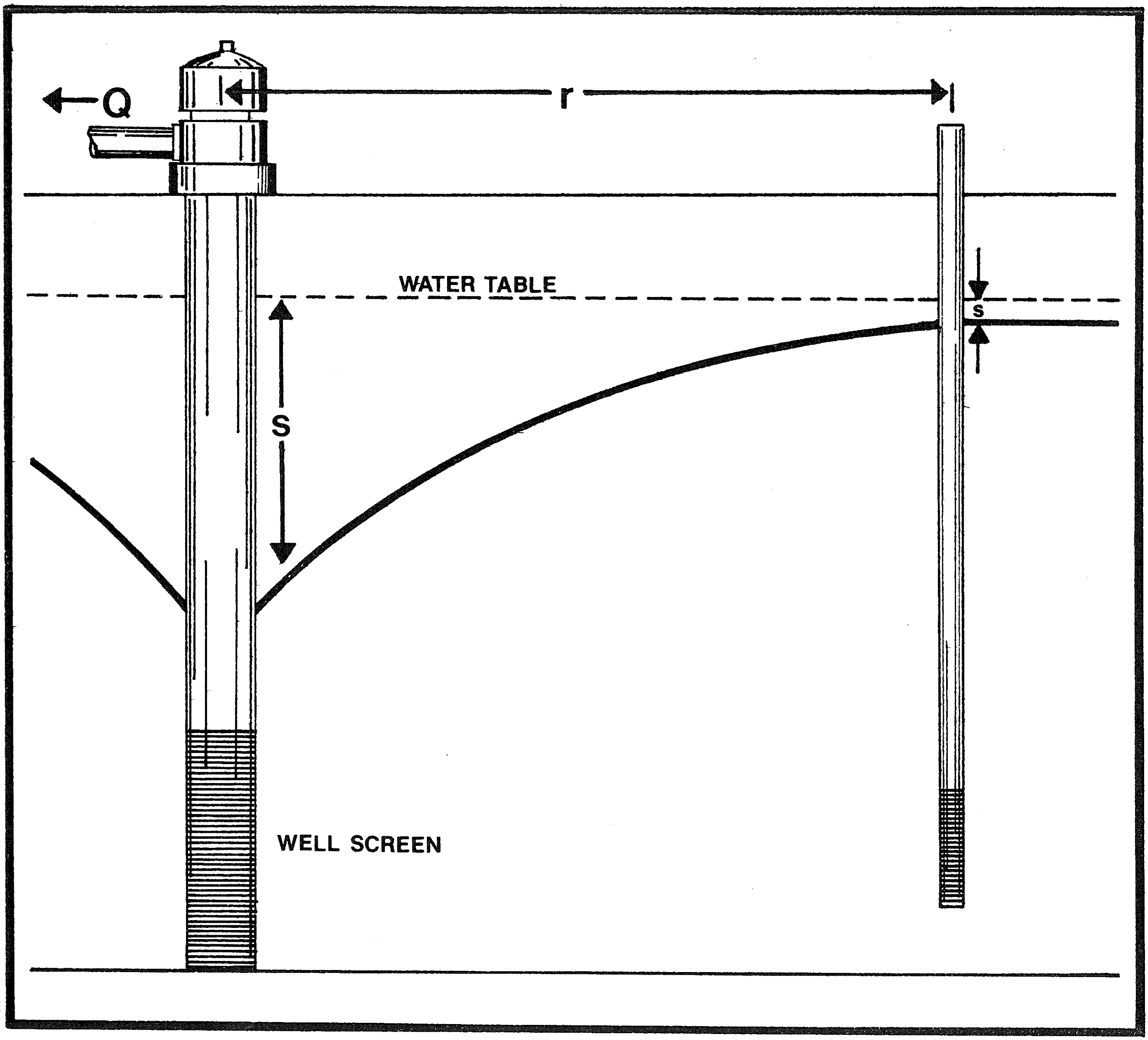
TECHNICAL PAPER NO. 5

GROUND WATER and AQUIFER TESTS



MINNESOTA DEPARTMENT OF NATURAL RESOURCES
DIVISION OF WATERS

OCTOBER 1977
[Revised Edition, February 1978]

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GROUND WATER and AQUIFER TESTS

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DIVISION OF WATERS

by Dennis G. Woodward

ST. PAUL, MINNESOTA
OCTOBER 1977
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ACKNOWLEDGEMENTS

Materials presented in this ground-water training manual were gathered from a variety of sources. U.S. Geological Survey publications have been liberally and literally used, as have some Johnson Well Screen periodicals. Minnesota Geological Survey papers have also provided geologic contributions. This manual is not intended to be the final word in the field operation of aquifer testings, but it is hoped that a sufficient level of information can be gained from its use so that the reader will be familiar with the methods and precautions needed to assure meaningful results from an aquifer test.

A successful aquifer test requires considerable planning and site-specific information. Assistance, guidance, or information regarding aquifer tests should be directed to:

Ground Water Group
Hydrology Section
DNR - Waters
444 Lafayette Road
St. Paul, Minnesota 55101
Phone: (612)-296-4800

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MINNESOTA'S WATER SOURCE

For practical purposes, the source of all Minnesota's water is precipitation in the form of rain and snow. How is it that we don't run out, for we use so much? To understand, we must consider the HYDROLOGIC CYCLE (Fig. 1). The hydrologic cycle is a natural machine, a constantly running distillation and pumping system. The sun supplies heat energy, and this together with the force of gravity keeps the water moving from the earth to the atmosphere as evaporation and transpiration; from the atmosphere to the earth as condensation and precipitation; and between places on and in the earth as streamflow and ground-water movement. This cycle has neither end nor beginning; but, from Minnesota's point of view, the Pacific Ocean and the Gulf of Mexico are the major sources, the winds from the Dakotas are the major deliverer, and the land is the major user.

Of Minnesota's share of precipitation, part becomes runoff in streams, part is evaporated, part is consumed or transpired by vegetation; the remainder seeps into the subsurface and becomes ground water.

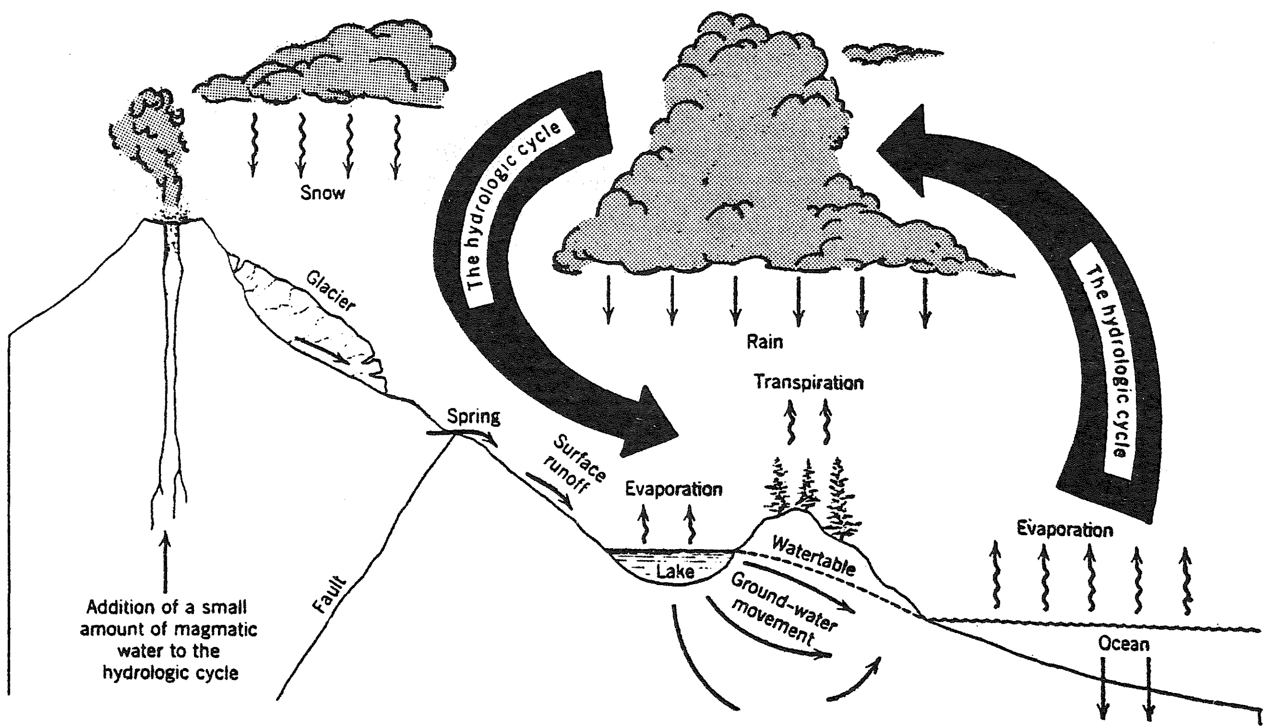


FIGURE 1 The transportation and distillation of water is accomplished by a continuous sequence which is part of a larger interaction between earth, sun, sea, and atmosphere. In a natural refining process that uses about one-third of all solar energy reaching the earths surface, some 10 million billion gallons of water are evaporated each year. About one-fifth comes from the land; the rest is from the sea. Evaporation distills ocean water as it escapes as vapor into the atmosphere.

