HYDROGEOLOGY OF A SUBSURFACE RADIOACTIVE WASTE MANAGEMENT SITE IN A SHALLOW GROUNDWATER FLOW SYSTEM

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ABSTRACT

The hydrogeologic properties of a shallow subsurface radioactive waste management site were studied by means of test drilling, aquifer performance testing, hydraulic head and major ion distribution studies, and radiotracer monitoring. The study area is located at the Whiteshell Nuclear Research Establishment 65 miles northeast of Winnipeg, Manitoba and includes a site where radioactive wastes are stored at depths up to seventeen feet below ground surface. The most hazardous wastes are isolated in subsurface concrete or steel containers from which leakage is unlikely. The groundwater zone is regarded as an extra containment medium in the event of leakage.

Field duties conducted during the investigation indicate that the general flow system has not varied significantly over the last four years. The analysis of data obtained during this four-year period and the installation of additional wells and piezometers in the study area were used to define the anomalies in the flow system. These flow gradient anomalies alter the expected direction and/or rate of groundwater flow. Hydrochemical patterns corroborate the groundwater flow pattern indicated by hydraulic head distributions.

Groundwater flow rates and residence times were determined for a portion of the confined sandy aquifer in the study area. Flow rates were calculated using the observed hydraulic gradients, an average effective porosity, and hydraulic conductivities obtained through

analysis of aquifer performance pumping tests. Water-level drawdown response tests provided general conductivity values. Monitoring of a radiotracer injected into the aquifer allowed direct measurement of groundwater flow velocities.

The feasibility of hydrogeologic manipulation of a groundwater flow system was proven. Manipulation schemes were suggested which would involve the pumping of water from or into basal sand deposits in the study area. This method was used to reverse the hydraulic gradient in a portion of the Whiteshell Nuclear Research Establishment Waste Management Area. Staggered groundwater migration paths induced by controlled pumping were suggested. To increase the flow gradient and allow earlier withdrawal of the contaminant from the flow system, pumping water into the basal sand aquifer was also considered.

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Test drilling was conducted under contract by Mobile Augers and Research Limited of Edmonton and Great Plains Augering Limited of Saskatoon. Well construction was done by the Prudin Drilling Company of Selkirk, Manitoba.

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TABLE OF CONTENTS

Page

Page

LIST OF FIGURES

Figure		Page

Figure | Page

INTRODUCTION

Scope and Objectives

The Whiteshell Nuclear Research Establishment (WNRE) located in southeast Manitoba (Fig. 1) includes one of Canada's two major radioactive waste management areas. Hydrogeologic studies of the WNRE general study area and the Waste Management (WM) Area began in 1968. Field studies continued through to the end of 1972.

This thesis describes the results of field studies conducted at the WNRE between May, 1970 and September, 1971. The thesis primarily deals with the detailed stratigraphy of the present WM Area. Included are the design and installation of a well network in the WM Area and the testing of the hydraulic behaviour of that area under pumping conditions. The study is one of the very few detailed investigations of small, shallow groundwater environments to be conducted in western Canada. Analysis of the data was used to determine the conditions by which the groundwater zone can be manipulated to obtain hydrogeologic containment if radionuclide contamination were to occur. The study involved the evaluation of hydraulic head distribution, groundwater chemistry and temperature data, and tritium tracer data. A major portion of these data were obtained from instrumentation installed by previous investigators. The continued collection of field data resulted in a more detailed interpretation of the groundwater flow system than was previously possible.

Description of the Study Area

The general study area is a four square mile tract located along the Winnipeg River about 75 miles northeast of Winnipeg (Fig. 2). The Waste Management Area lies within the general study area and is approximately 0.03 square miles in area. Figure 3 is a photograph of a portion of the study area and the perimeter and installations of the WM Area.

Pleistocene glacial and glaciolacustrine deposits comprise this study area. The deposits overlie the Precambrian erosion surface of the western Canadian Shield. In general the area is one of low relief and swampy ground. A sandy rise approximately 1500 feet east of the WM Area produces an elevation difference of approximately 20 feet relative to the adjacent western lowlands (Fig. 4). The relief varies between 840 feet above sea level at the Winnipeg River to 906 feet in the sandy uplands.

Reimer (1970) describes the climate of the area as having an annual mean daily temperature of approximately 35° F. Temperature extremes of -53.5° F and 108°F have been recorded. Beswick (1971) reports a precipitation mean of 20 inches per year. The greatest amounts of precipitation have been observed during late spring and early summer.

Existing Waste Management Practices

The Waste Management Area is a 500 by 400 foot site where solid and containerized liquid wastes having low, intermediate, and high levels of radioactivity are retained. Low, intermediate, and high levels of activity are descriptions of nuclear wastes depending upon the volume of material involved and the amount and forms of radionuclides present. The wastes are deposited and stored in various containers and trenches in the Pleistocene deposits at depths up to 17 feet below ground surface. Storage and disposal facilities consist of concrete bunkers, reinforced concrete standpipes, open trenches which are covered after filling, and two 100 gallon stainless steel tanks (Fig. 5).

Solid wastes having a low level of radioactivity consist of cloth and papers irradiated through accidental spills and dry wastes from the research facilities. Disposals of such packaged and dry wastes are in unlined trenches excavated in the surficial clay of the Waste Management Area (Fig. 6). After filling, the trench is covered with the previously excavated material. Liquid wastes consisting of very low-level activated organic coolants and associated solvents are stored above ground in mild-steel cans for short periods and then incinerated.

Solid and liquid wastes of intermediate- and high-level activities are defined as special disposals and are placed in concrete bunkers or asphalt-lined reinforced concrete standpipes. Special disposals consist of dry wastes having an intermediate level of activity, bottled radioactive liquids, and experimental-loop ion exchange columns and filters. Figure 7 is a photograph of the reinforced concrete standpipes. The standpipes vary from 18 to 36 inches in diameter and average 10 feet in depth. The bunkers are divided by vertical concrete walls.

Most acidic liquid wastes having a high level of activity result from fuel reprocessing experiments. They are stored at the Waste Management Area in 2-litre flasks encased in mild and stainless steel cans surrounded by vermiculite. The vermiculite is a safety feature providing absorption and an ion exchange capacity of approximately 0.7 milliequivalents per gram (Burns, 1960).

Future containment of strongly acidic irradiated liquors at the WM Area will be in two 100 gallon stainless steel tanks set at about 15 feet below ground level and equipped with fluid-level sensors and intake and outlet piping. The tanks are double-walled and set in concrete. Figure 8 is a photograph of the above-ground feed and sensor lines and protective bunker.

The WNRE Health and Safety Division considers the groundwater flow system only as a secondary line of defense in the containment of these radioactive wastes. It is appropriate to regard the hydrogeologic environment in the WM Area as a containment medium. The type and degree of the containment is the focus of this thesis.

PREVIOUS INVESTIGATIONS

Shawinigan Engineering Limited (1960) supervised the preliminary geologic assessment of the Whiteshell Nuclear Research Establishment (WNRE). Aggregate availability studies and laboratory permeability tests were carried out by Templeton Engineering Company Limited (1960). Shelby-tube and split-spoon samples were obtained and two $1\frac{1}{2}$-inch diameter well points were installed in the general study area. The wells are now either abandoned or plugged. Little of the information gathered at that time was of use in the present investigation.

Geophysical Engineering and Surveys Limited (1960) conducted a seismic profile in the southern portion of the study area. This work indicated a broken rock/bedrock contact. This has subsequently been shown to be the overburden/bedrock contact.

Parsons (1963) examined the WNRE reactor building excavation. Groundwater flow had developed in a fractured area in the southeast corner of the excavation. A flow of 5 to 10 gallons per minute was observed to move upward from the fracture. Sumps and drainage ditches were recommended.

Charron (1964) conducted a brief groundwater study in the vicinity of the WM Area. His study consisted only of surface observations of the terrain conditions and three shallow testholes bored by a small portable auger. He did not obtain sufficient data to describe the major stratigraphic characteristics of the area or the properties of the groundwater flow system.

Lund (1967) conducted a shallow radiotracer injection experiment at a site adjacent to the WM Area. The results indicated anomalously high groundwater flow velocities. This to some extent prompted a much more detailed hydrogeologic study of the area which began in the spring of 1968. This study was undertaken by faculty and graduate students of the University of Manitoba.

Mills and Zwarich (1970) described the cation exchange potentials in the study area. Soil samples were collected at depths up to 30 feet from five boreholes in the WM Area.

The Department of Earth Sciences undertook a comprehensive hydrogeologic investigation of the general study area in 1968. The groundwater flow system was instrumented with auger-installed piezometers and water-table wells (Fig. 9). Three radiotracer injection sites were installed. The results of field studies conducted during 1968 and 1969 were described by Beswick (1971) who collected water-level data and began the tritium tracer monitoring programme. Beswick also conducted a number of piezometer response tests and groundwater temperature observations.

Chagarlamudi (1971) conducted seismic and surface resistivity profiles along the east/west and north/south roads in the area. The bedrock depths determined by Chagarlamudi were used in the preparation of this thesis.

Papers by Cherry, et al. (1970 and 1971) and Cherry (1972) have described the geochemical processes in the groundwater zone and the properties of the various segments of the groundwater flow system in the area.

The continuation of field data collection during this study made possible a comprehensive view of the long-term flow system behaviour. Up to four years of recorded data were available.

METHODS OF INVESTIGATION

Drilling and Sampling

During the thesis investigation 27 piezometer nests were installed in the study area. They were placed in areas unaccessible to the equipment used by previous investigators. This brought the piezometer network to a total of 67 piezometer nests, or approximately 240 individual piezometers and water-table wells (Fig. 9).

The piezometers were constructed of 0.07 foot inside diameter polyvinylchloride piping hand-slotted at the bottom three feet. A fiberglass wrap served as a screen in the intake zone. Construction details are shown in Figure 10. Most of the piezometers were placed in boreholes drilled by an auger mounted on a tracked vehicle. Seven of the piezometers and piezometer nests were installed in boreholes drilled by a truck-mounted auger. The auger flights were four to six inches in diameter; both solid- and hollow-stem augers were used. Washed silica sand was placed about the piezometer intake area which was then isolated from overlying units by a concrete seal placed immediately above the slotted length. During the piezometer installation disturbed soil samples were collected from the auger flights; an error of ± one foot in the well log intervals is assumed.

Five screened wells were installed in the WM Area in 1971 using a truck-mounted cable tool drill. Both suction and dart-valve bailer sampling were used as well as split-spoon coring. Detailed stratigraphic information in the WM Area was obtained.

Design and Installation of Wells

Four of the five screened wells installed encircle the WM Area while one well is set at its centre (Fig. 11). A 6-inch diameter water-table well was installed in a borehole adjacent to each screened well. The screened wells and water-table wells are of a large enough diameter to receive continuous chart water-level recorders. However recording well RW-2 is 2-inches in diameter as opposed to the 4-inch casings of the four remaining wells. The 2-inch piping and sand point were placed inside the outer 4-inch service casing and the casing pulled. All wells except RW-2 were equipped with Johnson stainless steel well screens telescoped into position inside the well casing. The well screen slot sizes were selected on the basis of cumulative weight percentages of sieved formation samples. Figure 12 shows some of the construction aspects of the five wells. Figure 13 is a photograph of the multi-slot screen used in well RW-5.

Pumping Tests

Three aquifer performance tests were conducted in 1971 using wells RW-1 and RW-3. This involved the pumping of either well while water levels were measured in the adjacent water-table wells, screened wells, and piezometers of the immediate area. Measurements were continued after pumping stopped until recovery of the piezometric level was at least 85 per-cent complete. By evaluating the rates of drawdown and recovery in the pumped well and observed wells, the hydraulic characteristics of the aquifer underlying the WM Area were determined. The aquifer performance tests provided transmissibility values and storage coefficients for the area within drawdown effect.

RW-1 was pumped at 1 gallon per minute for 21.0 hours with a maximum distance of hydraulic head interference of approximately 650 feet. RW-3 was pumped at 9 gallons per minute for 10.5 hours with a maximum distance of hydraulic head interference of approximately 1000 feet. The pumping of RW-3 created the greatest drawdown effects in the basal aquifer underlying the WM Area.

Prior to each test a centrifugal-jet pump was installed above ground with the pump intake immediately above the screen. A direct reading discharge meter was attached to the gate-valve controlled discharge line (Fig. 14). A trailer-mounted generator supplied the electrical power. The discharge was checked by the rate meter and by simple bucket measurements. Drawdown and recovery in the observation wells were measured by electric tape and by Stevens Type F continuous-chart water-level recorders. An electric tape was used to measure drawdown in the pumping well. Figure 15 shows the equipment used in the RW-1 pumping test.

<u>Water-level Drawdown Tests of Piezometer Response</u>

A second method used to determine the hydraulic characteristics of the deposits in the study area was a bail-down response test for piezometers which was developed by Hvorslev (1951). Each piezometer was flushed and bailed prior to the water-level drawdown response tests. This reduced the effect of possible plugging at the piezometer tip. Each piezometer was then bailed to a depth sufficient to allow a succession of recovery measurements. Measurements of the recovery water levels continued until at least 90 per cent of the original water level was observed.

A recovery ratio in terms of hydraulic head in feet was determined for each piezometer following bail-down. Using the rate of recovery, the hydraulic conductivity of the formation immediately surrounding the piezometer intake area was determined. Ninety per cent of all the piezometers were tested; thus, approximately 190 individual response time graphs were drawn and analyzed.

Monitoring of Piezometer Network

In order to define the hydraulic gradients of the study area, water levels were measured in each piezometer beginning in 1968. The continuance of this data collection has provided a longer record of the behaviour of the groundwater flow-system than was available to earlier investigators.

Using the water-level data collected in 1970 and 1971, a better areal coverage of the flow system was possible. This also allowed a more comprehensive description of the system based on a longer period of hydraulic head recordings.

Groundwater Chemistry Analyses

Water samples were collected from the intake zone of each piezometer using a polypropylene sampling tube and a vacuum pump. The samples were isolated from the atmosphere on removal to the surface and sealed in polypropylene bottles.

Field pH measurements were made using the Radiometer null-balance pH meter, model pHM-4. Groundwater samples were collected from the piezometer intake zone through a polypropylene sampling tube. Each sample was transferred directly to a sample bottle immersed in an ice-water bath. Constant pH buffer solutions were used in the field for calibration and determinations. Down-hole electrolytic conductivity was determined using an extended cable Solubridge conductivity cell and meter, model B3-338. The conductivity probe was lowered to the piezometer intake zone; electrolytic conductivity was measured in micromhos per cm.

Measurement of Groundwater Temperatures

The groundwater temperature at each piezometer was measured using a Whitney extended-cable thermistor, model TC-5A. The temperature cell was lowered to the piezometer intake zone and allowed to adjust to the down-hole temperature. All readings were measured with a precision of 0.01° C.

Sampling of Tritium Injection Sites

The three tritium injection sites located in Figure 9 were monitored for a period of two years. Beswick (1971) discussed the first six months of injection site monitoring. No significant movement of the injected tritium was observed at that time. This thesis describes the results of the last $1\frac{1}{2}$ years of monitoring.

Samples collected from the injection site piezometers were analyzed for tritium content using a Nuclear Chicago Mark IV liquid scintillometer. The samples were obtained using down-hole polypropylene sampling tubes and standard 250 millilitre vacuum flasks. A portable vacuum pump was brought to the field during sampling. Each injection site piezometer was equipped with a permanent tube and flask unit. These units were either totally or partially replaced in 1971 following bailing and flushing of the injection site piezometers.

STRATIGRAPHY

General Study Area

A lacustrine clay, lacustrine silt, clay-loam till, and beach and nearshore sand and gravel comprise the surficial units of the study area (Fig. 16). The basal sandy drift and a portion of the uplands sand and gravel comprise the basal sand aquifer. The bedrock is Precambrian granite.

The lacustrine clays and silts and clay-loam till overlie the basal sandy drift in the western half and southeastern section of the study area (Figs. 17 and 18). The upland sands and gravels in the northeast thin westward grading into the basal sandy drift. The basal sandy drift consists of medium and poorly sorted, clean to silty, fine sands and gravels. Thin clay and silt interbedding has been observed. The basal drift is equivalent to the Belair Drift described by McPherson (1968).

The basal sand aquifer consists of two stratigraphic units: the basal sandy drift west of the uplands high and the beach and nearshore sands and gravels between piezometer nests P-21 and P-22 (Fig. 17) which grade southward into the basal drift. The sand aquifer is confined by the less permeable overlying clay-loam till and impermeable granite bedrock. The thickness of this sandy two-part aquifer is shown by the isopach map of Figure 19. The determination of thickness and lithologic variation of the basal aquifer is an important feature of this thesis work.

Geologic cross sections A-A' and B-B' (Fig. 17 and 18) are based on drill logs obtained during installation of piezometers and wells between 1968 and 1971. The logs are described in Appendix A.

Bedrock Surface

Bedrock in the study area is a relatively impermeable Precambrian granite. In the general area outcrops along the Winnipeg River and exposures along access roads to the WNRE site show no open fractures. Templeton Engineering Company Limited (1960) described the bedrock which outcrops northeast of the area as a "dense, pink granite with occassional mafic zones". Parsons (1963) reported that a small portion, approximately 16 square feet, of the total bedrock surface exposed at the WNRE reactor building excavation appeared to be fractured (Fig. 20). The remaining exposed bedrock, approximately 10,000 square feet, was solid and relatively smooth.

The bedrock surface contours of Figure 21 were prepared from the geologic logs described earlier and the seismic and resistivity profiles of Geophysical Engineering and Surveys Limited (1960) and Chagarlamudi (1970).

Waste Management Area

Split-spoon cored samples of the stratigraphy in the WM Area were collected during cable-tool drilling in 1971.

Figure 22, a generalized three-dimensional stratigraphic cross section, was constructed from the geologic logs of these drillholes. Some stratigraphic information was obtained from the borehole sampling carried out during earlier piezometer installations in and near the WM Area. Figure 23 shows the lithologies and facies indicated by these test-drilling programmes. Appendix A lists the geologic logs of the large diameter screened wells installed in 1971.

Surficial units in the immediate vicinity of the WM Area consist of 8 to 10 feet of dark grey lacustrine clay and another 10 feet of clayey silt-till. Complexly interbedded and texturally varied sands and gravels comprise the basal sandy drift which underlies this silt-till. The average thickness of the basal sandy aquifer is 20 feet. Figure 24 is a photograph of a typical cored section from the basal sandy drift.

GROUNDWATER FLOW SYSTEM

Hydraulic Head Distribution

Water-level data recorded from the WNRE piezometer network between 1968 and 1972 allowed a long-term re-evaluation of vertical recharge and discharge gradients and lateral flow movements. This re-evaluation of head distribution supports the interpretation of Beswick (1971) for the portion of the system instrumented during his investigation. A general stability of the flow system is indicated.

Figure 25 shows the water levels recorded in the basal sandy aquifer and the uplands sand and gravel. Figure 26 shows the configuration of the water table. The zones of recharge, discharge, and transition were delimited (Fig. 27) after comparing the basal sand and water table head distributions.

Recharging flow gradients occur where the water levels in the basal sand aquifer are lower than that of the water table. Groundwater moves downward towards the basal sandy aquifer under the influence of this hydraulic gradient. Groundwater moves upward where the water level or hydraulic head in the basal sands is greater than that of the water table. Discharging vertical gradients occur where groundwater moves in this upward direction. Transition zones exist where the hydraulic heads of both the water table and basal sandy aquifer are equal.

Figure 25 shows lateral east to west groundwater flow in the basal sand aquifer. A slight northeast to southwest lateral movement from the northcentral portion of the study area joins this flow near the WM Area.

Though the principal lateral flow is to the Winnipeg River, a portion is directed northward by the hydraulic head "low" immediately adjacent to the western transition zone. A major portion of the groundwater flow which moves laterally beneath the WM Area is directed away from and parallel to the Winnipeg River by this "low". Groundwater residence time in the area of anomalous head distribution is significantly increased.

The head distribution in the basal sandy aquifer is influenced by stratigraphic variation. Geologic cross section B - B' (Fig. 18) shows that the basal sandy drift thins beneath the less permeable overlying till. Hydraulic head in the basal drift becomes higher than that of the water table. The head decreases as groundwater moves beneath the central discharge area into the western transition zone. The head in the basal sandy drift is then lower than the water table; a recharging hydraulic gradient is established. Lateral groundwater flow continues to a final discharge zone at the Winnipeg River.

Groundwater movement in the basal sandy aquifer along geologic cross section A - A' (Fig. 17) coincides with the hydraulic gradients generated by the uplands water-table aquifer grading into the thinner, more poorly sorted basal sandy drift. The change to a thinner, confined aquifer having poorer hydraulic characteristics creates a discharging head in the basal drift. Higher heads occur in this portion of the central discharge area because energy losses along groundwater flow lines from the uplands recharge area are less. As compared to geologic cross section B - B', the losses are less because the sandy deposits along A - A' are thicker and extend to the uplands recharge zone.

The northeast to southwest lateral flow that occurs in the central discharge area is a result of the hydraulic head differences in the basal sandy aquifer as observed along cross sections A - A' and B - B'. The groundwater "low" near the western transition zone is an additional complicating factor which ultimately reverses this trend.

Major ion distribution as well as pH values and total dissolved solids (TDS) concentrations indicate anomalous flow conditions in the area of the groundwater "low". This will be discussed in the following section.

Distribution of Major Ions

Major ion distribution and electrolytic conductivities were correlated to the geologic cross sections. The water quality variation duplicated the cross sectional flow patterns (Figs. 28 and 29). Definite indications of vertical and lateral flow are apparent in the increasing hydrochemical concentrations. The increases are in the direction of groundwater movement. Major hydrochemical anomalies in the area correspond to hydraulic head anomalies. The anomalous groundwater "low" near the western transition zone was indicated.

The groundwater flow system was also interpreted through contouring the TDS concentrations and pH of the water table (Figs. 30 and 31). Figure 32 shows the contoured pH values of the basal sandy aquifer. Zones of vertical discharging and recharging hydraulic gradients and the two transition zones are reflected by the hydrochemical contours. Northeast to southwest lateral flow in the central discharge zone is also indicated by the pH and TDS contours.

Higher TDS concentrations in the water table of the central discharge zone compared to the adjacent recharge zones indicate upward movement of groundwater from the basal sandy drift through the glacial and glaciolacustrine deposits. Dissolution of additional anions and cations accompanied by ion exchange occurs as groundwater moves vertically through the overlying loamy clay- and silt-tills and lacustrine clay. Evapotranspiration produces a final concentrating effect. The end result is a high TDS concentration in the water table.

A major portion of a chemical dissolution and precipitation sequence that originates in the uplands recharge zone and terminates at the Winnipeg River was studied. Appendix B describes a theoretical chemical evolution sequence starting in the uplands recharge area along cross section B - B' and ending at the water table of the central discharge zone. An indication of the masking potential of chemical precipitates upon ion exchange surfaces in the clays of the WM Area was obtained.

Groundwater Temperature Distribution

Groundwater temperatures in the study area varied from 5°C to 7°C. The maximum water-table temperature observed was 7°C in the uplands sand and gravel. The maximum temperature in the basal sandy drift was 5.8°C. Figures 33 and 34 are the contoured temperature distributions. Hydrothermal gradients were correlated with the groundwater flow pattern. Temperature variations in the water-table zone indicate the central discharging gradients and the western transition zone and groundwater "low". The northeast to southwest lateral flow in the basal sandy drift appears to have some effect on the water-table temperature. Anomalous temperature distribution in the basal sandy drift occur in zones which also have anomalous hydraulic head distribution.

Distribution of Natural Deuterium

The deuterium content of water samples collected from the piezometers along cross section A - A' was determined and the results related to the geologic cross section. As shown in Figure 35, 140.5 ppm deuterium is the apparent maximum concentration in the uplands recharge zone. The deuterium concentrations appear to increase westward along the flow system to a maximum of 146.0 ppm in the lacustrine silt of the lowlands recharge area. Some correlation of increase in deuterium content with groundwater flow direction appears possible though natural deuterium concentrations are normally independent of the flow gradients.

Groundwater Flow Rates

The groundwater flow rate in the basal sandy drift was calculated using the Darcy equation in the modified form as described by Todd (1959)

[1] $$V = (k)\ (\Delta h/\Delta x)\ (1/\theta)$$

where V is the average velocity of the groundwater flow,

k is the average hydraulic conductivity of the stratigraphic unit,

$\frac{\Delta h}{\Delta x}$ is the hydraulic gradient across the seepage area,

θ is the average effective porosity.

In earlier investigations (Cherry, et al., 1970) the above equation was used to estimate hydraulic conductivities by calculating average flow velocity "V" from the mean annual precipitation and the percentage of precipitation contributing to a particular recharge segment. Employing this mass-balance concept, the modified Darcy equation was used to determine the most probable hydraulic conductivity in the basal sandy drift of the WM Area. Using precipitation data obtained from Reimer (1970) and observed hydraulic gradients in the basal sandy aquifer, this was calculated to be 1×10^{-5} to 1×10^{-4} feet per second. This indicated a general flow rate of 10 feet per year. As recharge rates, recharge segment areas, and discharge effects on flow volume are approximated, the mass-balance method of calculating rate of groundwater flow may be subject to considerable inaccuracies.

In this study the hydraulic conductivities of the basal sandy drift were calculated from screened-well pumping tests and bail-down response testing of piezometers. The effective hydraulic conductivity of the basal drift in the WM Area was calculated to be 5×10^{-5} feet per second. This is further discussed in a later section.

A hydraulic gradient of 2.2×10^{-3} between piezometers P-3 and P-9 (Fig. 9) near the WM Area and a hydraulic conductivity of 5×10^{-5} feet per second were used in Equation 1. The horizontal hydraulic conductivity was determined from aquifer performance testing of the basal sandy drift in the WM Area. An average effective porosity of 0.33 was suggested by Bakhtiari (1971) for bulk sandy deposits of glacial origin. The flow rate in the basal drift aquifer was calculated to be 9 feet per year between piezometers P-3 and P-9. An increase in the hydraulic gradient by as little as 0.001 would increase this flow rate by approximately 70 per cent. Using an average effective hydraulic gradient of 3×10^{-3}, the flow rate across the WM Area is calculated to be approximately 15 feet per year. This is a more realistic, general value of groundwater flow rate in the area.

The tritium injection site monitoring programme provided an estimate of groundwater flow rate in the basal sandy drift at injection site I. Results gathered over the last year of study indicate flow rates in the range of 15 to 30 feet per year. The use of tritiated water as the injected radiotracer is acceptable; the observed rate of tritium movement is equivalent to the rate of groundwater flow (Theis, 1963). Figure 36 shows the extent and direction of the tritium movement.

A progressive increase in the tritium concentration at the intake zone of various piezometers in the injection site was observed. All increases were determined over a two-year tritium monitoring programme though the last one and one half years were the most significant. Increased tritium activities are given in relative units; i.e., one unit is equivalent to a 100 per cent increase over original activity levels.

Figures 37 and 38 show the groundwater flow directions indicated by tritium concentration increases at the numbers II and III injection sites. These sites are described by Beswick (1971). At the most northern of the two sites, sampling piezometers were set in the basal sandy drift. Injection site III immediately to the south is comprised of piezometers set in the clay-loam till. Both sites are located in the hydraulic head "low". At site II a northwesterly groundwater flow is indicated. At site III no definite flow direction is apparent. The anomalous flow directions correspond to the anomalous hydraulic head distribution of the groundwater "low".

HYDRAULIC PROPERTIES OF THE STRATIGRAPHIC UNITS

Hvorslev Response Tests

Horizontal hydraulic conductivities of the stratigraphic units in the study area were calculated using the water-level drawdown method described by Hvorslev (1951). A semi-logarithmic graph of hydraulic head ratio, the comparison of remaining drawdown at some point in recovery to original drawdown, versus time after recovery began was prepared for each piezometer tested. A valid head ratio was determined from this straight-line graph. Time corresponding to the valid head ratio was determined. Head ratio and time were used in Hvorslev's variable head formula shown in Equation 2.

$$[2] \quad K_h = \left[d^2 \cdot \ln \left(mL/D + \left[1 + m^2L^2/D^2 \right]^{\frac{1}{2}} \right) \right] \left[\ln (H/H_o) \right] \left[8 \cdot L \cdot (t_2 - t_1) \right]^{-1}$$

where K_h is horizontal hydraulic conductivity,

m is a transformation ratio equivalent to one,

d, D, and L are shape factors related to piezometer diameter and length of intake area, and

H/H_o is the ratio of remaining drawdown to original drawdown at time $t_2 - t_1$ which is the time after recovery begins or an interval of recovery.

ln indicates the natural logarithim of a quantity.

These factors are described in Figure 39 and Appendix C.

A semi-logarithmic plot (Fig. 40) indicates any deviation from normal piezometric response as departures from the slope of the straight line joining successive response test coordinates. Slope deviation may be caused by well-screen plugging, initial high permeability response in an artificially sand-packed well or piezometer, etc. Potential sources of slope deviation are described in Figure 41.

The standard Hvorslev equation for determining hydraulic conductivity uses the basic time lag which corresponds to a head ratio of 0.37 (Fig. 40). This equation was replaced by the variable head formula (Equation 2) because of the latter's independence of the time lag factor. Using Equation 2 an initial steep slope in a semi-logarithmic graph can be neglected if original drawdown is large enough to compensate for the abnormal portion of the graph.

Determination of hydraulic conductivity was simplified by using an Olivetti-Underwood Programma 101 for which a three-part programme was developed. Conductivity values were statistically analyzed using a procedure developed for the Programma 101 by Williams (1968). Hydraulic conductivities were entered in logarithmic form; thus, means and standard deviations were not weighted unevenly due to very high or very low orders of magnitude.

Figures 42 and 43 show the results of the Hvorslev tests. Mean horizontal hydraulic conductivities are listed below.

