An Appraisal of Ground Water for Irrigation in the Appleton Area, West-Central Minnesota

GEOLOGICAL SURVEY WATER-SUPPLY PAPER 2039–B

Prepared in cooperation with the WesMin Resource Conservation and Development Project Committee and the Minnesota Department of Natural Resources, Division of Waters, Soils, and Minerals

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By Steven P. Larson

CONTRIBUTIONS TO THE HYDROLOGY OF THE UNITED STATES

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CONVERSION FACTORS

Factors for converting English units to metric units are shown to four significant figures. However, in the text the metric equivalents are shown only to the number of significant figures consistent with the values for the English units.

English	Multiply by	Metric
in (inches)	25.4	mm (millimetres)
in (inches)	2.540	cm (centimetres)
ft (feet)	3.048×10^{-1}	m (metres)
mi^2 (square miles)	2.590	km^2 (square kilometres)
acres	4.047×10^{-1}	hm^2 (square hectometres)
acres	4.047×10^{-1}	ha (hectares)
ft^3/s (cubic feet per second)	2.832×10^{-2}	m^3/s (cubic metres per second)
gal/min (gallons per minute)	6.309×10^{-2}	l/s (litres per second)
acre-ft (acre-feet)	1.233×10^{-3}	hm^2 (cubic hectometres)
ft^2/d (feet squared per day)	9.290×10^{-2}	m^2/d (metres squared per day)
ft/d (feet per day)	3.048×10^{-1}	m/d (metres per day)
acre-ft/yr (acre-feet per year)	1.233×10^{-3}	hm^3/yr (cubic hectometres per year)

DEFINITIONS

The geologic and hydrologic terms pertinent to this report are defined as follows:

Aquifer. A formation, group of formations, or part of a formation that contains sufficient saturated permeable material to yield significant quantities of water to wells or springs.

Base flow. Sustained streamflow, composed largely of ground-water discharge.

Evapotranspiration. Water withdrawn by evaporation from water surfaces and moist soil and by plant transpiration.

Glacial drift. All deposits resulting from glacial activity.

Ground water. That part of subsurface water that is in the saturated zone.

Hydraulic conductivity. The rate of flow of water transmitted through a porous medium of unit cross-sectional area under a unit hydraulic gradient at the prevailing kinematic viscosity.

Loess. Wind-blown sand or silt.

Outwash. Sorted, stratified drift deposited beyond the ice front by meltwater streams.

Saturated zone. Zone in which all voids are ideally filled with water. The water table is the upper limit of this zone, and the water in it is under pressure equal to or greater than atmospheric.

Specific yield. The ratio of (1) the volume of water which is saturated rock or soil will yield by gravity to (2) its own volume.

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. In an unconfined aquifer, it is virtually equal to the specific yield.

Till. Unsorted, unstratified drift deposited directly by the glacial ice.

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

Water table. That surface in an unconfined water body at which the pressure is atmospheric.

AN APPRAISAL OF GROUND WATER FOR IRRIGATION IN THE APPLETON AREA, WEST-CENTRAL MINNESOTA

By STEVEN P. LARSON

ABSTRACT

Supplemental irrigation of well-drained sandy soils has prompted an evaluation of ground water in the Appleton area. Glacial drift aquifers are the largest source of ground water. The surficial outwash sand and gravel is the most readily available and the most areally extensive drift aquifer, and it underlies much of the sandy soil area. Saturated thickness of the outwash is more than 80 feet (24 m) in places, and potential well yields may exceed 1,200 gal/min (76 l/s) in some areas. In about 17 percent of the area, yields of more than 300 gal/min (19 l/s) are obtainable.

Recharge to the outwash aquifer occurs primarily during the spring thaw and averages about 5 inches (12.7 cm) annually. Most discharge from the aquifer appears as base flow in the Pomme de Terre River. Despite dissolved-solids concentrations ranging from 280 to 1,350 mg/l, the water is chemically suitable for irrigation.

Mathematical models of a part of the aquifer were made to evaluate the effects of 20 successive years of ground-water withdrawal for three irrigation-development patterns. It was estimated that the present annual withdrawal rate of 1,410 acre-ft (1.74 hm^3) would result in water-level declines of less than 3 feet (0.9 m). However, annual withdrawals of 8,450 acre-ft (10.4 hm^3) would cause aquifer dewatering and decreased well yields in some places. After a new state of equilibrium was established in response to withdrawals, most of the withdrawal would be supplied by diverted base flow from the Pomme de Terre River.

INTRODUCTION

PURPOSE AND SCOPE

In recent years, irrigation has increased crop productivity in many sandy soil areas in Minnesota. In the past, lack of precipitation during critical periods in the growing season would generally result in poor productivity because the sandy soils are well drained. In some places, however, sandy soils are underlain by glacial outwash (sand and gravel), which can be a source of water to supplement precipitation and increase crop productivity.

The purpose of this investigation was to evaluate the characteristics of a glacial outwash aquifer near Appleton, Minn. and to determine the potential of the aquifer as a source of irrigation water. Although various other geologic units within the area may be acceptable sources of water, the outwash aquifer directly beneath the land surface is more extensive and more readily accessible than other aquifers. Therefore, this report focused on (1) determining the extent and thickness of the surficial outwash, (2) evaluating its water-yielding capability and the chemical characteristics of its water, and (3) estimating the long-term effects of development on this ground-water system. Some information on a buried glacial aquifer that is also a source of irrigation water is included.

LOCATION AND DESCRIPTION OF STUDY AREA

The study area consists of about 160 mi^2 (414 km^2) in Big Stone, Swift, and Chippewa Counties, west-central Minnesota (fig. 1). It is limited by the extent of sandy soils and by the northern Swift County boundary.

The study area is a part of the Big Stone Lake, the Pomme de Terre River, and the Chippewa River watershed units (Minnesota Division of Waters, 1959). The central and eastern parts are drained by the Pomme de Terre and the Chippewa Rivers, respectively. The western part drains directly into the Minnesota River. A dam in Appleton regulates the flow of the Pomme de Terre River.

The area is relatively flat except the eastern and southern parts, which are moderately undulating. Lowland swamps are common.

Average annual precipitation is about 24 inches (610 mm), of which 70 percent occurs from May through September. Average annual lake evaporation is 31 inches (790 mm) (Kohler and others, 1959) and occurs almost totally from April to October. Winter precipitation is stored as snow until the spring thaw.

PREVIOUS INVESTIGATIONS

Early hydrogeologic investigations, which included the study area, were made by Hall, Meinzer, and Fuller (1911) and by Thiel (1944). The primary glacial features were outlined and were described by Leverett (1932) and were more recently reinterpreted by Wright and Ruhe (1965). Sardeson (1919) discussed formation of outwash deposits in the Pomme de Terre valley. Hydrologic reconnaissances of the watershed units mentioned previously were made by Cotter, Bidwell, Oakes, and Hollenstein (1966), Cotter and Bidwell (1966), and Cotter, Bidwell, Van Voast, and Novitzki (1968).

METHODS OF INVESTIGATION

Data for this study were collected and were analyzed during a 3-year period beginning in July 1971.

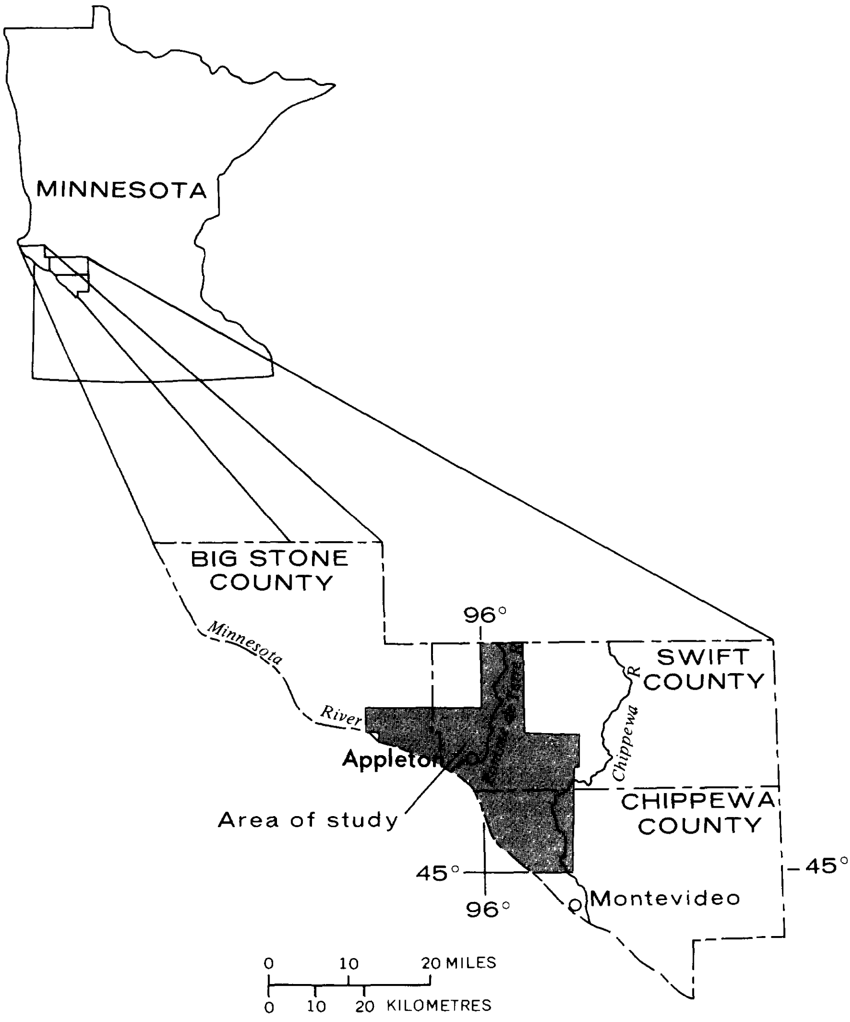


FIGURE 1.—Location and extent of the Appleton area.

The surficial geology was defined from aerial photographs, soils maps, field mapping, and published reports. The extent and thickness of the surficial outwash was delineated primarily from about 130 test holes drilled as a part of this study and from information on about 100 other drill holes in and near the study area.

Characteristics of the outwash sand and gravel were determined by analyzing the textural and hydraulic properties of samples collected during test drilling. Also, aquifer tests at three locations helped to describe the hydraulic properties of parts of the outwash aquifer.

Discharge from the surficial aquifer to the Pomme de Terre River was estimated by measuring streamflow during periods of low flow (Aug. 11, 1964, and Sept. 11–12, 1973). Streamflow records for the river at a gage in Appleton provided additional information on low-flow characteristics. Water-table fluctuations were monitored in 16 observation wells to observe water-level trends and to determine the distribution of recharge to the surficial aquifer from precipitation. Chemical properties of ground water and surface water were analyzed from samples collected at 10 sites and from review of historical water-quality records.

Data describing the physical characteristics of the surficial outwash ground-water system were used to construct a mathematical model. Effects of present and hypothetical ground-water development were evaluated with the aid of the model.

WELL-NUMBERING SYSTEM

The system of numbering wells and test holes in Minnesota is based on the U.S. Bureau of Land Management's system of subdivision of public lands. The Appleton area is in the fifth principal meridian and base-line system. The first segment of a well or a test-hole number indicates the township north of the base line; the second, the range west of the principal meridian; and the third, the section in which the well or test hole is located. The lowercase letters, a, b, c, and d, following the section number, locate the well within the section. The first letter denotes the 160-acre (65-ha) tract, the second, the 40-acre (16-ha) tract, and the third, the 10-acre (4-ha) tract, as shown in figure 2. The letters are assigned in a counterclockwise direction, beginning in the northeast quarter. Within one 10-acre (4-ha) tract, successive well numbers, beginning with 1, are added as suffixes. Figure 2 illustrates the method of numbering a well or test hole. The number 121.42.29abd1 indicates the first well or test hole in T. 121 N., R. 42 W., sec. 29, SE¼NW¼NE¼.