DEFINITION OF GROUND WATER

One thing ground water is not, it is not mysterious. It does not, as some believe, run in veins beneath the ground. The closest thing to veins carrying ground water are solution-enlarged fractures (or joints) in limestone and narrow, sinuous stream-channel deposits of sand and gravel buried beneath layers of till. (See GLOSSARY).

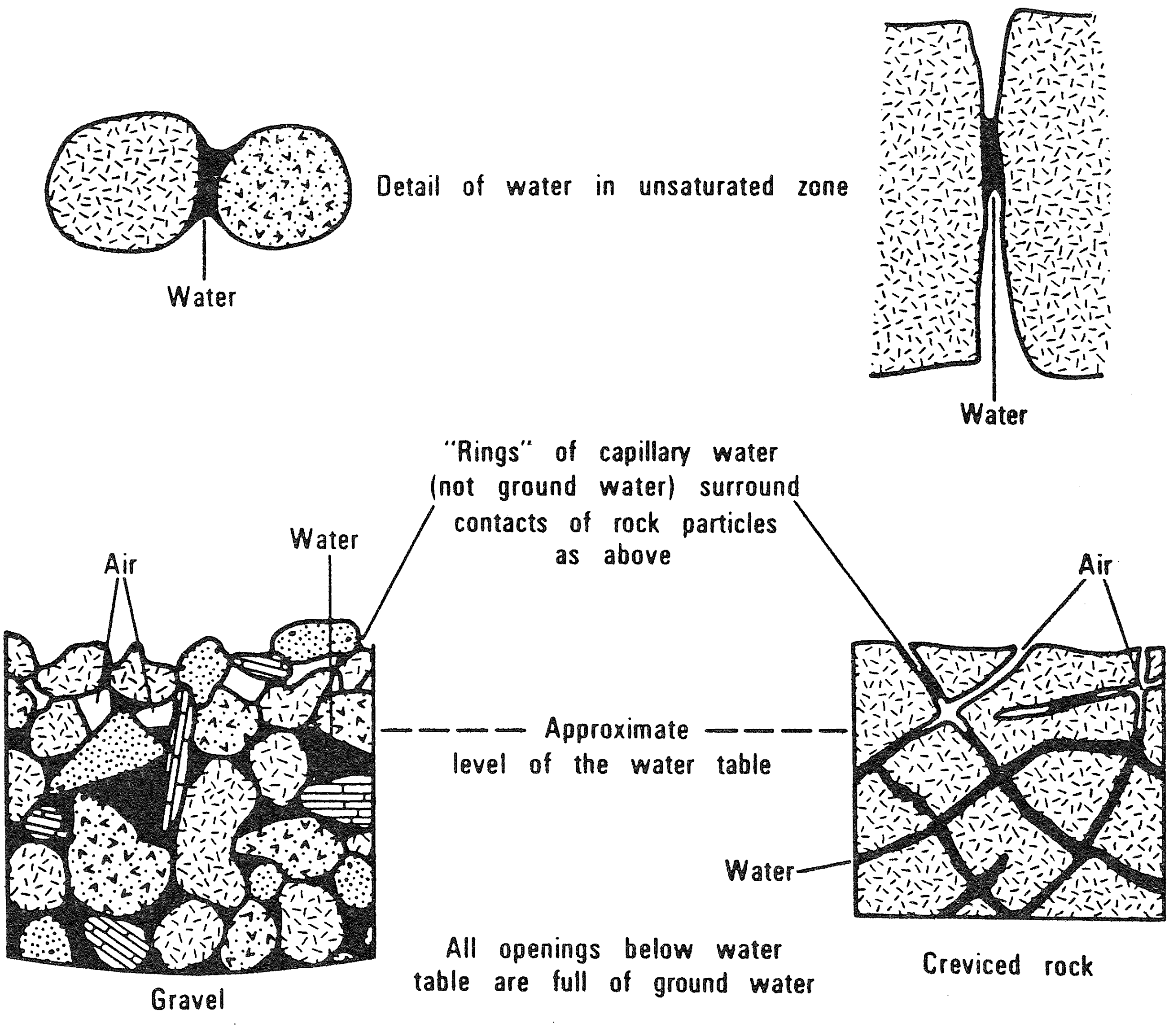
Not all water beneath the land surface is ground water. In most places, there is an unsaturated zone. In swampy areas, this zone may be very thin or practically absent. That part of precipitation that does not run off in streams infiltrates the land surface and supplies soil-moisture needs, soil being the top of the unsaturated zone. Some water that infiltrates is retained in the unsaturated zone and is partly available for plant use. (Fig. 2, upper part). The rest is moved by gravity through the unsaturated zone to become ground water.

Technically, ground water is water in the saturated zone. The saturated zone is that part of the earth's crust beneath the deepest water table. All openings in rocks (into which water may percolate) in this zone are ideally filled with water under pressure greater than atmospheric. The water is stored in intergranular pores in the rocks, such as in sands and gravels, or in crevices in the rock, such as in fractures and jointed bedrock. (Fig. 2, lower part). The ability of a rock to store water is dependent on its porosity. Porosity is the ratio of total volume of the openings to total volume of the rock, usually stated as a percentage. The ability of a rock to transmit water, and thus supply a pumping well, is dependent on the rock's permeability, that is, the interconnection between pores by passages of greater than capillary size. A porous rock is not necessarily very permeable. A fine-grained deposit such as silt or clay may have a high porosity and contain a large volume of water when saturated, but the interspaces are so small that most of the water is held by molecular attraction and very little can pass through. A sand and gravel deposit may have a fraction of the porosity of clay, but because its interspaces are relatively large, it transmits water freely and yields large amounts of water to wells.

Ground water occurs either under water-table or artesian conditions. Ground water in contact with the atmosphere either directly or through the unsaturated zone immediately below the land surface is under water-table conditions and is unconfined. Under artesian conditions, the aquifer is overlain by a confining layer of lower permeability. Water in the aquifer is under sufficient pressure to rise above the base of the confining bed in a well or an open hole. The level to which the water will rise is independent of the water table and is called the hydrostatic or potentiometric head. Potentiometric surface (or piezometric surface) is a surface which represents the hydrostatic head.

The response of confined and unconfined aquifers to pumping may differ greatly. The diffusivity (spread of response to pumping) of an unconfined aquifer is much less than that in a confined aquifer. In an unconfined aquifer, discharge from a well is supplied from storage by gravity drainage of the aquifer materials immediately surrounding the well bore, and those materials within the influence of the well's pumping are dewatered. The spread of the effects of pumping are slow. In a confined aquifer, well discharge before dewatering and interception of boundaries is supplied mainly by compression of the aquifer and to some extent by an expansion of the released water. The effects of pumping are spread through pressure, not dewatering and are, thus, rapid. For practical reasons, then, wells completed in water-table aquifers can generally be closer together without pronounced mutual interference than wells completed in artesian aquifers.

FIGURE 2. How water occurs in the rocks



MINNESOTA'S AQUIFERS

The major aquifers in Minnesota may be divided into three major geological domains. These domains are distinctly different, but within each there are many variations in aquifer characteristics. To a large degree, the surface and near-surface hydrology and landscape of Minnesota is dominated by its recent glacial history. Glacial sediments of many types, and post-glacial alluvial deposits constitute one geological domain. Well-stratified Paleozoic and Precambrian sandstones, limestone, and dolomites form a second domain. Beneath these sedimentary deposits throughout Minnesota is a basement of Precambrian crystalline rocks which comprise the third domain.