HYDROSTRATIGRAPHIC UNIT	MEAN HYDRAULIC CONDUCTIVITY ft/sec	cm/sec
Lacustrine Silt	2.04×10^{-8}	6.22×10^{-7}
Lacustrine Clay	2.09×10^{-9}	6.37×10^{-8}
Clay-loam Till	1.05×10^{-8}	3.20×10^{-7}
Basal Sandy Drift	1.38×10^{-7}	4.21×10^{-6}
Lacustrine Sand	1.91×10^{-6}	5.82×10^{-5}

Means and standard deviations of the hydraulic conductivities are expressed in their logarithmic equivalents (Figs. 42 and 43). For example, the mean hydraulic conductivity in feet per second for the basal sandy drift is $\overline{7}.86$ or the logarithim 3.14 - 10. In whole numbers this value becomes 1.38×10^{-7} feet per second. The standard deviation is 5.13×10^{-1}.

Graphs in Figure 44 show the ranges of hydraulic conductivity in the sandy deposits and clay-loam till. Low values of conductivity are dominant in the till. The few high values are probably due to secondary permeability features such as fractures. Maximum hydraulic conductivities in the sandy deposits vary from 10^{-7} to 10^{-5} feet per second. Cedergren (1967) suggests a horizontal hydraulic conductivity of 10^{-5} feet per second for deposits texturally equivalent to the basal sandy drift of the WM Area. A hydraulic conductivity of 10^{-5} feet per second is the general order of magnitude in terms of most probable conductivities suggested by the mass-balance and modified Darcy equations discussed earlier and the aquifer pumping tests described below.

Aquifer Pumping Tests

Recording well RW-3 was pumped for 10.5 hours on August 24, 1971. Figure 45 shows the extent and configuration of the drawdown cone. The well was pumped at a controlled rate of 9 gallon per minute with a maximum fluctuation of 2 gallon per minute. Initial available drawdown was 21 feet. Specific capacity of the well at a time of one hour was approximately 1.1 gallon per minute per foot of drawdown. Figure 46 shows the drawdown and recovery data from RW-3 plotted in the standard semi-logarithmic manner described by Jacob (1950). The Jacob straight-line analysis is valid as long as the assumptions of constant aquifer thickness and non-leakiness are adhered to. The drawdown and recovery for a period of one log cycle were determined from the straight-line graph. This produced the drawdown/recovery rate $\Delta S'$. A transmissibility of 250 gallon per day per foot was calculated using the method shown in Figure 46 (Johnson, 1966).

Similar graphs of drawdown versus time were prepared for observation wells RW-1, RW-2, RW-4, and piezometers P-17(32) and P-5(28) set at 32 and 28 foot depths respectively (Figs. 47 through 51). Local transmissibilities were determined from the graphs. The values apply to the areal extent of the drawdown cone produced. Transmissibilities calculated from these data are between 500 and 900 gallon per day per foot. Using an effective aquifer thickness of 20 feet and the relation

/37

$$T = Kb$$

where T is transmissibility in gallon per day per foot,

K is horizontal hydraulic conductivity in feet per second, and

b is aquifer thickness in feet,

the hydraulic conductivity was calculated to be 8×10^{-5} feet per second for a transmissibility of 900 gallon per day per foot. A transmissibility of 500 gallon per day per foot is equivalent to a hydraulic conductivity of 5 x 10^{-5} feet per second using an aquifer thickness of 20 feet. This is slightly greater than the maximum Hvorslev hydraulic conductivity of 3 x 10^{-5} feet per second calculated for the sand deposits in the study area.

Some high transmissibilities are expected in the clean, coarse sand and gravel lenses of the WM Area. As the basal sandy drift is neither homogeneous nor isotropic, no constant value of transmissibility or storage coefficient is possible. The heterogeneity of the basal sandy drift assures varied transmissibilities and storage coefficients. However a transmissibility of 500 gallon per day per foot is a realistic, general value for the basal drift of the WM Area. The storage coefficients calculated from the drawdown data (Figs. 47 through 51) range from 10^{-4} to 10^{-3} and are typical of sandy confined aquifers (Walton, 1970).

At the end of pumping recording well RW-3, the drawdown cone shown in Figure 45 negated or reversed the vertical hydraulic gradient in only a portion of the WM Area. To reverse the vertical gradient in the entire WM Area by pumping RW-3, a minimum drawdown of 3.5 feet at observation well RW-1 was necessary. This would have required an additional 22 hours of continuous pumping at 9 gallons per minute.

Figures 52 through 56 are arithmetic graphs of drawdown versus time for the observation wells RW-1, RW-2, RW-4, and RW-5 and the pumped well RW-3. Lowering of the hydraulic head distribution in the basal sandy drift aquifer is shown. The behaviour of water-table levels is also shown. Observation well RW-4 and the adjacent water-table well RWT-4 (Fig. 55) appear to be hydraulically connected. This is a very unexpected result in light of the lack of water-table response elsewhere in the WM Area. Hydraulic connection may be the result of an adjacent abandoned borehole left by earlier investigators or fractures and desiccation cracks in the overlying units.

Well RW-1 was pumped on August 26, 1971 following the recovery of the drawdown caused by pumping RW-3. Well RW-1 which had a static level at ground surface and an available drawdown of 24 feet was initially pumped at a rate of 2 gallons per minute. After 108 minutes the pump broke suction and the test ended. Figure 57 shows the extent and configuration of the drawdown cone.

Following the recovery of RW-1, it was again pumped but at a reduced rate of 1 gallon per minute. The test continued for 21 hours. Figure 58 shows the semi-logarithmic graph of drawdown versus time. During the latter part of the test, the slope of drawdown versus time decreased. Theis (1940) suggests such decreases are attributable to recharge from lateral groundwater flow or from vertical leakage. Observations of water-table levels and water levels in the overlying till during the RW-1 pumping tests did not conclusively indicate vertical leakage. Long-term pumping tests by Grisak in 1972 (personal communication) indicate that vertical leakage becomes significant as pumping continues.

The transmissibility determined from the pump well drawdown (Fig. 58) is approximately 40 gallon per day per foot. This low value may be a result of insufficient well development. A mean storage coefficient of 7×10^{-4} was calculated using the Jacob graphs prepared for observation piezometers P-5(28), P-57(41), and I-5(29) as shown in Figures 59 through 61. The mean transmissibility calculated from these graphs was approximately 200 gallons per day per foot, a more realistic value considering transmissibilities indicated by the RW-3 pumping test.

After pumping RW-1 for 21 hours, the drawdown cone had encompassed the WM Area (Fig. 62). The rate of expansion had decreased considerably as the areal extent of the drawdown cone was sufficient to supply the low pumping rate of 1 gallon per minute. Drawdown values recorded for the basal sandy drift were relatively low compared to the drawdown of the RW-3 test. This was a result of the poorer aquifer characteristics at well RW-1. The specific capacity of RW-1 was only 0.1 gallon per minute per foot of drawdown at a time of one hour after pumping began.

Figures 52 through 56 show the effects that pumping of well RW-1 has on the drawdown of the basal sandy drift hydraulic head and on the behaviour of the water table. No hydraulic connection between the basal drift and the overlying till and clay was observed.

Wells RW-2, RW-4, and RW-5 were not used for long-term aquifer performance testing during the study. Wells RW-2 and RW-4 do not have a sufficient well yield. RW-5 was not developed at the time of study.

The following table summarizes aquifer characteristics calculated from test data obtained by the pumping of wells RW-1 and RW-3.

PIEZOMETER OR WELL OBSERVED	PUMPING TEST OF RW-1		PUMPING TEST OF RW-3	
	T*	S**	T*	S**
Recording Well RW-1	38	---	540	1.3×10^{-4}
Recording Well RW-2	--	---	450	0.8×10^{-4}
Recording Well RW-3	--	---	250	---
Recording Well RW-4	--	---	630	2.4×10^{-4}
Piezometer P-17(32)	--	---	920	1.0×10^{-3}
Piezometer P-5(28)	200	6.3×10^{-3}	360	6.6×10^{-4}
Piezometer P-57(41)	280	1.7×10^{-4}	---	---
Piezometer I-5(29)	220	4.1×10^{-4}	---	---

*Transmissibility in gallon per day per foot **Storage Coefficient

Discussion

Hvorslev response testing placed each stratigraphic unit in a range of horizontal hydraulic conductivities. A conductivity of approximately 3×10^{-5} feet per second was the maximum value determined by this method for the sand deposits in the area. This is equivalent to a transmissibility of 340 gallons per day per foot which is in the range of transmissibilities calculated from data obtained by the pumping of wells RW-1 and RW-3.

The aquifer pumping tests allowed the calculation of approximate transmissibilities and storage coefficients of the basal sandy drift in the immediate vicinity of the WM Area. The transmissibility in the vicinity of RW-1 is approximately 200 gallons per day per foot. This is equivalent to a horizontal conductivity of 1.3×10^{-5} feet per second.

Higher transmissibilities were indicated by the pumping test of well RW-3. Unexpectedly high values were observed in the direction of piezometer P-17(32). Hydraulic conductivities as great as 8×10^{-5} feet per second were indicated. Though transmissibility and storage coefficient calculated using drawdown data from a particular observation well depend on the aquifer characteristics of the entire drawdown cone area, the characteristics between the pump well and the observation well are particularly important. This suggests that a high conductivity zone may exist between piezometer P-17(32) and the pump well RW-3. Storage coefficients of 1×10^{-4} to 5×10^{-3} were calculated and are in an acceptable range for sandy confined aquifers.

HYDROGEOLOGIC PROCESSES IN THE WASTE MANAGEMENT AREA

Flow Conditions

As the WM Area is located in the discharge zone, natural dissolved groundwater constituents in the till and clay must be carried upward to the water table. This process is confirmed by the hydrochemical patterns discussed earlier. It can therefore be concluded that if radionuclides were to enter the groundwater in the disposal zone, they also would be carried upward. Contaminated liquid, if not significantly more dense than the natural groundwater, would be transported upwards to the water table and the root zone.

Movement of contaminated liquids could possibly occur along the outside of a standpipe or bunker where the annulus between the exterior of the containing installation and the soil is improperly sealed. Backfilling with sandy material or large blocks of till or clay would have the effect of a high permeability channel directing liquid contaminants to the water table and root zone. A high rate of radionuclide transport must be considered possible.

Owing to the lack of detailed information on methods of backfilling containment facilities in the WM Area, a calculated rate of groundwater flow along the exterior surface of the standpipes or bunkers may be an order of magnitude in error at best. Assuming the excavated clay or till was replaced around the exterior of the containing unit and lightly compacted, a vertical hydraulic conductivity equivalent to or greater than that of the basal sandy aquifer might apply. The material would be disturbed and all low permeability field characteristics would be destroyed.

If contaminated liquids were to leak slowly into the discharging flow system of the WM Area, they would move upward through till and/or clay providing the contaminated liquid was not significantly more dense than the groundwater. If the clay-loam till and lacustrine clay are considered a continuous unit, the vertical hydraulic conductivity should be no greater than 5×10^{-8} feet per second. If considerably larger vertical hydraulic conductivities were to occur as a continuum in these units, more water would be transported upward to the water table in the central discharge zone than is available to the system from precipitation in the uplands recharge area. An average effective porosity of 0.05 is acceptable. The average distance from the base of the clay-loam till to the water-table zone is 20 feet. There is an average hydraulic head difference of 3 feet. The maximum rate of flow as determined from the modified Darcy equation is 5 feet per year.

If a liquid contaminant has a density significantly greater than the groundwater, it could flow against the discharging gradient and enter the basal sandy drift aquifer. A westward flow towards the anomalous "low" near the western transition zone would occur. The maximum rate of groundwater flow in the basal sandy drift was calculated using Equation 1 and a hydraulic conductivity of 8×10^{-5} feet per second. A flow rate of approximately 25 feet per year was indicated using an effective porosity of 0.33 and a hydraulic gradient of 0.003, the horizontal gradient between the WM Area and the western transition zone.

If a contaminated liquid were to move laterally in the basal sandy aquifer at a flow rate of 25 feet per year, it would reach the hydraulic head "low" in approximately 150 years. At this time the already diluted contaminant would be further mixed. The effect of the "low" would be to alter the flow rate and flow direction of contaminated groundwater moving laterally westward from the WM Area. The groundwater would be directed northward and parallel to the Winnipeg River by the lateral flow in the basal drift of the anomalous area. Groundwater residence time in the basal sandy drift would be significantly increased.

Possibilities for Ion Exchange

Ion exchange in the deposits underlying the WM Area may cause cation retardation if the direction of contaminant movement is toward the water table or the Winnipeg River. Exchange of one ion for another on the clays and silts could remove the long-lived radionuclides Sr^{90} and Cs^{137} from the groundwater flow.

Back and Hanshaw (1965) indicate that Sr and Cs have a relatively large affinity for being adsorbed. However the number of exchange sites on the clay particles are limited. If similar concentrations of exchangeable cations are present in water, a tendency for selective preference of the exchangeable ions occurs. Back and Hanshaw suggest that

$$Ba^{++} > Sr^{++} > Ca^{++} > Mg^{++}$$

and

$$Cs^{+} > Rb^{+} > K^{+} > Na^{+} > L^{+}$$

where $>$ indicates "a greater exchange affinity than".

If the water contains large quantities of competitor ions, the ability of a given ion to occupy exchange sites on the clay or silt particles can be reduced. The capacity of a porous medium to adsorb Sr and Cs can be appreciably reduced if the pore water contains Na^{+}, Ca^{++}, and/or Mg^{++} in concentrations much greater than the Sr or Cs. Natural strontium is also a competitor with radiostrontium.

In the central discharge area, the groundwater contains relatively high concentrations of the competitor ions. The concentrations of Ca^{++}, Mg^{++}, and Na^{+} in groundwater moving upward to the WM Area water table through the clay-loam till and clay are approximately 300 ppm, 200 ppm, and 70 ppm respectively. This could appreciably reduce the cation exchange capacity of the clayey deposits with respect to Sr and Cs.

Mills and Zwarich (1970) investigated the exchange potential of the clays and till. Disturbed samples were collected from five boreholes near the WM Area. The samples were disaggregated in the laboratory; all field structure was destroyed. The tests were conducted under controlled, laboratory conditions. Their results indicate greater ion exchange potential in the lacustrine clay as opposed to the clay-loam till. The affinity for Cs was significant while that for Sr was relatively low.

However the precipitation of carbonates and sulfates along the joints and desiccation cracks of the surficial clay and till units may block the ion exchange surfaces. This would significantly decrease the expected ion exchange capacities. Beswick (1971) and the Templeton Engineering Company Limited (1960) report calcite and gypsum coatings on numerous joints and fractures in the upper 10 feet of surficial deposits in the WM Area.

Ion exchange in the basal sandy drift was considered in view of the clays and silts that are present. Though the clay to sand ratio of the basal drift is much lower than that of the overlying till and lacustrine clay, even a small percentage of fine clayey sand and clay can provide significant cation exchange potential. Parsons (1961) in a discussion on the Chalk River, Ontario soils states that "roughly one half of the cation-exchange capacity [is] due to the dispersed clay mineral (1%) and the remainder [is] due to absorption on the fine sand and silts (99%)". The fine silty, clayey sands in the basal sandy drift of the WM Area may provide limited capacity for retarding the westward movement of radionuclide contaminants. Where clean, coarse sands are involved, the ion exchange and absorptive effects would be negligible.

Merritt and Mawson (1967) also suggest that the rate of nuclide transport may be considerably less than that of the groundwater flow. This is due to retardation of the nuclide movement by ion exchange effects as described earlier. Merritt and Mawson state that "the rate of movement of Sr^{90} through the soil [of the Perch Lake drainage basin near Chalk River, Ontario] is 0.027 times the rate of movement of the groundwater". Apparently the sandy soil of the Chalk River area does not have a significantly greater fine sand and clay content than the basal sandy drift of the WNRE. The ion exchange potential of the Chalk River soil cannot be much greater than that of the basal drift aquifer. It is possible that the residence time of radionuclides in the sandy drift may be many times that of the groundwater itself.

CONTAINMENT BY MANIPULATION

As indicated above, the natural hydrogeologic environment in and near the WM Area would provide a relatively high degree of containment of radionuclides if contamination of the groundwater zone should occur. Two problems, however, could arise if appreciable quantities of radionuclides were to enter the groundwater zone in the clay or till. Firstly, upward migration to the soil zone could transport fission products to the root zone allowing them to cycle through the ecosystem. And secondly, if dense liquid waste were to leak into the groundwater zone, it could depending on its density move downward against the direction of natural groundwater movement. The dense contaminant might conceivably enter the basal sandy aquifer. If either of these events occurred, remedial measures would be desirable. One approach is to manipulate the groundwater flow pattern to achieve a desired direction and rate of migration of the contaminants.

At least four general types of manipulation schemes are possible using the pumping wells installed in the WM Area:

1) If radionuclides were to migrate upwards to the water table, the migration direction could be reversed by reducing the hydraulic head in the sandy aquifer. The head could be lowered by pumping until all water levels measured in the observation wells set in the basal aquifer and encircling the WM Area are equal to or lower than those measured in the adjacent water-table wells. Pumping

would continue for a period of days or until the drawdown in the basal sandy aquifer significantly lowers the water-table level through vertical leakage. Pumping would be discontinued before the contaminant was drawn into the basal sands. It would be resumed upon recovery of the basal sandy aquifer hydraulic head distribution.

2) If potential contamination of the soil zone is such that burrowing animals, vegetation, or surface runoff would tend to cause dispersion into the food chain, it may be desirable to cover the ground surface with an impermeable cover or pavement. This procedure would lead to further difficulties due to the discharging groundwater unless the upward groundwater gradients are nullified or reversed by reducing the hydraulic head in the basal sandy aquifer. Pumping would produce this lowered hydraulic head in the manner described above.

3) If radionuclides move downward into the sandy aquifer because of density difference, it may be desirable to

   a) remove the fission products by pumping the wells set in the basal drift. Installation of low-yield large diameter wells set at depths of 15 feet in and near the WM Area would be necessary if simultaneous removal of fission products from the water table is desired. This would accelerate removal of radionuclides from the flow system though only to a slight degree.

b) control the migration directions and rates by changing the hydraulic head distribution in the aquifer. In order to take advantage of the cation exchange properties of the aquifer, curved or even staggered migration paths may be induced. This would create long travel distances in a relatively small area. Hydraulic gradients would be produced in the direction of the pumping well.

4) If it is desired to prevent downward migration of dense contaminants, the upward hydraulic gradient in the till and clay could be increased by injecting water into the basal sandy aquifer through the screened wells. This would increase the aquifer pressure much above natural levels. Natural hydraulic gradients would be strengthened and a hydraulic head "mound" would be produced beneath the WM Area. Dense contaminants would migrate towards the water table with the more effective discharging hydraulic gradient. The contaminant would be prevented from reaching the water table by allowing the "mound" to decrease through discontinuing the injection pumping. The procedure could be repeated as required.

All of the above manipulation schemes depend on one basic factor—controlling the hydraulic head in the sandy aquifer. The results of the pumping tests indicate that such control would be feasible. Some examples of control procedures are described below.

Upon detection of a nuclide contaminant in the flow system, wells RW-1, RW-3 and RW-5 could be pumped at the respective rates of 1, 8, and 4 gallons per minute. This would lower the hydraulic head of the basal sandy aquifer.

Pumping could be continued until the water-level elevations measured at observation wells RW-2 and RW-4 and the observation piezometers about the WM Area are lower than the initial water-table elevations measured at RWT-1, RWT-2, RWT-3, RWT-4, and RWT-5. Intermittent pumping would follow the general lowering of the hydraulic head below the water table. Continuous pumping could create strong recharge gradients causing the contaminant to migrate downward to the basal sandy drift. This should be avoided as the groundwater flow velocities in this aquifer are significantly higher than those in the overlying clay-loam till and lacustrine clay.

The radionuclides would diffuse laterally in the water table while the wells are being operated. After initial measurement of the water-table levels, observation water-table wells nearest the contaminant location could be pumped at very low rates. The potentially active pump water could then be monitored and if necessary discharged to a covered trench lined with a high cation exchange capacity clay. A shallow trench lined with a thick layer of montmorillonitic clay is sufficient. Such an emergency retention basin is described by Reichert and Fenimore (1962).

This basin would also receive discharge waters from the screened wells if the contaminant migrated to the basal sandy drift. Wells down-gradient of the contaminant would be pumped at their maximum yield while those up-gradient would remain off. The drawdown cone would intercept the contaminant and produce relatively large volumes of active discharge water.

Spreading montmorillonitic clay over the water surface of the emergency retention basin at intervals during the retention period would accelerate the ion exchange process. When the activity of the effluent is reduced below the maximum permissible activity level for waste effluents containing Sr^{90} or Cs^{137}, the effluent could be discharged to the groundwater flow system. The active clays remaining in the trench would be contained in place.

SUMMARY OF CONCLUSIONS

The major results of this study are:

1) The general geology of the study area as indicated by the investigations of Beswick (1970) and Cherry, et al. (1971) between 1968 and 1970 was generally corroborated. The stratigraphic units were defined by additional test drilling and formation sampling. The thickness of the basal sandy aquifer was determined and the bedrock surface elevations were mapped. Lower bedrock elevations and thicker sandy deposits were observed than had been previously indicated.

2) The boundaries of the flow system were defined and the flow gradient established as stable over a four-year period. The transition zones were delineated. New piezometer installations allowed more complete coverage of the study area.

3) A hydraulic head "low" was indicated near the western transition zone. The anomalous head distribution in the area of the "low" was obtained from the additional piezometers installed in 1970 and 1971.

4) Major ion distributions indicate the groundwater flow direction. Total dissolved solids and pH indicate the transition zones and the hydraulic head "low". A northeast to southwest lateral flow in the basal sandy drift was also established. A previously suggested east to west lateral flow in the basal sandy aquifer was corroborated.

5) The stratigraphy of the area was defined in greater detail. It is comprised of a surficial silty clay and clayey silt, an underlying

clay-loam till, and a complex texturally varied basal sandy drift. In the southeastern quarter of the WM Area, the basal drift aquifer becomes finer and siltier with increased clay interbedding. The main portion of the basal drift in the southwestern quarter of the WM Area is comprised of coarse, clean sands and gravels; variably sorted and sized materials occur in the northern half.

6) A maximum transmissibility of 900 gallons per day per foot was calculated from pumping test data for the basal aquifer in the WM Area. A more representative transmissibility is 500 gallons per day per foot. The storage coefficient of the basal drift in the WM Area is between 10^{-4} to 10^{-3}. The maximum hydraulic conductivity is 8×10^{-5} feet per second.

7) Flow rates determined by tritium tracer monitoring are between 15 and 30 feet per year in the basal sandy drift near the WM Area. Flow rates of 15 to 25 feet per year were calculated using representative hydraulic conductivities of 5×10^{-5} to 8×10^{-5} feet per second. The conductivities were obtained from the analysis of pumping test data. The maximum Hvorslev hydraulic conductivity determined for the basal sandy deposits of the study area was approximately 3×10^{-5} feet per second. A flow rate of at least 10 to 15 feet per year in the clean sand lenses of the basal sandy drift aquifer was indicated.

8) Hydrogeologic manipulation of the WM Area flow system is possible. The hydraulic head in a portion of the basal sandy drift aquifer was lowered by pumping and a partial reversal of the natural hydraulic gradient was created. Various manipulation schemes were suggested by which radionuclide migration could be controlled by pumping water from or into the basal sandy aquifer.

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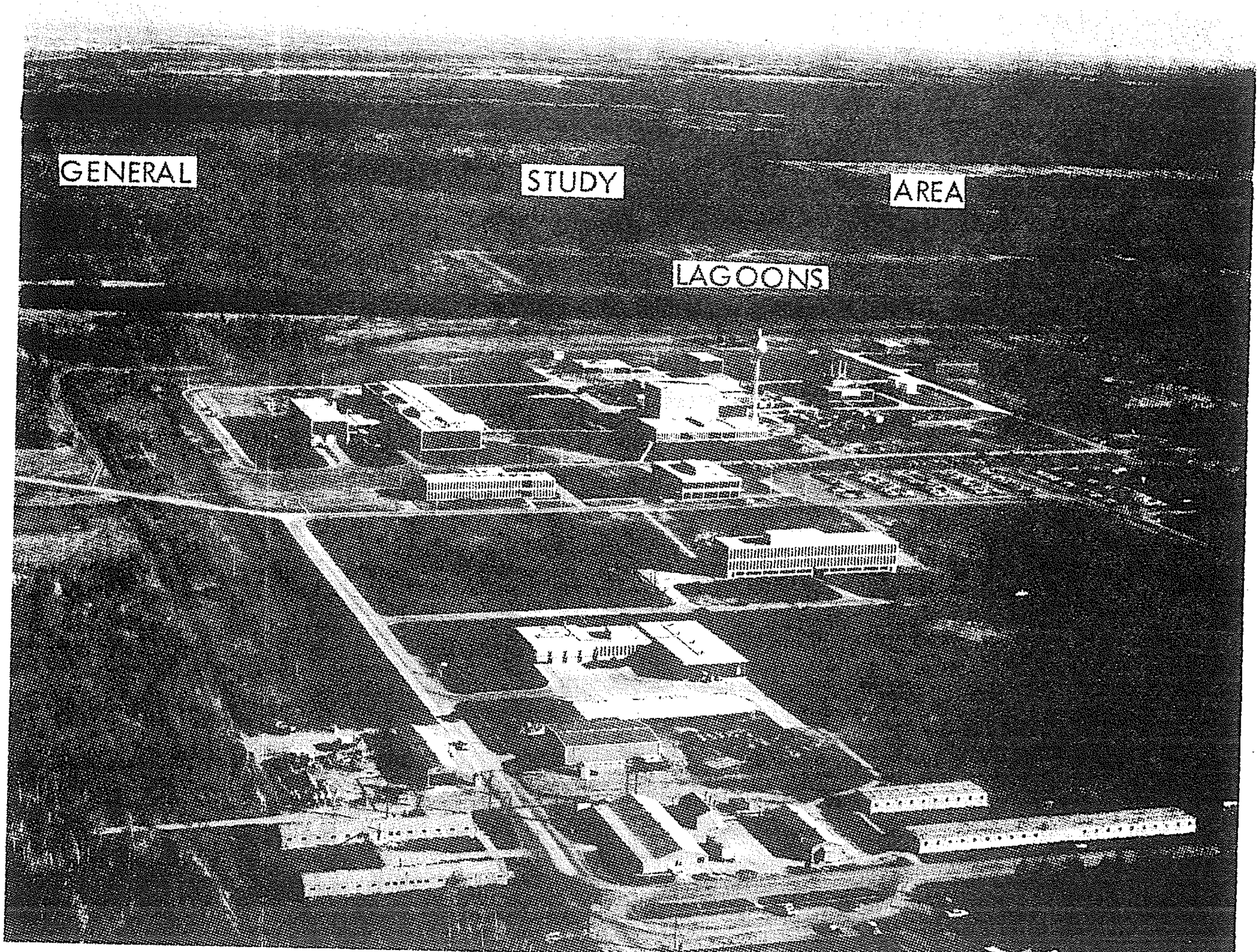


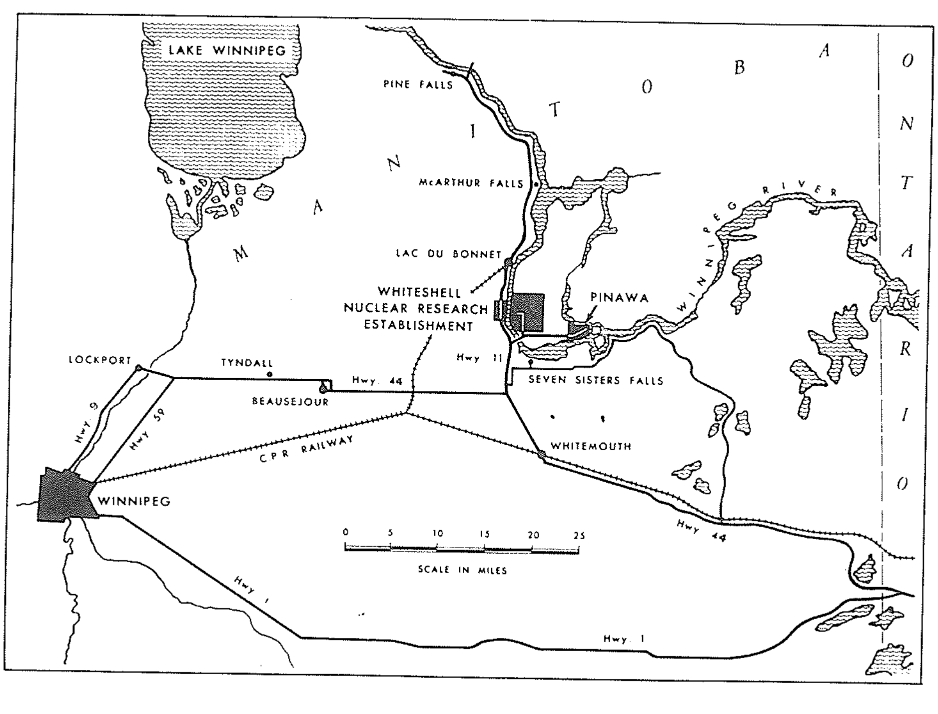
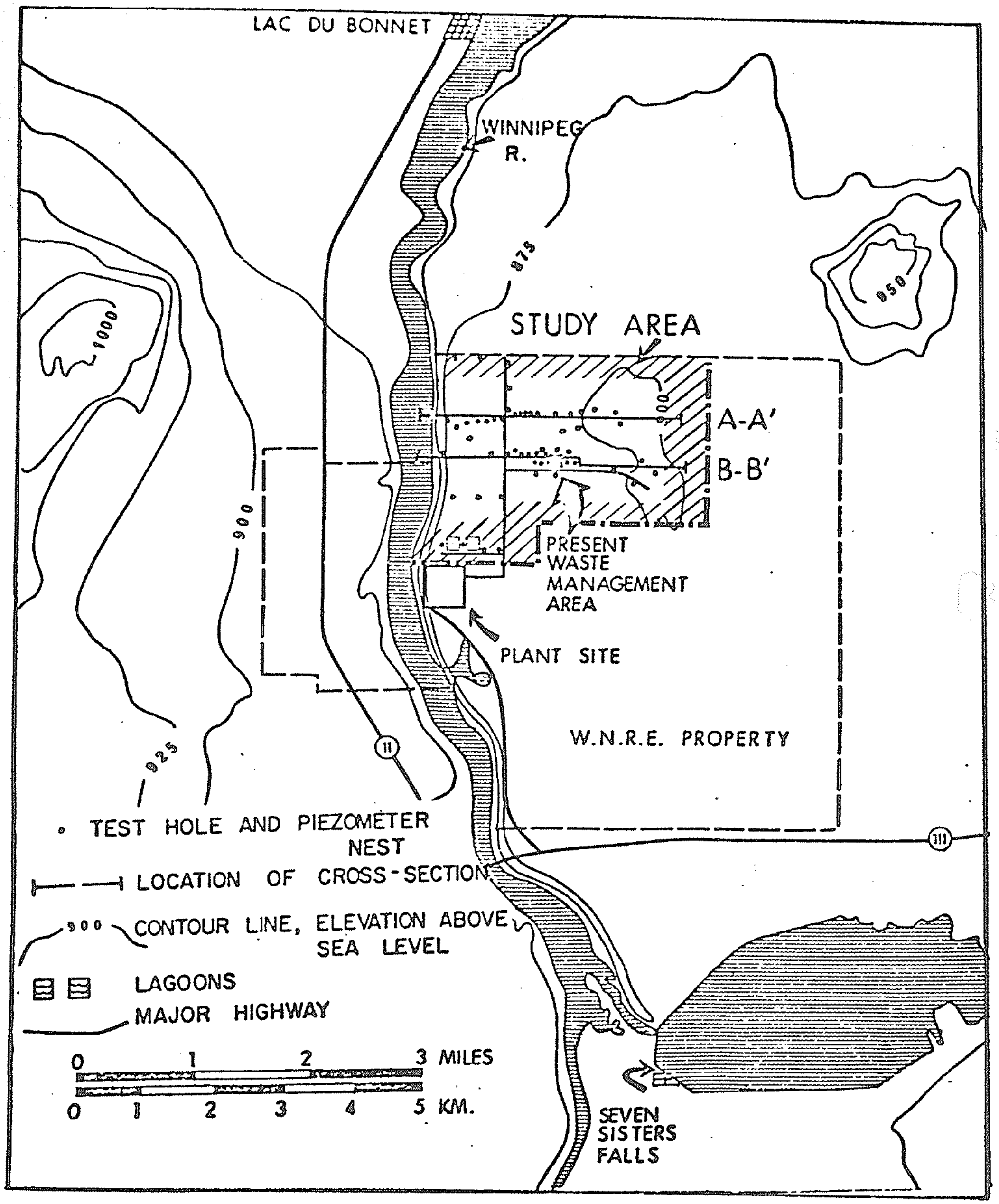


Figure 1. Location and illustration of the Whiteshell Nuclear Research Establishment (WNRE).