ACKNOWLEDGEMENTS

This investigation was conducted by the U.S. Geological Survey in cooperation with the WesMin (Western Minnesota) Resource Conservation and Development Project Committee and the Minnesota Department of Natural Resources, Division of Waters, Soils, and Minerals. The writer is grateful for information provided by property owners and well drillers. Special thanks are also extended to those who permitted the drilling of test holes and the installation of observation wells on their land and to irrigators who permitted use of their wells and equipment for aquifer tests.

GEOLOGY

Bedrock in the study area consists of Precambrian crystalline rocks and Cretaceous sandstones and shales. The Cretaceous rocks are not present

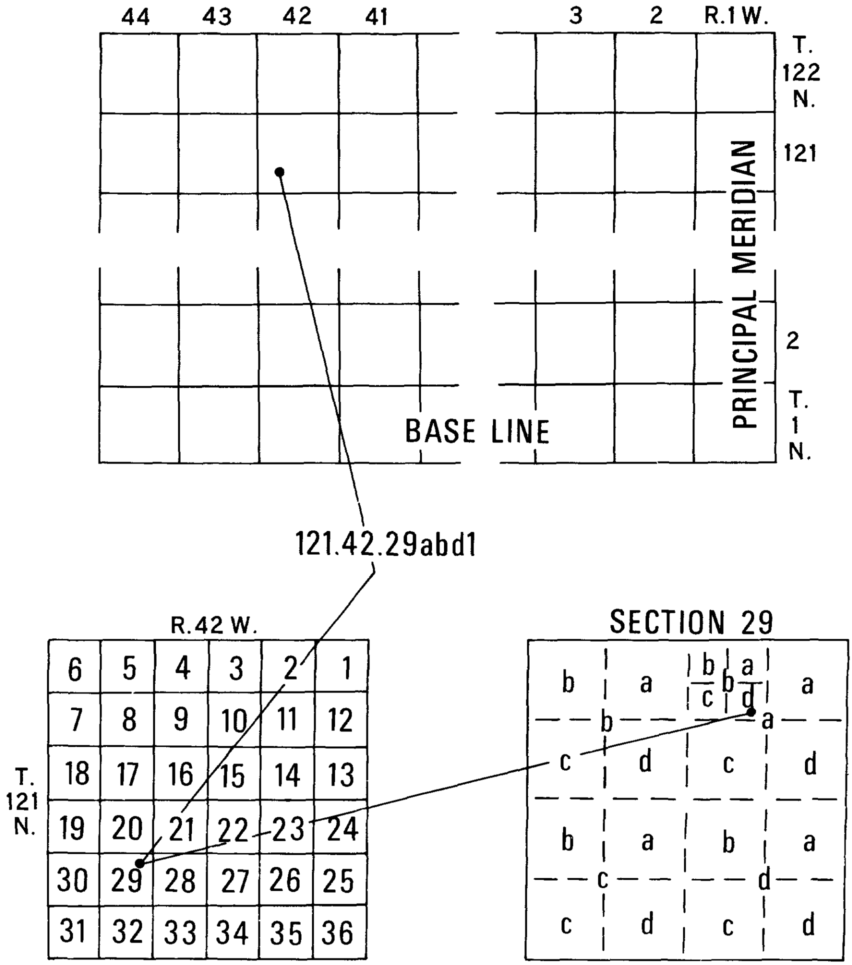


FIGURE 2.—System of numbering wells and test holes in Minnesota.

over the entire area and are generally less than 100 feet (30 m) thick. Glacial drift, ranging in thickness from about 150 feet (46 m) to 300 feet (91 m) overlies the bedrock and is the most important source of ground water.

Glacial drift representing the Wisconsin Glaciation forms the land surface, although pre-Wisconsin drift may be present in the subsurface. The drift is generally of two main types: till, an unstratified, unsorted mixture of clay, silt, sand, and gravel deposited directly by glacial ice; and outwash, stratified beds of sand and gravel deposited by glacial melt waters. Buried lake deposits (clay) and well-sorted, uniform sands also occur within the drift.

The drift was deposited by the Des Moines lobe of glacial ice (Wright and Ruhe, 1965), which advanced southeastward across western Minnesota. When the ice retreated to the Big Stone moraine (approximately along the northern boundary of the study area, excluding the northern extent of the Pomme de Terre valley), large amounts of outwash were deposited, forming the bulk of the surficial outwash aquifer studied. Further retreat filled the Pomme de Terre valley north of the Big Stone moraine with outwash (Sardeson, 1919).

The surficial outwash is more than 100 feet (30 m) thick in places and is underlain by gray silty till. The configuration of the till surface is shown on plate 1*A*. Deposition of the surficial outwash followed a period when the till was deeply eroded in part of the study area. This resulted in the interconnection between a buried sand layer and the surficial outwash, as illustrated by the cross section on plate 1*A*. Hydrologic problems created by this phenomenon will be discussed later. In the eastern and southern parts of the area, outwash deposits are confined to narrow channels and are generally less than 40 feet (12 m) thick.

Plate 1*A* also shows places where outwash deposits are minimal or do not occur. The land surface in these places is generally composed of till or loess, and sand thickness is less than 10 feet (3 m). Here, then, the aquifer is considered of negligible thickness and is not considered as a potential source of irrigation water.

GROUND-WATER HYDROLOGY

Most ground water in the Appleton area occurs in pores or openings between rock particles in the glacial drift. The size and orientation of the openings determine how much water is stored and how easily water moves. Physical characteristics of the rock particles have a significant effect on the water quality, as water moves at a relatively slow rate from places of recharge to places of discharge.

OCCURRENCE AND MOVEMENT

The primary source of water for irrigation in the area is the surficial outwash aquifer. The underlying till is much less permeable than the sand and gravel of the surficial aquifer and, for practical purposes, forms a lower boundary of the aquifer. Other sand and gravel zones buried within the drift may provide adequate quantities of water for irrigation, but they are much more difficult to delineate and are not as easily developed as the surficial aquifer. Precambrian and Cretaceous rocks buried beneath the drift are considered insignificant as a source of water for irrigation.

Depth to the water table in the outwash area is generally 20 feet (6 m) or less (pl. 1*B*). In places near Appleton, where the water table altitude is relatively low (pl. 1*C*), the depth to water is nearly 50 feet (15 m). In most low areas, it is generally less than 10 feet (3 m). The altitude of the water table is primarily controlled by the location of discharge areas, and thus, depth to water is greatly dependent upon land-surface altitude.

The surficial aquifer is recharged by precipitation. Ground-water movement is to places of discharge, as shown on plate 1*C*. The Pomme de Terre River is the primary discharge area. Five Mile Creek, many ephemeral drainage ways, and swamps are also places of discharge.

WATER-LEVEL FLUCTUATIONS

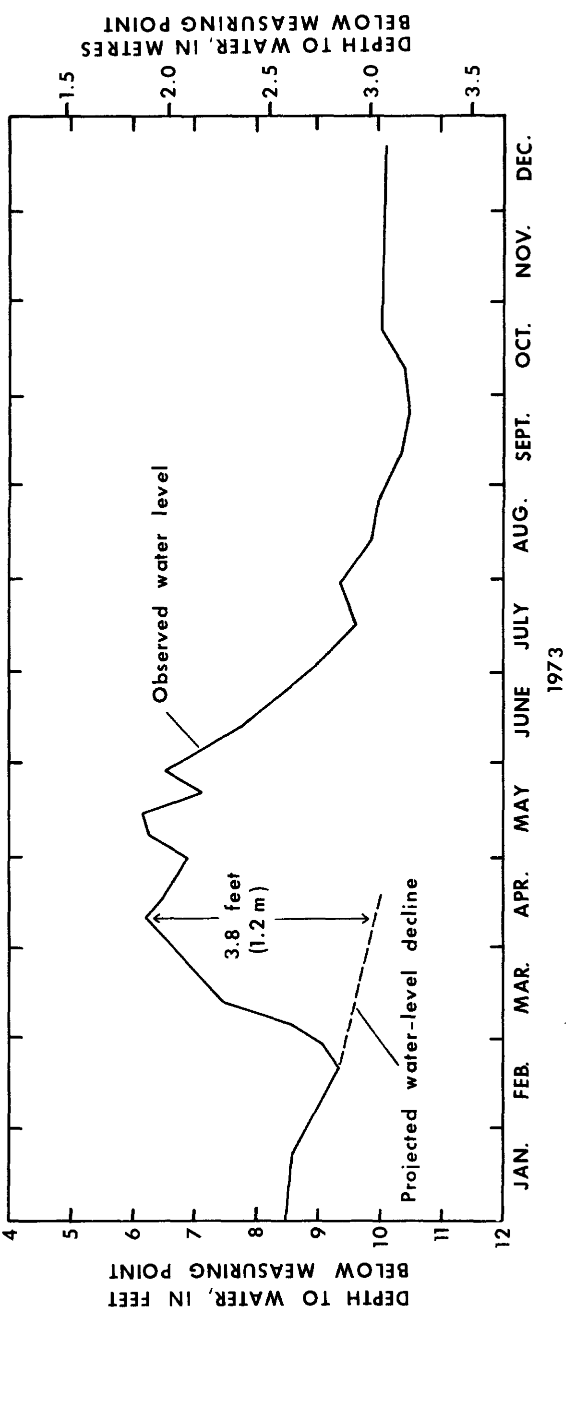
Ground-water levels fluctuate seasonally in response to climatic conditions. Spring rains and snowmelt are major sources of recharge to the surficial aquifer and cause water levels to rise significantly (fig. 3). During the summer, evapotranspiration uses most of the available precipitation, and recharge to the aquifer is negligible. Water levels decline during the summer as ground water is discharged into streams. During fall, when evapotranspiration decreases, some recharge may result from precipitation and water levels may rise slightly. Water levels decline during winter, when precipitation is stored on the land surface as ice and snow, and typically reach a low point before the spring thaw.

The magnitude and duration of water-level fluctuations are functions of many factors, including rate of recharge, physical properties of the subsurface materials, and relative location of discharge areas. During 1973, fluctuations in the surficial aquifer ranged from 0.5 feet (0.15 m) to 3.9 feet (1.2 m).

If the physical properties of the aquifer are known, the amount of recharge represented by these fluctuations can be estimated. Specific yield is the volume of water involved in gravity draining or refilling of a porous material per unit volume of material. (See page V.) Thus, the volume of water associated with an increase or decrease in water level can be determined by multiplying the specific yield by the water-level change. In the Appleton area, specific yields were determined in the laboratory on selected samples of well cuttings collected during the drilling of observation wells. Figure 3 illustrates the method of computation of spring recharge from the hydrograph of an observation well. Spring recharge was estimated to average 8.4 inches (21 cm) in 1972 and 5.0 inches (12.7 cm) in 1973 on the basis of the analysis of hydrographs of several observation wells. Areal distribution of recharge was fairly uniform for both years.

SURFICIAL AQUIFER DISTRIBUTION

Saturated thickness of a water-table aquifer is an important factor in determining the expected yield of water to wells. It is defined as the vertical distance between the water table and the bottom of the aquifer. Saturated thickness is critical because it decreases in a water-table aquifer in response to pumping and can significantly limit the yield from the aquifer.



Hydrograph for observation well 120.42.4ddd

Recharge (due largely to snowmelt and early spring rain) = (water-level rise) × (estimated specific yield)

=3.8 feet (1.2 m) × 0.14

= 0.53 foot (0.16 m)

= 6.4 inches (16.3 cm)

FIGURE 3.—Example of hydrograph showing method of estimating recharge during the spring to the surficial aquifer in the Appleton area.