Minnesota is heavily covered with glacial drift. Only in the northeast "Arrowhead" region, in the southeastern "Driftless Area", in a strip along the Minnesota River Valley, and in east-central Minnesota is the glacial drift less than 100 feet thick. In the western part of the state glacial drift up to 600 feet thick has been encountered.

Glacial morainal deposits generally have a high clay content and poor permeability and porosity. Large ground-water resources in glacial areas occur mainly in shallow aquifers resulting from sand and gravel valley trains, outwash plains, and modern flood plains where glacial sediments have been reworked by water. In the Red River Valley, once the location of post-glacial Lake Aggasiz, the lake beds are typically rather silty and impervious, but there are numerous beach sands and gravels, marking strand lines formed at various stages of the lake, and also sands and gravels in channels and bars that yield water supplies.

Glacial till that has not been reworked and redeposited by flowing water has small and erratic permeability, and thus produces limited and erratic ground-water yields. In the western part of the State, where water resource problems are most acute, the great thickness of till suggest that the deposits of a number of ice advances and retreats are superposed. Little is known of the buried stratigraphy of the older drift deposits. Certainly, opportunities exist for development of prospective buried outwash aquifers, when detailed hydrogeologic investigations are conducted.

The largest ground-water resources of the State are contained in the Paleozoic and Precambrian domain comprising a thick sequence of well-stratified sedimentary rocks underlying the southeastern quadrant of the State. These rocks formed during a long period of marine inundation in the early Paleozoic (around 600 million years ago), during which a sequence of sandstones, dolomitic limestones, and shales were deposited in a large embayment of the sea extending eastward from the vicinity of Blue Earth County into Wisconsin and northward at least 50 miles beyond the Twin Cities. In the center of this embayment near Austin, Minnesota, a test hole penetrated 1,629 feet of sedimentary rocks. Within the major embayment there are areas of differential subsidence and uplift which have produced a series of sedimentary basins with intervening uplifed areas, notably beneath the Twin Cities where a secondary basin forms an important hydrologic structure. The warping was also accompanied by widespread but minor faulting which has provided avenues for the vertical percolation of ground water.

Outside the area where Paleozoic rocks form a major ground-water domain, the rest of the State is underlain by a Precambrian crystalline rock complex. With few exceptions, this extremely varied basement complex has one thing in common with respect to the storage and transmission of ground water - almost all the rocks tend to be partially crystallized or thoroughly cemented. The result is that they lack porosity. Available ground water is limited almost entirely to fracture zones and joints; this means that ground-water resources are sporadic and unpredictable. Notable exceptions include the Keweenawan Volcanic Rocks Aquifer, Sioux Quartzite Aquifer, and the Animikie Group Aquifer.

Where it is necessary to develop a ground-water supply in Precambrian rocks, because alternatives such as shallow drift aquifers or surface water supplies are unavailable, close attention should be paid to geological evidence for the existence of fault zones where fracturing might be expected. It is advised that if water is not encountered within 200 feet, there is generally little to be gained by drilling deeper because fracture zones tend to become tighter and less frequent at depth.

Most of the water in all the bedrock aquifers is under artesian pressure. Water-table conditions prevail in the Prairie du Chien - Jordan Aquifer in a small region. Artesian conditions prevail in the St. Peter Aquifer where it is fully saturated and overlain by the Glenwood Shale. Where the aquifer is overlain by and in hydraulic connection with sand and gravel aquifers in the glacial drift, it is probably under water-table conditions. Water-table conditions also prevail where the St. Peter Aquifer is exposed and is not fully saturated.

Water in buried outwash deposits within the glacial drift is artesian in most places. The permeability of the overlying till is so low in comparison to that of the outwash that it acts as a confining bed. Water in the surficial outwash, valley train, and sand and gravel alluvial deposits is under water-table conditions, except locally where the deposits are fully saturated and are overlain by a relatively impermeable layer of recent alluvial deposits of silt or clay.

POLITICAL ASPECTS OF MINNESOTA'S GROUND WATER

The Commissioner of Natural Resources, under authority contained in Minnesota Statutes 105, is given responsibility for regulating the appropriation or use of ground water in the State. It is unlawful for any person, corporation, or political subdivision of the State to appropriate or use any waters of the state, surface or underground, without a written permit from the Commissioner. However, this does not apply to use of water for domestic purposes serving less than 25 persons.

Permit applications for appropriation of ground water for purposes of agricultural irrigation shall be processed as either Class A or Class B applications. Class A applications are for wells located in areas for which the Commissioner of Natural Resources has adequate ground-water availability data. Class B are those for all other areas. The Commissioner shall evaluate available ground-water data, determine its adequacy, and designate areas A and B statewide. The Commissioner shall solicit, receive, and evaluate ground-water data from soil and water conservation districts, and where appropriate revise his area A and B designations.

Class B applications are not complete until the applicant has supplied the following data:

(a) A summary of the anticipated well depth and subsurface geologic formations expected to be penetrated by the well. For glacial drift aquifers, this data shall include the logs of test holes drilled for the purpose of locating the site of the proposed production well;

(b) The formation and aquifer expected to serve as the ground-water source;

(c) The maximum daily, seasonal, and annual pumpage expected;

(d) The anticipated ground-water quality in terms of the measure of quality commonly specified for the proposed water use;

(e) THE RESULTS OF AN AQUIFER TEST SUPERVISED BY THE COMMISSIONER OR HIS DESIGNEE, CONDUCTED AT A RATE NOT TO EXCEED THE PROPOSED PUMPING RATE FOR A PERIOD NOT TO EXCEED 72 HOURS FOR WELLS UNDER WATER-TABLE CONDITIONS AND NOT TO EXCEED 24 HOURS FOR WELLS UNDER ARTESIAN CONDITIONS. Before, during, and after the aquifer test the Commissioner shall require monitoring of water levels in one observation well located at such distance from the pumping well which he has reason to believe may be affected by the new appropriation. The permit applicant shall be responsible for all costs of the aquifer tests and monitoring in the one observation well. He shall be responsible for the construction of this one observation well if suitable existing wells cannot be located for this purpose. If the Commissioner believes that more than one observation well is needed, he shall instruct the applicant to install and monitor additional observation wells. The Commissioner shall reimburse the applicant for these added costs; and

(f) Upon determination of the area of influence of the proposed well, the location of existing wells within the area of influence which were reported pursuant to Section 156A.07, together with readily available facts on depths, geologic formations, pumping and nonpumping water levels and depths of well construction as related to the Board of Health "Water Well Construction Code."

Also listed in the newly-passed ground-water legislation is the following:

THE COMMISSIONER SHALL ESTABLISH A STATEWIDE TRAINING PROGRAM TO PROVIDE TRAINING IN THE CONDUCT OF PUMPING TESTS AND DATA ACQUISITION PROGRAMS.

This report is intended to provide an introduction to Minnesota's ground-water resource in a brief overview of the hydrogeologic environments within each Department of Natural Resource region. A generalized manual on the field procedures of an aquifer test is also included.

To date, the majority of ground-water investigations conducted in Minnesota have been directed by the Water Resources Division of the United States Geological Survey in cooperation with the Minnesota DNR - Division of Waters. In 1965, the first of a series of Hydrologic Investigations Atlases covering each watershed unit in the state was published. These atlases provide basic hydrologic, geologic, and climatologic data in map, graph, and chart form. Figure 3 lists the name, U.S.G.S. number, and D.N.R. Watershed Unit number for the Hydrologic Investigations Atlases series.