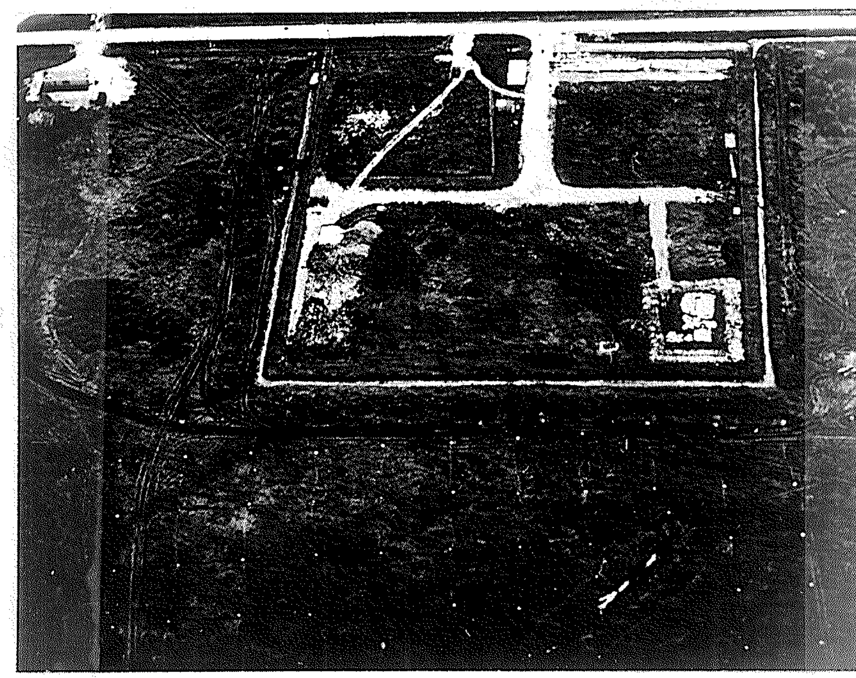


Figure 2. Location of the WNRE study area. Figure 3. The WNRE Waste Management Area.

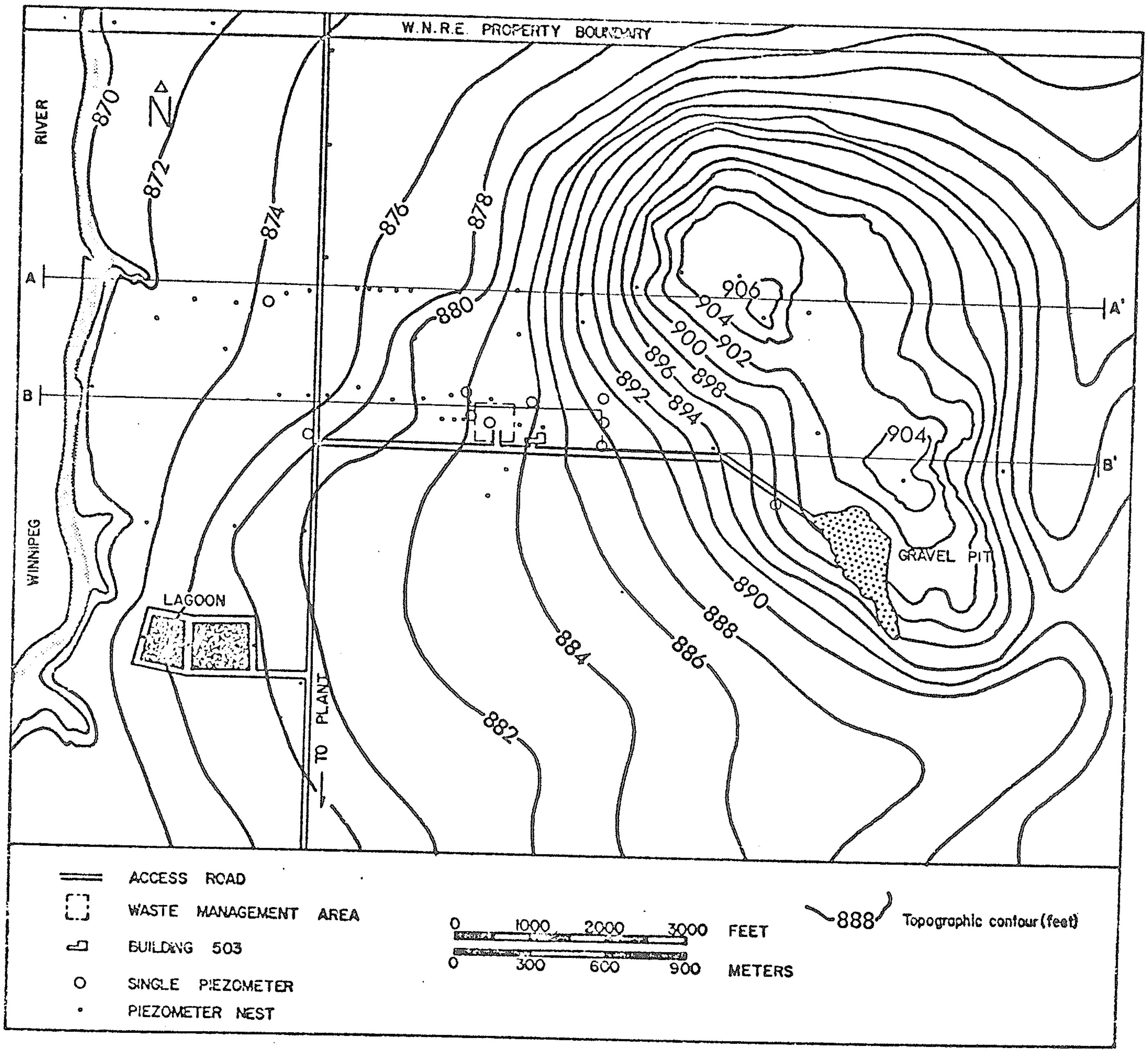


Figure 4. Topography of the WNRE study area.

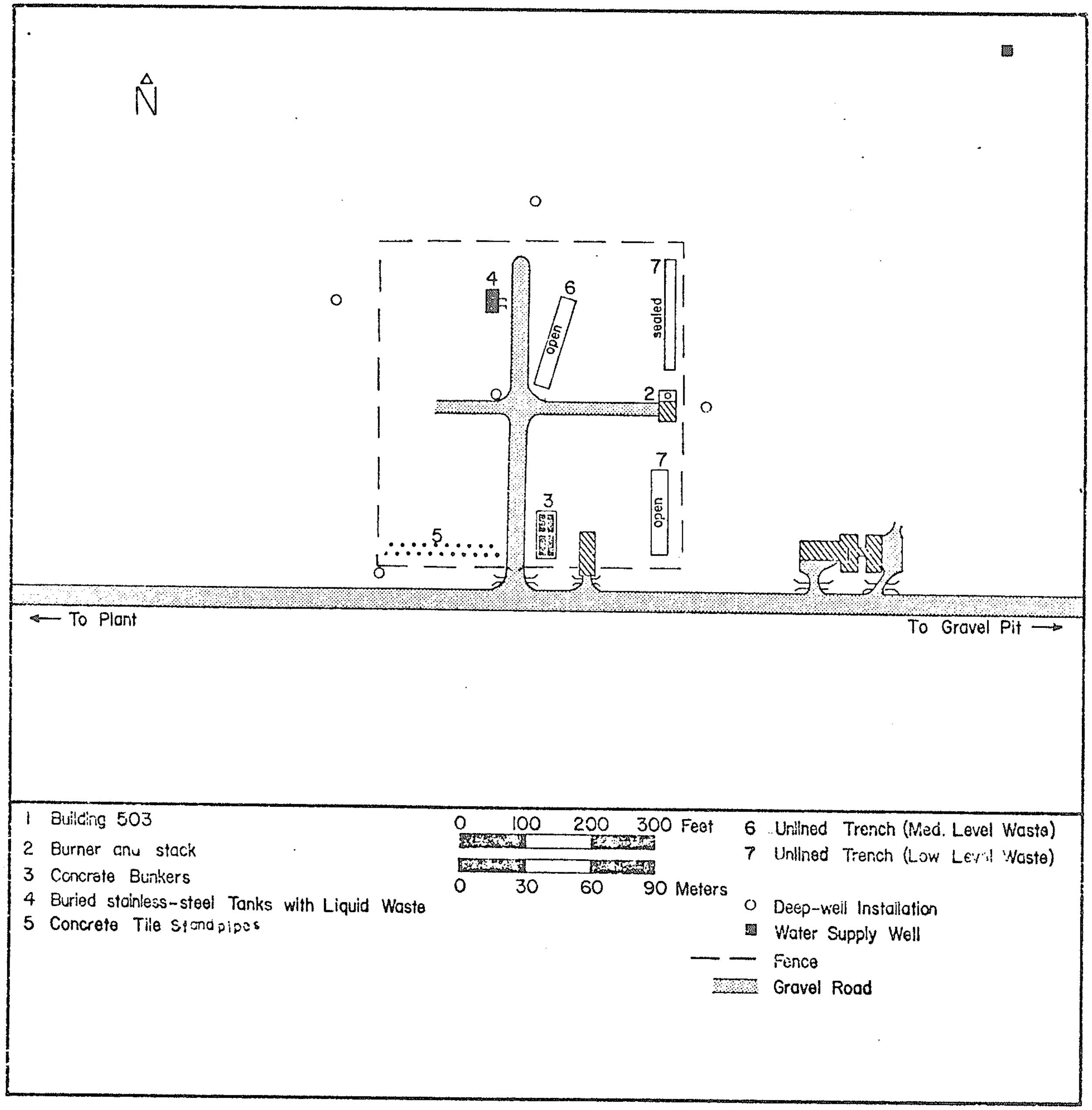


Figure 5. Waste containment facilities and wells of the Waste Management Area.

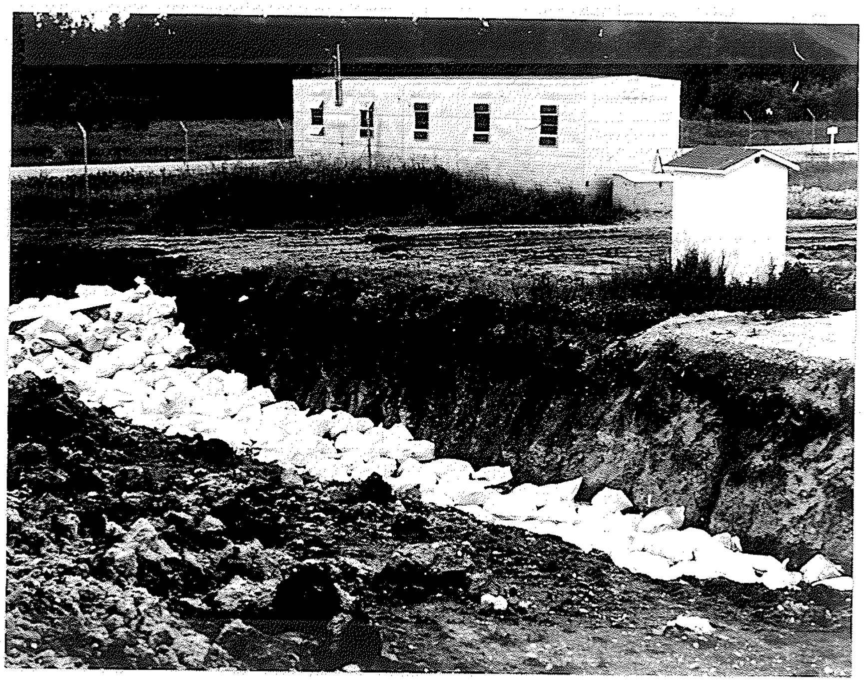


Figure 6. Solid wastes of low-level activity, method of disposal.

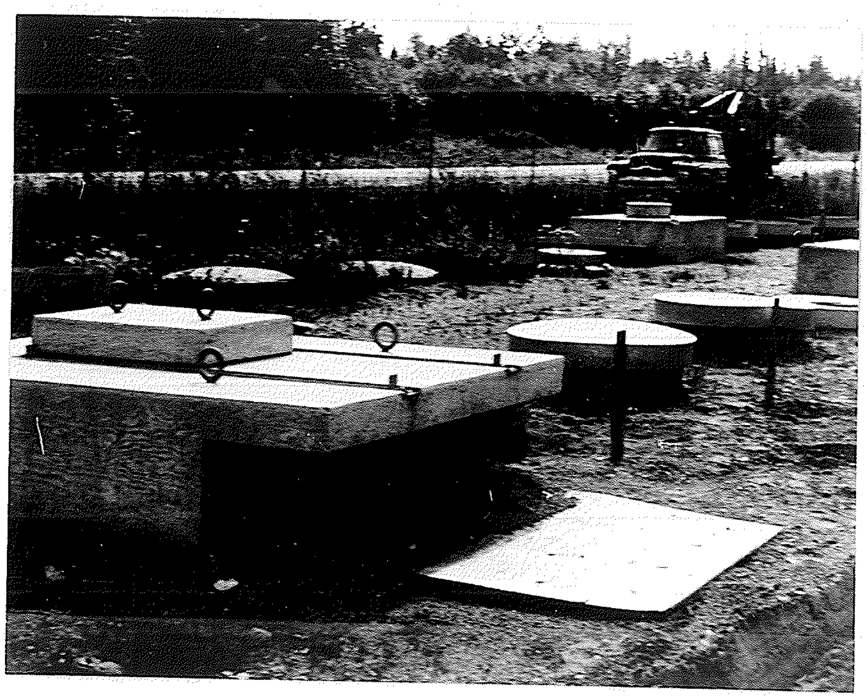


Figure 7. Concrete standpipes, Waste Management Area.

Figure 8. Subsurface containment site for liquid waste having a high level of radioactivity.

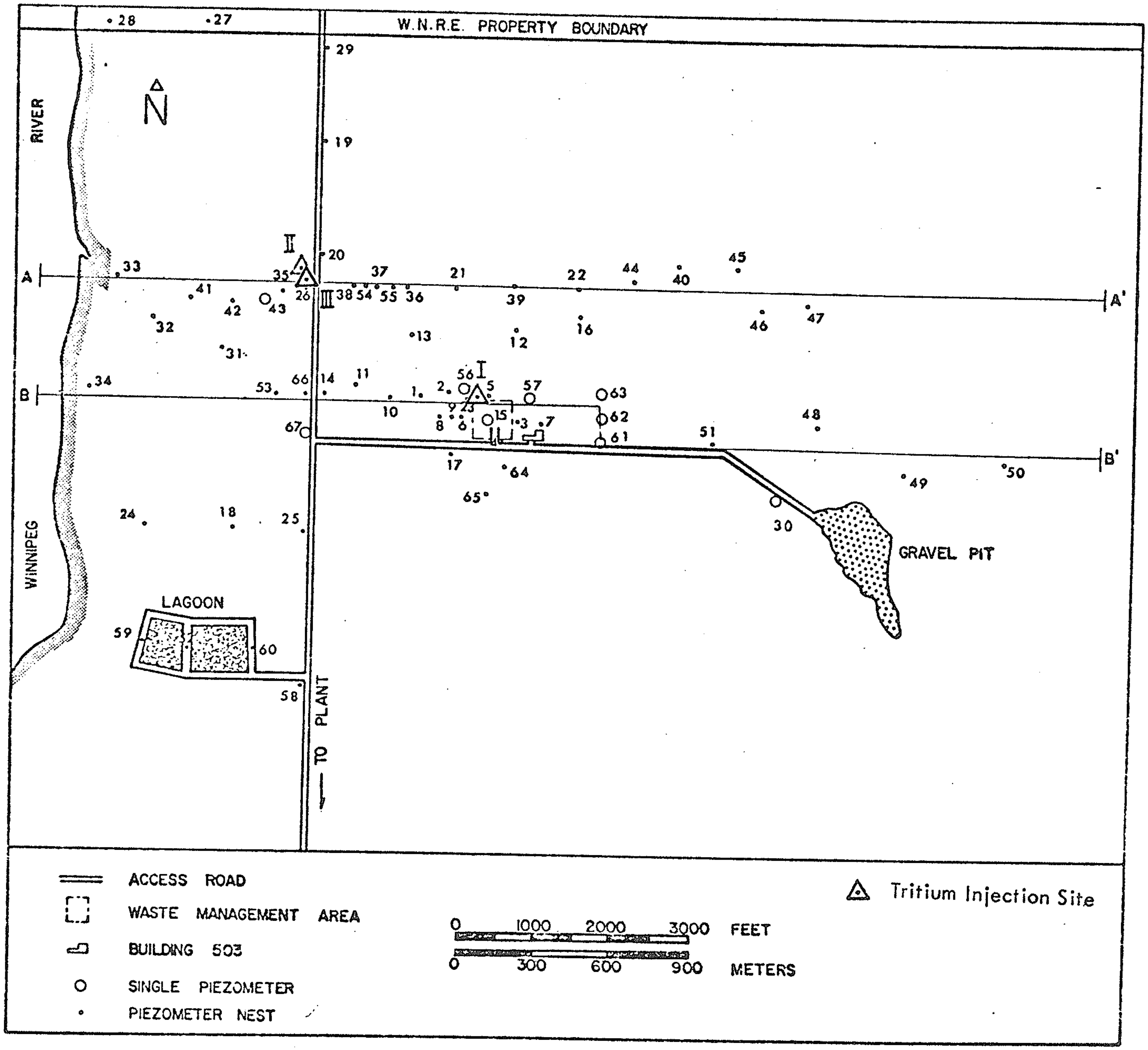


Figure 9. Piezometer installations within the WNRE study area.

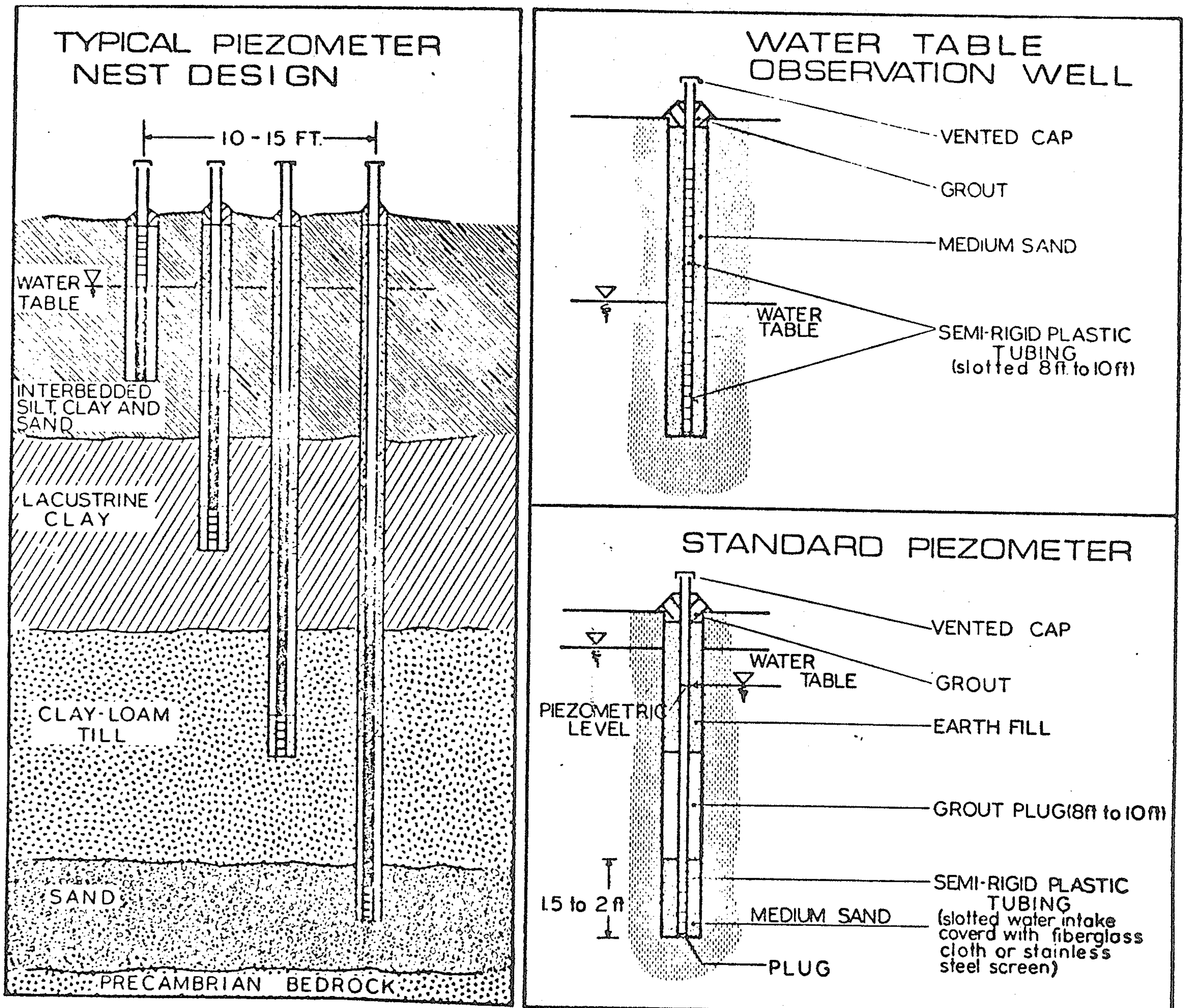


Figure 10. Construction details of plastic-walled piezometer and water-table installations (after Beswick, 1971).

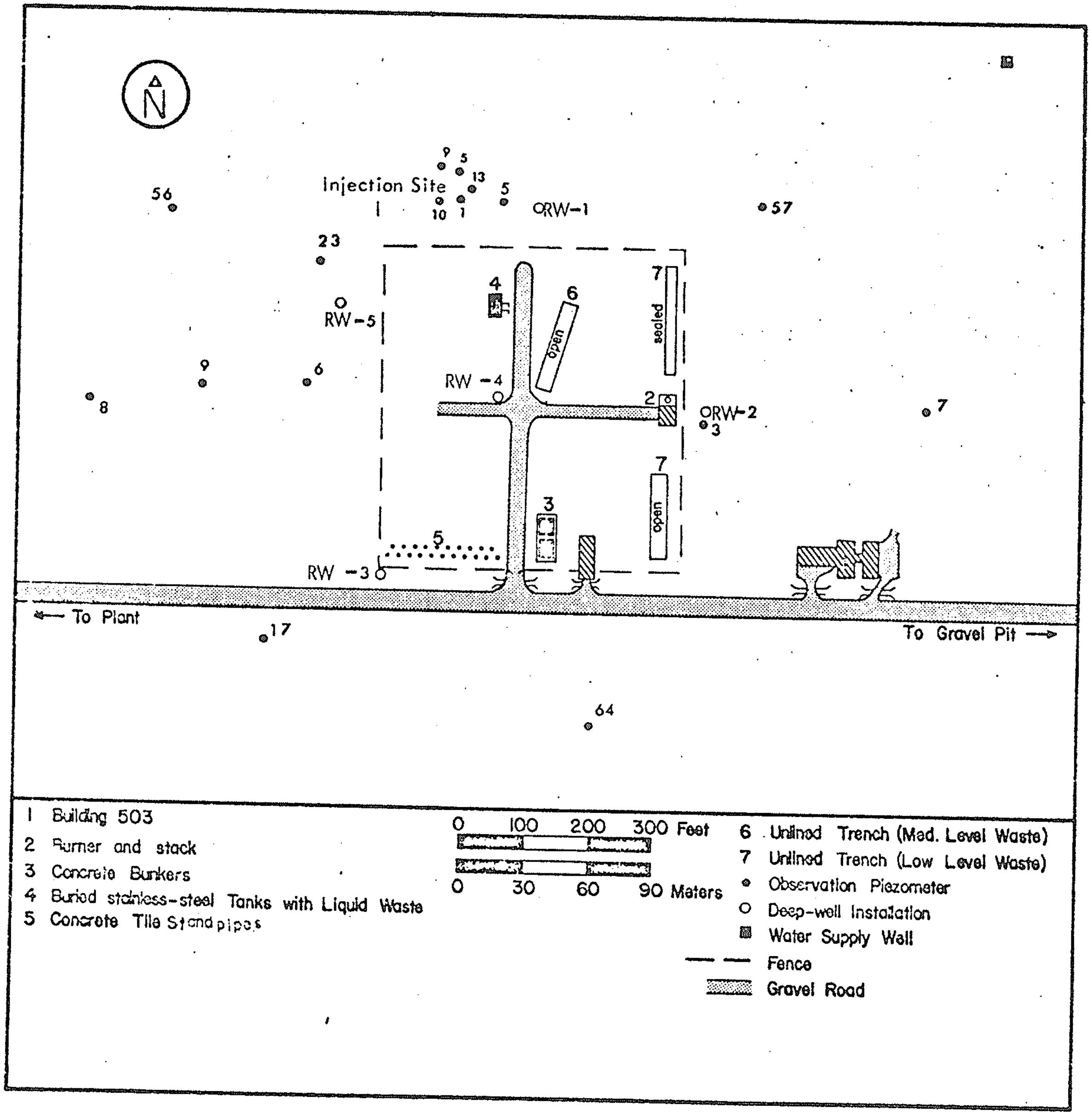


Figure 11. Locations of piezometers and observation/pump wells installed at the WNRE Waste Management Area.