In the study area, saturated thickness of the surficial aquifer ranges from a few feet to more than 80 feet (24 m) (pl. 2*A*). In the eastern, western, and southern parts, it is generally less than 30 feet (9 m). Saturated thickness is greatest in the northern part along the Pomme de Terre valley and in the area of interconnection between the surficial outwash and the buried sand, as shown on plate 2*A*. Thicknesses in the latter area are speculative because test drilling during this study was limited to a depth of 100 feet (30 m), and the underlying till was not reached by most of the test holes.

SURFICIAL AQUIFER CHARACTERISTICS

The primary hydraulic characteristics of an aquifer are its hydraulic conductivity, saturated thickness, and storage coefficient. Hydraulic conductivity and saturated thickness are commonly combined as transmissivity (hydraulic conductivity times saturated thickness), and storage coefficient is essentially equal to specific yield in unconfined (water-table) aquifers. These parameters can be used to determine the rate and the magnitude of water-table declines resulting from withdrawal of water from an aquifer.

Hydraulic characteristics of the surficial outwash aquifer were determined from data collected during three aquifer tests. Results from analyses of the test data are summarized in table 1. The predominant aquifer material at the first two locations was coarse sand and gravel. Although the complete lithology at the third location was unknown, material penetrated during observation well installation was mostly gravel.

TABLE 1.—*Results of aquifer tests in the Appleton area*

Location	Length of test (hours)	Average pumping rate (gal/min)	Aquifer characteristics		
			Transmissivity (ft^2/d)	Average hydraulic conductivity (ft/d)	Specific yield
121.42.31bdb	44	475	9,600	344	0.15
120.43.2cbd........	56	1,150	14,700	306	0.2
122.42.29bac[1]......	65	495	31,000	561	0.27

[1] Porosity determined by tracer test was 0.39.

Values of aquifer characteristics determined by the aquifer tests are representative only in the immediate area of the test location. Guided by aquifer test results, however, values were estimated at other locations based on examination of samples collected during test drilling, laboratory analyses of samples, and published data for similar materials. Laboratory analyses indicated specific yields ranging from 0.1 to 0.4. Values from 0.15 to 0.25 were considered representative. The relation of particle-size classification to hydraulic conductivity is shown in table 2. This relationship was used to estimate the hydraulic conductivity at the test-hole sites. Lower conductivity values in each range were assigned to relatively poorly sorted material and higher values were assigned to well-sorted material. Transmissivity was then determined by multiplying the estimated hydraulic conductivity by the saturated thickness (pl. 2*A*).

TABLE 2.—*Values of hydraulic conductivity for surficial outwash in the Appleton area*

Predominant material (Wentworth scale)	Hydraulic conductivity (ft/d)
Clay or silt	<10
Sand, very fine	10–70
Sand, fine	70–130
Sand, medium	130–400
Sand, coarse or very coarse	130–540
Gravel	130–670

Laboratory analyses also revealed differing characteristics of the buried sand and the surficial outwash (pl. 1*A*). The buried sand is finer grained overall than the surficial outwash (fig. 4). Sand was the predominant material in the area of interconnection between the buried sand and the surficial outwash. Estimates of hydraulic conductivity were weighted to reflect the relative saturated thickness of each type of material.

THEORETICAL WELL YIELDS

Calculations of a theoretical optimum yield of a properly constructed well were made to evaluate the surficial aquifer as a source of irrigation water. The following assumptions were made in the calculations:

1. The aquifer is homogeneous and of infinite areal extent.
2. The well is screened over the entire saturated thickness of the aquifer, is 100 percent efficient, and is of large diameter (24 in. (61 cm)).
3. The well is pumped continuously for 30 days.
4. Drawdown, the decrease in water level in the well caused by pumping, is two-thirds of the original saturated thickness. Theoretically, this corresponds to 90 percent of the maximum yield for unconfined aquifers and is generally accepted as the optimum design specification (Edward E. Johnson, Inc., 1966, p. 107–108).

Based on these assumptions, the nonequilibrium equations of Theis (1935), with a drawdown correction for unconfined aquifers (Jacob, 1944), can be used to compute well discharge. Although some assumptions may never be fully satisfied, the method produces a quantitative measure of the aquifer's water-yielding potential.

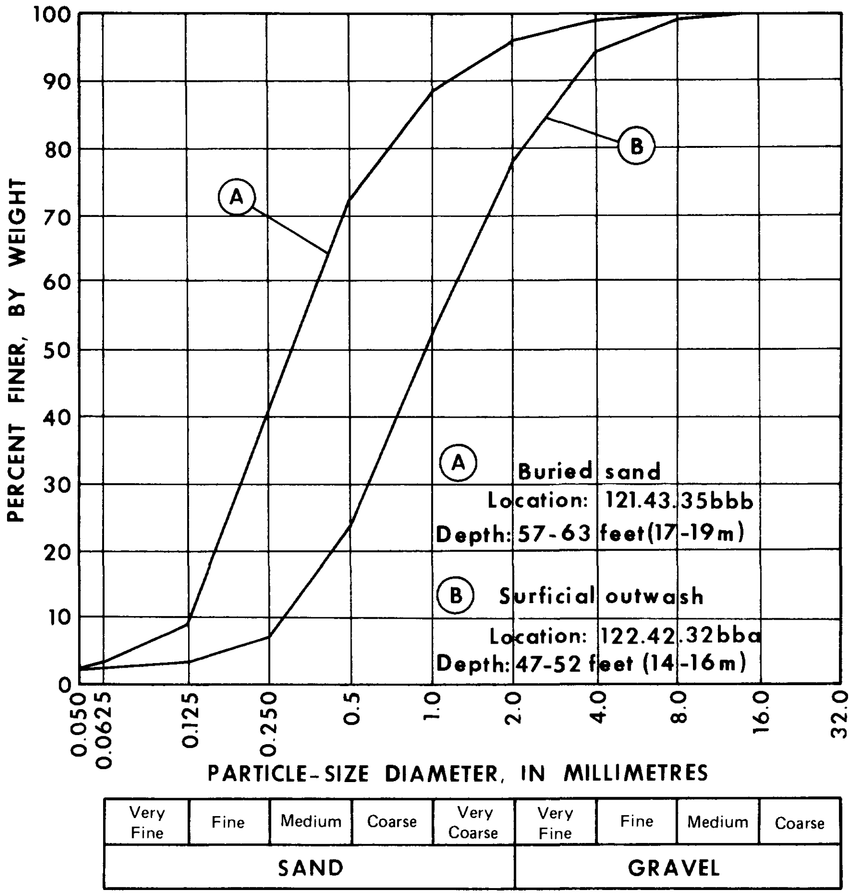


FIGURE 4.—Representative particle-size distribution for buried sand and surficial outwash.

Water-yielding potential of the surficial aquifer, as shown on plate 2*B*, closely follows the distribution of saturated thickness (pl. 2*A*). Areal variation of hydraulic conductivity is not as significant as variation of saturated thickness. Also, variations in specific yield of as much as three times have minimal effect on computed well yields; so, to be conservative, a uniform value of 0.1 was used in the yield computations.

Theoretical yields shown on plate 2*B* are for individual wells and exceed 1,200 gal/min (76 l/s) in places. However, individual wells in about 72 percent of the study area will yield less than 100 gal/min (6 l/s). In approximately 17 percent of the area, yields exceed 300 gal/min (19 l/s). In areas of marginal irrigation water supply, pits or multiple wells might be used to obtain adequate yields. Also, well yields could increase or decrease, depending on proximity to streams, lakes, aquifer boundaries, or other wells, and (or) on long-term water-level declines associated with climatic factors or intense ground-water development.

GROUND-WATER—SURFACE-WATER RELATIONSHIPS

Surface water is closely related to the ground-water flow system in the study area. During sustained dry weather, baseflow in the Pomme de Terre River is mostly ground-water discharge. Also, two small, shallow lakes, with no surface inflow or outflow, that intercept the water table, discharge water by evaporation. Recharge of stream water to the aquifer occurs in short reaches. Water-level declines resulting from heavy pumping could induce additional recharge from the stream or capture ground water that under nonpumping conditions would be discharged to the stream.

Measurements of streamflow during baseflow periods were made at various points along the river to determine the quantity of ground-water discharge. Results of measurements made on September 11 and 12, 1973, are shown in figure 5. The total gain in streamflow was 16.2 ft^3/s (0.46 m^3/s) or 11,700 acre-ft (14.4 hm^3) per year. Measurement of a smaller segment of the river on August 11, 1964, showed a gain of 6.0 ft^3/s (0.17 m^3/s). This same segment had a gain of 5.2 ft^3/s (0.15 m^3/s) in the 1973 measurement.

The rate of ground-water discharge increases in the lower reaches of the river below Mill pond (fig. 5), near the exit point of the river from the outwash area. The density of water-table contours in this area (pl. 1C) indicates that a major part of the ground-water discharge probably occurs here. Impoundments above dams, shown in the stream profile in figure 5, cause river levels to exceed surrounding ground-water levels, thus creating short reaches of ground-water recharge. Streamflow decrease caused by Mill pond dam was about 1.8 ft^3/s (0.05 m^3/s) during the 1973 measurement.

Under equilibrium conditions, the average rate of ground-water discharge into the Pomme de Terre River is virtually equal to the average rate of recharge from precipitation in that part of the aquifer that contributes to the discharge. Evapotranspiration from the aquifer in this area is considered small. Streamflow records for the Pomme de Terre River indicate that discharge during summer and fall of 1973 was slightly above average. The streamflow gain determined by the 1973 seepage measurement represents a discharge rate of 4.9 inches (12.4 cm) per year for the contributing area. Observation well hydrographs in this area correspondingly show an average of 4.8 inches (12.2 cm) of recharge in the spring of 1973. As shown in figure 3, most recharge (water-level increase) occurs in the spring. The aquifer discharges (water-level decrease) to the river throughout most of the year.

Because intensified pumping could induce recharge to the aquifer from

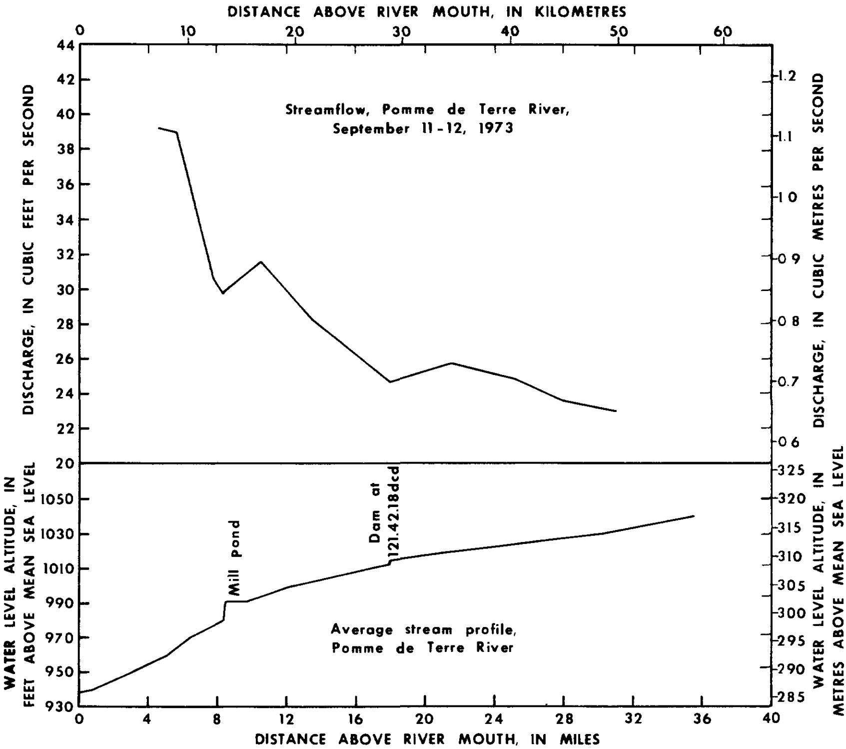


FIGURE 5.—Streamflow and stream profile of the Pomme de Terre River, September 11-12, 1973.

streamflow, low-flow characteristics of the river are important. Frequency curves for various periods of sustained low flow during the irrigation season are shown in figure 6. The example in the figure indicates that a discharge of less than 3.4 ft^3/s (0.1 m^3/s) for 14 consecutive days occurs about once in 10 years. Thus, these curves can be used to predict the probability of sustained periods of low streamflow.