WATERSHED UNIT	U.S.G.S. HYDROLOGIC INVESTIGATIONS ATLAS NUMBER	D.N.R. DIVISION OF WATERS NUMBER
Blue Earth River	HA-525	27
Big Fork River	HA-549	5
Big Stone Lake	HA-213	20
Buffalo River	HA-307	9
Cannon River	HA-522	34
Cedar River	HA-552	37
Chippewa River	HA-286	23
Cottonwood River	HA-466	26
Crow River	HA-528	17
Crow Wing River	HA-380	16
Des Moines River	HA-553	38
Kettle River	HA-437	30
Lac Qui Parle River	HA-269	22
Lake Superior (Not Published)	HA-582	2
Lake of the Woods	HA-544	6
Little Fork River	HA-551	4
Lower Minnesota River	HA-526	29
Lower St. Croix	HA-490	32
Metropolitan	HA-	33
Middle River	HA-201	12
Minnesota River-Hawk Creek	HA-391	28
Mississippi Headwaters	HA-278	15
Mississippi-Sauk	HA-534	19
Mustinka-Bois de Sioux	HA-272	7
Otter Tail River	HA-296	8
Pomme de Terre River	HA-220	21
Rainy Lake	HA-556	3
Red Lake River	HA-346	11
Redwood River	HA-345	25
Rock River	HA-555	39
Root River	HA-548	36
Roseau River	HA-241	14
Rum River	HA-509	18
St. Louis River	HA-	1
Snake River	HA-488	31
Two Rivers	HA-237	13
Wild Rice River	HA-339	10
Yellow Medicine River	HA-320	24
Zumbro River	HA-543	35

FIGURE 3

AQUIFER TESTS

The worth of an aquifer as a fully developed source of water depends largely on two inherent characteristics: its ability to store water and its ability to transmit water. These two parameters, referred to as the coefficient of storage (S) and transmissivity (T), cannot be measured directly. If, however, we remove water from an aquifer, as in a pumping test, the aquifer responds to the removal of water. This response is the drawdown measured in a pumping well and in nearby observation wells. The amount of this drawdown is related to the transmissivity and storage of the aquifer. The relationship, therefore, between a certain pumping rate (Q) and the drawdown (s) it causes is used to determine the T and S of an aquifer.

An aquifer test is a *controlled* field experiment made to determine the hydraulic properties of water-bearing rocks. Results from aquifer tests properly conducted can be used in many ways. Well information determined from an aquifer test includes the expected maximum yield, its efficiency potential, observed drawdown (for setting bowls of a turbine pump at proper depth), specific capacity of wells of different diameters, and predictions of the behavior of a well at some time in the future under a given set of conditions. Aquifer properties derived from an aquifer test include the determination of coefficient of storage (S) and transmissivity (T) and permeability, measured and expected interference caused by pumping, area of influence created by cone of depression surrounding a pumping well, aquifer recharge characteristics, aquifer boundary conditions, and expected yield of an aquifer under given drawdown conditions and after given time periods.

DEFINITION OF TERMS

It is important to understand clearly the meaning of some common terms relating to the aquifer test. Some of the terms used are defined as follows:

STATIC WATER LEVEL - Level to which water rises when well is not being pumped. It is generally the level of the water table except in the case of artesian wells where the static level may be above or below the water table. In wells which do not flow, the static water level is measured from the ground surface (or from an established measuring point near the ground surface) to the water level in the well. In wells which flow at the ground surface, the static water level is above the ground surface, and is measured after shutting off the flow of the well. The static water level in this case is commonly referred to as "shut-in head", or simply "head". If we say a well has a head of 10 ft. at the surface, it means that water under artesian pressure would rise 10 feet above the surface from a well in a pipe.

PUMPING LEVEL - Level at which water stands in a well when pumping at any given rate. Also called "dynamic water level".

DRAWDOWN - Distance the static water level lowers under a given rate of pumping. It is the actual distance in feet between the static water level and the pumping level over a given time of pumping. Referred to as "s".

RESIDUAL DRAWDOWN - After pumping is stopped, water levels rise and approach the static water level observed before pumping started. During such a recovery period, the distance that the water level is found to be below the initial static water level is called the residual drawdown. Referred to as "s' ".

WELL YIELD - Volume of water per unit of time discharged from a well, either by pumping or by flow. It is commonly measured as the pumping rate in gallons per minute (gpm). Referred to as "Q".

SPECIFIC CAPACITY - Yield of a well per unit of drawdown, usually expressed as gallons per minute per foot of drawdown. Dividing the yield by the drawdown (Q/s), each measured at the same time, gives the value of the specific capacity of a well.

STORAGE COEFFICIENT - Volume of water an aquifer releases from or takes into storage per unit surface area of an aquifer per unit change in water level. Referred to as "S". Values for S for water-table aquifers range from 0.01 to 0.35; values for artesian aquifers range from 0.00001 to 0.0001.

TRANSMISSIVITY - Usually measured in gallons per day per foot (gpd/ft) and describes the rate at which an aquifer transmits water. Transmissivity values are highly dependent on the saturated thickness of the aquifer. Referred to as "T". Values of T range from less than 1,000 to over 1,000,000 gallons per day per foot.

GENERAL PROCEDURE

It can't be stressed enough that an aquifer test is a *controlled* field experiment. Briefly, this test consists of pumping one well and recording both the drawdown in that well and the drawdown caused by this pumping in other nearby observation wells, all opened to the same aquifer. The measurements to be made during this test include the static water levels before pumping is started, the pumping rate or rate of discharge from the pumped well, pumping levels at various time intervals during the pumping period, time of starting the pump, time of any change in discharge rate, and time of stopping the pump. Measurements of dynamic water levels after cessation of pumping are also valuable for a study of the water-level recovery. Quite often these aquifer recovery tests provide better data than that collected during the pumping period.

Aquifer tests require three phases as follows: design, field data collection, and data analysis.

I. DESIGN

This phase is probably the most important but least recognized aspect of aquifer tests. The cost of an aquifer test ranges from a few hundred dollars for the least complicated to several thousands of dollars for the most sophisticated, depending on the manpower and equipment allocated to the experiment. Careful and complete data collection must follow design.

A. SITE EVALUATION

The cost of aquifer testing is frequently reduced by using combinations of production and abandoned wells rather than installing new wells. However, few existing well configurations are suitable for test purposes, and most wells are ill-equipped for observation. Evaluation of existing well facilities in the area where the test is proposed to find those wells which are potentially usable is the first step in design.

1. Control Well:

a. If it is to be pumped, the control well must be equipped with a reliable pump and power source.

Maintaining a constant well discharge is essential. The type of pump - piston, turbine, etc. - used for the test is not critical. What is important is that the pump be correctly sized for the desired pumping rate. If, to deliver this rate, the pump must operate at maximum capacity, the operator will find it difficult, if not impossible, to maintain a constant pumping rate. Maintaining a constant pumping rate will also be difficult if the pump is grossly oversized. The pump should operate at 1/2 to 3/4 its maximum capacity.

The engine or motor should also be correctly sized and be in good working order. If a gasoline or diesel engine is used, the fuel tank should have adequate capacity to last for the duration of the test, or the tank should be refueled without shutting the engine off.

b. The water discharged must be conducted away from the control and observation wells so that it cannot return to the aquifer during the test. This is of special importance in testing shallow unconfined aquifers. In general, water from the pumped well should be piped to a distance at least equal to the distance from the control well to the farthest observation well and in the opposite direction.

c. The wellhead and discharge lines should be accessible for installing discharge regulating and monitoring equipment.
Control of the pumping rate during the testing requires an accurate device for measuring the discharge of the pump and a convenient means of adjusting the rate to keep it as

nearly constant as possible. Trying to control the pumping rate by changing the pump speed is not always satisfactory. A valve in the discharge line of the pump provides the best control. There are many devices available for measuring well discharges, and it is now assumed that the well owner will arrange for the installation of a satisfactory device.

d. It should be possible to measure depth to water in the control well before, during, and after pumping. Many pumps are so tightly sealed to the casing that access to the water level in the control well is not possible. In some, the pump occupies such a large part of the casing cross-section that it is virtually impossible to lower a tape or any other measuring equipment to the water surface.

e. The diameter, depth, and position of all intervals open to or screened from the aquifer in the control well should be known, as should total depth.

A ready entrance of ground water from the aquifer to the production well must be provided. In consolidated formations (i.e. bedrock), where the material of the well wall is stable, water enters directly into the uncased portions of the production well. In unconsolidated deposits (i.e. glacial drift), a screen or perforated casing is required to hold back sand grains and to allow water to flow into the production well without the passage of fine materials during pumping. This information will identify the aquifer(s) being affected by pumping.

2. Observation Wells:

a. Response of all wells to changing water levels should be observed by injecting a known volume of water into each well and measuring the subsequent water level. The initial rise of water should be dissipated within a few minutes (to within about 0.01 foot or 1/8 inch) if the observation well is to reflect changes of water level of the aquifer during the test satisfactorily. Long abandoned or little used wells tend to become clogged, and consequently the response test is one of the most important prepumping examinations to be made if such wells are to be used for observation.

b. Total depth, diameter, and screened interval should be known for each observation well.

c. Radial distance from the control well to each of the observation wells must be determined.

