO 116 N=1,L
      IF(WT(I,J).LT.(SPJ(I,J)+SM(N))) GO TO 117
      EM=SM(N)
  116 EP=SP(N)
  117 DM=WT(I,J)-SPJ(I,J)-EM
      IF(EM.LE.0.) GO TO 126
      EP=(EM+DM)/(EM/EP+DM/P(N))
      EM=EM+DM
      GO TO 175
  125 EM=SM(L)
      EP=SP(L)
      GO TO 175
  126 EM=WT(I,J)-SPJ(I,J)
      EP=P(N)
      GO TO 175
C  DRIFT TYPE AT SURFACE
C  SKIP IF WATER-TABLE ALTITUDE BELOW PRAIRE DU CHIEN-JORDAN STRUCTURE
C  CONTOUR (R=-3)
  130 IF(WT(I,J).LE.SPJ(I,J)) GO TO 180
      L=7-IRK(I,J)
      IF(IRK(I,J).NE.7) GO TO 135
C  DETERMINE AGGREGATE HYDRAULIC CONDUCTIVITY OF DRIFT TYPE IF NO INTERVENING
C  BEDROCK LAYERS PRESENT AND COMPUTE THICKNESS
      EM=WT(I,J)-SPJ(I,J)
      K=7-ISUR(I,J)
      EP=1./((1.-M(K))/P(K)+M(K)/PST)
      GO TO 175
C  DETERMINE AGGREGATE HYDRAULIC CONDUCTIVITY OF DRIFT TYPE AND INTERVENING
C  BEDROCK LAYERS AND COMPUTE THICKNESS.  IF WATER-TABLE ALTITUDE IS BELOW
C  BASE OF DRIFT, GO TO BEDROCK SECTION (STATEMENT 115)
  135 IF(WT(I,J).LT.(SPJ(I,J)+SM(L))) GO TO 115
      DM=WT(I,J)-SPJ(I,J)-SM(L)
      EM=DM+SM(L)
      K=7-ISUR(I,J)
      EP=EM/((1.-M(K))*DM/P(K)+M(K)*DM/PST+SM(L)/SP(L))
      GO TO 175
C  COMPUTE LEAKAGE, FEET/YEAR
  175 R(I,J)=365.*EP*(WT(I,J)-POT(I,J))/EM
C  CHECK FOR REDUCTION IN HEAD GRADIENT OWING TO DROP OF POTENTIOMETRIC
C  SURFACE BELOW STRUCTURE CONTOUR
      IF (POT(I,J).LT.SPJ(I,J)) R(I,J)=R(I,J)*(WT(I,J)-SPJ(I,J))/
     1(WT(I,J)-POT(I,J))
      GO TO 200
  180 R(I,J)=-3.
      GO TO 200
  190 R(I,J)=-2.
  200 CONTINUE
      DO 202 I=1,NR
C  PRINT RESULTS
      PUNCH 205,I,(R(I,J),J=1,NC)
  202 PRINT 205,I,(R(I,J),J=1,NC)
  205 FORMAT(1X,I2,10(2X,G10.4),/,(3X,10(2X,G10.4)))
      STOP
      END
```

```
      PROGRAM RECH(INPUT,OUTPUT,PUNCH,TAPE8)
C PROGRAM TO COMPUTE HYDRAULIC CONDUCTIVITY REQUIRED TO TRANSMIT UNIFORM.
C VERTICAL LEAKAGE UNDER PREVAILING VERTICAL HEAD GRADIENTS
C PROGRAMMED BY STEVEN P. LARSON, WRD, ST. PAUL, MINN.