BURIED AQUIFERS

Buried aquifers have been developed in some areas where surficial outwash did not provide an adequate supply. Data from deep wells and test holes indicate that the buried sand shown in the cross section on plate 1*A* extends beyond the area of interconnection with the surficial outwash. The buried sand is finer grained than the surficial outwash (fig. 4), but thicknesses of as much as 80 feet (24 m) and well yields of more than 700 gal/min (44 l/s) have been reported. Definition of the extent and the thickness of this buried sand beneath the till was beyond the scope of this report; however, the sand seems to have significant water-yielding potential in areas where yields from the surficial outwash are marginal.

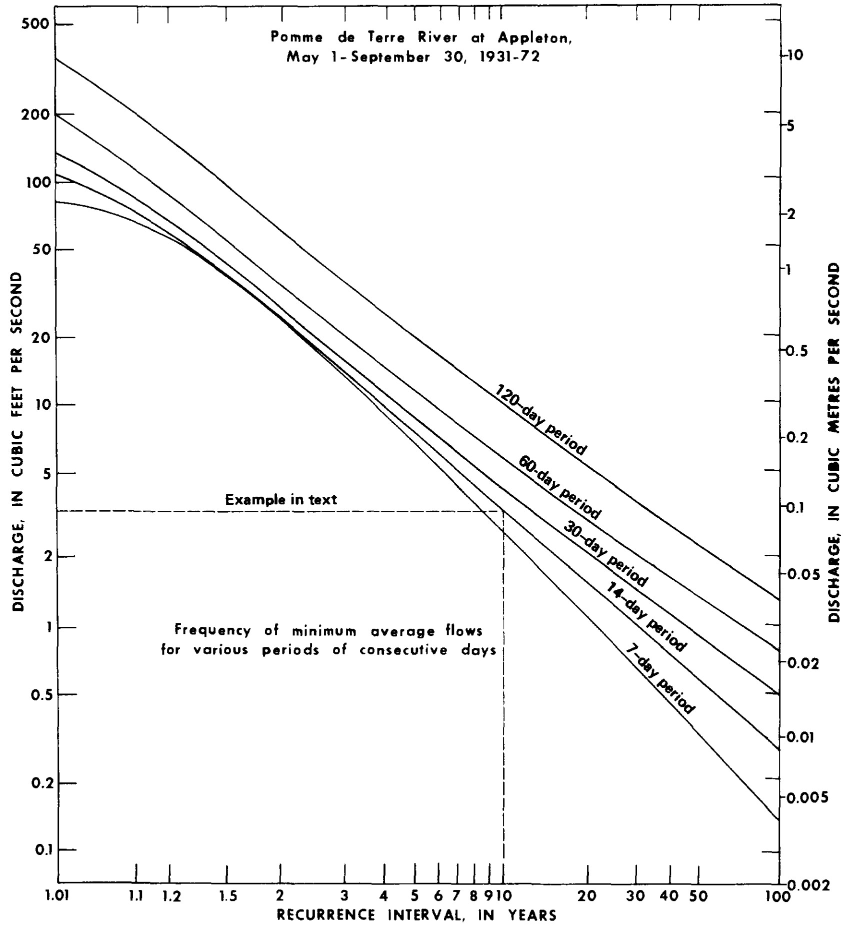


FIGURE 6.—Low-flow frequencey curves for the Pomme de Terre River at Appleton during irrigation period (May 1—September 30).

Elsewhere in the study area, especially in the southern and eastern parts, many domestic wells tap buried aquifers, but it is not known if adequate irrigation supplies could be developed.

WATER QUALITY

The amount of dissolved solids, the relative proportions of certain ions, and the concentrations of certain individual ions in irrigation water may affect plant growth. Dissolved solids, concentration of boron, and the ratio of sodium to other cations, as measured by the sodium-adsorption-ratio, are generally used to determine the suitability of water for irrigation.

Chemical characteristics of water obtained from the surficial aquifer and from buried aquifers in the Appleton area are shown in table 3. The water is primarily of the calcium bicarbonate type, and dissolved-solids concentration ranges from 280 to 1,350 mg/l (milligrams per litre). The water is generally very hard (>180 mg/l) except for some from deeply buried aquifers, such as that represented by the sample collected in well 120.43.23aba.

The diagram shown in figure 7 was developed by the U.S. Salinity Laboratory (1954) and is commonly used in evaluating water for irrigation. The specific conductance, in micromhos per centimetre, is an indicator of the dissolved-solids concentration in the water, and, in the study area, dissolved solids are about 0.6 – 0.7 times the specific conductance. The sodium hazard of water from all surficial (water-table) aquifer samples was low. Water from a deeply buried aquifer showed a very high sodium hazard. This water is a sodium bicarbonate type and is not suitable for irrigation without treatment.

Although all the analyses indicate that water from the surficial and buried aquifers has a medium to high salinity hazard, salt accumlation has

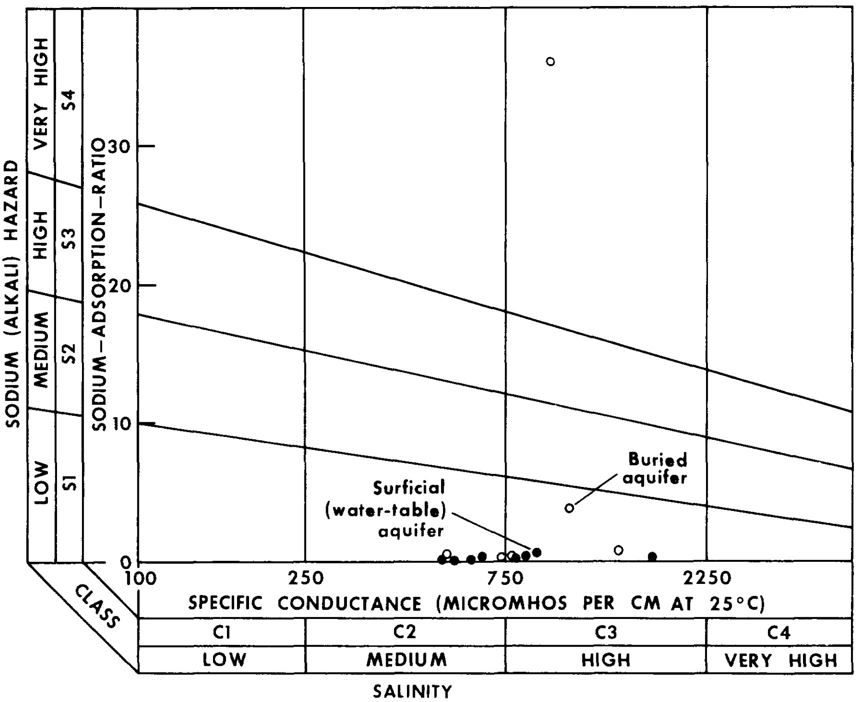


FIGURE 7.—Suitability of ground water for irrigation in terms of sodium-adsorption-ratio and specific conductance (U.S. Salinity Laboratory, 1954).

TABLE 3.—*Chemical analyses of ground*

[Constituents in milligrams

Location	Depth (ft)	Aquifer type and composition	Sample: Date of collection	Sample: Temperature (°Celsius)	Analysis by	Silica (SiO_2)	Iron (Fe)	Manganese (Mn)	Calcium (Ca)	Magnesium (Mg)	Sodium (Na)	Potassium (K)
120.43.2bbd	68	Water table, sand and gravel	7—12—73	10	USGS[1]	26	0.44	0.21	85	33	11	3
121.42.31bca	40	...do...	7—12—73	8	USGS	25	.58	.21	110	37	10	3.6
121.42.29aac	40	...do...	7—13—73	8	USGS	26	.27	.25	77	26	2.3	2.2
120.43.3bbd	105	...do...	7—31—73	9	USGS	27	1.2	.58	110	40	17	5.0
121.42.17abb	32	...do...	8—1—73	8	USGS	26	.80	.26	82	32	11	2.7
120.43.13dac	59	...do...	8—2—73	9.5	USGS	28	.40	.24	75	23	3.6	1.9
120.43.16acb	[2]0	...do...	9—13—73	9	USGS	73	.10	.67	91	27	4.3	1.7
122.42.29bac	10	...do...	9—13—73	8.5	USGS	28	.84	.47	110	43	28	3.9
119.41.29ddd	14	...do...	9—26—73	8.5	USGS	28	3.7	.35	260	84	22	6.4
121.42.35bba	45	...do...	8—25—65	...	MDH[3]	...	.08	.14	...	...	13	3.8
118.41.17bab	200	Buried sand and gravel	8—25—65	...	USGS	...	1.5	.06	20	9.2	206	4.8
120.43.14bcc	90	...do...	6—24—64	10	USGS	27	1.1	.48	83	47	19	5.8
122.42.30acc	33	Water table, sand and gravel	8—6—64	12	USGS	...	.16	.00	93	37	12	2.0
121.43.31cdc	79	Buried sand and gravel	11—22—63	11	MDH	...	5.6	.33	72	22	8	3
118.41.21adal	53	...do...	6—24—64	10	USGS	28	1.5	.02	175	74	49	5.4
119.42.26cdd	132	...do...	8—5—64	12	USGS	...	23	.27	33	41	17	4.3
120.43.23aba	387	...do...	8—5—64	11	USGS	...	2.3	.00	2.4	.5	235	2.6
120.42.30bbb	200	...do...	8—5—64	9	USGS	...	1.1	.04	64	31	150	4.3
119.42.12cca	68	...do...	8—26—65	...	USGS	...	.01	.06	96	93	13	5.4
119.42.7ccc	108	...do...	10—6—64	...	USGS	...	5.6	[4]<.02	...	...	19	6

[1]U.S. Geological Survey.
[2]Spring.
[3]Minnesota Department of Health.
[4]<, less than.

not been a problem in irrigated areas probably because of flushing of the well-drained soils. However, inasmuch as flushed salts may return to the ground-water system, and, under greater irrigation development, may remain in the system, water-quality and soil-salinity monitoring would be practical.

Boron concentrations are less than 0.3 mg/1 for water from the surficial aquifer and are thus below the tolerance limits for even boron-sensitive crops. Water from a well tapping a deeply buried aquifer had a boron concentration of 4 mg/l.

Abnormally high concentrations of nitrate occur locally in the study area, often in water from shallow water-table aquifers subject to pollution from barnyards, septic-tank effluent, agricultural fertilizers, or similar sources. Increased use of fertilizers that may accompany irrigation could result in increased nitrate concentrations.