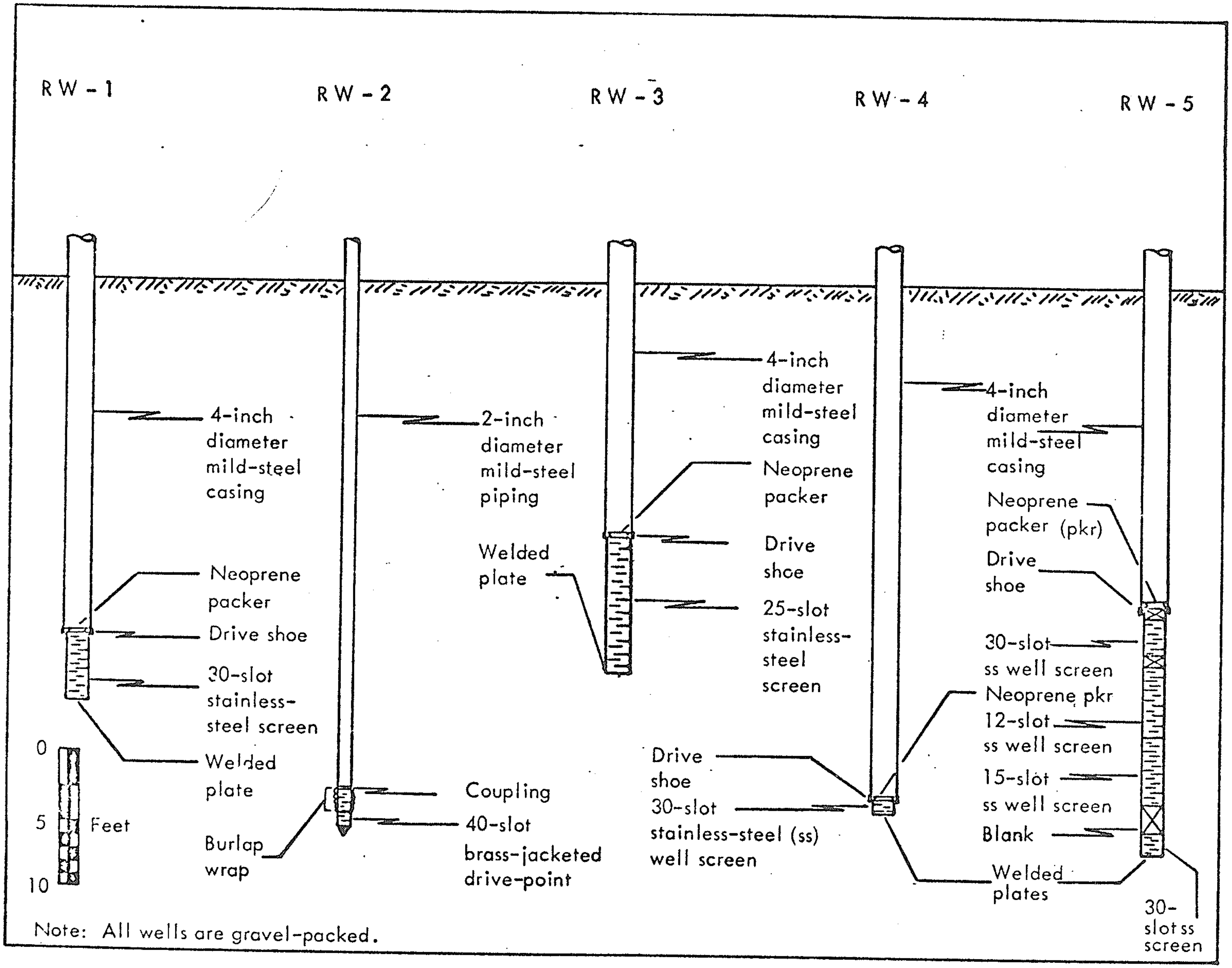


Figure 12. Construction details of the observation/pump wells installed at the WNRE Waste Management Area.

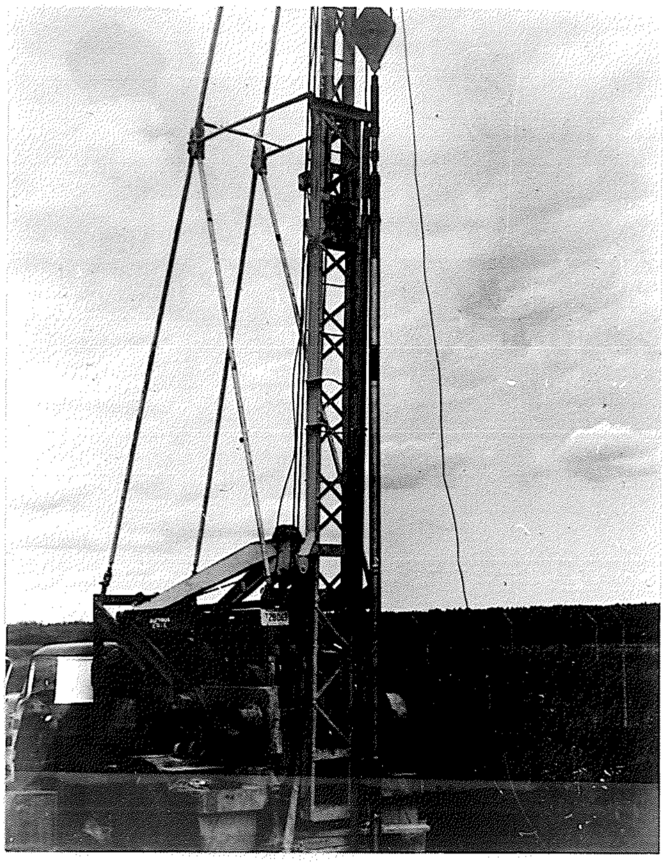


Figure 13. Installation of well screen at Recording Well RW-5.

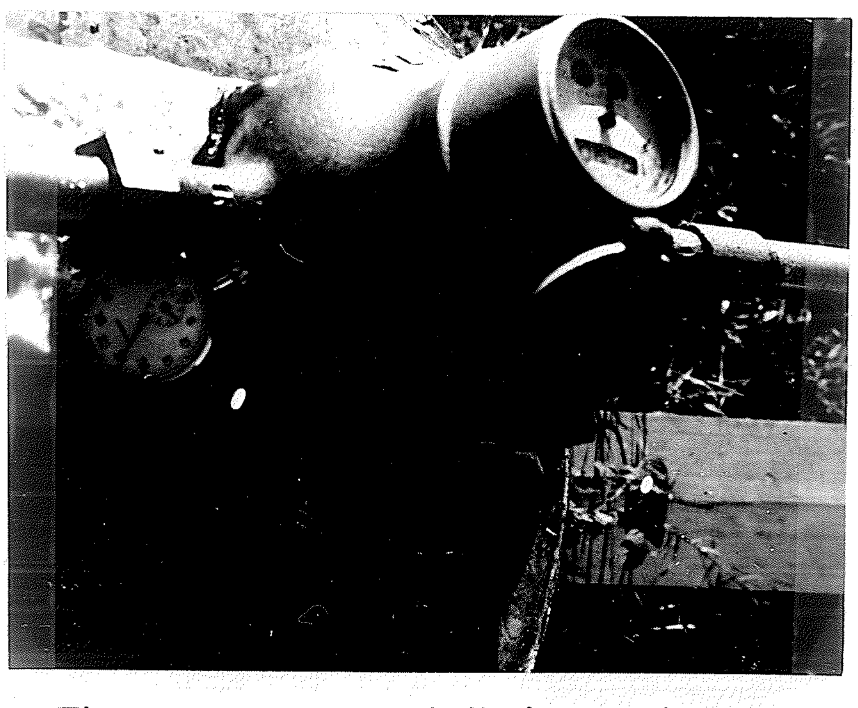


Figure 14. Flow rate meter and discharge pipe.

Figure 15. Aquifer pumping test of pump well RW-1.

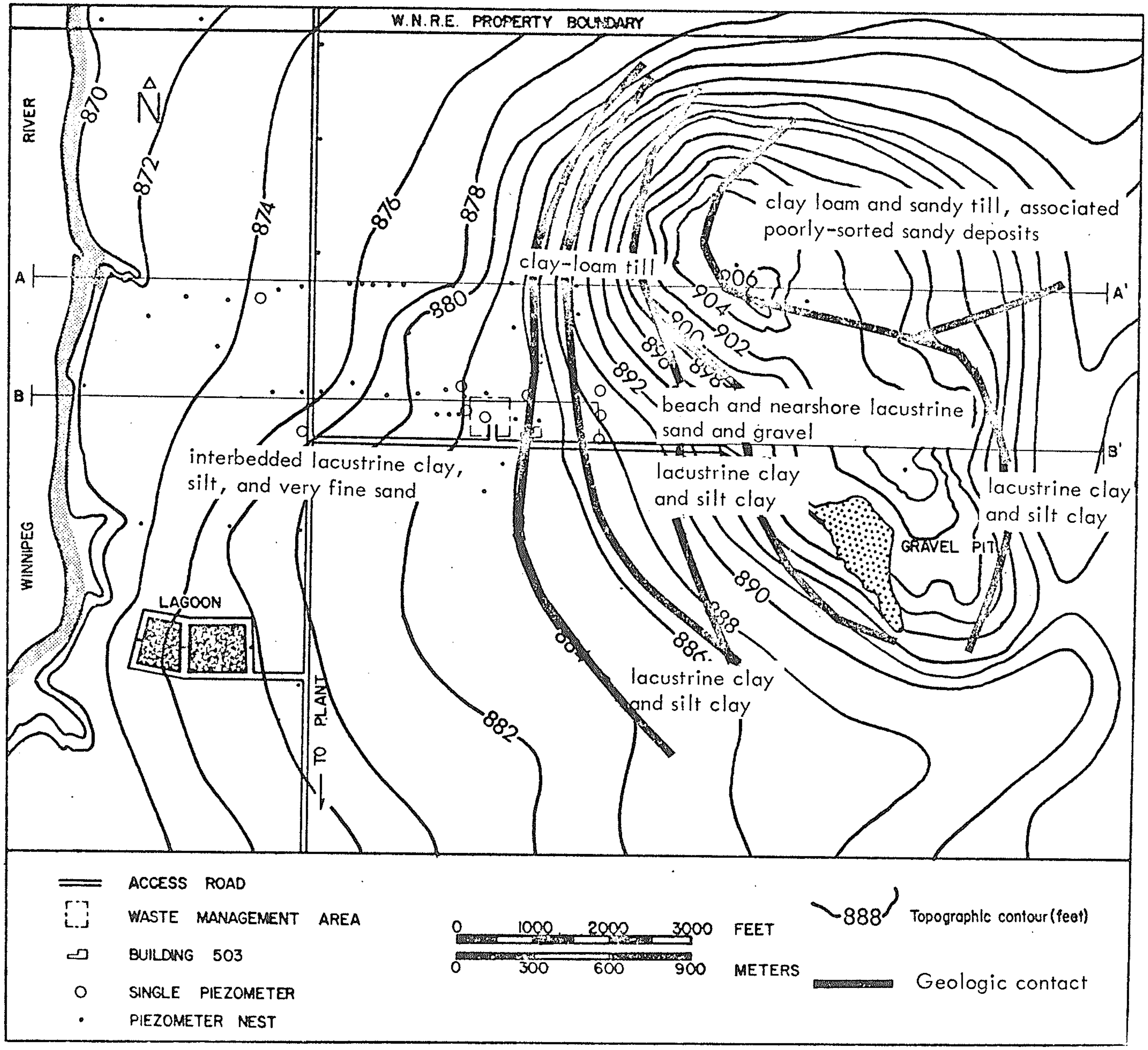


Figure 16. Surficial deposits of the WNRE study area.

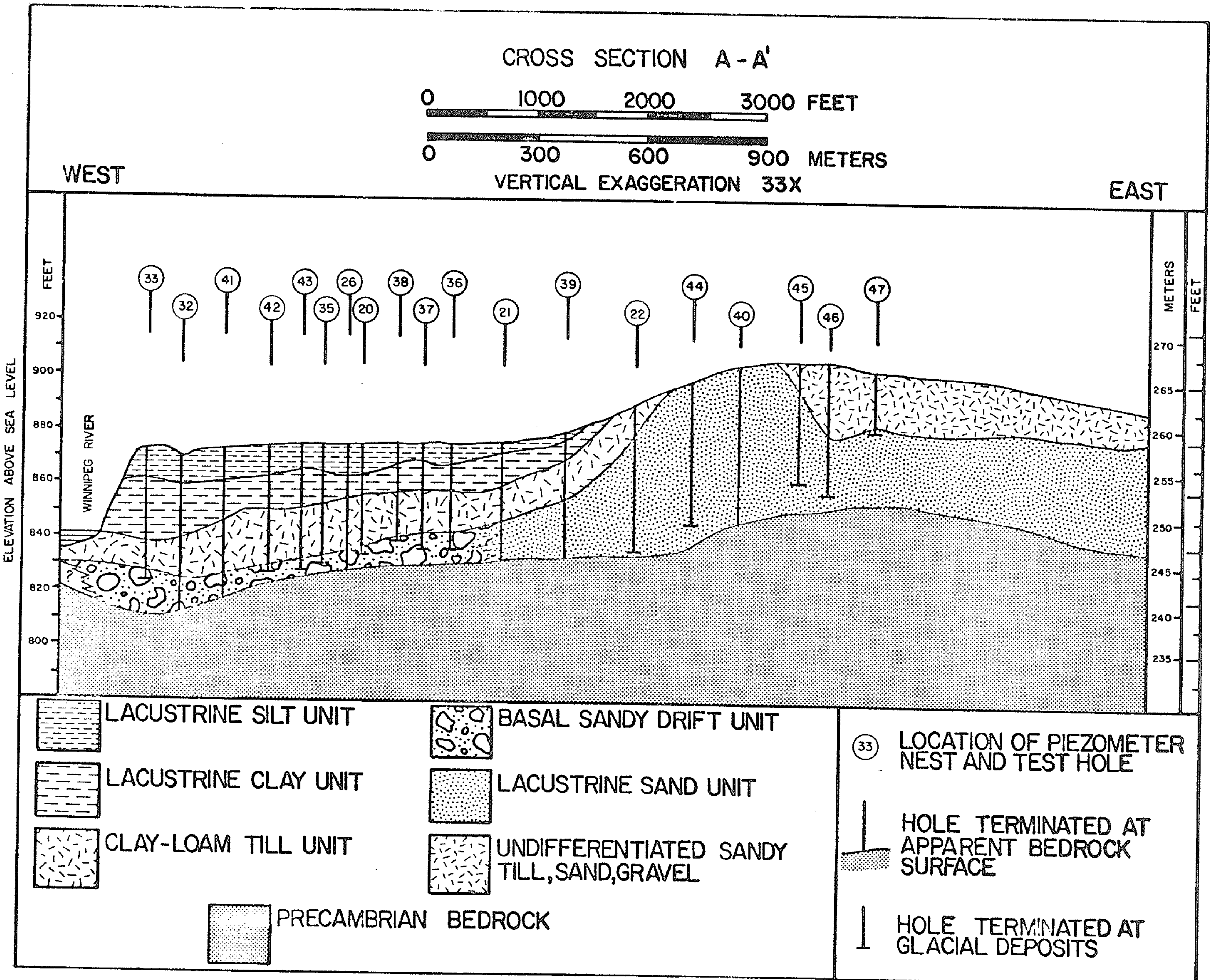


Figure 17. Stratigraphic cross section A - A' through the study area.

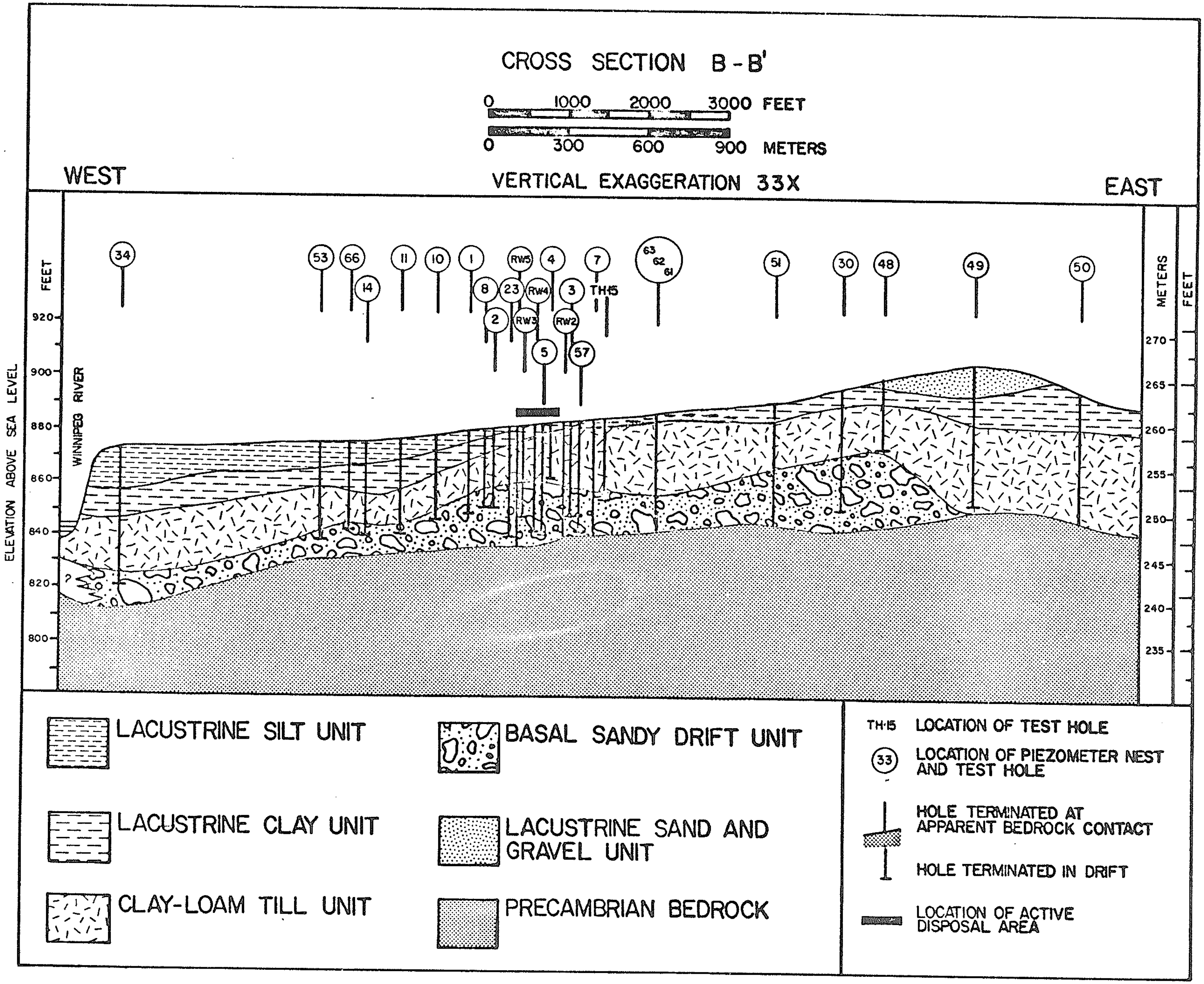


Figure 18. Stratigraphic cross section B - B' through the study area.

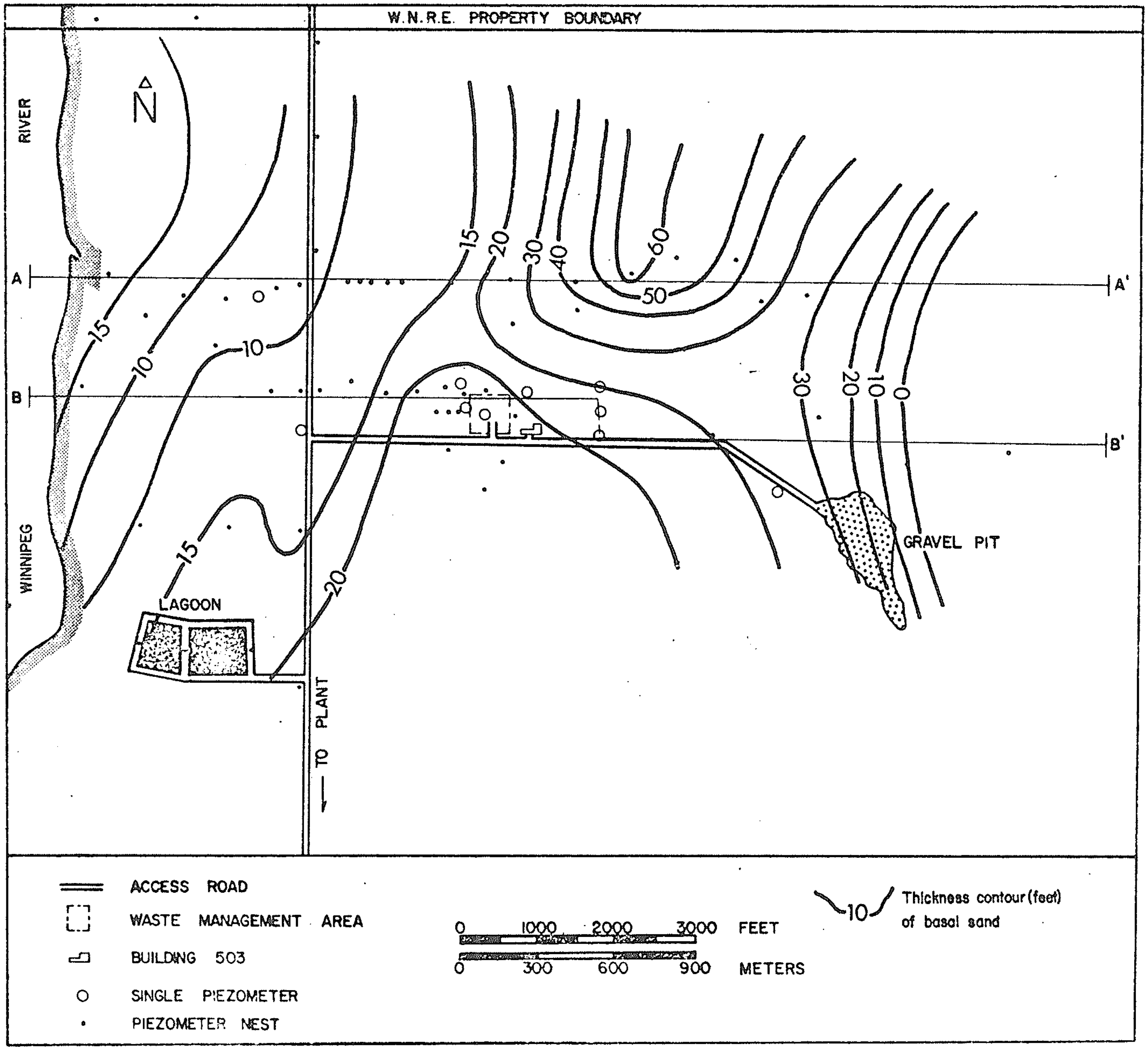


Figure 19. Isopach contour map of the basal sand units in the study area.

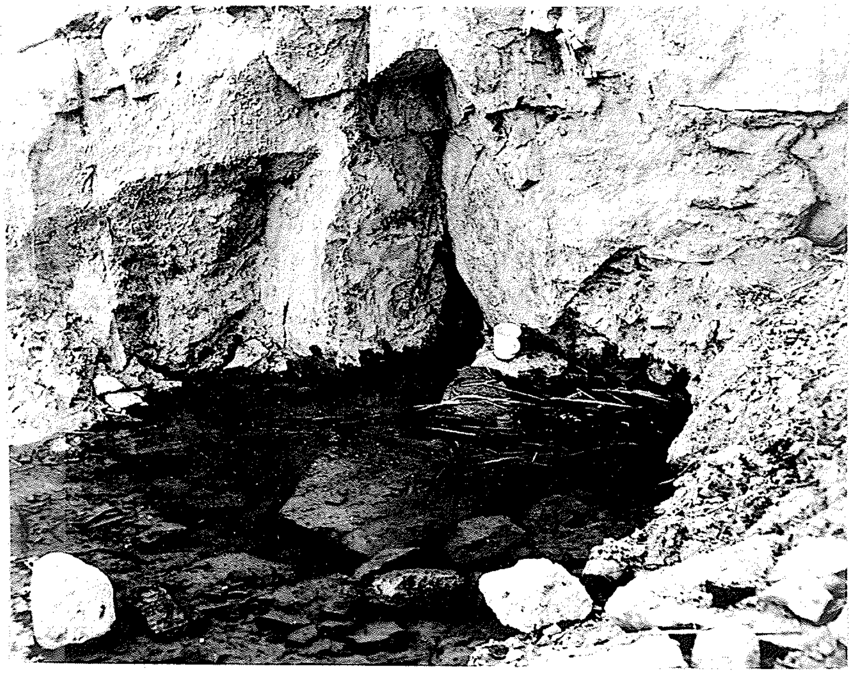


Figure 20. Exposed surface of Precambrian bedrock at the WNRE plant site excavation.

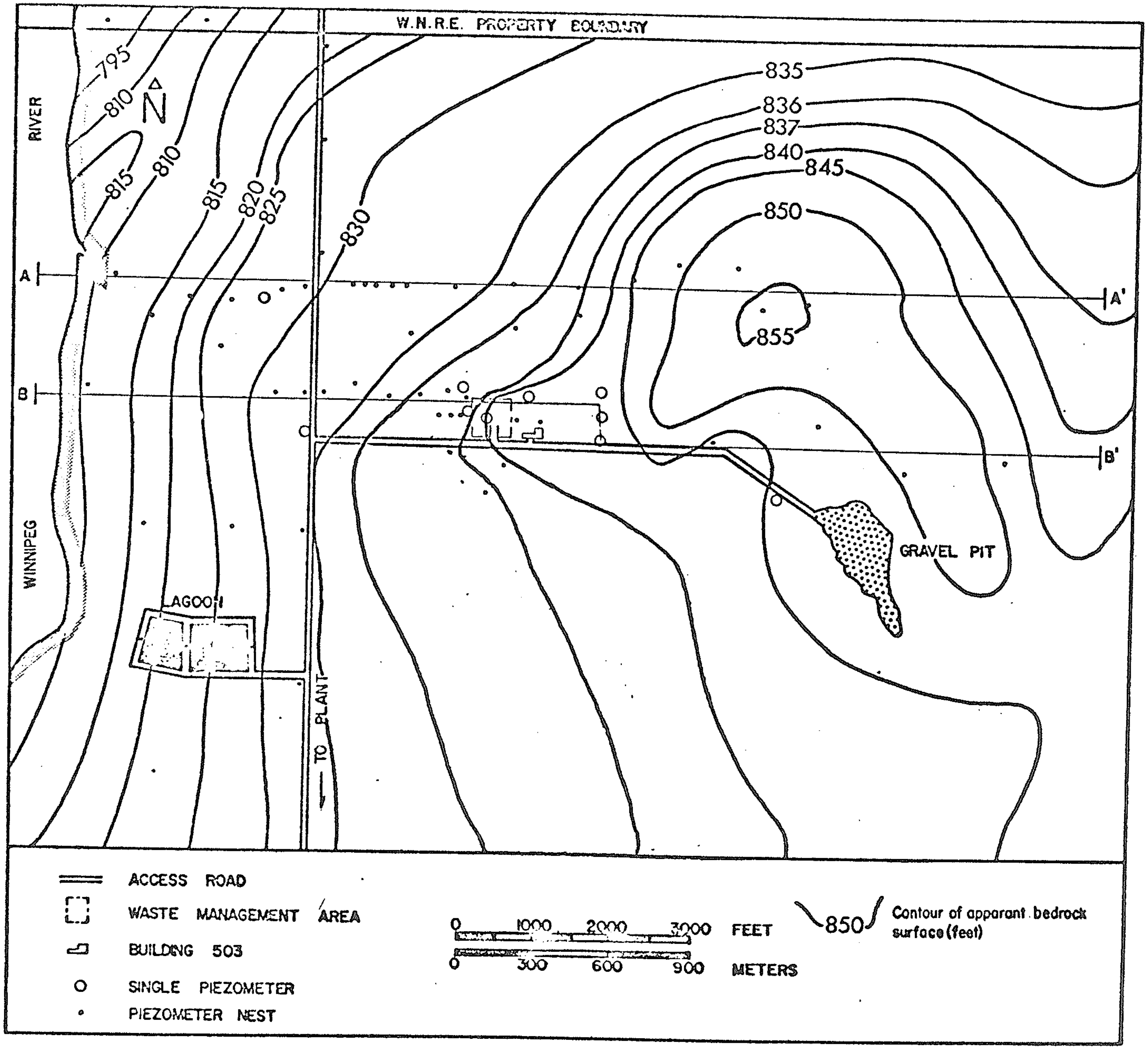


Figure 21. Contour map of the apparent WNRE bedrock surface.

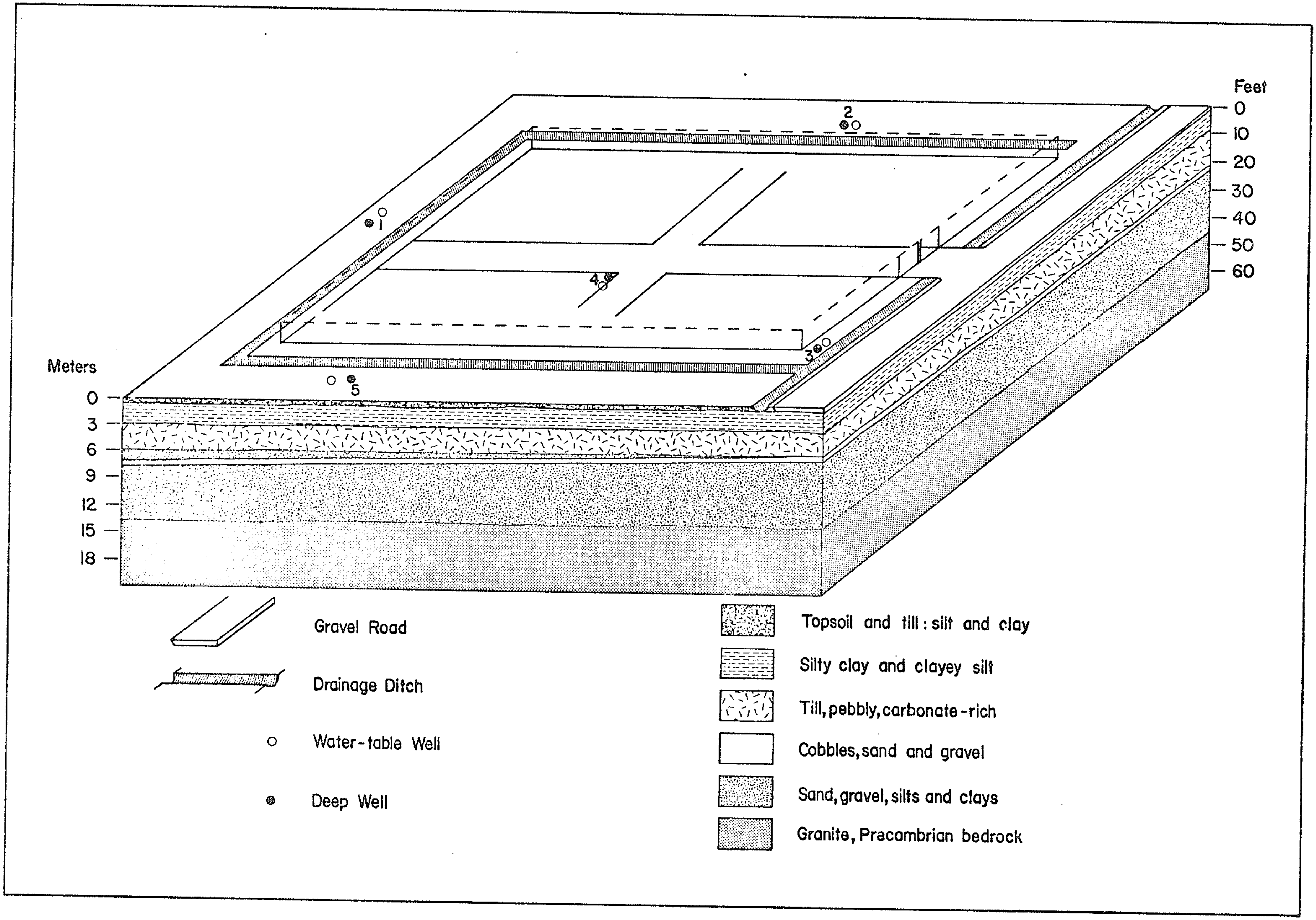


Figure 22. Well location and general lithology in the Waste Management Area.