C INPUT VARIABLES----
C   CARD 1--FORMAT(2I10)
C     NR-NUMBER OF ROWS IN INPUT DATA MATRIX
C     NC-NUMBER OF COLUMNS IN INPUT DATA MATRIX
C   DATA SET 1-FORMAT(20F4.0)
C     WT-WATER-TABLE ALTITUDE FOR EACH NODE, FEET ABOVE MSL
C         (ALL DATA SETS HAVE NR*NC VALUES AND EACH ROW BEGINS ON A NEW CARD)
C   DATA SET 2-FORMAT(20F4.0)
C     POT-ALTITUDE OF PRAIRIE DU CHIEN-JORDAN POTENTIOMETRIC SURFACE, FEET
C         ABOVE MSL
C   DATA SET 3-FORMAT(20F4.0)
C     SPJ-ALTITUDE OF PRAIRIE DU CHIEN-JORDAN STRUCTURE CONTOUR, FEET ABOVE MSL
C*************************************************************************
      DIMENSION ISHR(50,76),IRK(50,76),WT(50,76),POT(50,76),
     1  SPJ(50,76),R(50,76)
      REAL M
C READ INPUT DATA
      READ 10,NR,NC
   10 FORMAT(2I10)
      DO 20 I=1,NR
   20 READ 30,(WT(I,J),J=1,NC)
   30 FORMAT(20F4.0)
   35 FORMAT(20I4)
   40 FORMAT(/,1X,I2,20(1X,F5.0),/,(3X,20(1X,F5.0)))
      DO 50 I=1,NR
   50 READ 30,(POT(I,J),J=1,NC)
      DO 60 I=1,NR
   60 READ 30,(SPJ(I,J),J=1,NC)
C ASSIGN UNIFORM LEAKAGE DESIRED, FEET/YEAR
      PST=.47
      PRINT 90,NR,NC
   90 FORMAT(/,2X,I10,2X,I10)
C CALCULATE HYDRAULIC CONDUCTIVITY FOR ASSIGNED LEAKAGE AT EACH NODE
      DO 200 I=1,NR
      DO 200 J=1,NC
      R(I,J)=-1.
C SKIP IF NO DATA FOR NODE (R=-1)
      IF(WT(I,J).LE.0..OR.POT(I,J).LE.0.) GO TO 200
C SKIP IF WATER-TABLE LESS THAN POTENTIOMETRIC SURFACE (R=-3)
      IF(WT(I,J).LE.POT(I,J)) GO TO 180
C SATURATED THICKNESS
      X=WT(I,J)-SPJ(I,J)
C SKIP IF SATURATED THICKNESS IS LESS THAN OR EQUAL TO ZERO (R=-2)
      IF(X.LE.0.) GO TO 190
C HEAD GRADIENT
      DH=WT(I,J)-POT(I,J)
C CHECK FOR REDUCTION IN HEAD GRADIENT OWING TO DROP OF POTENTIOMETRIC
C SURFACE BELOW STRUCTURE CONTOUR
      IF(POT(I,J).LT.SPJ(I,J)) DH=WT(I,J)-SPJ(I,J)
C COMPUTE HYDRAULIC CONDUCTIVITY, FEET/DAY
      R(I,J)=X*PST/(DH*365.)
      GO TO 200
  180 R(I,J)=-3.
      GO TO 200
  190 R(I,J)=-2.
  200 CONTINUE
      DO 202 I=1,NR
C PRINT RESULTS
      PUNCH 205,I,(R(I,J),J=1,NC)
  202 PRINT 205,I,(R(I,J),J=1,NC)
  205 FORMAT(1X,I2,10(2X,G10.4),/,(3X,10(2X,G10.4)))
      STOP
      END
```

```
      PROGRAM RECH(INPUT,OUTPUT,PUNCH,TAPE8)
C PROGRAM TO COMPUTE INCREASED SUMMER LEAKAGE GIVEN EFFECTIVE HYDRAULIC
C CONDUCTIVITY OF ALL GEOLOGIC UNITS
C PROGRAMMED BY STEVEN P. LARSON, WRD, ST. PAUL, MINN.