Dissolved iron and manganese in water from the surficial aquifer generally exceed the U.S. Public Health Service (1962, p. 43, 47) recommended drinking-water standards of 0.3 mg/l and 0.05 mg/1, respectively. However, use of water containing high concentration of these elements for irrigation has no apparent harmful effects on plants.

water from aquifers in the Appleton area

per litre, except as indicated]

Bicarbonate (HCO_3)	Sulfate (SO_4)	Chloride (Cl)	Fluoride (F)	Nitrate (NO_3)	Boron (B)	Disolved solids (residue on evaporation at 180°C)	Hardness as $CaCO_3$		Sodium-adsorption-ratio	Specific conductance (micromhos per cm at 25° C)	pH	Color	Use
							Total	Noncarbonate					
124	130	7.8	0.3	20	0.24	497	350	250	0.3	847	7 4	4	Irrigation.
345	160	4.3	.2	0.95	.10	531	430	140	.2	800	7.4	5	Do.
271	70	5.7	.2	1.9	.30	366	300	77	.1	570	7.6	4	Do.
355	180	4.7	.2	.81	.11	596	440	150	.4	843	7.4	2	Do.
289	130	2.7	.2	.45	.08	451	340	99	.3	664	7.5	1	Observation well.
284	55	3.4	.2	.81	.02	345	280	49	.1	532	7.7	5	Irrigation.
311	78	9.5	.1	2.7	.03	397	340	83	.1	622	7.4	1	None.
281	250	3.4	.1	1.2	.16	639	450	220	.6	892	7.4	2	Irrigation.
433	640	6.3	.4	.02	.17	1350	1000	640	.3	1690	7.1	2	Observation well.
317	130	16	.26	1.0	..	510	390	130	...	...	7.4	...	Municipal.
268	214	66	.9	5.3	4	704	88	...	...	1100	8.0	...	Domestic.
368	124	7.6	.2	.2	.13	540	401	99	.4	788	7.8	5	Municipal.
329	81	8.4	...	57	...	485	385	115	.3	738	8.2	...	Domestic.
305	38	.5	.31	<1	...	458	290	40	.	...	..	...	Do.
452	437	3.4	.3	1.9	.29	1080	740	369	.8	1400	7.3	1	Municipal.
174	128	4.8	...	4.6	..	332	250	107	.5	544	7.9	...	Domestic.
564	1.0	28	...	.6	..	599	8	0	36	960	8.5	...	Do.
581	70	7.2	...	29	...	697	286	0	3.9	1060	8.4	...	Do.
226	185	80	.4	195	.2	881	623	...	...	1240	7.9	...	Do.
...	<1	1.6	.07	1.6	...	280	180	...	...	...	...	...	Do.

Surface water in the area during baseflow is primarily derived from ground-water discharge and has chemical characteristics similar to ground water (table 4). During high discharge associated with surface runoff, a decrease in dissolved-solids concentration can be detected. Nitrate concentration seems to be highest in the latter part of March when much of the streamflow is derived from snowmelt. Chemical quality of the Pomme de Terre River could become an important factor if increased development causes stream water to be recharged to the surficial aquifer.

SURFICIAL AQUIFER SYSTEM

The untapped surficial aquifer system was in dynamic equilibrium; that is, although rates and locations of recharge and discharge varied from year to year, over a long period, inflow to the system approximately equaled outflow, and storage remained virtually constant. Ground-water withdrawals will change the natural system, and, if they are continuous, a new state of dynamic equilibrium will eventually result, providing that ground-water discharge does not exceed ground-water recharge.

INFLOW AND OUTFLOW

Inflow to the system consists of recharge from precipitation or streamflow and underflow (ground-water flow across natural or artificial

TABLE 4.—*Chemical analyses of*

[Analyses by U.S. Geological Survey.

Station			Date of collection	Discharge (cfs)	Temperature (°Celsius)	Silica (SiO_2)	Iron (Fe)	Manganese (Mn)
Identification number	Name	Site Location						
05294000	Pomme de Terre River at Appleton	120.43.14bcc	10—3—60	42	11	14	0.02	. . .
	. . .do. . .	120.43.14bcc	3—19—61	68	2	10	.02	0
	. . .do. . .	120.43.14bcc	5—15—61	128	13	9.4	0	.05
	. . .do. . .	120.43.14bcc	3—29—62	42	0.5	6.6	.12	0
	. . .do. . .	120.43.14bcc	2—28—63	24	. . .	16	.09	.02
	. . .do. . .	120.43.14bcc	3—29—67	844	.5	13	. . .	. . .
	Pomme de Terre River near Fairfield	122.42.4ccd	9—14—73	[1]20	14.5	18	.03	.75
05293006	Five Mile Creek near Correll	120.44.12bac	9—27—63	2.7	13	. . .	.04	. . .

[1] Estimated.

system boundaries). Recharge from precipitation is estimated to average 5 inches (13 cm) per year. Although about 85 percent of annual percipitation is concentrated from April through October, it is nearly all evaporated and transpired during this period, and only a small amount recharges the surficial aquifer. Recharge from streamflow occurs only in short reaches, as discussed on page B12. Under intensive pumping, however, ground-water discharge to streams would be reduced, and recharge from streams would increase. Most of the underflow enters the study area across the northern boundary in the Pomme de Terre valley (pl. 1*C*) and is estimated to be 485 acre-ft (0.60 hm^3) per year. Underflow across boundaries between surficial outwash and till is assumed to be negligible.

Outflow from the system consists of evapotranspiration, discharge to streams, and underflow. Evapotranspiration is operative where the water table is near land surface or where lakes have no surface inflow. The potential rate wil be that part of potential evapotranspiration at land surface not satisfied by precipitation, and evapotranspiration will decrease with increased depth to water. The potential rate of evapotranspiration is about 5 inches (130 mm) per year and, for modeling purposes, is assumed to decrease linearly to zero at a water-table depth of 5 feet (1.5 m) below land surface. Underflow out of the system is small and ground-water discharge occurs primarily as base flow in streams. However, because some streamflow enters across the northern boundary, base flow at Pomme de Terre gage in Appleton will not be totally indicative of ground-water discharge from the surficial aquifer.

MATHEMATICAL MODEL

A mathematical model was used to simulate the surficial-aquifer system and to evaluate the effects of ground-water withdrawals. The model was

surface water in the Appleton area
Constituents in milligrams per litre, except as indicated]

Calcium (Ca)	Magnesium (Mg)	Sodium (Na)	Potassium (K)	Bicarbonate (HCO_3)	Sulfate (SO_4)	Chloride (Cl)	Fluoride (F)	Nitrate (NO_3)	Boron (B)	Dissolved solids (residue on evaporation at 180° C)	Hardness as $CaCO_3$ Total	Hardness as $CaCO_3$ Noncarbonate	Sodium-adsorption-ratio	Specific conductance (micromhos per cm at 25° C)	pH	Color
35	86	26	7.1	337	210	8.7	0.2	1.7	0.2	600	442	166	0.5	874	7.6	7
66	41	20	7.1	270	144	7.1	.2	3.3	.13	450	335	114	.5	683	7.4	18
89	51	23	7.0	327	198	6.6	.2	1.4	.13	579	430	162	.5	848	8.0	15
22	9	4.5	5.9	71	36	2.9	.2	11	.03	163	92	34	.2	228	6.5	45
124	71	28	8.2	498	238	4.6	.4	1.5	.18	777	601	193	.5	1100	8.0	9
43	26	8.1	8.0	190	69	4.4	.1	3.5	.07	296	212	56	.2	439	8.1	32
98	58	27	7.1	345	240	6.4	.2	.05	.2	653	480	200	.5	950	8.2	7
				394	0	4.3		3.0	.		496	173	...	1030	8.2	...

developed by Trescott (1973) and is programmed on a digital computer to solve equations describing ground-water flow. If certain aquifer characteristics, such as transmissivity or storage coefficient (specific yield), can be determined, the model can be used to calculate water levels under equilibrium conditions or changes in water levels as a result of withdrawals. More importantly, the effects of aquifer boundaries, streams, lakes, and ground-water evapotranspiration can be determined.

The model does not describe the system in every detail and, therefore, is somewhat of an approximation. However, it is a valuable tool for predicting long-term regional effects of ground-water withdrawals. Although a model of this type can be applied to determine local short-term responses, other theoretical techniques, to be discussed later, are easier to apply and give adequate results.

MODEL DEVELOPMENT

The model was formulated to produce an approximate solution to a generalized form of the ground-water flow equation as given below (Pinder and Bredehoeft, 1968):

$$T_{xx}\frac{\partial^2 h}{\partial x^2}+\frac{\partial T_{xx}}{\partial x}\frac{\partial h}{\partial x}+T_{yy}\frac{\partial^2 h}{\partial y^2}+\frac{\partial T_{yy}}{\partial y}\frac{\partial h}{\partial y}=S\frac{\partial h}{\partial t}+\frac{W'}{\rho}(x,\ y,\ t)b \qquad (1)$$

where

x and y are the coordinate axes $[L]$,
T_{xx} and T_{yy} are the principal components of the transmissivity tensor in the x and y dimensions respectively $[L^2T^{-1}]$,
h is the hydraulic head $[L]$,
S is the storage coefficient [dimensionless],
t is time $[T]$,

b is aquifer thickness $[L]$,
ρ is the density of the fluid $[M\ L^{-3}]$,
W' is the function describing mass flux of the fluid into or out of the system $[M\ T^{-1}\ L^{-3}]$.

Finite difference techniques are used to approximate equation 1, and the iterative alternating direction implicit technique is used to produce a numerical solution. For details on the mathematics of the model the reader is referred to Trescott (1973) or Pinder and Bredehoeft (1968).

Only a part of the study area was selected for modeling. In general, areas (pl. 2*B*) were not included where individual wells can yield no more than 300 gal/min (18.9 l/s). Computer efficiency and hydrologic boundaries of the ground-water system also governed selection of model boundaries.

The area modeled was subdivided into two units, as shown on plate 3*A*. Some reasons for the subdivision were:

1. Anticipated computational problems associated with interconnection of the surficial outwash and the buried sand. (See page B6.)
2. Detail required to simulate the system adequately would not allow the entire area to be modeled within the limits of available computer core storage.
3. The Pomme de Terre River formed somewhat of a hydrologic boundary between the two units, and, in view of the necessity to divide the area, it provided a logical place of division.

The following conditions are imposed upon the boundary of the modeled area. External boundaries for both model units are assumed to be impervious (no flow) except for three segments that are modeled as constant head along the northern and southern boundary of model unit 1 (pl. 3*A*). These segments are located where the aquifer extends beyond the modeled area. Underflow across the segments would probably be simulated best by a constant flux condition. However, computational difficulties forced the use of a constant head condition. The flux (underflow) across these boundaries was carefully monitored so as not to exceed reasonable amounts.

The impervious condition assumed for most of the remainder of the boundary represents outwash-till contact that allows little or no ground-water flow across it. However, the boundary segment of model unit 2, west of Spring Lake and within the study area boundary (pl. 3*A*), represents a ground-water divide and is considered to be impervious (no flow). Although withdrawals (pumping) from model unit 2 would displace the divide to the west, water-level declines would be somewhat less than those predicted by assuming the divide to be stationary. The small area of unsaturated conditions within model unit 2 (pl. 3*A*). is also considered impervious along its border.

An impervious condition was assigned along the segments of overlap between the two model units. The Pomme de Terre River is assumed to effectively control water levels in this area, and thus water-level declines were not allowed to extend beyond this boundary. Intense withdrawals would cause the assumption to be violated; however, the magnitude of the declines extending beyond the boundary was not considered to be significant.

Inflow and outflow from the ground-water system (W') function in equation 1 are modeled as follows:

1. Evapotranspiration is maximum for water levels at the land surface and decreases linearly to zero for water levels more than 5 feet (1.5 m) below land surface, as discussed on page B18. Evapotranspiration from Shible and Spring Lakes is simulated at a maximum rate for water levels above the lake bottom. For water levels below the lake bottom, it is considered to occur as outlined previously.
2. The Pomme de Terre River is constant head above a semipervious streambed. Recharge or discharge will occur depending on the relation between stream level and water level in the aquifer.
3. Recharge from precipitation, as discussed on page B18, is assumed to be uniform for the modeled area.
4. Underflow is allowed to occur along constant head boundary segments.