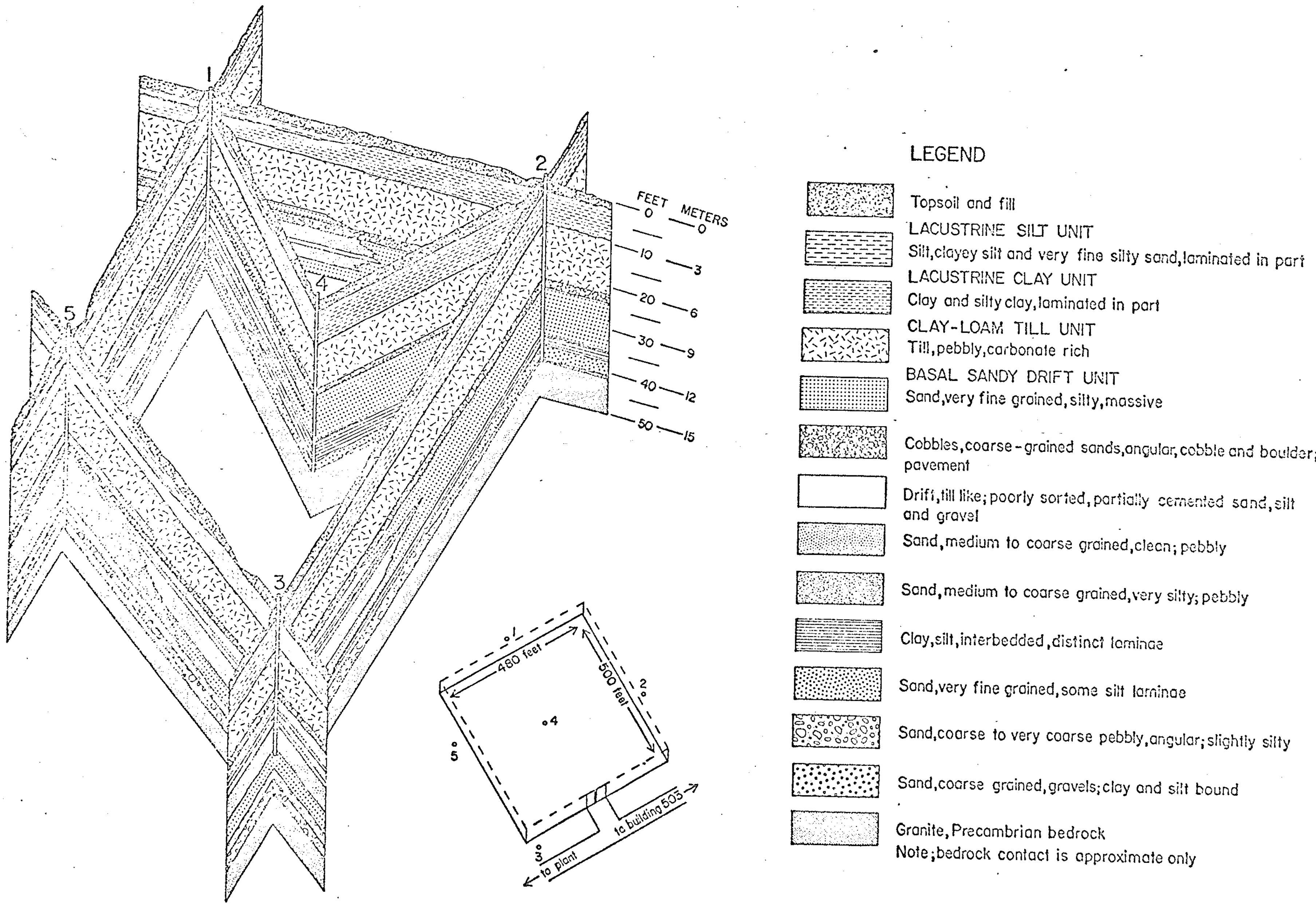


Figure 23. Fence diagram of the WNRE Waste Management Area stratigraphy.

Figure 24. Split-spoon cored sample of the basal sandy drift.

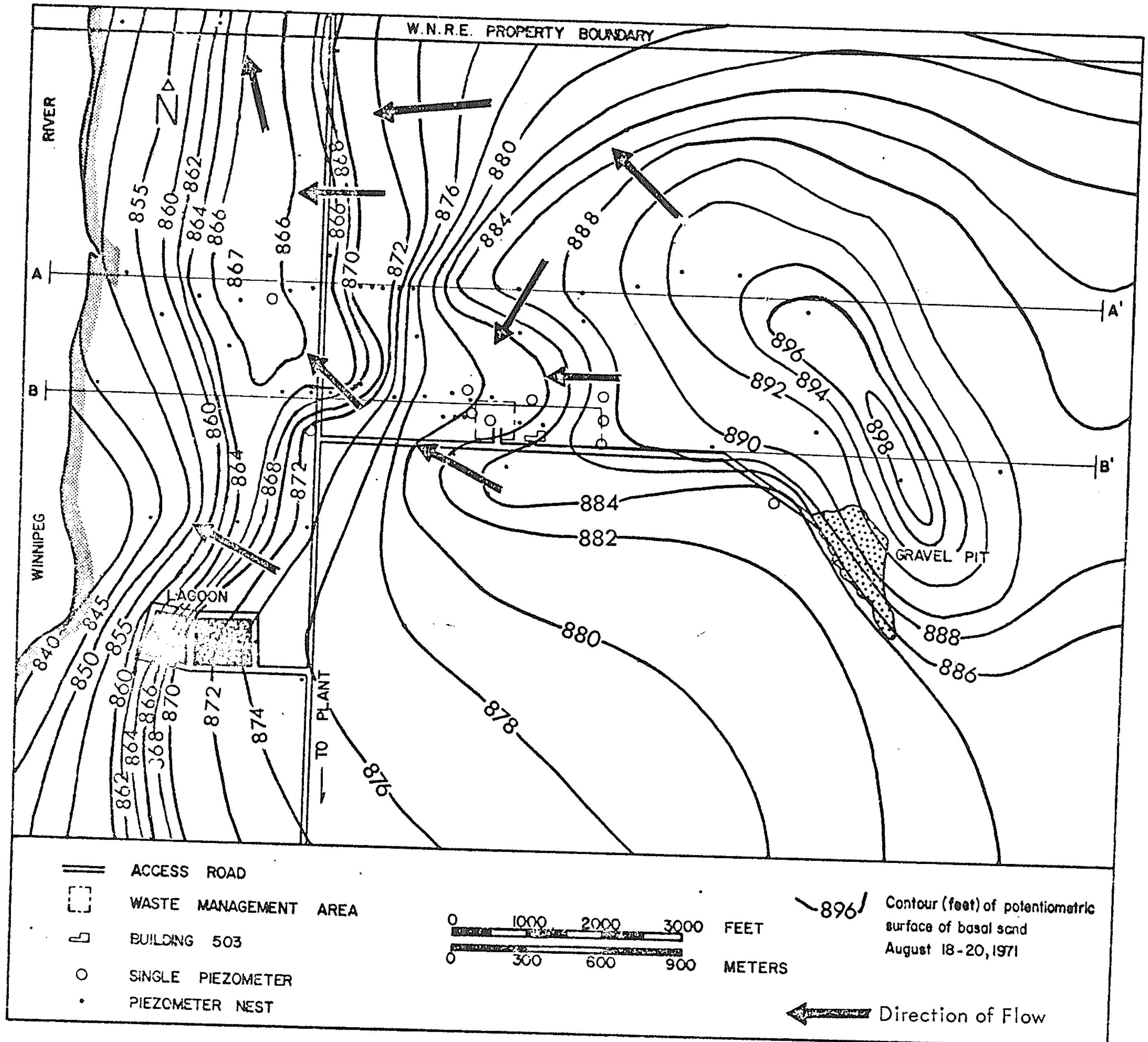


Figure 25. Contour of hydraulic head distribution in the basal sand aquifer.

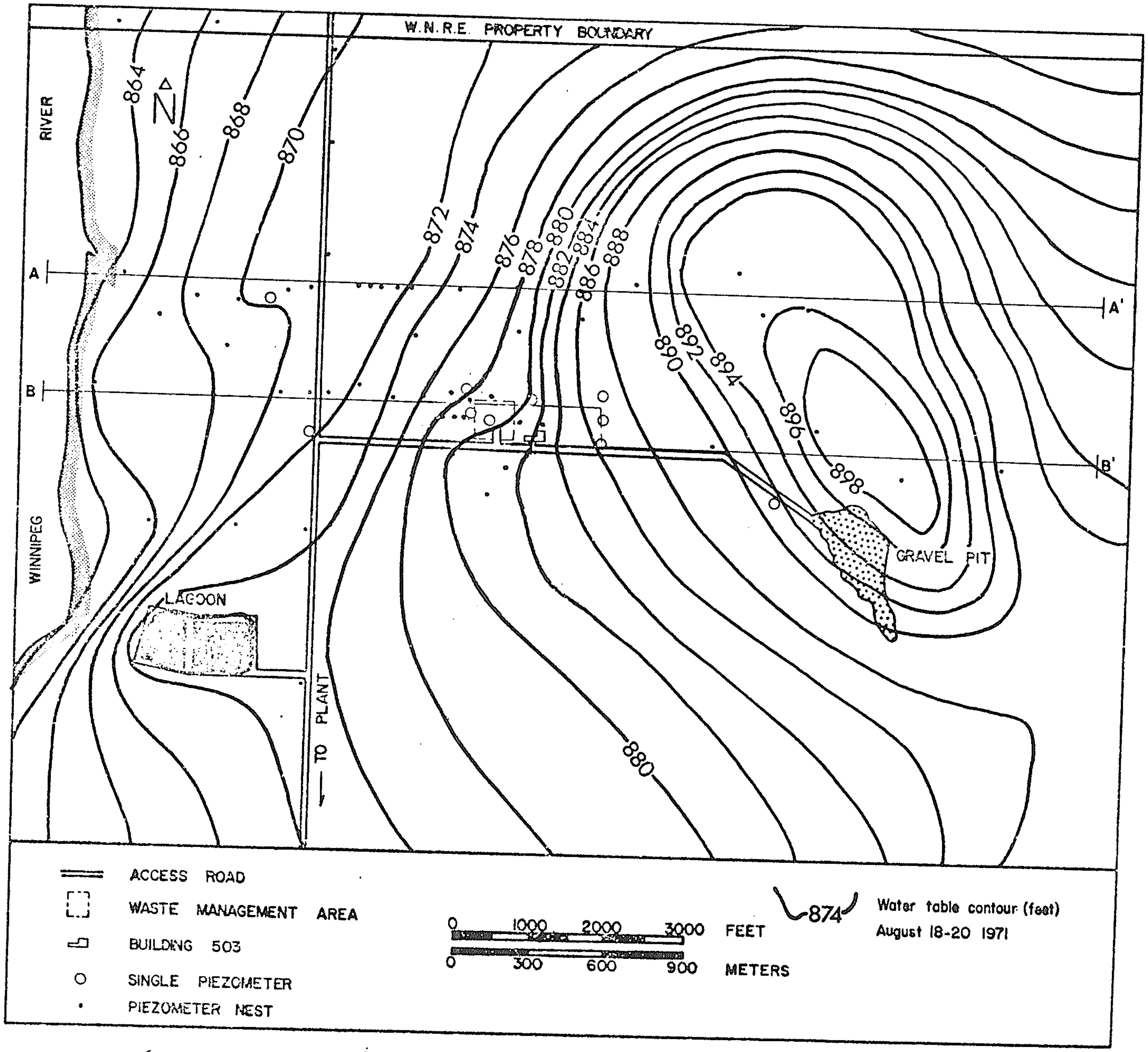


Figure 26. Contour of water-table elevations.

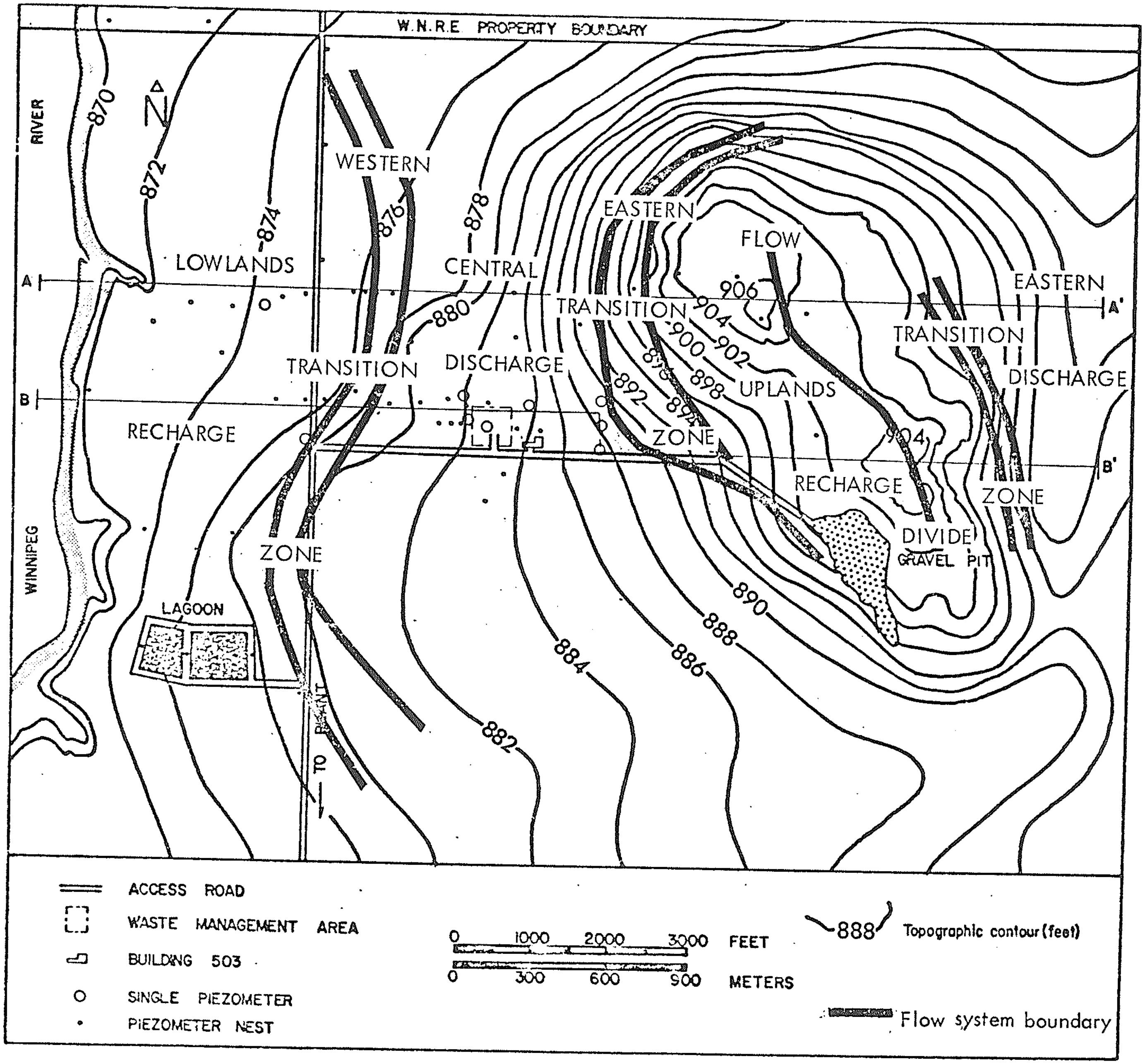


Figure 27. General pattern of the groundwater flow system.

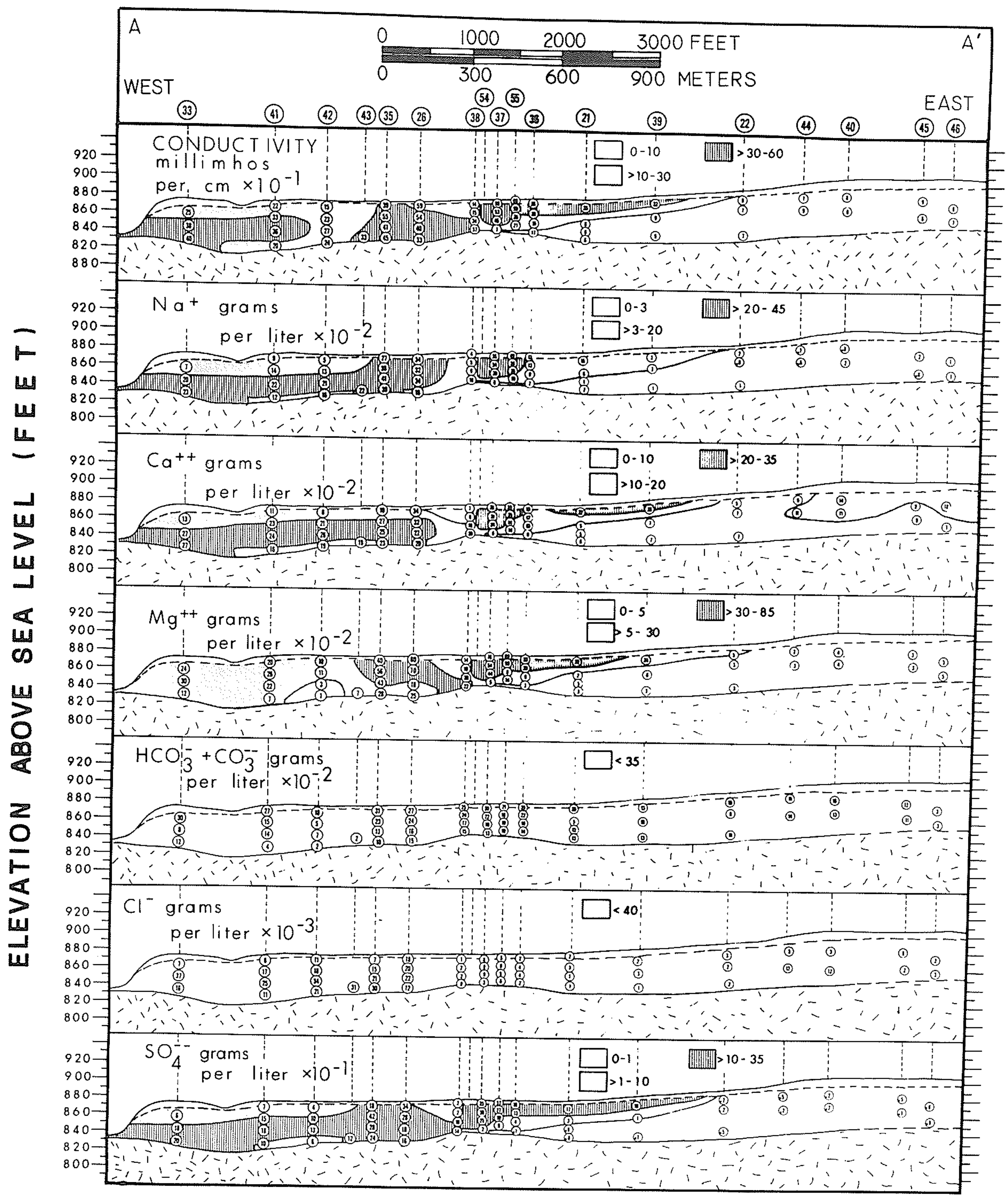


Figure 28. Hydrochemical concentration patterns along cross section A - A'.

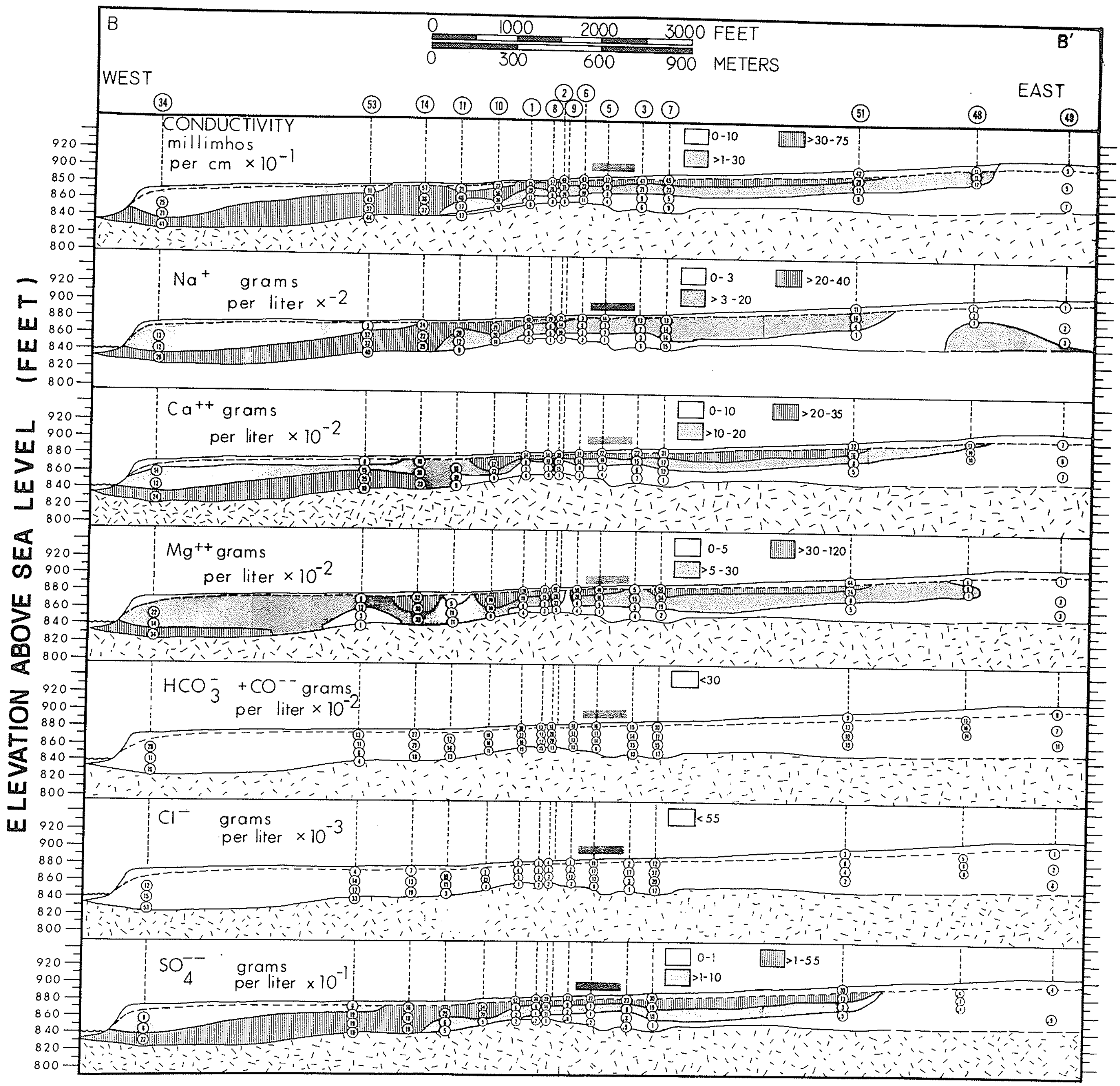


Figure 29. Hydrochemical concentration patterns along cross section B - B'.

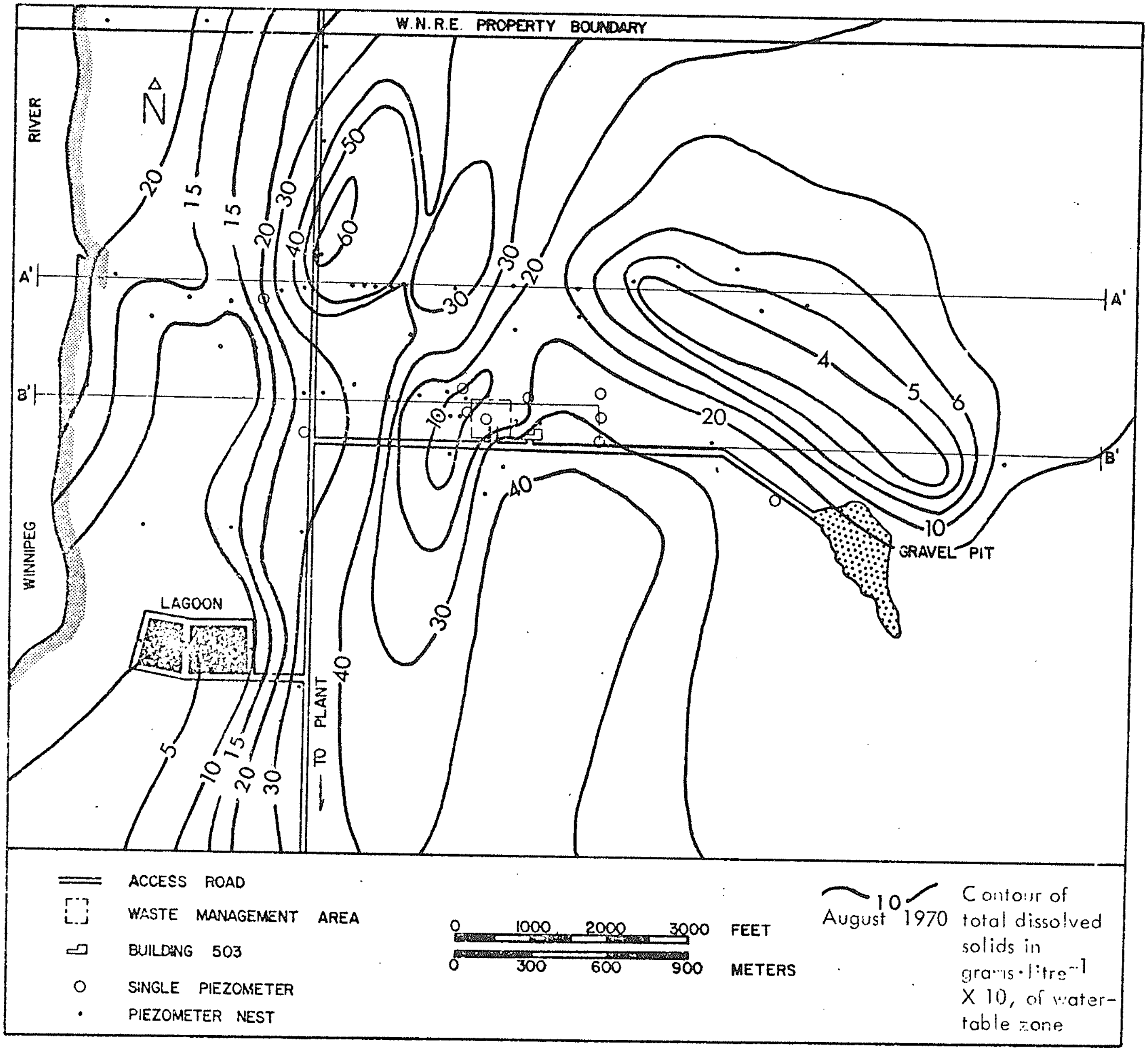


Figure 30. Contour of total dissolved solids in the water table.

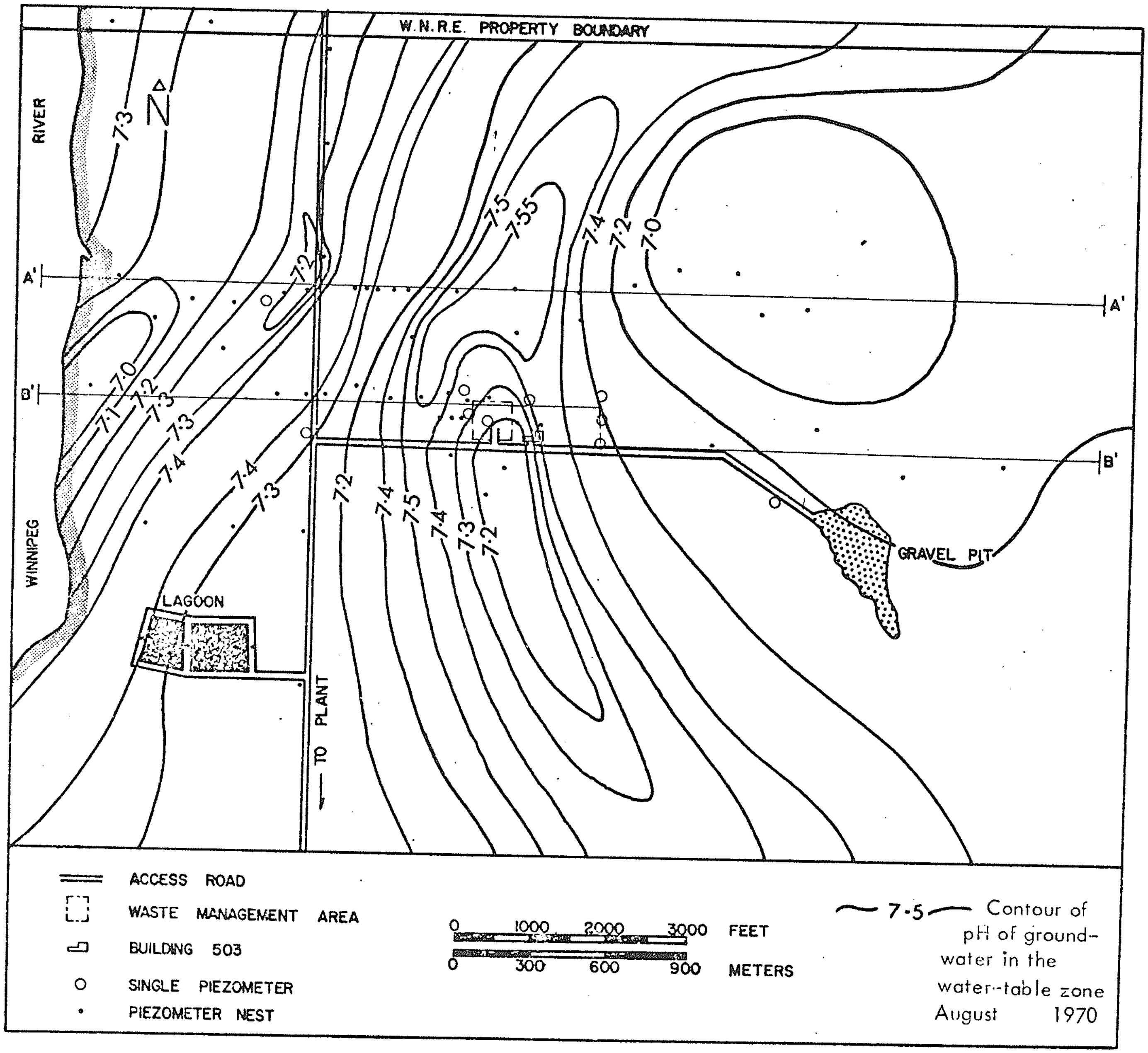


Figure 31. Contour of water-table pH.