The radius of the cone of depression (referred to as "R") is that distance from the control well beyond which no further drawdown is present. A typical value for R for water-table aquifers is 500 feet and for artesian aquifers, 5000 feet. Of course, R values are site specific dependent upon a wide range of variables. Installing observation wells at distances of 100 to 300 feet from the control well in an unconfined aquifier, and 300 to 700 feet in an artesian aquifer will work out best in most cases. Another point should be made about installing observation wells; these wells should be installed to about the same depth as the middle of the well screen or open hole section of the control well. Obser-vatiion wells should also be cased and equipped with screens 3 to 6 feet long - all of which can be recoverable after the completion of the aquifier test. These wells should be developed to the extent that the screens are known to be satisfactorily open to the aquifier.

3. Aquifer:

a. Depth to, thickness of, and areal distribution of the aquifer to be tested should be known.

Lithology of the control and observation wells are generally determined by interviewing the well owners and/or the well drillers. Usually the determination can then be made whether the aquifier is unconfined or artesian. The Minnesota Geological Survey, Minnesota Department of Health and Department of Natural Resources - Division of Waters are in the process of developing a well lithology log index for water wells existing in the state. U.S. Geological Survey Hydrologic Atlas information sets exist for almost the entire state. These include generalized hydrogeologic data and maps for watershed units which can be very helpful.

b. Nearby sources of aquifer interference caused by discharging wells, changes in lithology, presence of large surface water bodies, or irrigation systems should be noted. Factors which affect aquifer discharge or recharge occurring within the controlled environment created for an aquifer test must be identified before the test is begun. Efforts to minimize their interference should be initiated, i.e. discharging wells shut off, or pumped at a constant rate throughout testing period.

c. Sufficient background information on water-level fluctuations at the test site must be obtained. The changes in depth to water observed during the aquifer test may include components due to other variables such as recharge or barometric response. It is, therefore, necessary to observe depths to water for a time before testing to determine the trend of the water level for use in determining drawdowns. In many artesian wells, water levels fluctuate in response to changes of barometric pressure - sometimes as large as a foot or more in a few days.

B. TEST ORGANIZATION

When the number of people involved in an aquifer test, the amount of equipment necessary, and the number and accuracy of the prescribed measurements are considered, the need for an overall "plan of attack" becomes apparent.

1. Well Locations:

Positions of the test site with respect to a regional land-survey net (township, range, section) or in some cases, by longitude and latitude is required so that the data obtained can be effectively used to portray the regional characteristics of the aquifer. An accurate location in a cross-sectional view of observation wells, referenced to the position of the control well, is especially important in a test involving multiple aquifers, or discontinuous aquifers.

2. Equipment:

In order to obtain usable data, the proper equipment must be used for the aquifer test. Equipment necessary for conducting a basic aquifer test include devices to measure: (1) accurate elapsed time since beginning of test in minutes for each well involved in test, (2) control-well discharge, and to be able to maintain a constant discharge rate, (3) water levels in each well to nearest 0.01 foot (1/8 inch), (4) depth of each well, distance from control well to each observation well, diameter of casing, and distance of measuring point of each well from ground surface, and (5) ground water temperature. A variety of tools should be standard equipment for handling emergencies or preparing for access to wells. Often special conditions may exist where arrangements will have to be made for providing the necessary additional equipment, i.e. a jack for pulling wells, discharge pipe, radio communication equipment, pump, gate valves, flashlights or lanterns, barometer, brunton compass, installation of observation wells, etc. Simple, but complete, recording forms upon which all measurements and remarks are to be kept should be compiled at each well. These forms become part of the permanent records on ground water resources maintained by the DNR - Division of Waters. See Figures 4, 5, and 6.

3. Personnel:

During the first 2-3 hours of the test, ideally an observer should be stationed continuously at the control well and each nearby observation well. After the test has progressed about 5 hours (t=300 minutes), drawdown measurements are usually nearly 2 hours apart, and it becomes a relatively simple task for one observer to "make the rounds". Of course, when automatic continuous water-level recorders are used, personnel requirements are proportionally reduced. It is desireable to have an individual whose sole responsibility focuses on the control and operation of the control well and pump facilities.

4. Plan of Operations:

The prime coordinating factor considered in an aquifer test is one of scheduling. Division of Water personnel or its designees, the involved well owner(s), and perhaps a drilling/pumping representative must agree on a date of the test. The available background data and necessary equipment should be accumulated and transported to the test site in time so that the additionally needed background data can be collected. The observations and information needed to measure the aquifer response adequately are then determined, and field personnel should be acquainted with their responsibilities, the recording forms, and the required timing and accuracy of measurements to be collected.

If you are called upon to respond to a problem involving a ground water situation or a well complaint, a copy of "Basic Well Data" form (Fig. 7), should be sent to the person making the complaint, and after the form is completed, it should be forwarded to DNR - Division of Waters central office. Assistance in designing or implementing an aquifer test can be obtained from calling the Ground Water Group, Hydrology Section, DNR Waters, at (612) 296-4800.

II. FIELD DATA COLLECTION

The collected data required for analysis and the accuracy in measurement generally considered acceptable are as follows:

1. Control-well discharge rate [±3 percent accuracy, ±10 percent variation in rate].
2. Depth to water in wells below measuring point (±0.01 foot, or 1/8 inch).
3. Distance from control well to each observation well (±0.5 percent).
4. Time of drawdown measurement (±1 percent of time since control started).
5. Description of measuring point.
6. Elevations of measuring points (nearest 5 feet from contour maps sufficient).
7. Vertical distance between measuring point and land surface (±0.1 foot, or approximately 1 inch).
8. Total depths of all wells (±1 percent).
9. Depth and length of screened intervals of all wells (nearest foot)
10. Diameter, casing type, screen type, and date and method of construction of all wells.
11. Location of all wells in plan view, relative to land-survey net - township, range, section, and fraction of section to quarter/quarter/quarter.

A. DISCHARGE

There are several methods available for measuring the discharge from the control well. These range from simply measuring the length of time required to fill a five gallon pail (for yields of less than 200 gallons per minute) to employing a precision-built water meter. A circular orifice weir is the device used most commonly to measure relatively high flow rates.

The discharge rate should never be allowed to vary more than ±10 percent, if practicable, because such variations produce changes in drawdowns that are difficult to treat in data analysis. No matter what means of measuring the discharge rate is chosen, the control of the pumping rate should be by the use of a valve on the discharge of the pump, and the valve should be opened between 1/2 and 3/4 when test is in operation.

FIGURE 4.

Individual Well Information

Pumped Well/(Observation Well)

Well no. (U.S.G.S.)____ Recorded by SAM SOIL

Well location T104N, R53W, NW SW NW SECTION 6

Well no. (town)____

Type of aquifer SURFICIAL OUTWASH

Log available NO by ____ (see reverse)

Depth 43 FEET

Diameter 6" CASING

Length and slot size of screen 6 FOOT SCREEN; FROM 37-43'; 60 SLOT

Condition of well GOOD CONDITION, DRILLED IN 1972

Measuring point TOP OF CASING

Ground level elevation 1175 FEET

Height of MP above ground level 1.75 FEET

Method of measurement STEEL TAPE

Static water level 24.05 FEET BELOW MEASURING POINT

If Pumped Well

Type of pump and H.P.____

Discharge (Q)____

Method of measuring discharge____

Water sample____ Water temp.____

If Observation Well

Distance and direction from pumped well 208 FEET TO NORTH

Results of Test (for this well)

Drawdown time____

Recovery time____

Drawdown (ft)____

Recovery (ft)____

Specific capacity (if pumped well)____

T____ Method____

S____ Method____

P____ Method____

Boundary conditions____

Time-drawdown curve____

Distance-drawdown curve____

Estimate of accuracy of coefficient____

SAMPLE

DATA SHEET:

PUMPING WELL

OWNER Farmer Brown

LOCATION Next to shed

MEASURING POINT DATA:
Top of drawpipe, 2.3' above ground

FIELD OBSERVATIONS By Sam Soil								ANALYSIS		REMARKS
DATE 1972	TIME OF DAY	TIME SINCE START	TAPE HELD	TAPE CUT	DEPTH TO WATER	DRAW-DOWN / RECOVERY	DIS-CHARGE, G.P.M.			PROBE CORRECTION, MEASURING DEVICE USED, ETC.
8/10	6:45 pm		25'	1.73'	23.27'					Background static
8/11	7:45 A		25'	1.72'	23.28'	Static				Background static
	8:00	-0-					300			Pump start
		30 sec.	26	0.43	25.57	2.29	306			
		1 min.	28	0.79	27.21	3.93				
		2 min.	30	0.51	29.49	6.21				
		3 "	32	0.89	31.11	7.83	303			
		4 "	32	0.41	31.59	8.31				
		5 "	32	0.19	31.81	8.53				
		7 "	33	0.91	32.09	8.81				
		8 "	33	0.47	32.53	9.25	303			
		10 "	33	0.20	32.80	9.52				
		15 "	34	0.98	33.02	9.74				
		17 "	34	0.63	33.47	10.19				
		20 "	34	0.32	33.68	10.40	305			

SAMPLE

FIGURE 5.