As a result of the mathematics needed to obtain a numerical solution to equation 1, each model unit is outlined on a grid. For this area, each grid block, called a node, is a square, 0.25 mile (0.4 km) on each side, or an area of 160 acres (65 hm^2). Aquifer properties and data quantifying external factors, such as stream-aquifer relationships or evapotranspiration, are determined as an average for each nodal area. Because of the areal uniformity of the outwash, hydraulic conductivity and storage coefficient (specific yield) are considered to be 267 ft/d (81 m/d) and 0.15, respectively, for all nodes except those within the area of contact between the outwash and the buried sand (pl. 1*A*). For these nodes, hydraulic conductivity is reduced to 134 ft/d (41 m/d) to account for the finer grained character of the buried sand. For other aquifer properties, such as aquifer base altitude (till surface underlying outwash), values assigned at each node are determined from maps.

The effect of the buried sand shown in the cross section on plate 1*A* was modeled only where the sand was interconnected with the surficial aquifer. Withdrawals of water from the buried sand beyond the area of connection will affect the surficial-aquifer flow system. However, model limitations and lack of data on the extent and the thickness of the buried sand prohibited its inclusion in the analysis.

CALIBRATION OF EQUILIBRIUM MODEL

Before the model was used to predict the effects of withdrawals, it was calibrated under equilibrium conditions. Using the data and boundary conditions outlined previously, water levels and distribution of ground-water discharge under equilibrium conditions were computed and were compared with the average water table (pl. 1*C*) and with measured discharge to the river (fig. 5).

Reasonable adjustments were made to various parameters until equilibrium conditions were adequately simulated. The most significant adjustments were made on the thickness and the hydraulic conductivity of the streambed. Lack of field data on these parameters necessitated trial and error estimates of their values. The values selected, reported here as an aggregate of thickness divided by hydraulic conductivity of the streambed, were 1.7×10^6 seconds for model unit 1 and 1.5×10^5 seconds for model unit 2. The smaller quotient can be attributed to a more permeable streambed caused by greater stream slope in model unit 2. (See fig. 5.) Minor adjustments were made to aquifer base altitude and land surface altitude (controlling evapotranspiration), but the adjustments did not change the conceptual representation of the aquifer system.

Flow rates at equilibrium associated with the various components of the surficial aquifer system are tabulated in water-budget form below for each model unit.

Model unit 1

	Acre-feet per year	*Cubic hectometres per year*
Inflow		
Recharge	5,900	7.3
Underflow	485	0.6
Total	6,385	7.9
Outflow		
Discharge to Pomme de Terre River	5,140	6.3
Evapotranspiration	615	0.8
Underflow	630	0.8
Total	6,385	7.9

Model unit 2

	Acre-feet per year	Cubic hectometres per year
Inflow		
Recharge	5,545	6.8
Underflow	0	0
Total	5,545	6.8
Outflow		
Discharge to Pomme de Terre River	5,030	6.2
Evapotranspiration	515	0.6
Underflow	0	0
Total	5,545	6.8

ANALYSIS OF DEVELOPMENT

The calibrated model was used to study effects of ground-water withdrawals associated with irrigation. The scale of the model was specifically chosen to give a regional assessment of system response. That is, calculated water-level changes represent average changes for each nodal area of 160 acres (65 hm^2).

Ground-water withdrawals from the surficial aquifer will change the equilibrium recharge-discharge relationships. Water-level declines (drawdown) from equilibrium positions will be produced so that water is transmitted to places of withdrawal. As a result of the declines, water may be released from storage within the aquifer, may be diverted from discharge to streams or evapotranspiration, or may be induced as recharge from streams. In addition, flow across system boundaries (underflow) may be reduced or increased. If withdrawals continue at an equal annual rate and do not exceed the total inflow to the system, a new state of equilibrium will result.

Three patterns of irrigation development, as outlined below, were studied, and aquifer response was simulated for a 20-year period.

1. Present development—locations shown on plate 3*B* represent present irrigation systems tapping the surficial aquifer. An average annual withdrawal rate of 8 inches (20 cm) of water for the irrigated acreage was assumed.
2. Maximum irrigation development—A hypothetical development pattern, including that of the present, shown on plate 3*C*. Irrigable areas greater than 80 acres (32 hm^2) and having a potential yield (pl. 2*B*) of more than 300 gal/min (19 l/s) were selected. Average annual withdrawal was also assumed to be 8 inches (20 cm).
3. Fifty percent of maximum development—The same pattern as maximum development except that average annual withdrawal was reduced to 4 inches (10 cm).

Although the withdrawal rate for pattern 3 does not satisfy the average annual irrigation requirement of 8 inches (20 cm), aquifer response to this pattern should be similar to withdrawals of 8 inches (20 cm) of water per year from about half the locations shown on plate 3*C*, assuming the locations are uniformly distributed within the area of withdrawal. Eight inches (20 cm) of water per year on 160 acres (65 hm^2) corresponds to a pumping rate of 805 gal/min (51 l/s) for 30 days. In some areas where withdrawals of this magnitude are simulated, single wells may not be able to yield the required volume in 30 days; thus, multiple wells are assumed.

Calculated response of the surficial aquifer system to present development is illustrated in figure 8 and on plate 3*D*. Fourteen pumping centers (see pl. 3*B*) irrigating 2,120 acres (858 hm^2) at a rate of 8 inches (20 cm) per year resulted in water-level declines of less than 3 feet (0.9 m) after 20 years (pl. 3*C*).

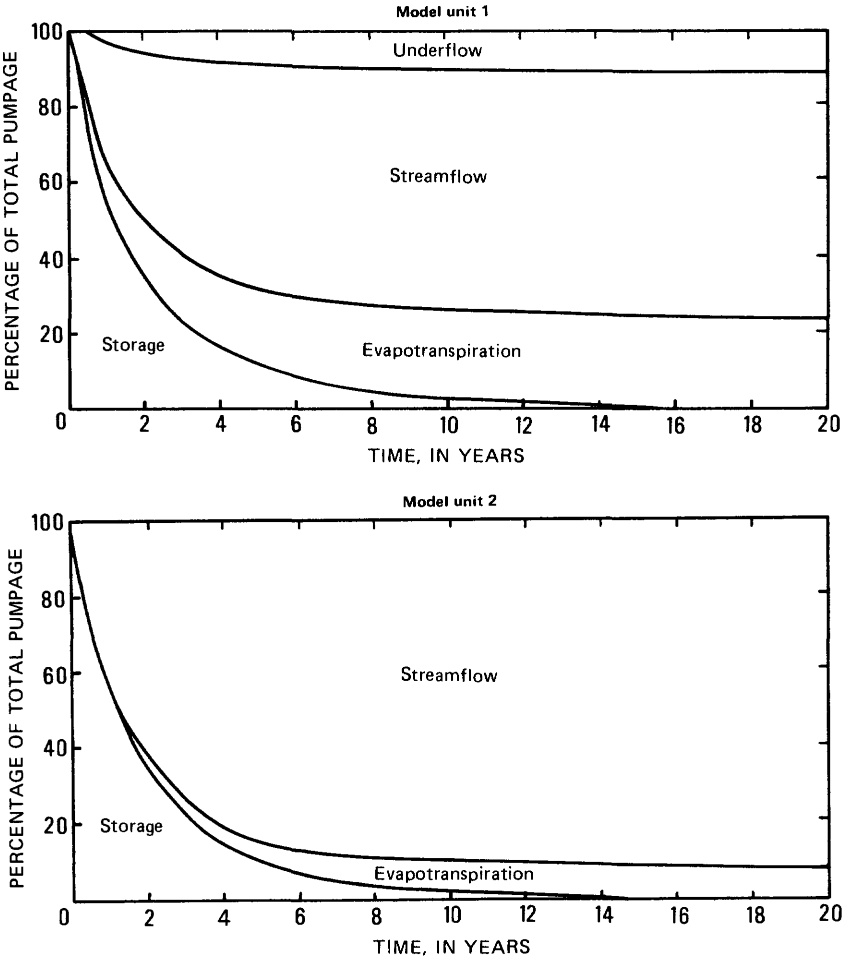


FIGURE 8.—Predicted source of pumped water during 20 years of present development (withdrawals of 1,410 acre-ft/yr (1.74 hm^3/yr)).

The source of the pumped water during the 20-year period, expressed as a percentage of the total pumpage, is shown in figure 8. The categories in figure 8 are outlined as follows:

1. Storage—Represents water released from storage within the aquifer.
2. Evapotranspiration—Represents water diverted from ground-water discharge as evapotranspiration.
3. Streamflow—Represents water diverted from ground-water discharge to streams and water induced as recharge from streams.
4. Underflow—Represents increased or decreased ground-water flow across model boundaries.

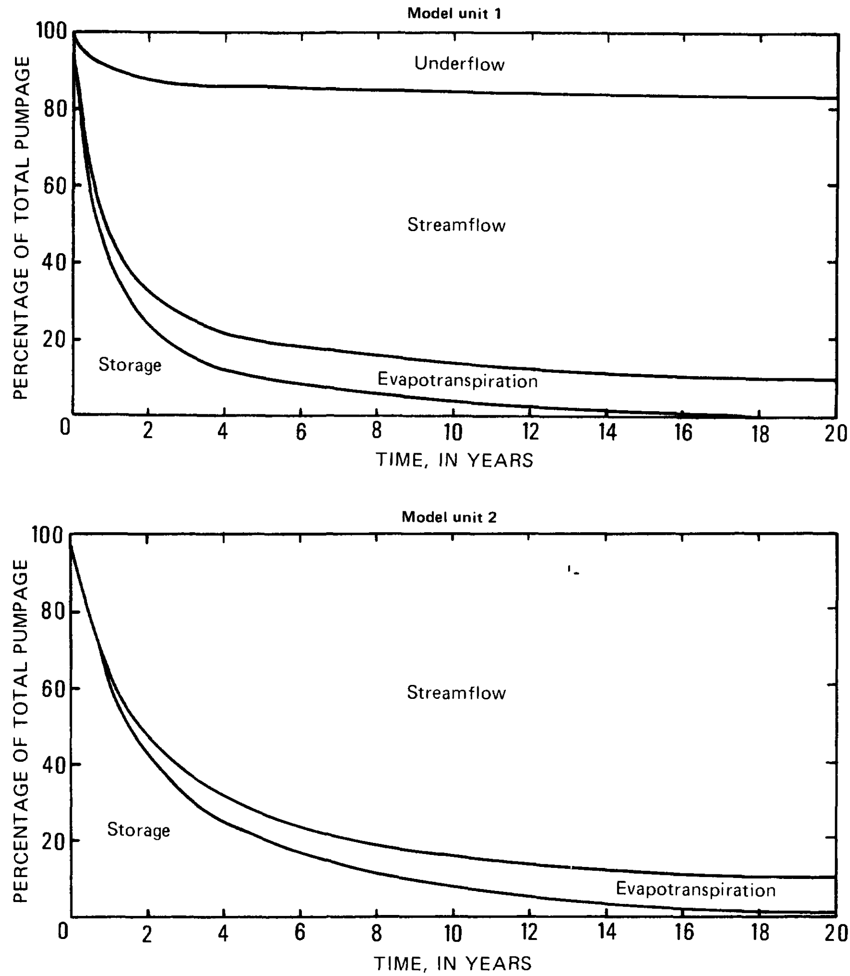


FIGURE 9.—Predicted source of pumped water during 20 years of maximum (hypothetical) development (withdrawals of 8,450 acre-ft/yr (10.4 hm^3/yr)).

During the first year of development, most of the total pumpage is supplied by water released from storage. After about 12 years, however, a new state of equilibrium is reached, and only a small percentage of the total pumpage is derived from storage. For example, in model unit 1, after 12 years, of the total pumpage derived, 64 percent is from streamflow, 24 percent is from evapotranspiration, 10 percent is from underflow, and only 2 percent is from storage. Thus, after the first few years, streamflow is the primary source of pumped water.