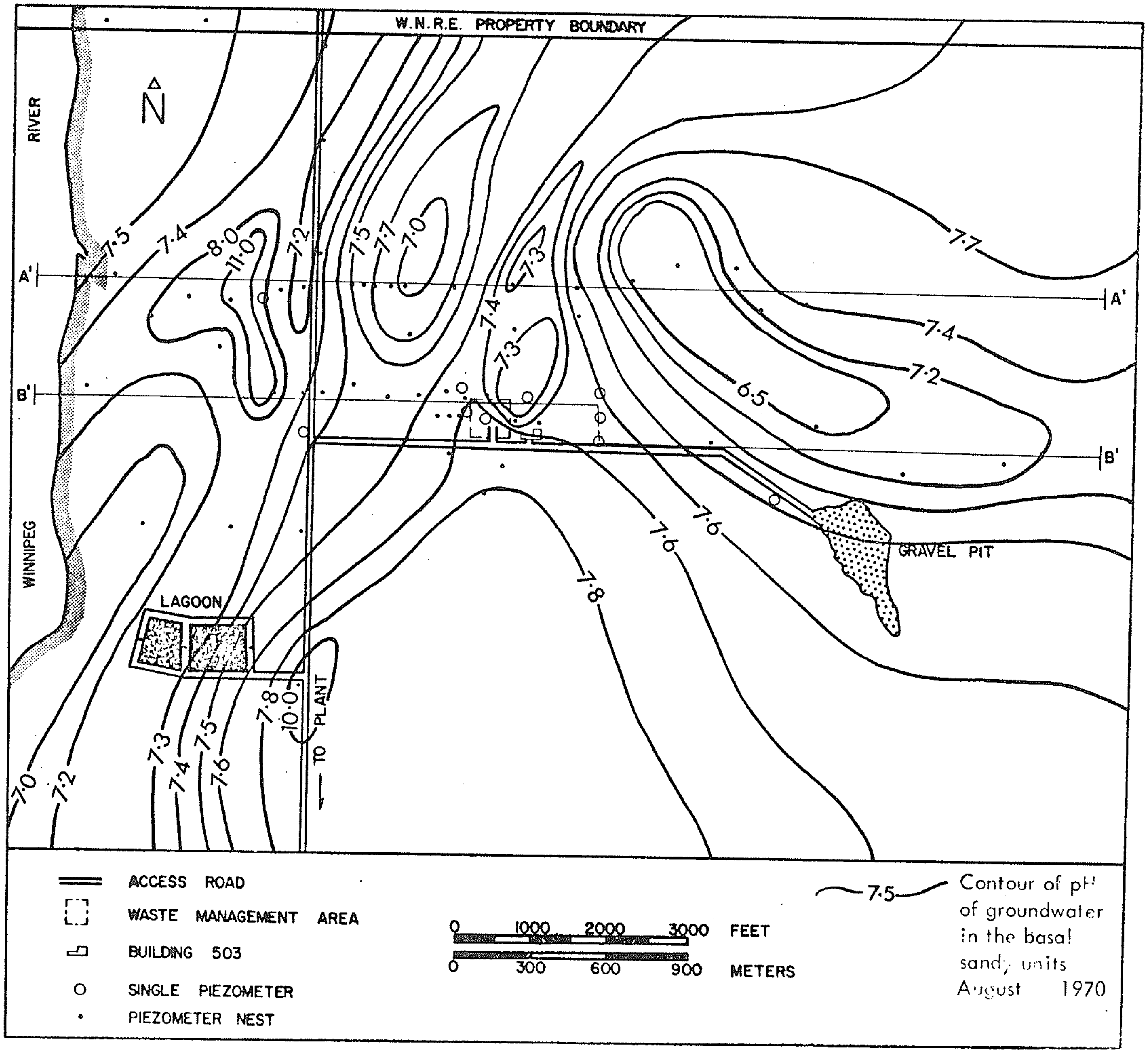


Figure 32. Contour of groundwater pH in the basal sand aquifer.

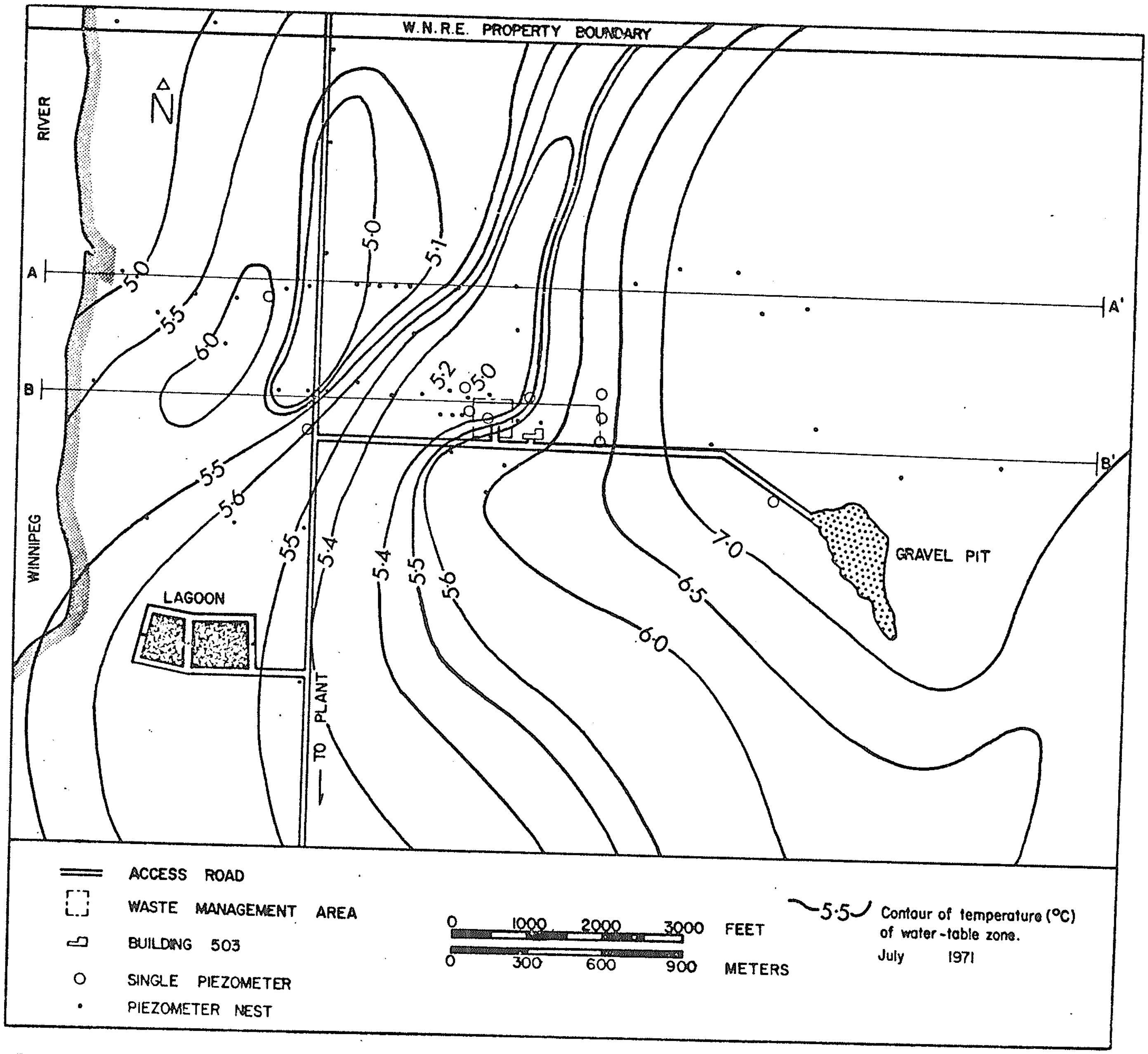


Figure 33. Contour of groundwater temperature in the water table.

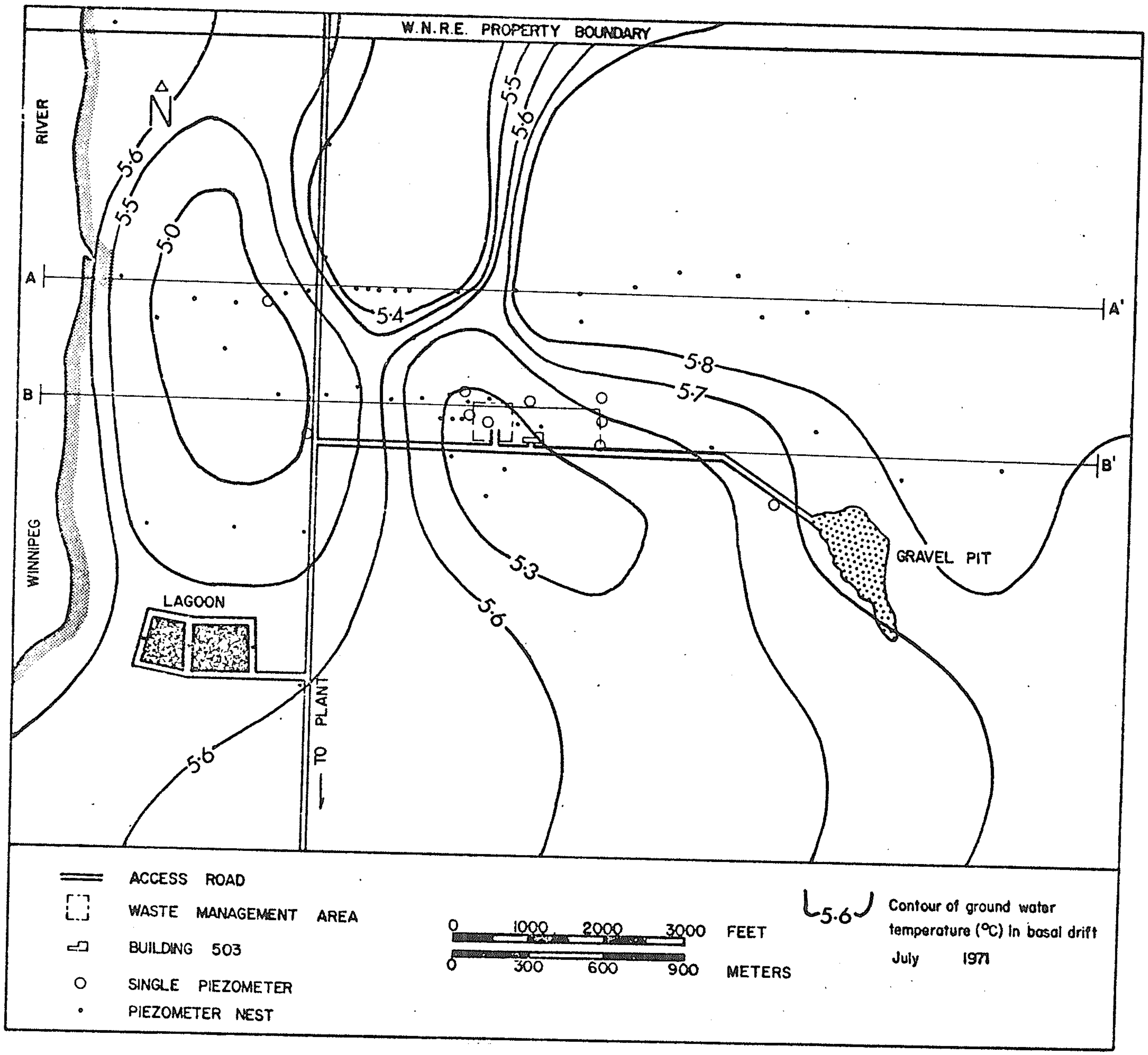


Figure 34. Contour of groundwater temperature in the basal sandy drift.

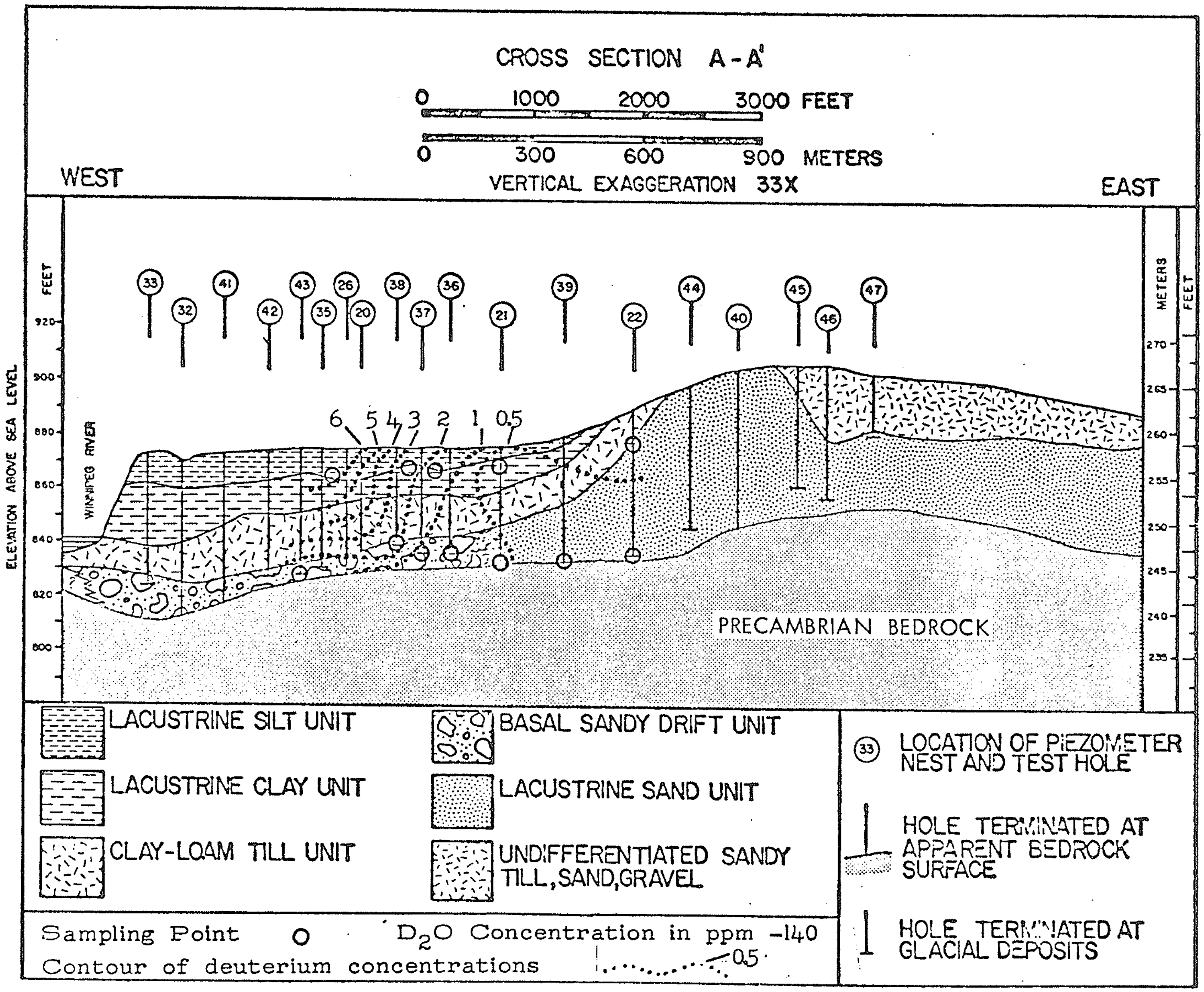


Figure 35. Deuterium concentrations along cross section A - A'.

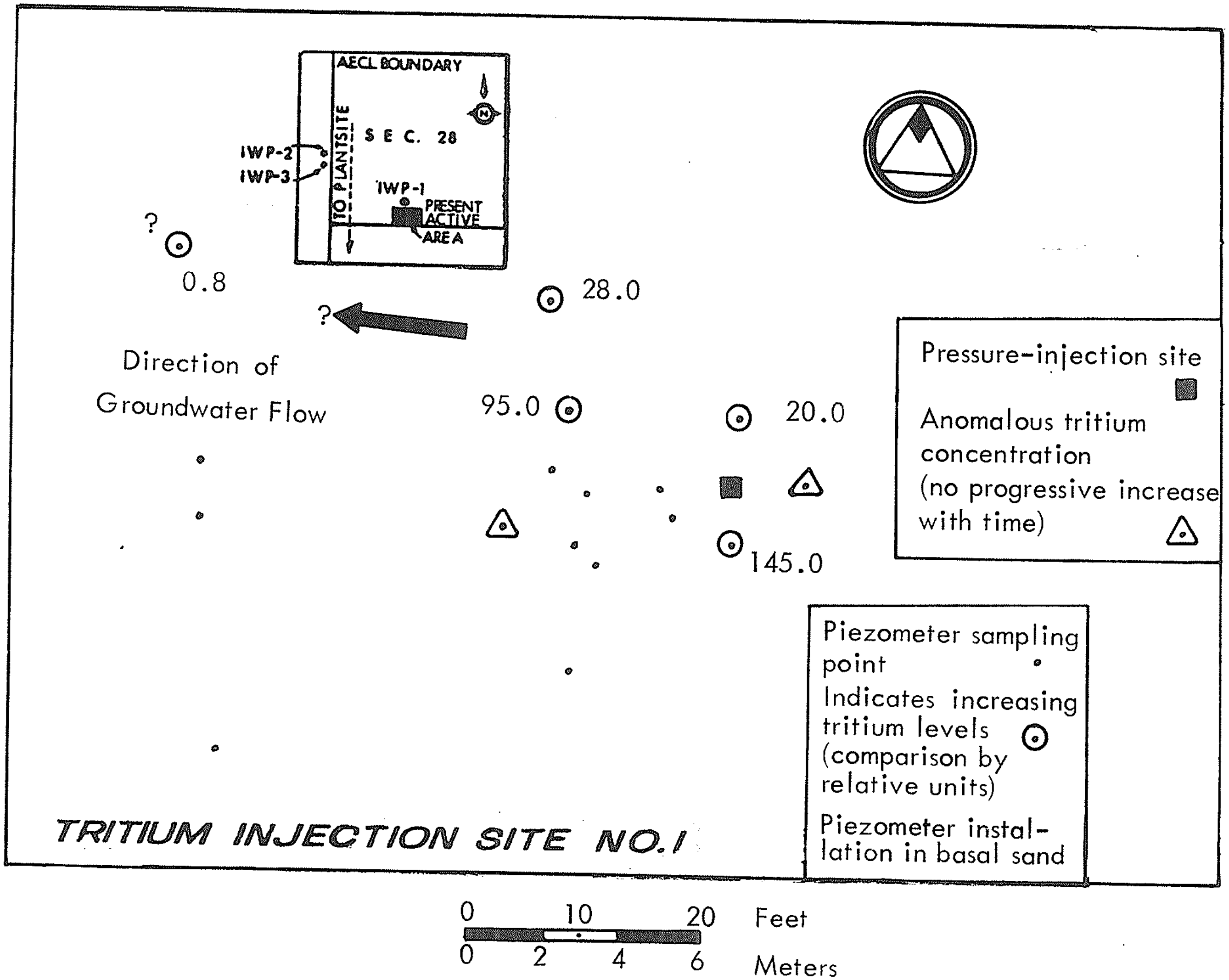


Figure 36. Groundwater flow movement in the basal sandy drift traced by pressure-injected tritiated water, Site I.

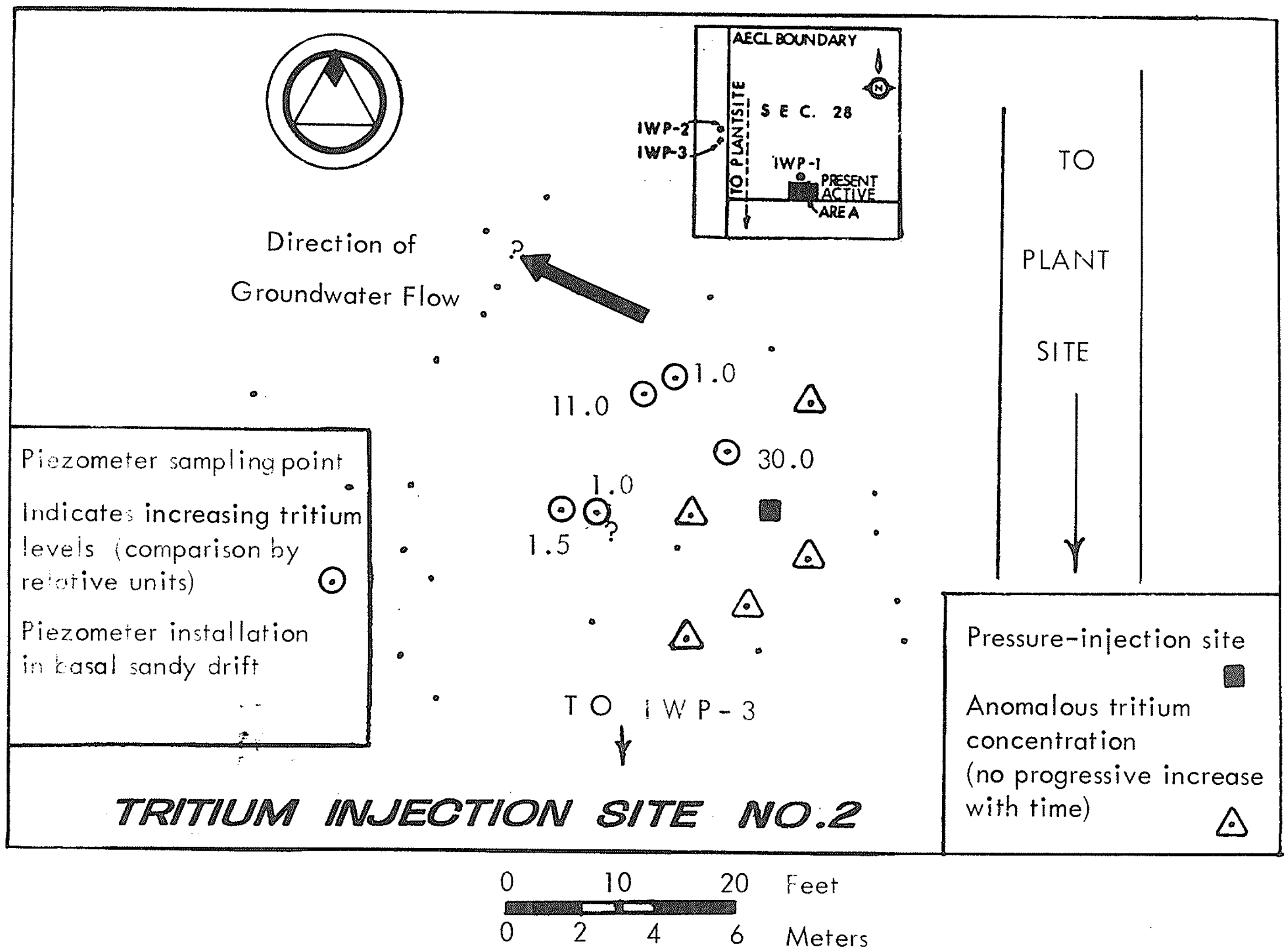


Figure 37. Groundwater flow movement in the basal sandy drift traced by pressure-injected tritiated water, Site II.

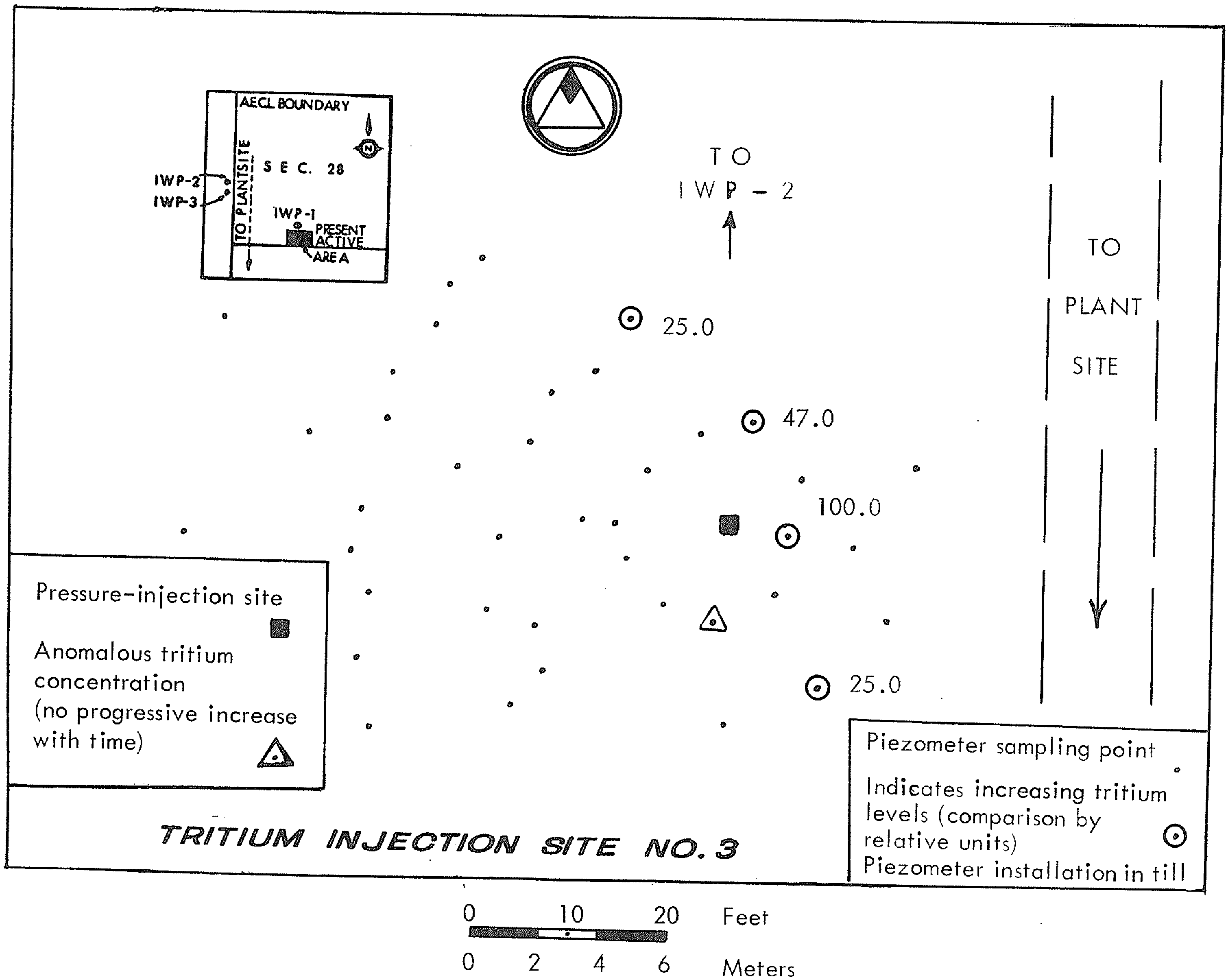


Figure 38. Groundwater flow movement in the clay-loam till traced by pressure-injected tritiated water, Site III.

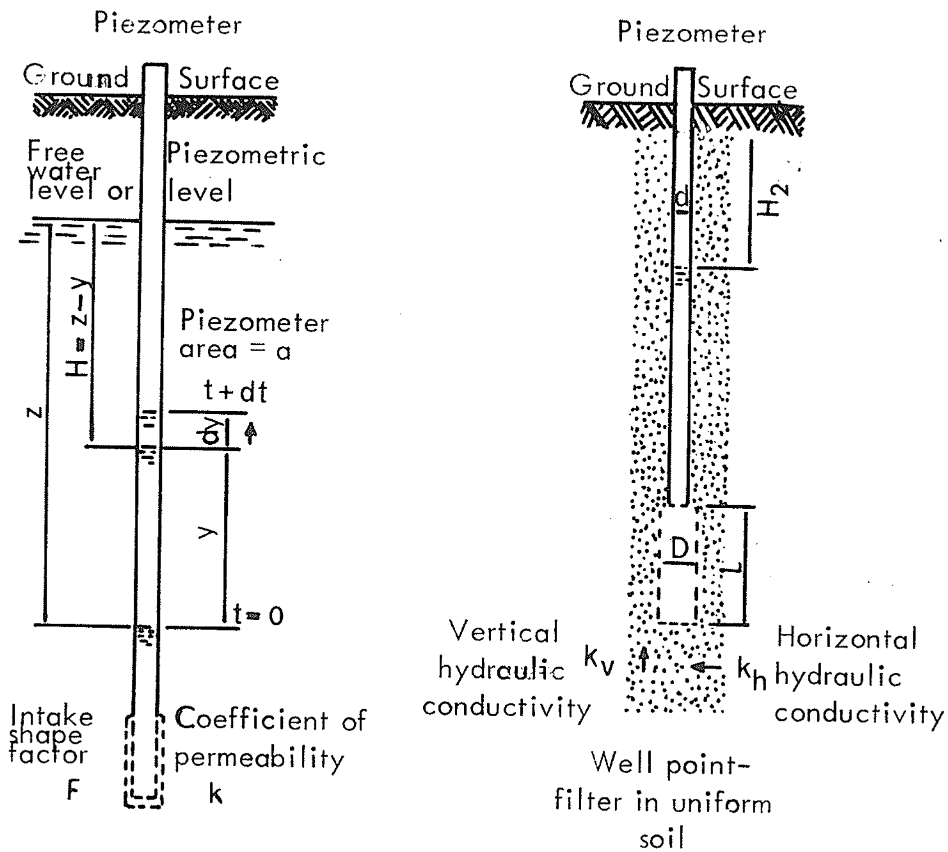


Figure 39. Factors in the Hvorslev method of determining hydraulic conductivity (after Hvorslev, 1951).