DATA SHEET:

OBSERVATION WELL

OWNER Farmer Brown

LOCATION 100' N. of Barn

MEASURING POINT DATA: Top of casing, 1.75' above ground level

DISTANCE FROM PUMPING WELL 208 feet

FIELD OBSERVATIONS BY Sam Soil

DATE 1972	TIME OF DAY	TIME SINCE START	TAPE HELD	TAPE CUT	DEPTH TO WATER	DRAW-DOWN / RECOVERY		ANALYSIS		REMARKS: PROBE CORRECTION, MEASURING DEVICE USED, ETC.
8/10	6:55 p.m.		26	1.97	24.03					Background static
8/11	7:40 a.m.		26	1.95	24.05	Static				Background static
	8:00 a.m.	-0-								Pump on
		-1-	26	1.95	24.05	0.00'				
		-2-	26	1.95	24.05	0.00'				
		3 min	26	1.94	24.06	0.01'				
		4 "	26	1.94	24.06	0.01'				
		5 "	26	1.95	24.05	0.00'				
		6 "	26	1.93	24.07	0.02'				
		7 "	26	1.91	24.09	0.04'				
		8 "	26	1.88	24.12	0.07'				
		9 "	26	1.86	24.14	0.09'				
		10 "	26	1.83	24.17	0.12'				
		12 "	26	1.80	24.20	0.15'				
		15 "	26	1.75	24.25	0.20'				
		20 "	26	1.65	24.35	0.30'				

SAMPLE

FIGURE 6.

How frequently the discharge needs to be measured and adjusted for a test depends on the pump, well, aquifer, and power characteristics. Output from electrically driven equipment nominally requires measurements, and possibly adjustment at 5, 10, 20, 30, 60, 120, 240, 480, 720, and 1,440 minutes after the pump is started and daily thereafter. All other pumping equipment requires more frequent attention. Engines, even though equipped with automatic speed control, produce discharges that vary as much as 25-50 percent between day and night. When there is doubt about control of discharge rates, the observer should continuously monitor the pumping equipment until experience indicates drift rates, and then monitor accordingly.

The validity of the data collected during an aquifer test depends on a constant pumping rate. The sooner this rate is stabilized, the better the test. Thus, it is advisable to set the valve adjustment the day before the test.

B. WATER LEVELS

There is a variety of equipment available for measuring water levels in pumping wells and observation wells. Any method which accurately measures the water level to the nearest 0.01 foot or 1/8 inch may be used.

An electric depth gauge is probably the handiest device to use to rapidly obtain drawdown measurements in the control well. A *shielded* electrode is suspended by a pair of insulated wires and a volt meter indicates a flow of current when the electrode touches the water surface. Flashlight batteries supply the current. To get accurate readings, the electrode and cable should be left hanging in the well above the water surface between readings. This eliminates any errors from kinks or bends in the wires which may change the length slightly when the probe is pulled up and let down. The depth to water level is determined relative to a measuring point and should be measured with a steel tape, using one of the markers attached to the cable (usually at 5-foot invervals) as a reference mark.

Automatic recorders may be used on the observation wells to make a continuous record of water level changes. The casing diameter of well must be known so that the proper diameter float or probe can be obtained. Depths to water in observation wells less than 100 feet are most commonly measured with a steel tape. The lower few feet of the tape is wiped dry and coated with blue carpenter's chalk and lowered a foot or so below the water level in the well. A convenient even-foot marker on the tape is held opposite the measuring point (at or near the top of the casing) for a fraction of a second. The elapsed time is noted, and the tape is reeled out of the well, and the length of tape wetted is precisely recorded along with the elapsed time. The wetted-length is subtracted from the value of the even-foot marker held on the measuring point to find the depth to water. A disadvantage of this method is that the approximate depth to water must be known so that a portion of the chalked section is submerged each time to produce a "wetted line". The wetted tape method is impractical for measuring water levels in the control well. Rapid measurements spaced 30 seconds apart are needed at the start of the test, and this speed may not be possible with a steel tape. Also, turbulence produced near the pumping level plus leakage from the column pipe above will tend to wet the tape throughout its length and obscure the point where the actual water surface wets the tape.

C. TIME OF DRAWDOWN MEASUREMENT

The exact time that the test begins must be recorded. A system of notifying personnel stationed at each observation well that the test has started should be developed. It is not necessary that drawdown measurements in all observation wells be made at exactly the same instant. It is necessary, however, that the time of measurement with respect to the time since pumping started be known. Therefore, all watches being used to time measurements should be synchronized prior to the start of pumping.

FIGURE 7.

BASIC WELL DATA

Please record information only when you are certain of answer. Contact the DNR-Division of Waters at (612) 296-4800 if you have questions.

Well Owner FARMER BROWN Phone Number (602) 123-4567

County	Township	Range	Section	Fraction Section	Minnesota Unique Well Number
FOREMAN	104 North	53 West	6	NW¼ SW¼ NW¼	

Name of Drilling Co. IRA MUDD AND SON, WATERVILLE, MN.

Date Drilling Completed: JULY 30, 1972

Well Depth When Drilled: 43 feet

Use of Water IRRIGATION (home, stock, irrigation, etc.)

Ground Elevation of Well, Above Mean Sea Level 1175 feet

On reverse side of sheet, show exact location of well in grid section with an "X".

Casing: Type: STEEL PIPE (Tile, concrete, steel pipe, etc.)

Diameter (if more than one, use second line):
6 inch set to 37 feet depth
____ inch set to ____ feet depth

Screen: Yes [X] or No, instead there is an open hole, [ ]

from ____ feet to ____ feet

Make HERCULES
Type WATERFLOW
Slot/Gauze 60 SLOT
Set Between 37 feet and 43 feet,
and ____ feet and ____ feet.

Diameter 6"
Length 6 FOOT

Amount of Water Pumped ____ gallons/day

Pump: Date Installed AUGUST 5 1972 Manufacturer Name HUGO

Length of drop pipe ____ Pump Capacity 500 gallon per minute

Type - Submersible [X]
Jet [ ]
Other [ ] ____
Reciprocating [ ]
Centrifugal [ ]