Calculated response to maximum development is shown in figure 9 and on plate 3*E*. Ninety-six pumping centers (see pl. 3*C*) irrigating 12,680 acres

(5,132 hm^2) at a rate of 8 inches (20 cm) per year are represented. Figure 9 shows that the source of pumped water follows a pattern similar to that of present development (fig. 8) except that 18–20 years is required to reach a new state of equilibrium. Water-level declines (pl. 3*E*), however, have significantly increased, and two parts of the aquifer have become dewatered. As a result, yields of wells in the southern part of the model unit 1 area would decrease, Shible Lake in model unit 2 area would probably be dry, and the level in Spring Lake would drop about 5 feet (1.5 m). The northern part of model unit 1 area is relatively unaffected because of less intense withdrawals and the proximity of pumping centers to the Pomme de Terre River.

Results shown in figures 10 and on plate 3*F* represent withdrawals of 4 inches (10 cm) of water per year from the same pumping centers as used for maximum development. As stated on page B23, response to this withdrawal should be similar to the response associated with withdrawals of 8 inches (20 cm) per year at about 50 percent of the pumping centers, assuming a uniform distribution of pumping within the area of withdrawal. Figure 10 shows sources of pumped water to be similar to those shown in figures 8 and 9. Equilibrium is reached in 16 to 18 years. Water-level declines (pl. 3*F*), however, are less than half the declines under maximum development. (See fig. 8.) Because saturated thickness is reduced by water-level declines, the capability of the aquifer to transmit water is also reduced, and water levels decline further. Thus, declines under maximum development are as much as three times greater than those under 50 percent of maximum development. Also, well yields in the southern part of model unit 1 area will not decrease nearly as much as under maximum development, and levels in Shible and Spring Lakes will decrease 3 and 2 feet (0.9 and 0.6 m), respectively.

Seasonal water-level declines will be greater than the regional long-term declines illustrated on plate 3*D, E,* and *F*; that is, declines will be greatest during irrigation season in response to withdrawals. Water levels will recover (rise) during the remainder of the year until the next irrigation period but will not quite reach prewithdrawal levels. Twenty annual pumping and recovery periods would result in regional long-term declines, as illustrated on plate 3*D, E,* and *F.* Figure 11 shows an example hydrograph of the predicted aquifer response during a 30-day pumping period and a 90-day recovery period. Thirty days of continuous pumping does not strictly correspond to realistic practices of short (3-day) pumping periods distributed throughout the irrigation season (about 90 days), but the resultant effect on water levels would be similar.

The model results are intended to guide in estimating future effects of ground-water development in the study area. No account is made in the models for annual variations in climate, streamflow, and withdrawal rates, which will have an effect on the aquifer system. Also, some of the

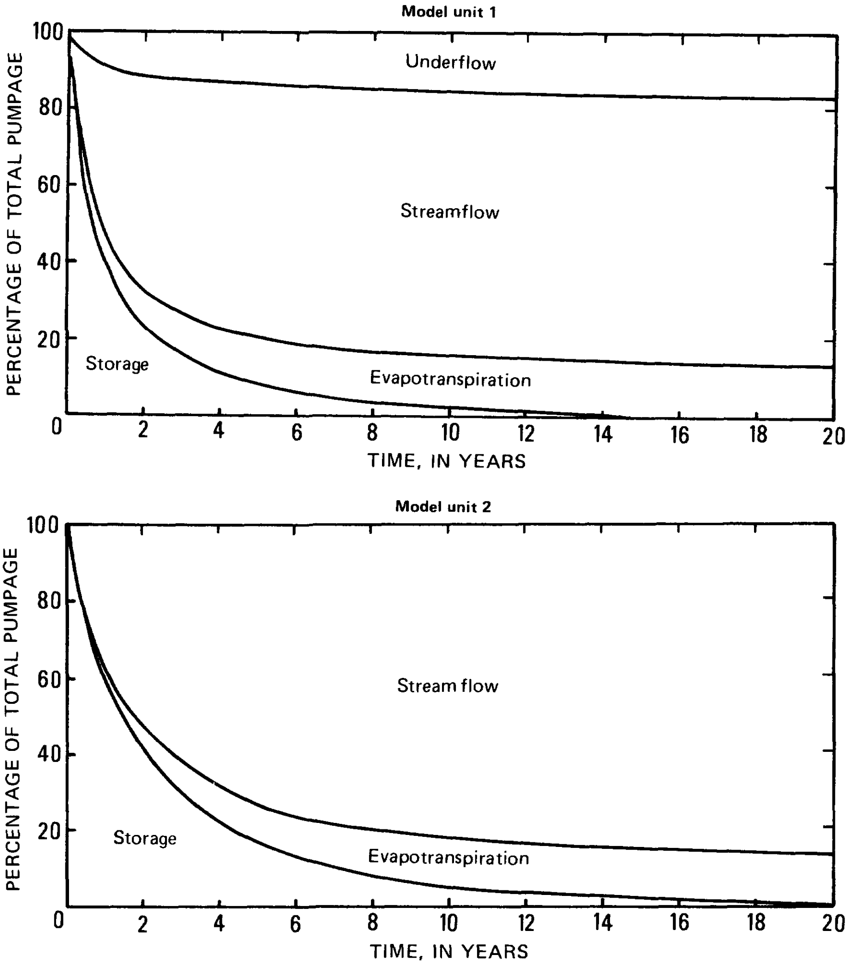


FIGURE 10.—Predicted source of pumped water during 20 years at 50 percent of maximum (hypothetical) development (withdrawals of 4,240 acre-ft/yr (5.23 hm^3/yr)).

results presented here apply to selected, hypothetical intensities of ground-water development. However, the models can be easily updated and can be used to evaluate other schemes of ground-water development, changes to the aquifer system, or changes in other hydrologic factors affecting the aquifer system.

LOCAL EFFECTS OF PUMPING

Although digital models can be used to study local effects of pumping, other methods are also applicable and can be used to obtain adequate estimates of aquifer response. Theoretical methods for determining

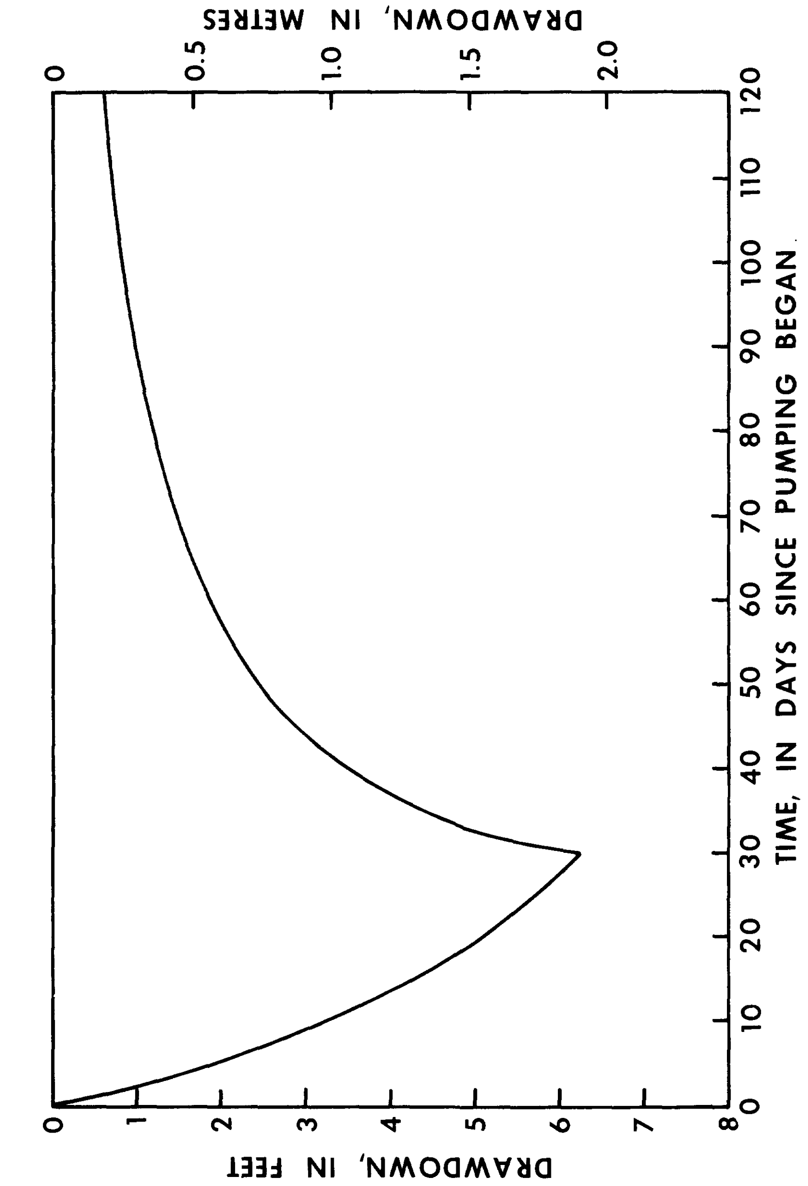


FIGURE 11.—Example hydrograph showing predicted aquifer response to seasonal withdrawal.

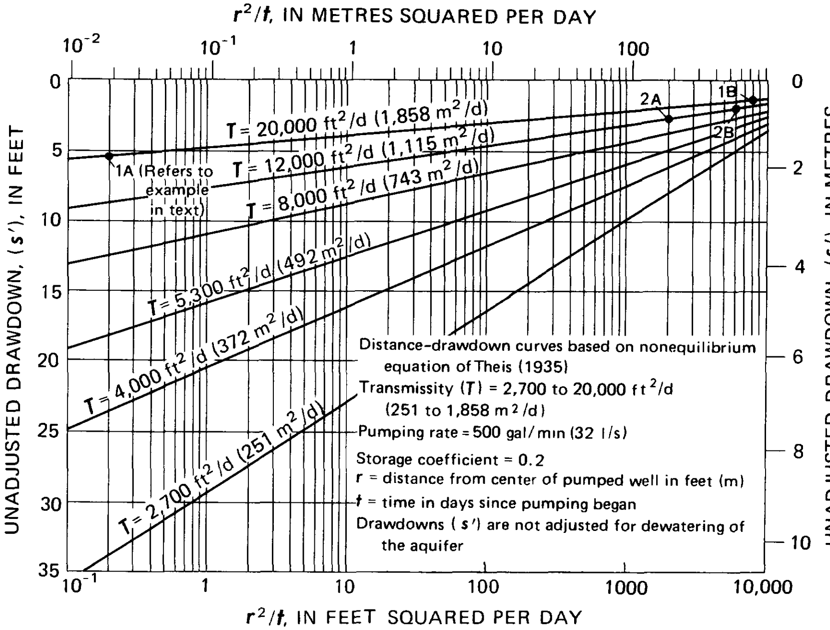


FIGURE 12.—Theoretical relation of drawdown to distance from a pumped well and time of pumping for a pumping rate of 500 gal/min (32 l/s).

water-level declines (drawdown) in the vicinity of a pumped well are available for a variety of aquifer characteristics. Using the nonequilibrium equation of Theis (1935), given below, theoretical relations of drawdown, unadjusted for dewatering, to distance from a pumped well and time of pumping are shown in figure 12 for various values of transmissivity:

$$s=\frac{Q}{4\pi T}W(u) \text{ and } u=\frac{r^2S}{4Tt}, \qquad (2)$$

where

s is drawdown at any point of observation in the vicinity of a well discharging at a constant rate [L],

Q is discharge of a well [L^3T^{-1}],

T is transmissivity [$L\ T^{-1}$],

r is the distance from the discharging well to the point of observation [L],

S is the coefficient of storage [dimensionless],

t is time since pumping started [T],

$W(u)$ is the negative of the exponential integral of $-u$, commonly known as the well function of u [dimensionless].

Although the pumping rate used is 500 gal/min (32 l/s), the curves are applicable to other rates because unadjusted drawdown is proportional to pumping rate. That is, if the rate were 1,000 gal/min (63 l/s), the unadjusted drawdown at a given distance and time would be twice as much as that indicated in figure 12.