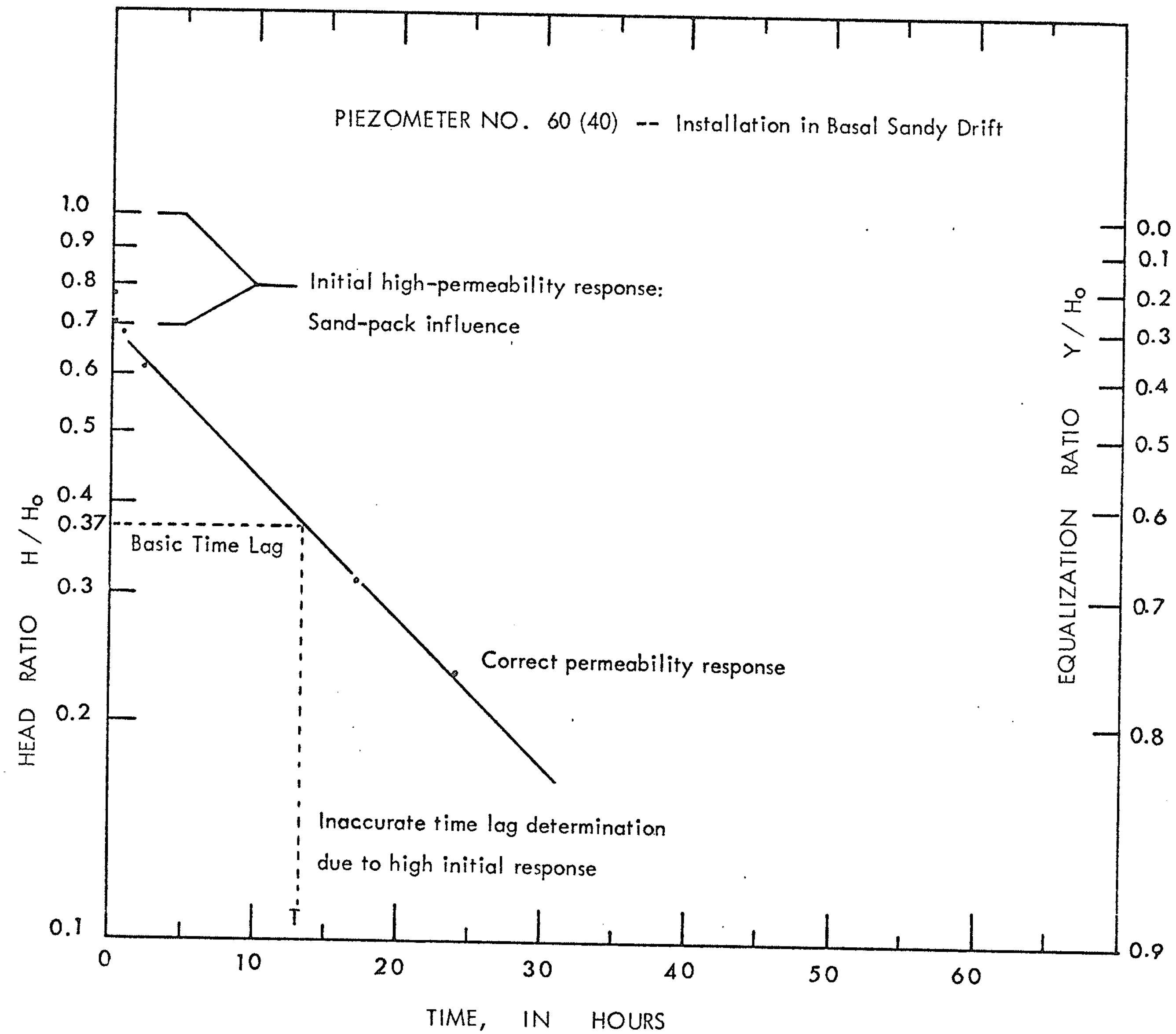


Figure 40. Relation of head and equalization ratios to time.

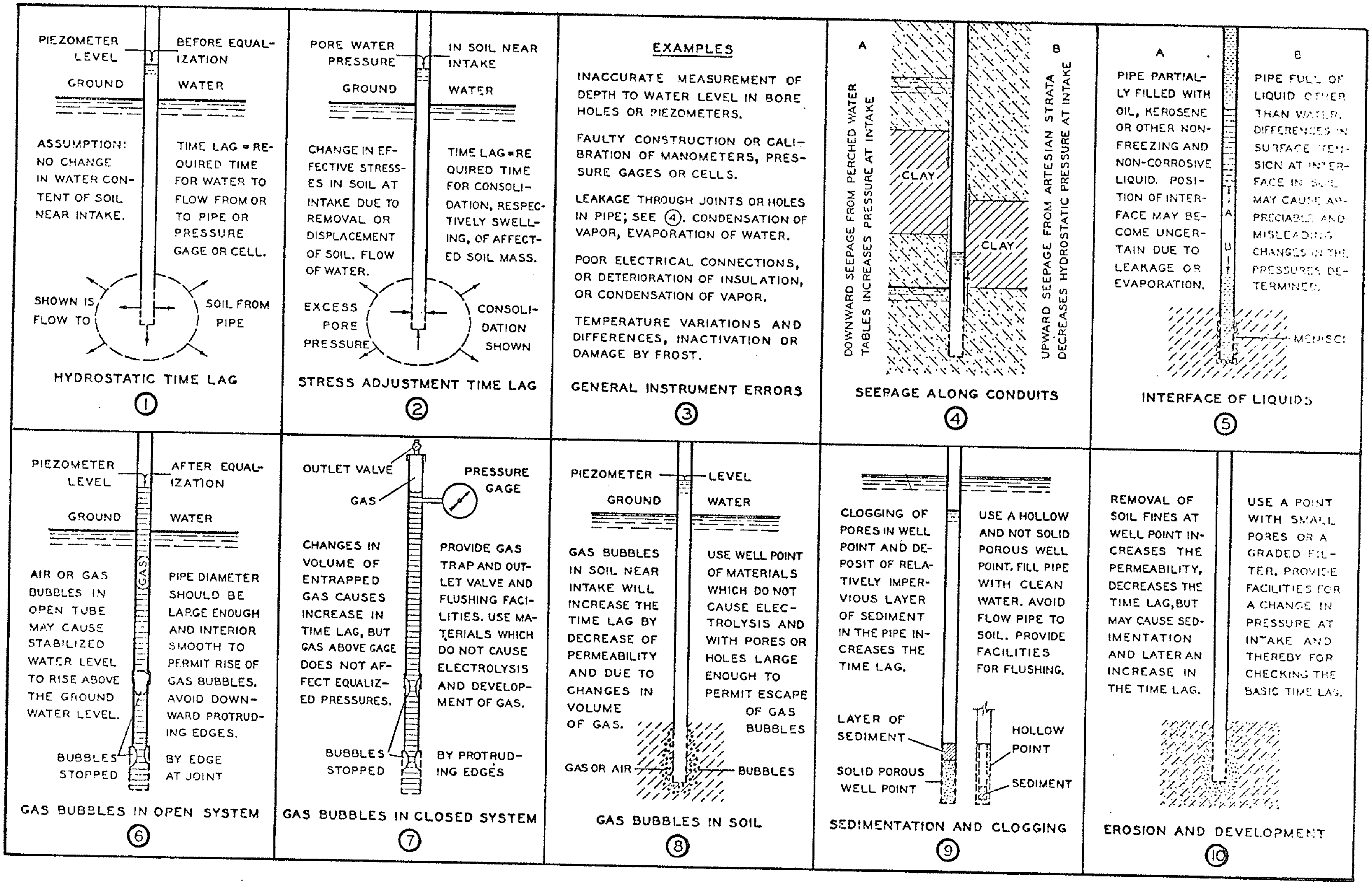
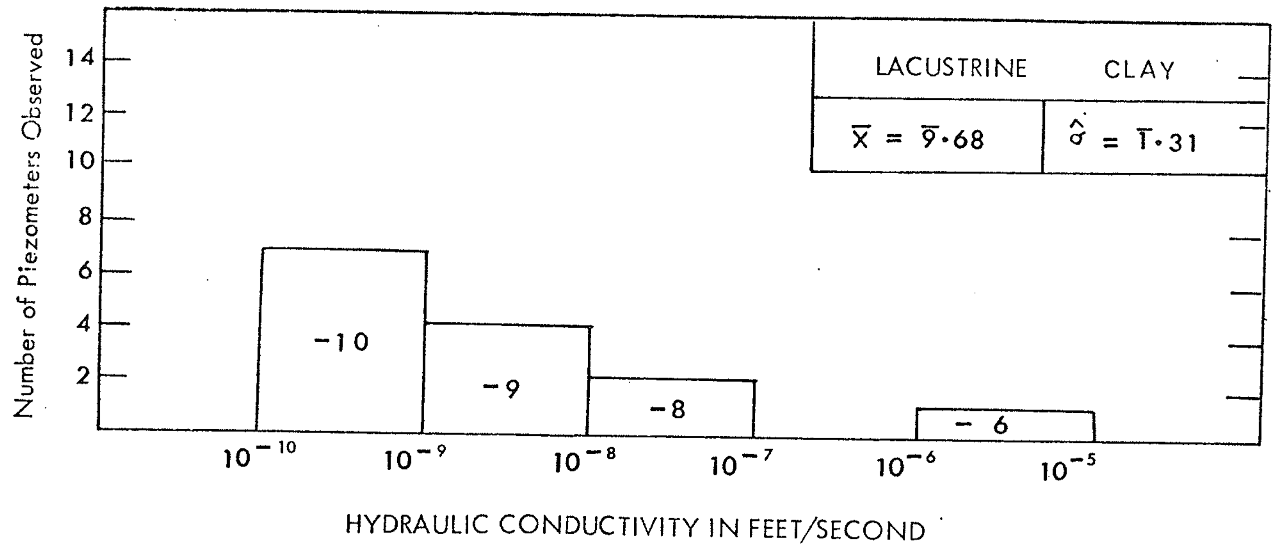
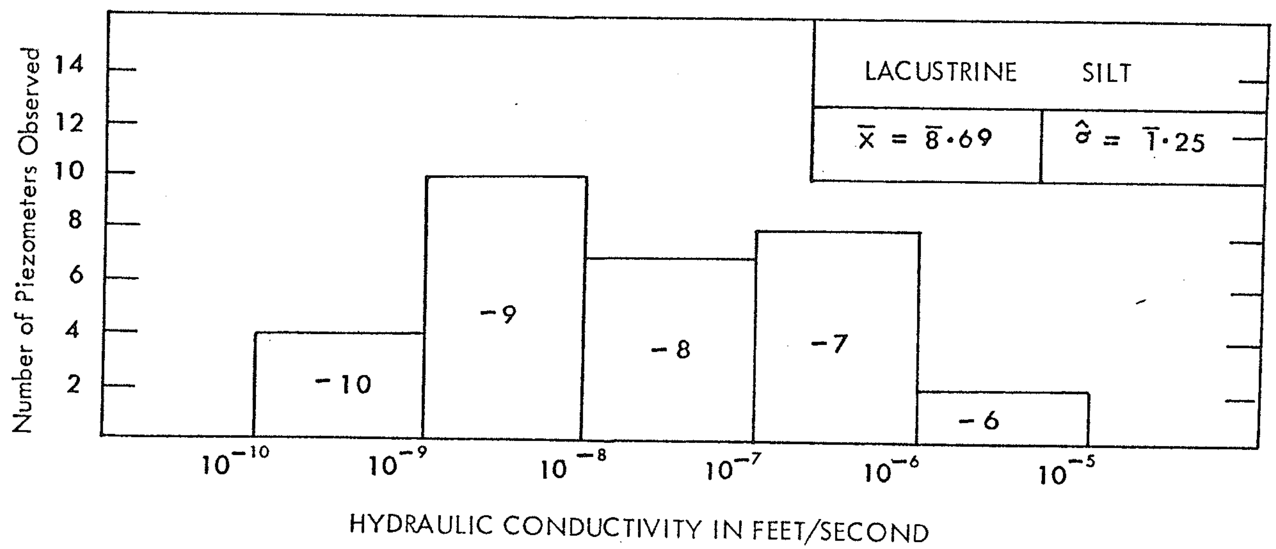


Figure 41. Possible cause for error in the Hvorslev calculation (after Hvorslev, 1951).





$\bar{X}$ = Unbiased estimate of logarithmic mean

$\hat{\sigma}$ = Logarithmic population standard deviation

Figure 42. Hvorslev horizontal hydraulic conductivities in the lacustrine silts and clays.

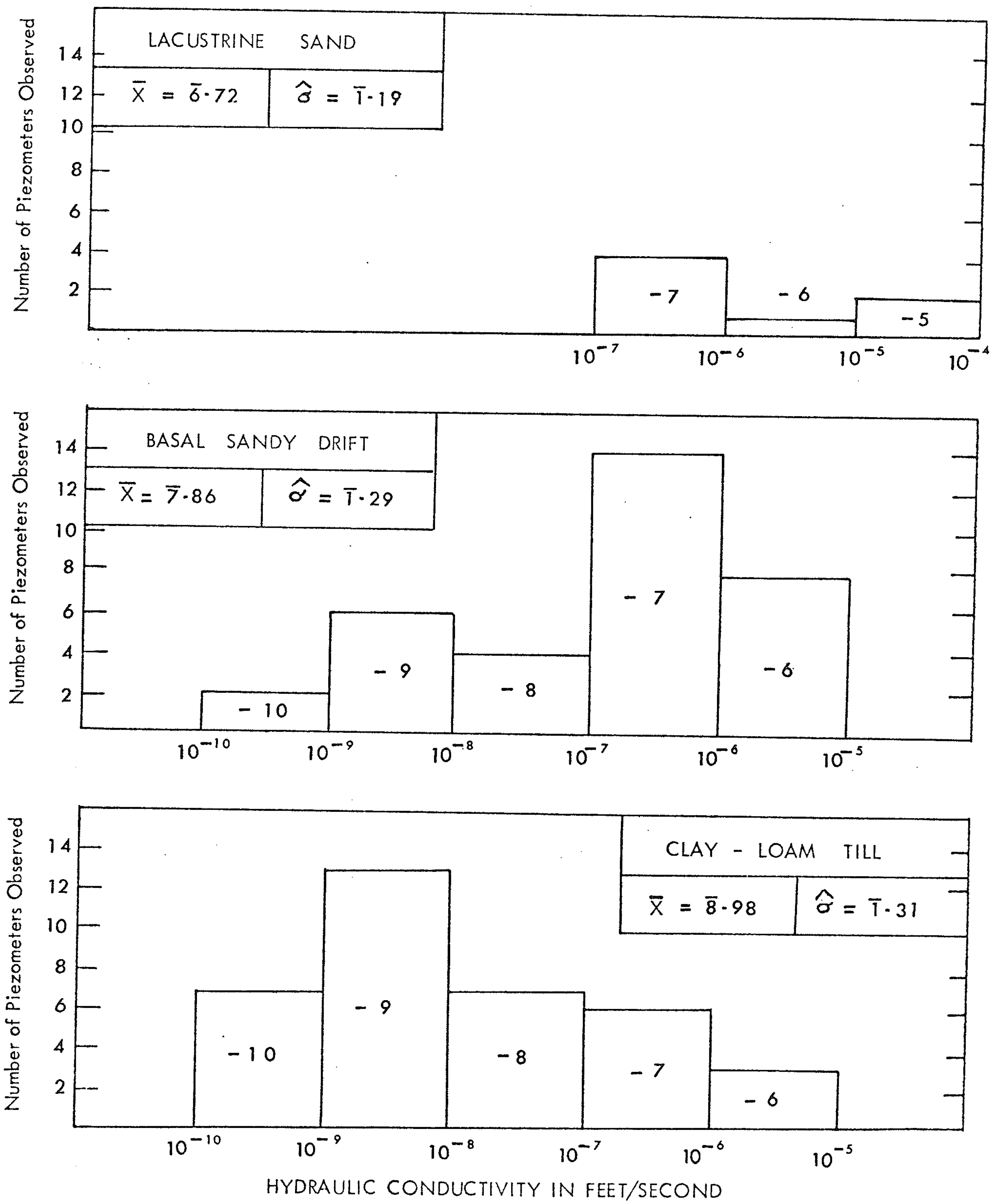


Figure 43. Hvorslev horizontal hydraulic conductivities in the till and basal sand units.

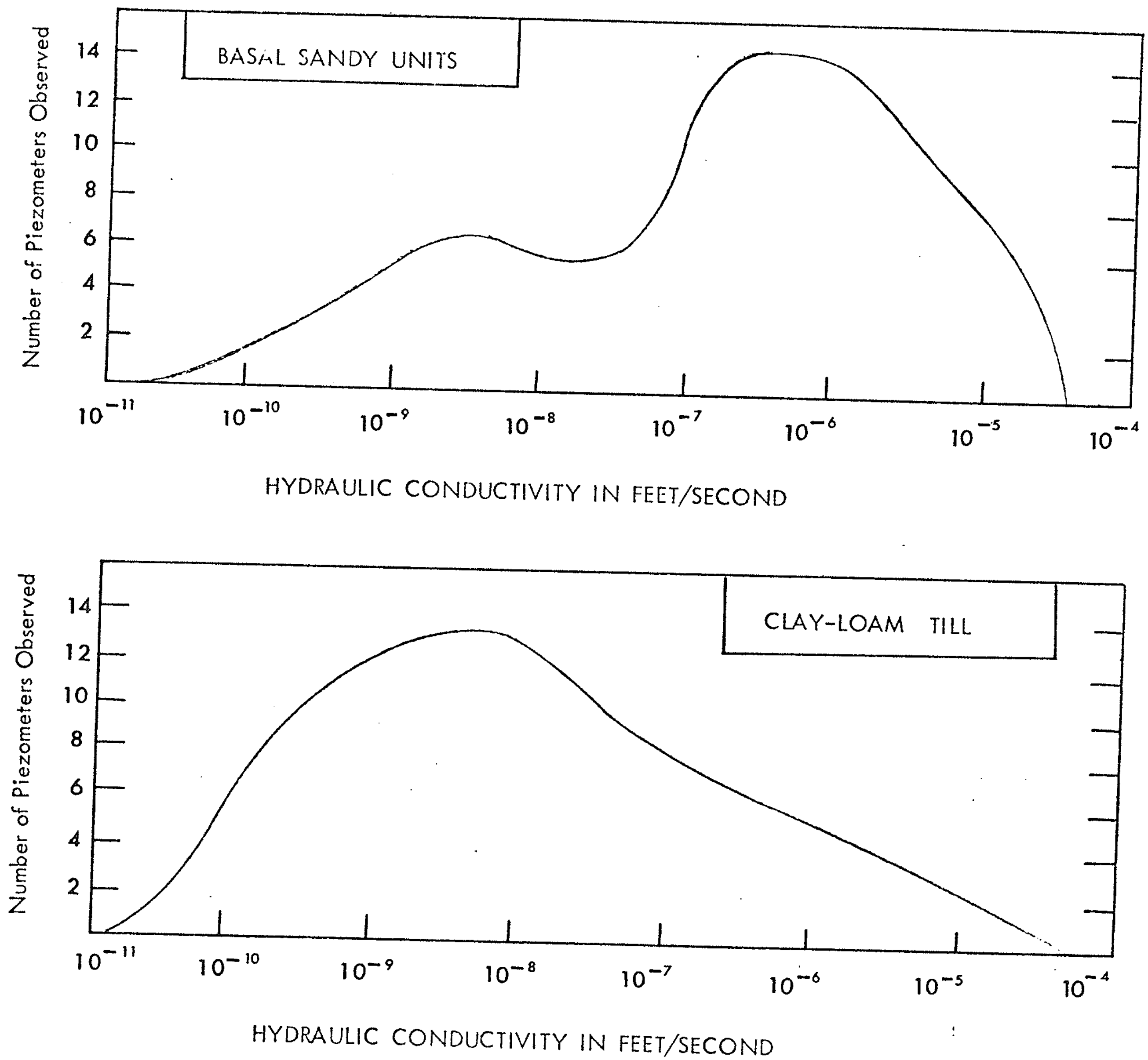


Figure 44. Hvorslev hydraulic conductivity spread in the till and basal sands.

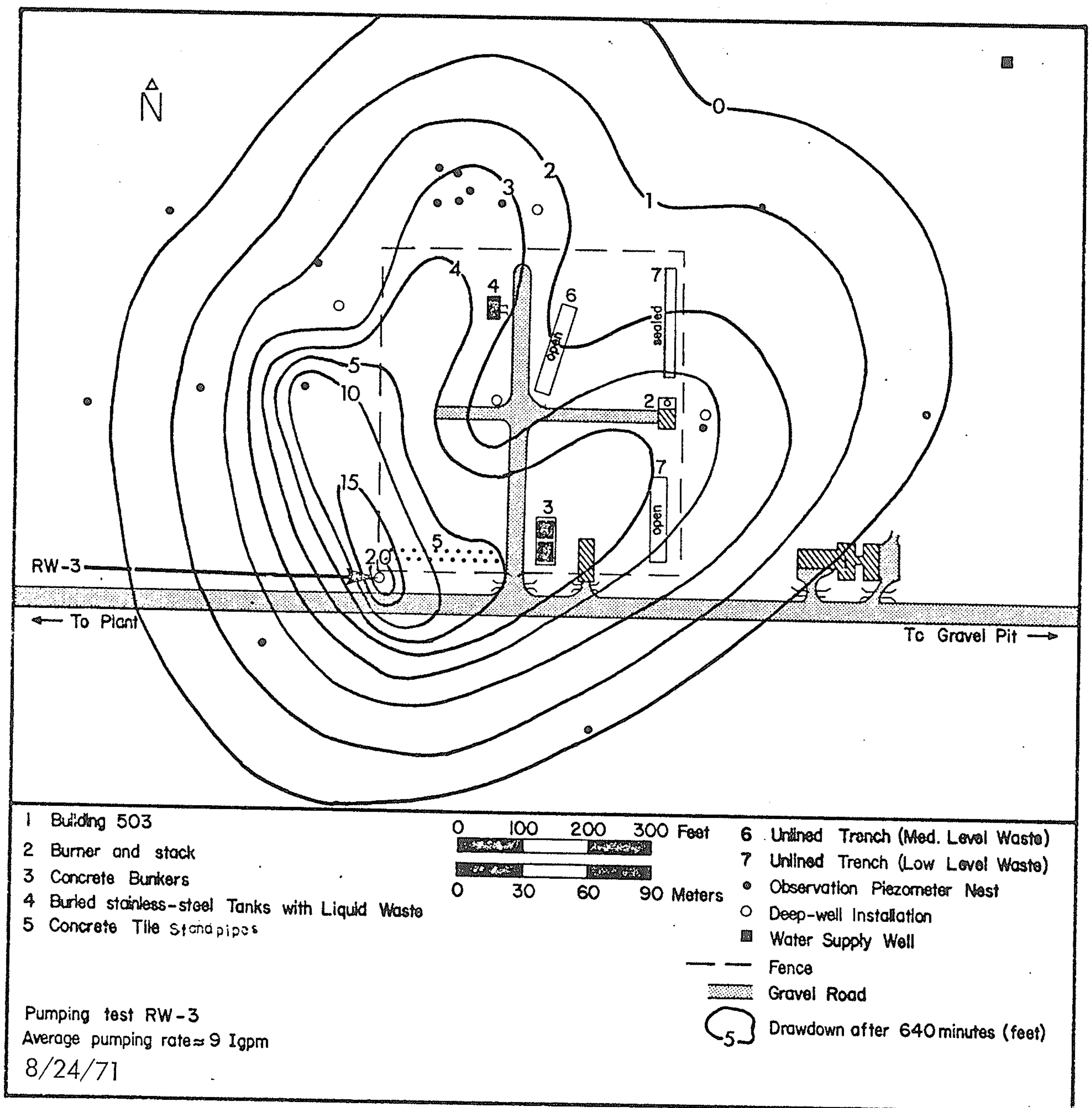


Figure 45. Drawdown cone influence at end of aquifer performance test, pump well RW-3.

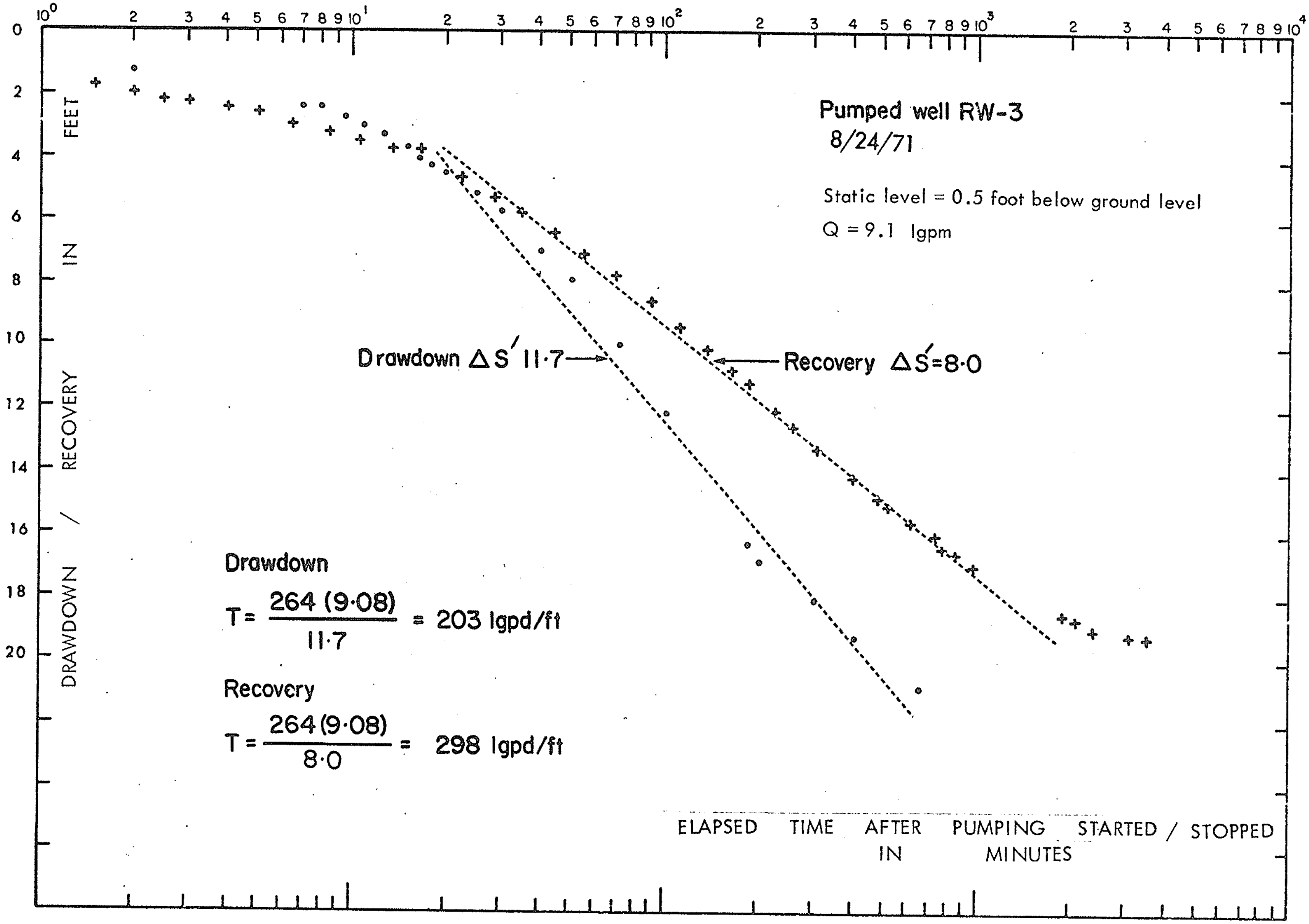


Figure 46. Semi-logarithmic plot of drawdown versus time, pump well RW-3.