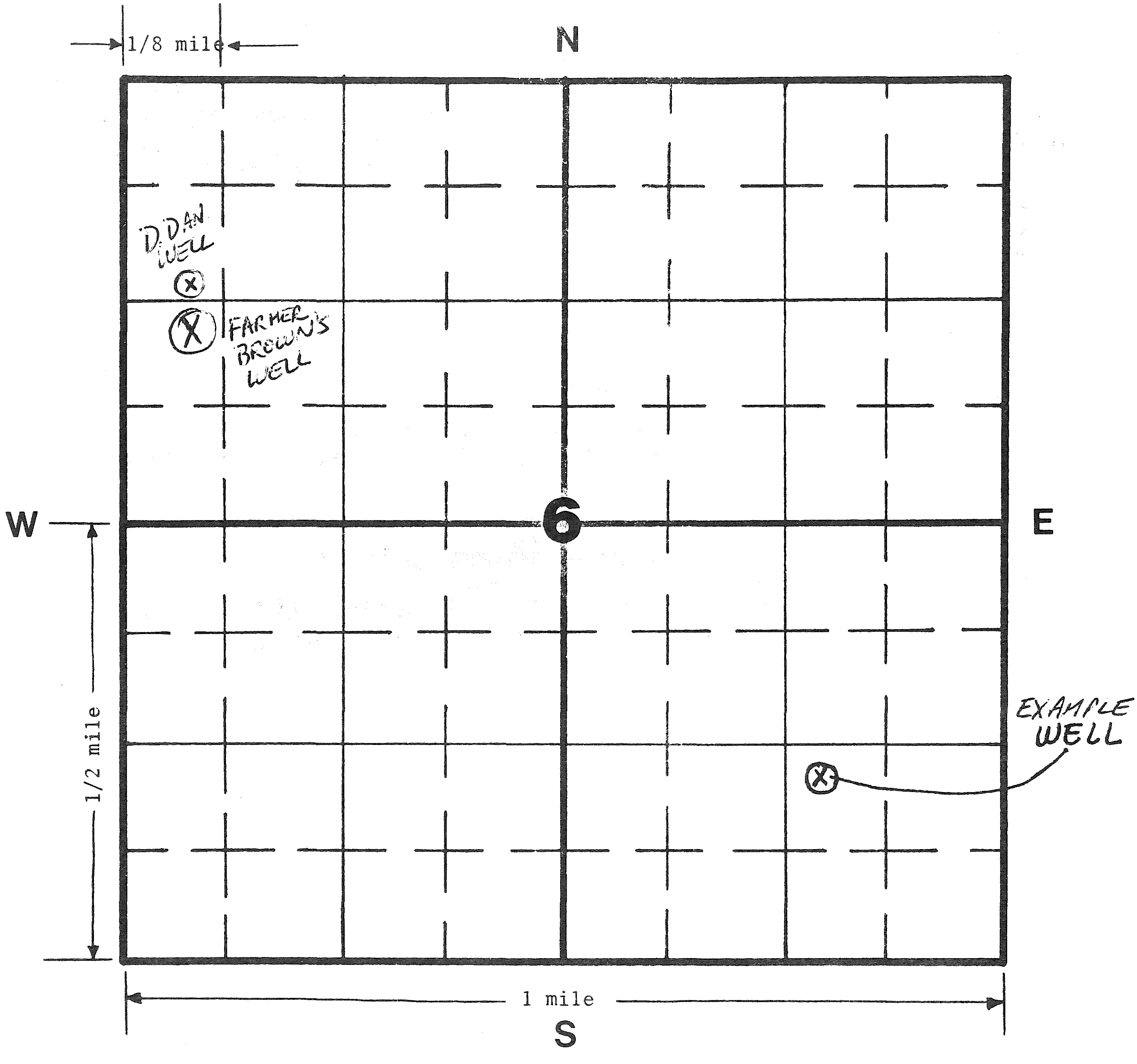
Non-pumping Water Level Below Surface 23 feet, or is well flowing [ ].
Date Measured JULY 30, 1972

Pumping Water Level Below Land Surface:
36 feet after 7 hours/~~minutes~~ pumping at 300 gpm.
____ feet after ____ hours/minutes pumping at ____ gpm.

Depth of Well Last Measurement 43 feet at 4/77 date
Method of Measurement: STEEL TAPE

SAMPLE

This is a section, one mile by one mile. The thickest lines outline 1/4 sections, the thin lines outline 1/4 of the 1/4 sections, and the thin dashed lines outline 1/4 of the 1/4 of the 1/4 sections.



Note: Indicate your well to the nearest 1/4, 1/4, 1/4, section by an "X". Grid equals one complete section. For example, the well already indicated is in the NW1/4 of the SE1/4 of the SE1/4 of this section.

SECTION 6

COMPLAINT SECTION

Attach any additional sheets, sketches, and maps needed to explain problem.

1) Explain the type of problem you have been experiencing, and when it started. Include any changes in the non-pumping water levels which have been observed, and when? MY STATIC WATER LEVEL HAS BEEN 23 FEET; BUT NOW SINCE MY NEIGHBOR DIRTY DAN DRILLED HIS IRRIGATION WELL JULY 1977, MY STATIC WATER LEVEL IS 30 FEET AND MY PUMP SUCKS AIR WHEN I TURN IT ON MORE THAN 5 MINUTES.

2) Do you feel the problem has been caused, at least in part, by the operation of a nearby high capacity well? If yes, who is the owner of the nearby well (or wells), how far is it from your well, and where is it located (describe location of the well to the nearest 40 acre tract within the appropriate Section, Township number, Range number and County.

SURE DO. DIRTY DAN'S IRRIGATION WELL IS 400 FEET NORTH OF MY WELL IN THE SW NW NW SECTION 6, T104N, R 53W. HIS WELL IS DRILLED TO A DEPTH OF 48 FEET.

3) What have you done to correct the problem? What was the cost?

NOTHING YET, BUT I'LL PROBABLY HAVE TO DEEPEN MY WELL.

4) Has a well driller or plumber inspected your well? If yes, list name and analysis of your problem.

YES, IRA MUDD CHECKED MY WELL LAST WEEK AND FOUND MY SCREEN TO BE CLEAN AND PUMP RUNNING GOOD.

5) Have any of your neighbors experienced similar problems? If yes, state their names, addresses and phone numbers.

NO. MY NEAREST NEIGHBORS ARE 3 MILES AWAY.

NAME F. BROWN

ADDRESS COUNTY RD. 6

FOREMAN CO, MINN.

PHONE NUMBER (602) 123-4567

*Be sure to provide as much information as possible about your well in the "Basic Well Data" Section. This will help investigators determine the cause of your problem.

Depth to water in all wells should be measured with sufficient frequency so that each logarithmic cycle in time on the data analysis plots contains at least 10 data points spread through the cycle. By examining the semi-logarithmic plot in Figure 8, it can be seen that the space covered by 0.1 minutes to 1.0 minute is the same as from 1.0 minute to 10 minutes, 10 minutes to 100 minutes and so on. Thus, after pumping starts (at t=0), depths to water should be measured in each well, as possible, at t= 1, 1.2, 1.5, 2, 2.5, 3, 4, 5, 6, 7, and 8 minutes, approximately and at all succeeding decimal multiples of these numbers (i.e., 10, 12, 15, 20 ... and 100, 120, 150, 200 ... minutes) to the end of the test. If the early measurement trends at observation wells indicate that measurable drawdown is not expected for a long time, the remaining early measurements may not be necessary.

When a confined (or artesian) aquifer is being pumped, the radius of influence expands quite quickly; therefore, a pumping period of 24 hours is usually considered adequate to reveal any significant recharge or barrier conditions. Since the radius of influence expands somewhat more slowly in an unconfined aquifer, a pumping period of 72 hours might be required to intersect any significant boundaries. In some cases, where the drawdown in all the wells does not increase anymore with time, the pumping may be terminated within an hour after such stabilization has occurred.

D. MEASURING POINTS

The measuring point at each well is a reference point, and as such, should be stable. More than one observer is generally employed on pumping tests, and unless measuring points are clearly described and recorded on observation sheets, each observer is likely to find and use his own. The vertical distance between the described measuring point and ground surface should carefully be measured and recorded.

E. RECOVERY PORTION OF AQUIFER TEST

So far, emphasis has been placed on the test design and collection of data obtained during the portion of an aquifer test when the control well is actually yielding water. When pumping of a well is stopped, water levels in the well and the aquifer recover from their dewatered condition toward their original pre-pumping levels. These measurements of the recovery rate of the water level after the pump has been shut off are as important as drawdown measurements. The rate at which recovery occurs provides a means for calculating T and S for the aquifer.

Theoretically, the analysis of time-drawdown measurements and time-recovery measurements should provide comparable results for the determination of aquifer characteristics. However, for recovery measurements to be valid, the pumping portion of the aquifer test must have been conducted at a constant pumping rate. Recovery measurements following a variable rate test, such as a "step-drawdown" test, cannot be utilized.

During the recovery portion, water level measurements are more reflective of true aquifer conditions because variations or disturbances from pumping have been eliminated. Where at least one observation well within a reasonable distance of the control well is available, the water level recovery data from that well fully reflects the hydraulic characteristics of the aquifer. Where no observation well data is available, the water level recovery data from the pumped well can be used for limited calculations of aquifer capabilities. One observation well, however, should be provided if at all possible.

The exact time at which measurements are made in the pumped well and the observation wells during the recovery portion must be noted. Frequency of measurements follows the same design as when a pumping portion begins. Readings should be taken until the wells have recovered to their static level, or until they have apparently stabilized. The return to static water level requires a recovery period considerably longer than the previous pumping period, except in cases where recharge to the aquifer occurs during the pumping and recovery periods.