The nonequilibrium method is not strictly applicable to water-table problems because saturated thickness changes as water levels change. However, drawdowns can be adjusted for the decrease in saturated thickness so as to reflect drawdowns in an equivalent unconfined (water-table) aquifer (fig. 13). This can be particularly important in the vicinity of a pumped well, where dewatering (decrease in saturated thickness) is greatest. Examples of the use of figures 12 and 13 are presented later in this section.

Variations in drawdown will occur locally where hydrologic boundaries exist (fig. 14). The rate of drawdown will be slowed or will be halted if the expanding cone of depression (area of drawdown) intercepts a stream or lake, and the rate of drawdown will increase if a relatively impermeable boundary is intercepted. The till which surrounds most of the study area can be considered an impermeable boundary in relation to the surficial aquifer.

Rate of drawdown will also increase when the cones of depression from individual wells overlap (fig. 14). Drawdown at a point affected by more than one pumping well is equal to the sum of the drawdown at that point caused by each well. Multiple wells may be required to obtain adequate irrigation supplies in some places, and estimates of well interference are useful in choosing optimum well spacing.

The use of figures 12 and 13 for estimating local effects of pumping is illustrated by the following hypothetical examples:

Example 1.—A well is pumping 1,500 gal/min (95 l/s) from an unconfined (water-table) aquifer where the saturated thickness is 40 feet (12 m), the hydraulic conductivity (see table 2) is 500 ft/d (152 m/d), and the storage coefficient is 0.2 The well is open to the full saturated thickness and is 100 percent efficient.

A. Find the drawdown 1 foot (0.3 m) from the center of the well after 5 days of pumping.

1. Transmissivity is 20,000 ft^2/d (1,860 m^2/d) [500 ft/d (152 m/d) ×40 ft (12 m)].

2. The value of r^2/t is 0.2 ft^2/d ($1.9 \times 10^{-2} m^2/d$) [1 ft (0.3 m) × 1 ft (0.3 m) ÷ 5 days].

3. From figure 12, the unadjusted drawdown for a well pumping 500 gal/min (32 l/s) is about 5.4 feet (1.6 m). For a well pumping 1,500 gal/min (95 l/s the unadjusted drawdown in 16.2 feet (4.9 m) [5.4 ft (1.6 m) × 3].

4. From figure 13, the adjusted drawdown is 22.5 feet (6.9 m).

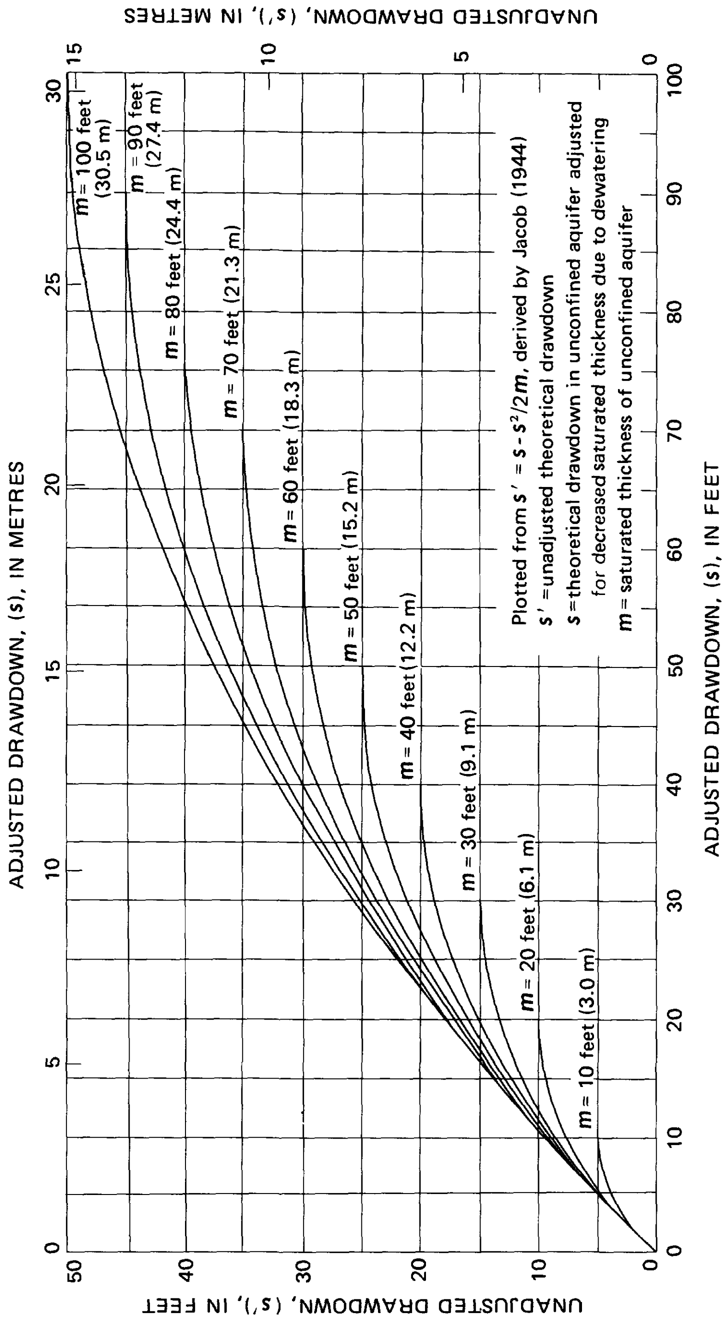


FIGURE 13.—Theoretical curves for adjustment of drawdown to compensate for dewatering of the unconfined aquifer.

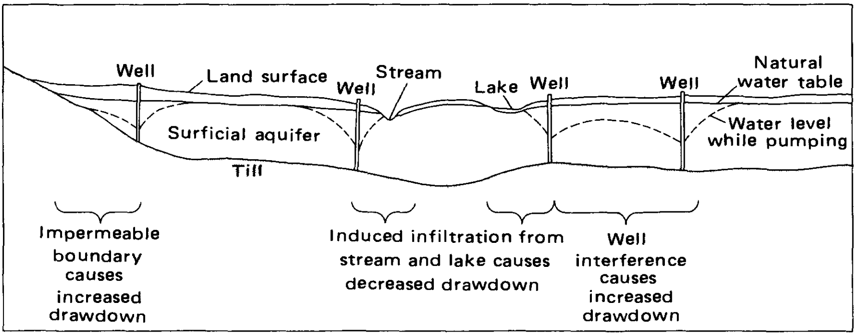


FIGURE 14.—Schematic cross section illustrating effects of nearby wells and hydrologic boundaries on cones of depression.

B. Find the drawdown 200 feet (61 m) from the center of the well after 5 days of pumping.

1. Transmissivity is 20,000 ft^2/d (1,860 m^2/d).
2. The value of r^2/t is 8,000 ft^2/d (743 m^2/d) [200 ft (61 m)×200 ft (61 m) ÷ 5 days].
3. From figure 12, the unadjusted drawdown for a well pumping 500 gal/min (32 l/s is 1.3 feet (0.4 m). For a well pumping 1,500 gal/min (95 l/s) the unadjusted drawdown is 3.9 feet (1.2 m) [1.3 ft (0.4 m) × 3].
4. From figure 13, the adjusted drawdown is 4.1 feet (1.2 m).

Example 2.—Two wells are 200 feet (61 m) apart. Each pumps 500 gal/min (32 l/s) from an unconfined aquifer where the saturated thickness is 30 feet (9 m), transmissivity is 12,000 ft^2/d (1,115 m^2/d) [hydraulic conductivity of 400 ft/d (122 m/d], and storage coefficient is 0.2. The wells are open to the full saturated thickness and are 100 percent efficient.

A. Find the drawdown midway between the two wells after 5 days of pumping.

1. The value of r^2/t for each well at a radius of 100 feet (30 m) is 2,000 ft^2/d (186 m^2/d [100 ft (30 m) × 100 ft (30 m) ÷ 5 days].
2. From figure 12, the unadjusted drawdown for each well is 2.6 feet (0.8 m).
3. From figure 13, the adjusted drawdown for each well is 2.7 feet (0.8 m).
4. The drawdown midway between the wells is 5.4 feet (1.6 m) [2.7 ft (0.8 m) + 2.7 ft (0.8 m)] which is the sum of the drawdowns caused by each well at that point.

B. How far apart should the wells be placed if not more than 4 feet (1.2 m) of drawdown is desired midway between them after 5 days of pumping?

1. The adjusted drawdown caused by each well midway between them is intended not to exceed 2 feet (0.6 m)[½ × 4 ft (1.2 m)].
2. From figure 13, the unadjusted drawdown caused by each well is about 1.9 feet (0.6 m).

3. From figure 12, r^2/t for an unadjusted drawdown of 1.9 feet (0.6 m) and a transmissivity of 12,000 ft^2/d (1,115 m^2/d) is about 6,000 ft^2/d (557 m^2/d). The value of r is 173 feet (53 m) if t is 5 days [square root of the quantity: 6,000 ft^2/d (557 m^2/d)× 5 days = 30,000 ft^2(2,787 m^2)]. The distance between the two wells must be at least 346 feet (105 m) [173 ft (53 m) × 2] if the drawdown midway between them is not to exceed 4 feet (1.2 m).

These examples illustrate a method of estimating aquifer response in the vicinity of pumped wells. It should be noted, however, that few wells are 100 percent efficient and drawdowns within wells will be somewhat greater than those predicted by this method.

SUMMARY

The most productive sources of ground water in the Appleton area are aquifers in the glacial drift which ranges in thickness from 150 to 300 ft (46–91 m). The areally extensive surficial outwash aquifer is of particular importance. Composed of stratified beds of outwash sand and gravel, it is more than 100 feet (30 m) thick in places and is underlain by relatively impermeable silty till. The aquifer is unconfined, and water levels are generally within 20 feet (6 m) of land surface. An average of 5 inches (130 mm) of water is recharged annually from precipitation. An equal amount is discharged annually, primarily into the Pomme de Terre River.

Saturated thickness of the aquifer is greatest [more than 80 ft (24 m)] in the northern part of the study area along the Pomme de Terre valley and in the west-central part where the aquifer is interconnected with a buried sand layer. In these parts, estimated well yields exceed 1,200 gal/min (76 l/s) are obtainable.

Yields greater than 700 gal/min (44 l/s) have been obtained from aquifers buried within the glacial drift in places where the surficial aquifer does not provide an adequate supply of water for irrigation. In places the buried sand is interconnected with the surficial aquifer, but its extent and thickness beyond the area of contact is unknown.

Ground water in the study area is primarily sodium bicarbonate type and is chemically suitable for irrigation with respect to sodium hazard and boron concentrations. Although dissolved-solids concentrations range from 280 to 1,350 mg/l, the associated salinity hazard is alleviated by adequate flushing of the root zone by precipitation and, perhaps, by over application of irrigation water. The proximity of the water table to the land surface has resulted in abnormally high nitrate concentrations in the ground water from surface contaminants in places.

A mathematical model of a part of the surficial aquifer was made to simulate ground-water movement in the system and to evaluate future effects of ground-water development. After 20 years at the present (1973) rate of withdrawal [1,410 acre-ft/yr (1.74 hm^3/yr)], water-level declines

were calculated to be less than 3 feet (0.9 m). Under maximum (hypothetical) development of 8,450 acre-ft/yr (10.4 hm^3/yr), dewatering of parts of the aquifer is predicted, and water-level declines would cause decreased well yields in some areas. Model results also show that a new state of equilibrium would be created in response to development, most of the withdrawal being diverted from ground-water discharge to the Pomme de Terre River or being induced as recharge from the river.

Seasonal declines, in addition to long-term regional declines, will occur at pumping centers and can be estimated using the nonequilibrium equation of Theis (1935). This equation can also be used to evaluate interference effects among multiple wells, which may be required to obtain adequate supplies in some parts of the area.

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