C INPUT VARIABLES----
C   CARD 1--FORMAT(2I10)
C      NR-NUMBER OF ROWS IN INPUT DATA MATRIX
C      NC-NUMBER OF COLUMNS IN INPUT DATA MATRIX
C   DATA SET 1-FORMAT(20F4.0)
C      WT-WATER-TABLE ALTITUDE FOR EACH NODE, FEET ABOVE MSL
C         (ALL DATA SETS HAVE NR*NC VALUES AND EACH ROW BEGINS ON A NEW CARD)
C   DATA SET 2-FORMAT(20F4.0)
C      POT-ALTITUDE OF PRAIRIE DU CHIEN-JORDAN POTENTIOMETRIC SURFACE,
C         FEET ABOVE MSL
C   DATA SET 3-FORMAT(20F4.0)
C      SPJ-ALTITUDE OF PRAIRIE DU CHIEN-JORDAN STRUCTURE CONTOUR, FEET ABOVE MSL
C   DATA SET 4-FORMAT(20F4.0)
C      IRK-CHANGE FROM WINTER TO SUMMER OF PRAIRIE DU CHIEN-JORDAN POTENTIOMETRIC
C         SURFACE, FEET
C   DATA SET 5-FORMAT(3X,10(2X,G10.4)), INPUT FROM UNIT 8
C      ISUR-EFFECTIVE HYDRAULIC CONDUCTIVITY OF GEOLOGIC UNITS, FEET/DAY
C***************************************************************************
      DIMENSION ISUR(50,76),IRK(50,76),WT(50,76),POT(50,76),
     1 SPJ(50,76),R(50,76)
      REAL R,IRK,ISUR
C  READ INPUT DATA
      READ 10,NR,NC
   10 FORMAT(2I10)
      DO 20 I=1,NR
   20 READ 30,(WT(I,J),J=1,NC)
   30 FORMAT(20F4.0)
   35 FORMAT(20I4)
   40 FORMAT(/,1X,I2,20(1X,F5.0),/,(3X,20(1X,F5.0)))
      DO 50 I=1,NR
   50 READ 30,(POT(I,J),J=1,NC)
      DO 60 I=1,NR
   60 READ 30,(SPJ(I,J),J=1,NC)
      DO 70 I=1,NR
   70 READ 30,(IRK(I,J),J=1,NC)
      DO 80 I=1,NR
   80 READ(8,205)K,(ISUR(I,J),J=1,NC)
      PRINT 90,NR,NC
   90 FORMAT(/,2X,I10,2X,I10)
C  CALCULATE INCREASED LEAKAGE FOR EACH NODE
      DO 200 I=1,NR
      DO 200 J=1,NC
      R(I,J)=-1.
C  SKIP IF NO DATA FOR NODE (R=-1)
      IF(WT(I,J).LE.0..OR.POT(I,J).LE.0.) GO TO 200
C  SKIP IF WATER-TABLE LESS THAN POTENTIOMETRIC SURFACE (R=-3)
      IF(WT(I,J).LT.POT(I,J)) GO TO 180
C  SKIP NODES WHERE NO HYDRAULIC CONDUCTIVITY WAS CALCULATED IN UNIFORM
C  LEAKAGE PROBLEM, R=-4 IF A CHANGE IN POTENTIOMETRIC SURFACE FROM WINTER TO
C  SUMMER EXISTS, R=-3 OTHERWISE
      IF(WT(I,J).EQ.POT(I,J).AND.IRK(I,J).GT.0.) GO TO 195
      IF(WT(I,J).EQ.POT(I,J)) GO TO 180
C  SATURATED THICKNESS
      X=WT(I,J)-SPJ(I,J)
C  SKIP IF SATURATED THICKNESS IS LESS THAN OR EQUAL TO ZERO (R=-2)
      IF(X.LE.0.) GO TO 190
      DH=IRK(I,J)
C  CHECK TO SEE IF INCREASED HEAD GRADIENT CAN INCREASE LEAKAGE
      IF(POT(I,J).LT.SPJ(I,J)) DH=0.
C  CHECK FOR REDUCTION IN HEAD GRADIENT OWING TO DROP OF POTENTIOMETRIC
C  SURFACE BELOW STRUCTURE CONTOUR
      IF(POT(I,J).GE.SPJ(I,J).AND.(POT(I,J)-IRK(I,J)).LT.SPJ(I,J)) DH=
     1 POT(I,J)-SPJ(I,J)
C  COMPUTE INCREASED LEAKAGE, FEET/YEAR
      R(I,J)=ISUR(I,J)*DH*365./X
      GO TO 200
  180 R(I,J)=-3.
      GO TO 200
  190 R(I,J)=-2.
      GO TO 200
  195 R(I,J)=-4.
  200 CONTINUE
      DO 202 I=1,NR
C  PRINT RESULTS
      PUNCH 205,I,(R(I,J),J=1,NC)
  202 PRINT 205,I,(R(I,J),J=1,NC)
  205 FORMAT(1X,I2,10(2X,G10.4),/,(3X,10(2X,G10.4)))
      STOP
      END
```