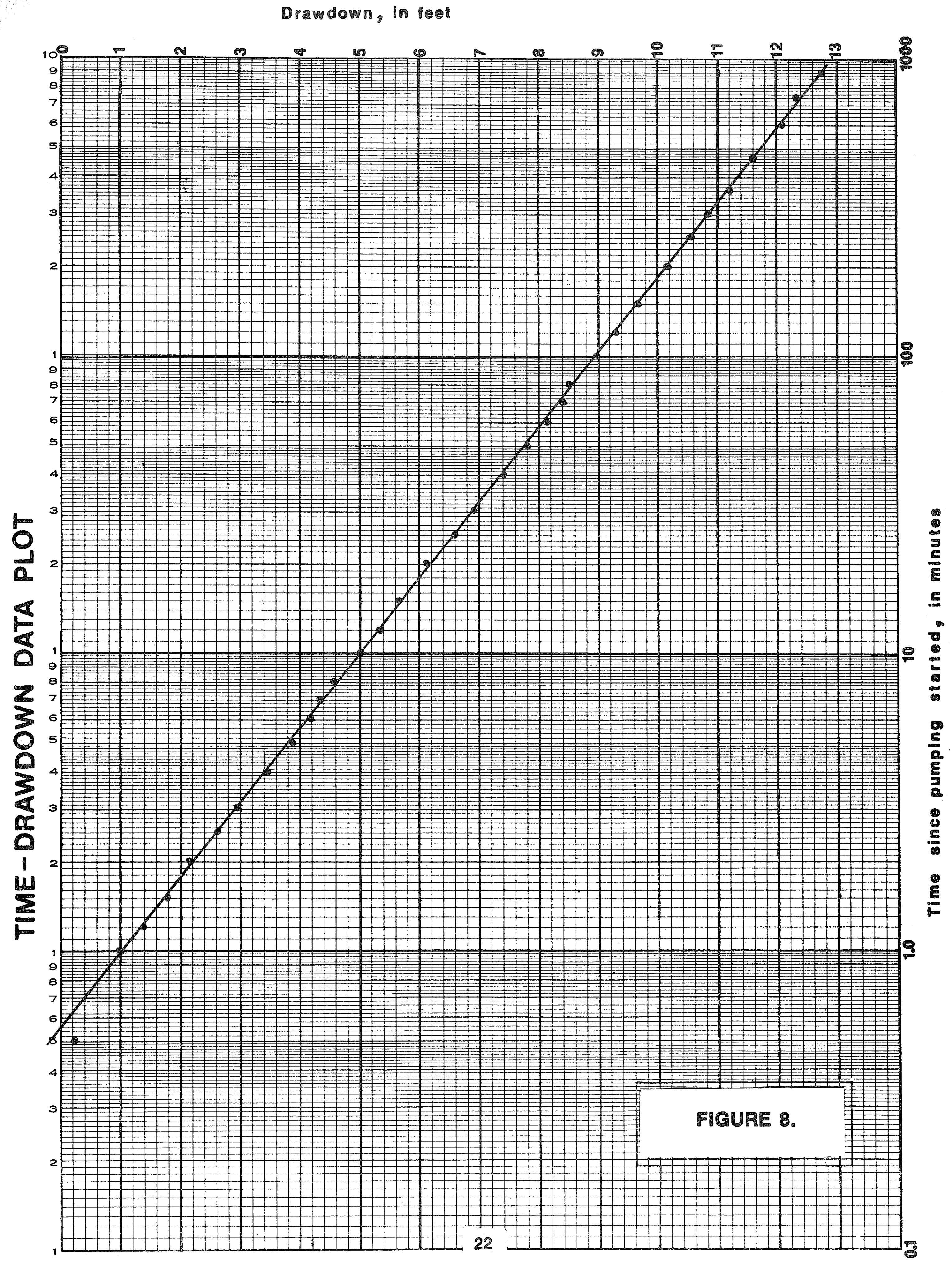

TIME-DRAWDOWN DATA PLOT
Drawdown, in feet
Time since pumping started, in minutes
0 1 2 3 4 5 6 7 8 9 10 11 12 13
0.1 1.0 10 100 1000

FIGURE 8.

F. ASSOCIATED OR POTENTIAL PROBLEMS

1. Equipment Malfunction:

Test all equipment before commencing test. Always bring extra batteries for electric recording devices and flashlights. It is essential that the contact probes on electric water level devices be inspected periodically to make sure waterproof connections are still intact. If pump develops major problems in early phase of test, test should be terminated and rescheduled.

2. Wells not Sufficiently Developed:

It may sometimes be noticed that in a pumped well, the pumping water level rises slightly as time passes. This almost always indicates that the well is developing and becoming more efficient. This phenomenon is unusual in screened wells as they are generally already developed and stabilized before test pumping begins. Bedrock wells, on the other hand, show this effect more commonly, as cracks and crevices are flushed by water moving toward the well.

3. Restarting an Aquifer Test:

If for any number of reasons an aquifer test has to be terminated prematurely and then restarted, the water levels in the control and observation wells must be allowed to recover to as near their static water level condition as possible.

III. DATA ANALYSIS

Copies of all field notes, maps, diagrams, and time-drawdown measurements should be mailed to:

Ground Water Group
DNR - Division of Waters
444 Lafayette Road
St. Paul, Minnesota 55101

Data analysis involves chiefly the transformation of raw field data into calculated values of hydraulic coefficients. A variety of techniques exist for analyzing the collected data. Formulas and analyzing techniques are all based on the following assumptions:

1) The water-bearing formation is uniform in character and permeability in both horizontal and vertical directions.
2) The formation has uniform thickness.
3) The formation has infinite areal extent.
4) The formation receives no recharge from any source.
5) The pumped well penetrates and receives water from the full thickness of the water-bearing formation.
6) The water removed from storage is discharged instantaneously with lowering of the head.

   Furthermore, other formulas require additional assumptions:
7) The pumping well is 100 percent efficient.
8) Neither the water table nor piezometric surface has any slope; both are horizontal surfaces.
9) The cone of depression has reached equilibrium so that both drawdown and radius of influence of the well do not change with continued time of pumping at a given rate.

As you can imagine, these assumptions would appear to severely limit the use of formulas based on them, but in reality they do not.

GLOSSARY

AQUIFER - A geologic formation, group of formations, or part of a formation that will yield sufficient water to be considered a source of supply.

BEDROCK - Consolidated or semiconsolidated rock formations or parts of formations that crop out at the land surface or underlie the glacial drift.

CONFINED - Water in an aquifer that is overlain by a layer of lower permeability. The water is under sufficient pressure to rise above the base of the confining layer in a well or open hole. Synonym: artesian condition.

DISCHARGE - Water removed from the saturated zone. Natural discharge includes flow to surface-water bodies, evaporation, and transpiration. Pumping from wells is artifical discharge.

DRIFT - A catchall term that includes all the rock materials that were deposited by continental glaciers. (Four such glaciers covered parts of Minnesota.) Drift is composed of stratified and nonstratified materials ranging in size from clay to boulders.

GROUND WATER - Subsurface water in the saturated zone. The saturated zone contains water under pressure equal to or greater than atmospheric. See WATER TABLE.

ICE-CONTACT DEPOSITS - Stratified and semistratified drift, largely composed of sand to boulder sizes, with one or more sides of the deposit having been in contact with standing walls of glacial ice.

LITHOLOGY - The scientific study of rocks. As used in this report, it is the rocks or makeup of rocks in the earth's crust.

MORAINE - A topographic feature in glaciated terrane. End (or terminal) moraines are nearly continuous ridges or belts of generally rugged topography built up at the terminus of a glacier. Ground moraines are extensive deposits having gently undulating surfaces, and are composed mostly of till.

OUTWASH - Stratified drift deposited by melt water flowing from a glacier. It is mostly sand and gravel, but clay to boulder sizes may be included.

POTENTIOMETRIC SURFACE - The surface that represents the nonpumping water level in an aquifer. It is the level to which water will rise in tightly cased wells. The water table is a particular potentiometric surface.

RECHARGE - Water added to the saturated zone; the main source of recharge is precipitation.

SATURATED ZONE - That part of the earth's crust beneath the deepest water table. All openings in rocks (into which water may percolate) in this zone are, ideally, filled with water under pressure greater than atmospheric.

TILL - A heterogeneous mixture composed of sand to boulder sizes imbedded in a silty clay matrix and deposited directly from glacial ice.

UNCONFINED - Water in an aquifer connected with the atmosphere either directly or through the unsaturated zone above the water table. Synonym: water-table condition.

UNSATURATED ZONE - That part of the earth's crust between the land surface and the deepest water table. Generally, water in this zone is under pressure less than atmospheric. Some of the rock openings may contain air or other gases at atmospheric pressure. Beneath flooded areas or in perched water bodies, the water pressure locally may be greater than atmospheric.

WATER TABLE - The surface in the ground at which the water pressure is atmospheric. The water table is the surface of the saturated zone.