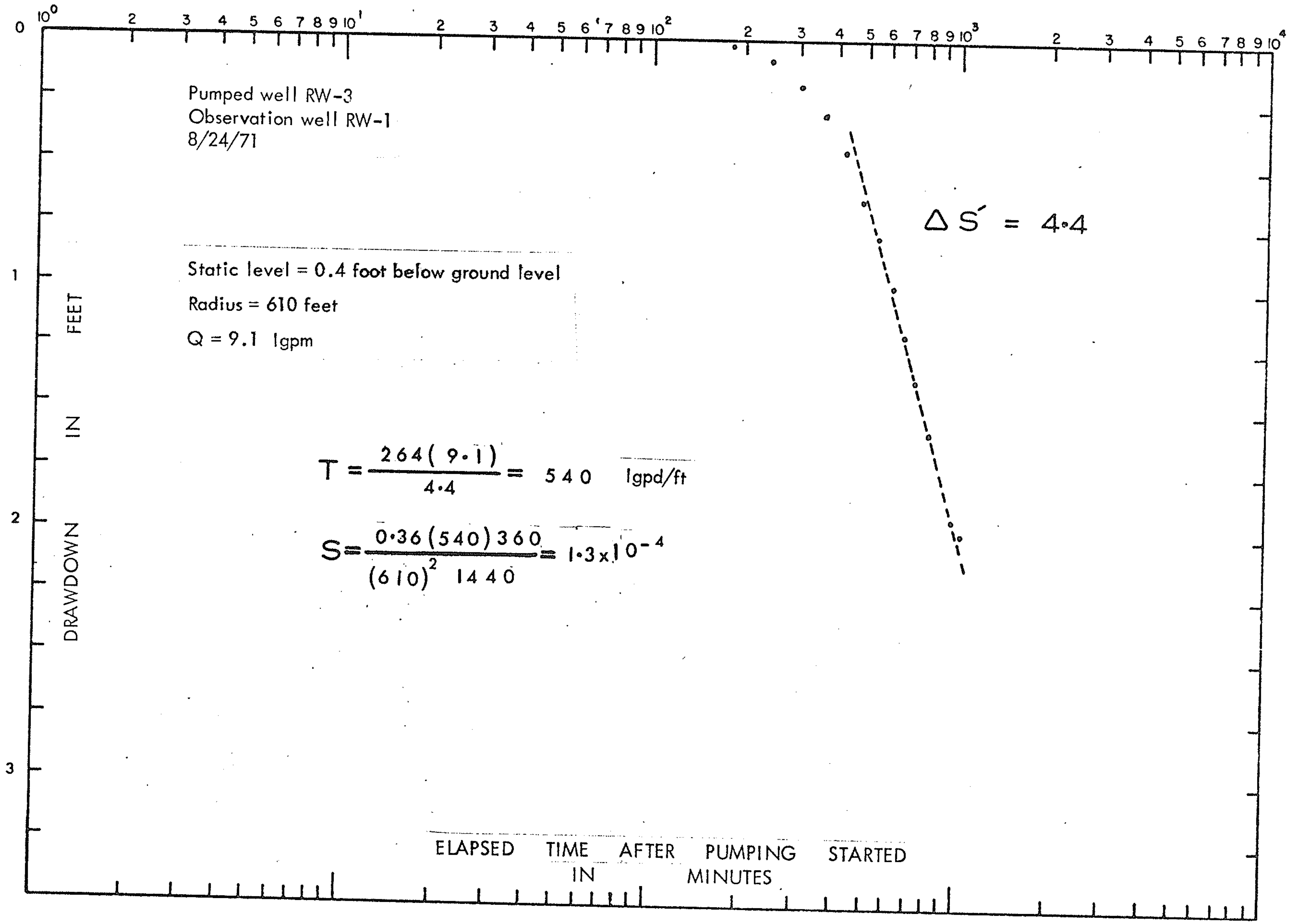


Figure 47. Semi-logarithmic plot of drawdown versus time, observation well RW-1.

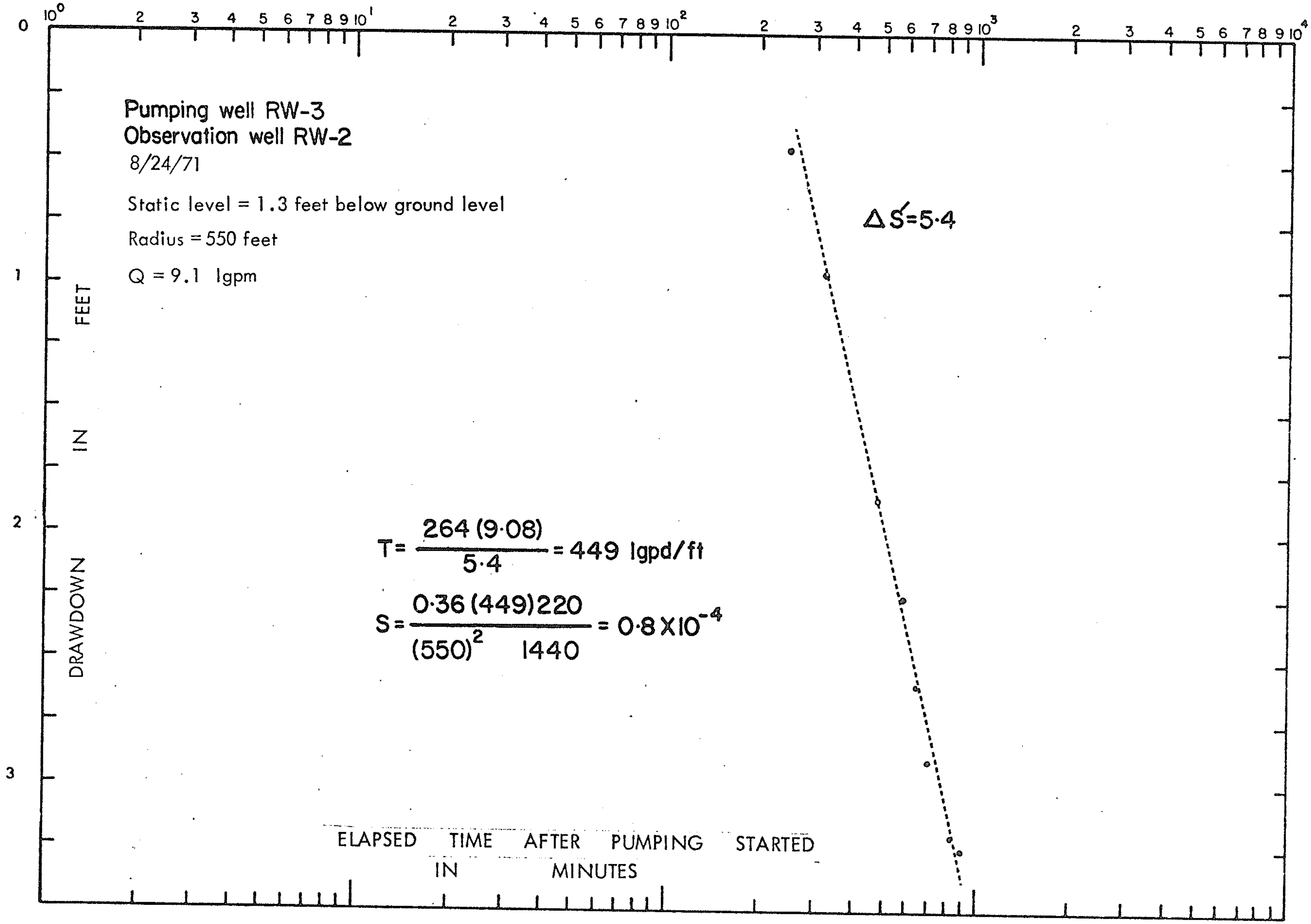


Figure 48. Semi-logarithmic plot of drawdown versus time, observation well RW-2.

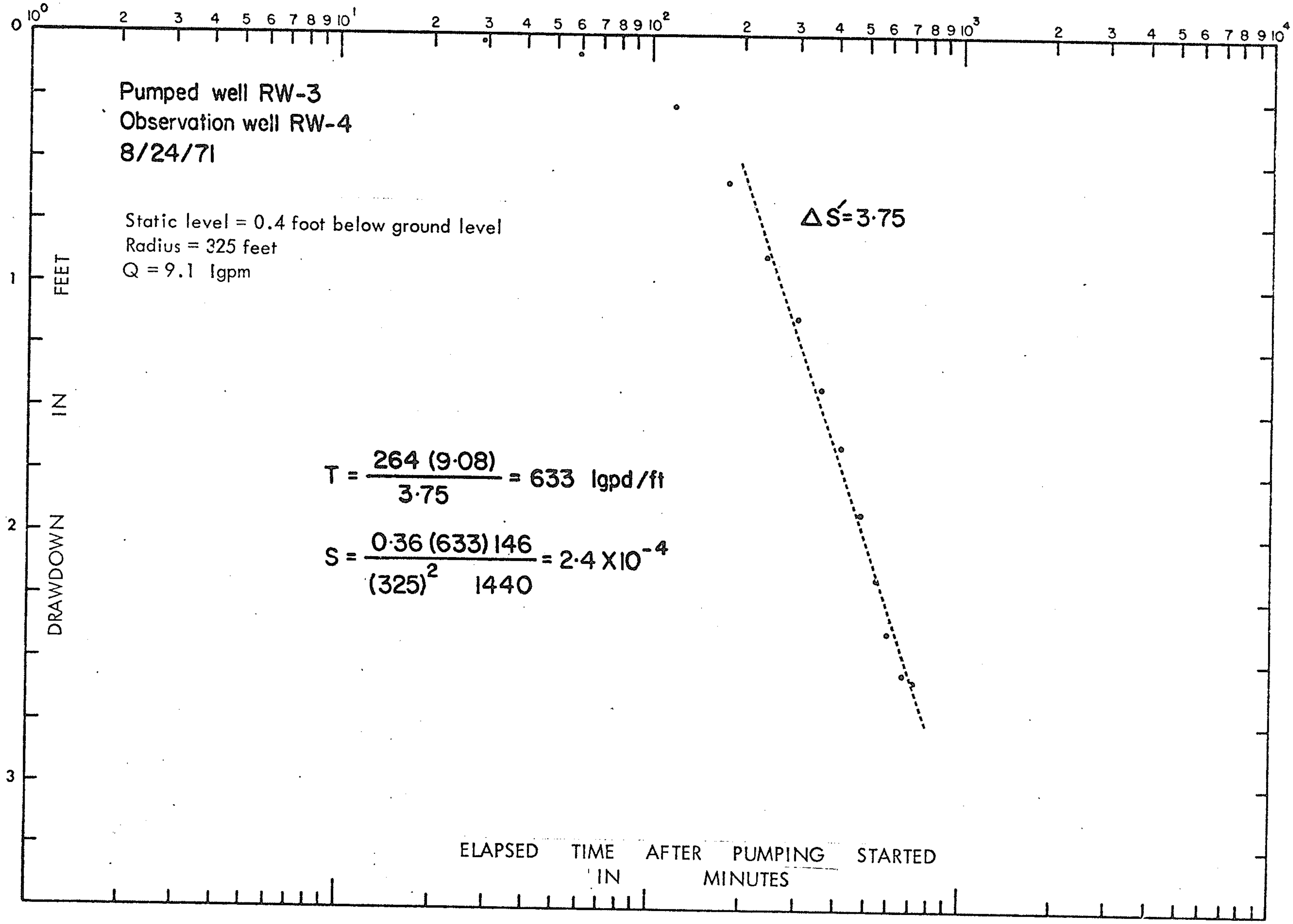


Figure 49. Semi-logarithmic plot of drawdown versus time, observation well RW-4.

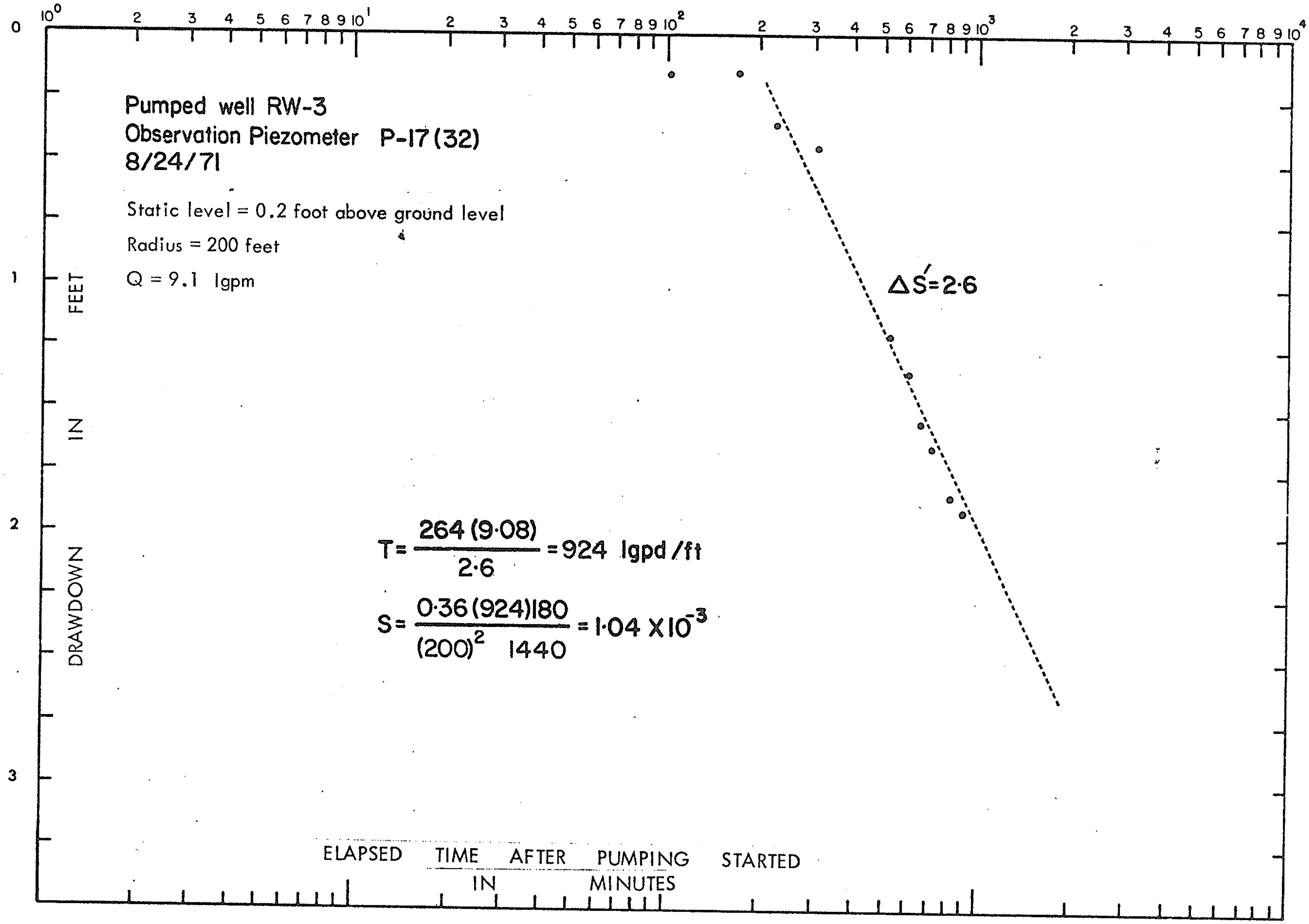


Figure 50. Semi-logarithmic plot of drawdown versus time, observation piezometer P-17(32) -- #17 at a 32 foot depth.

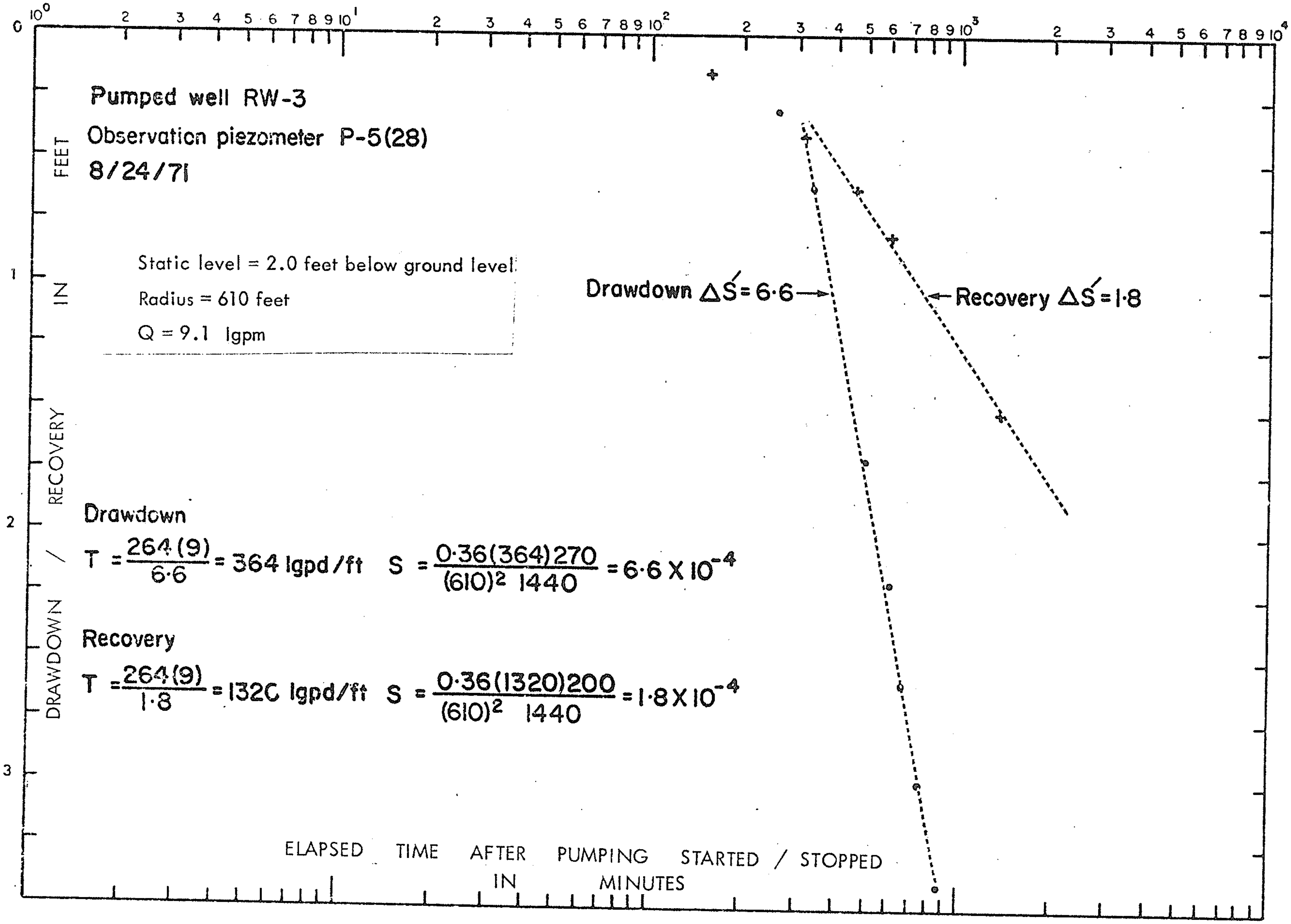


Figure 51. Semi-logarithmic plot of drawdown versus time, observation piezometer P-5(28) -- #5 at a 28 foot depth.

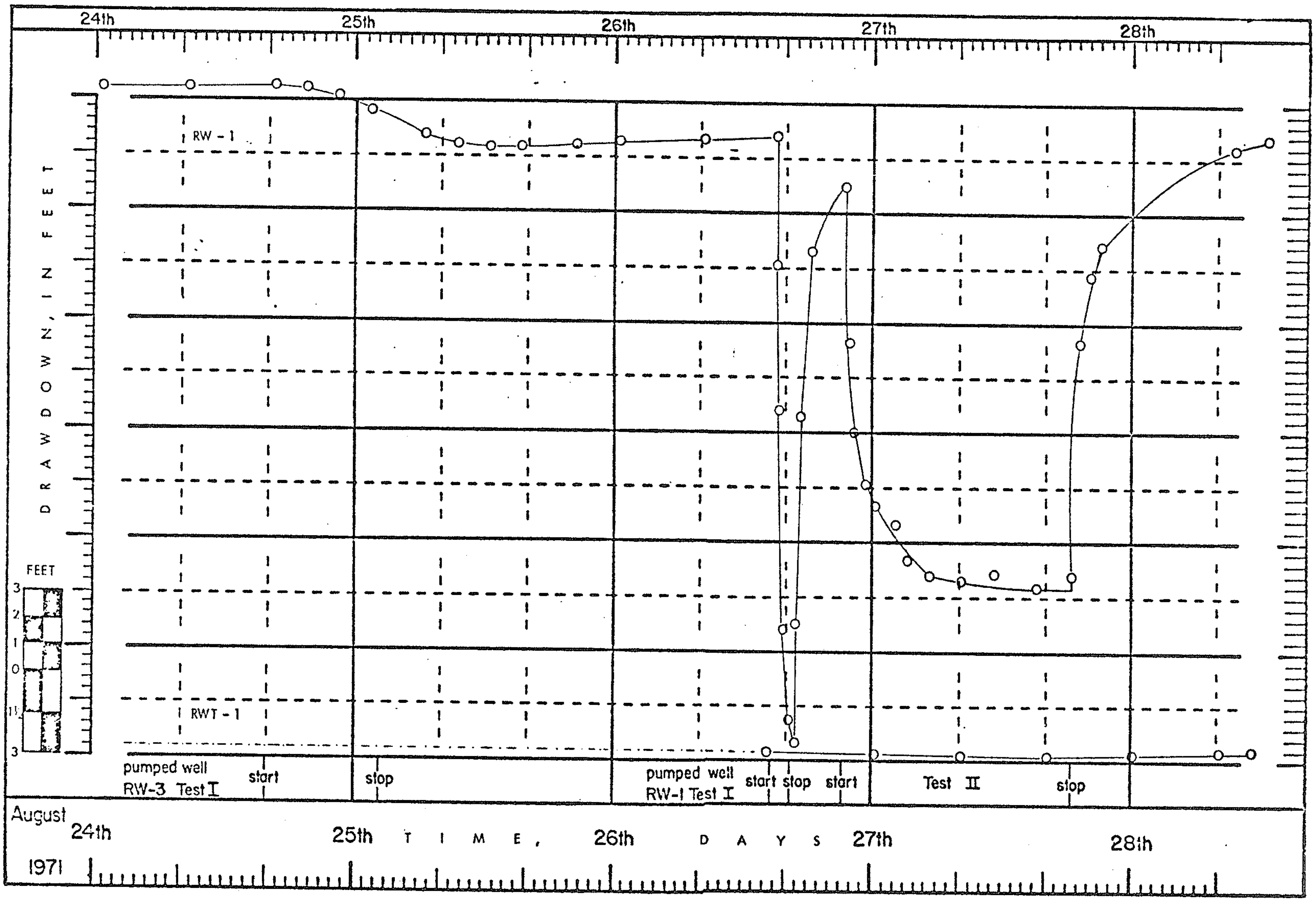


Figure 52. Arithmetic plot of drawdown versus time, RW-1.

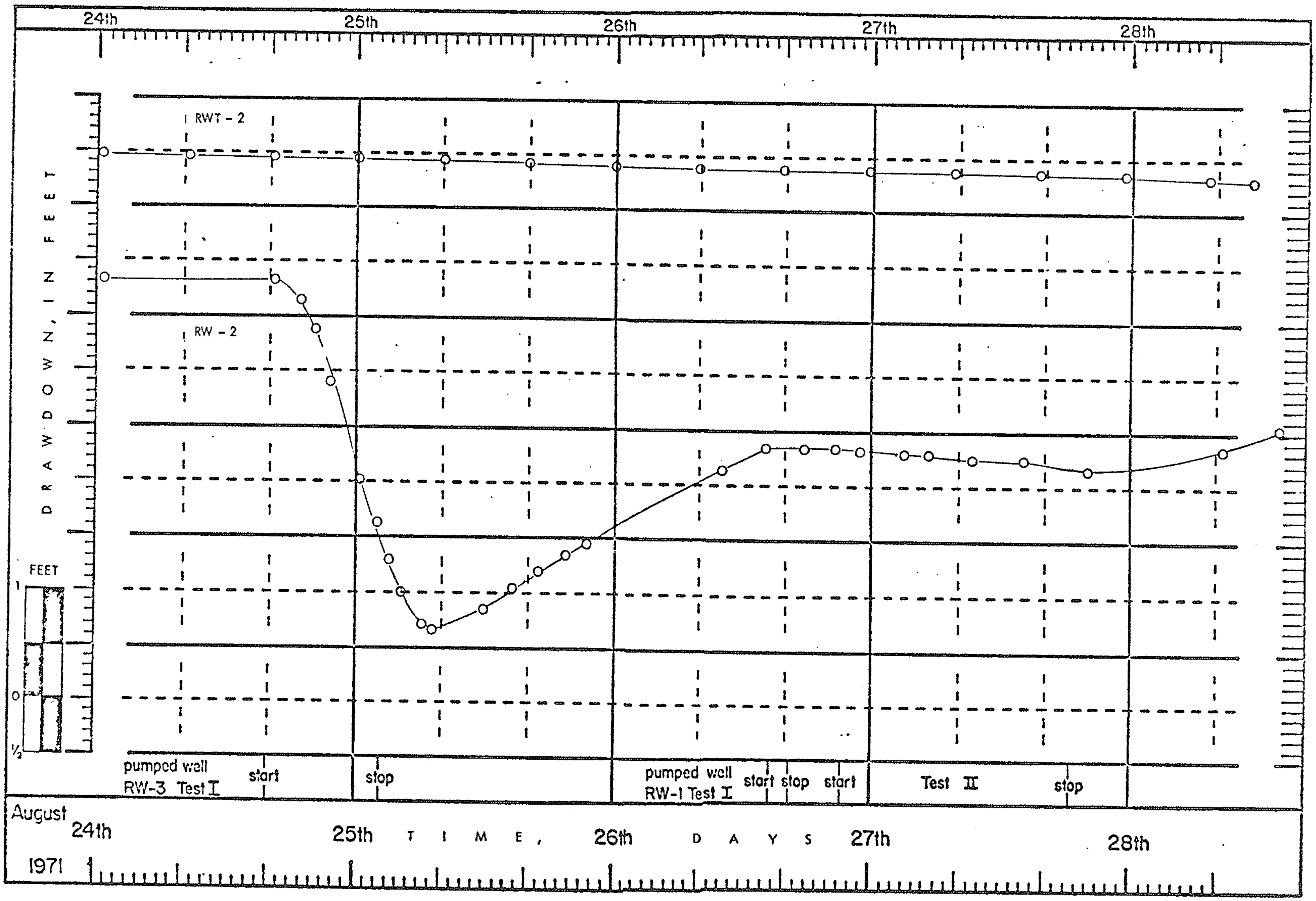


Figure 53. Arithmetic plot of drawdown versus time, RW-2.

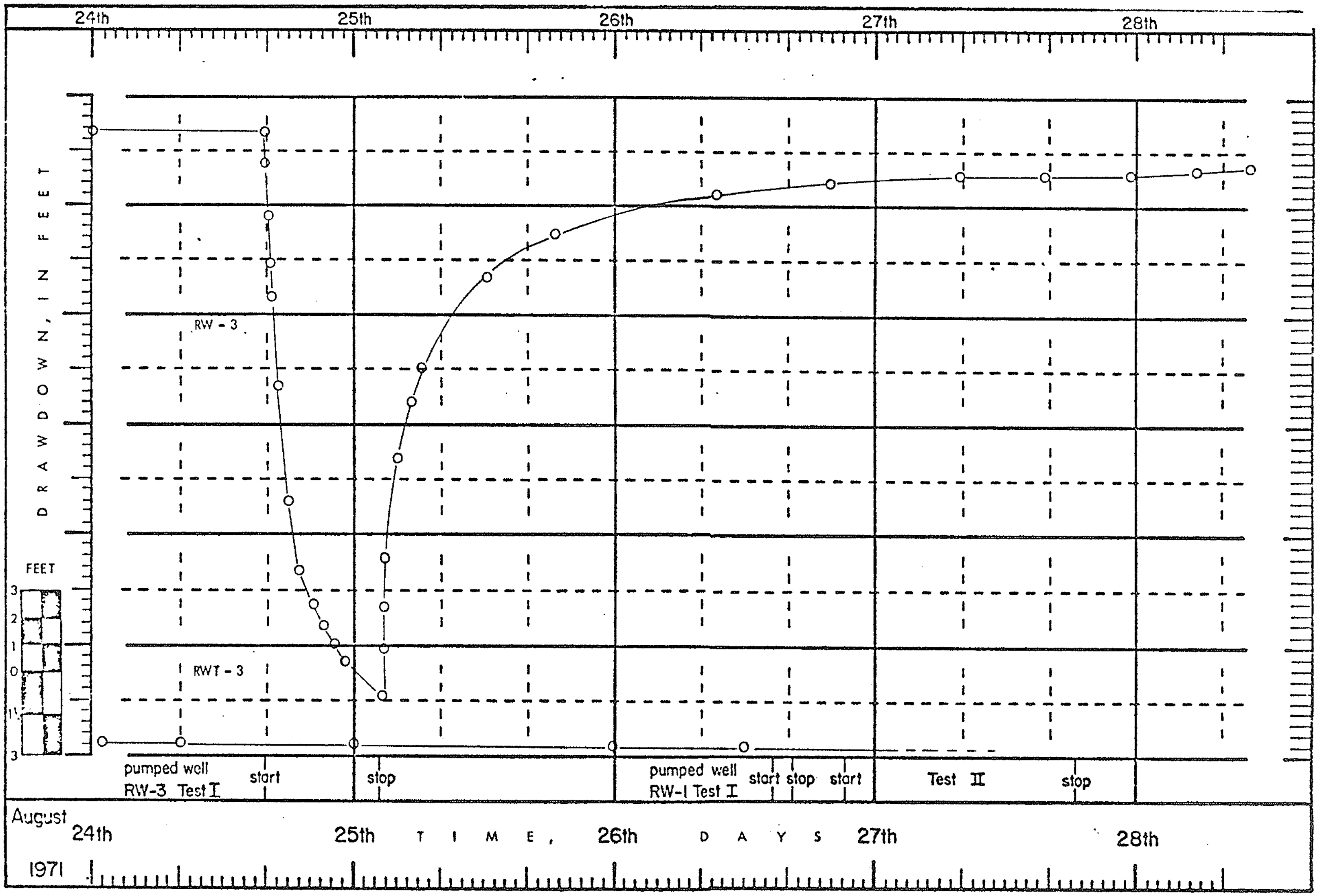


Figure 54. Arithmetic plot of drawdown versus time, RW-3.

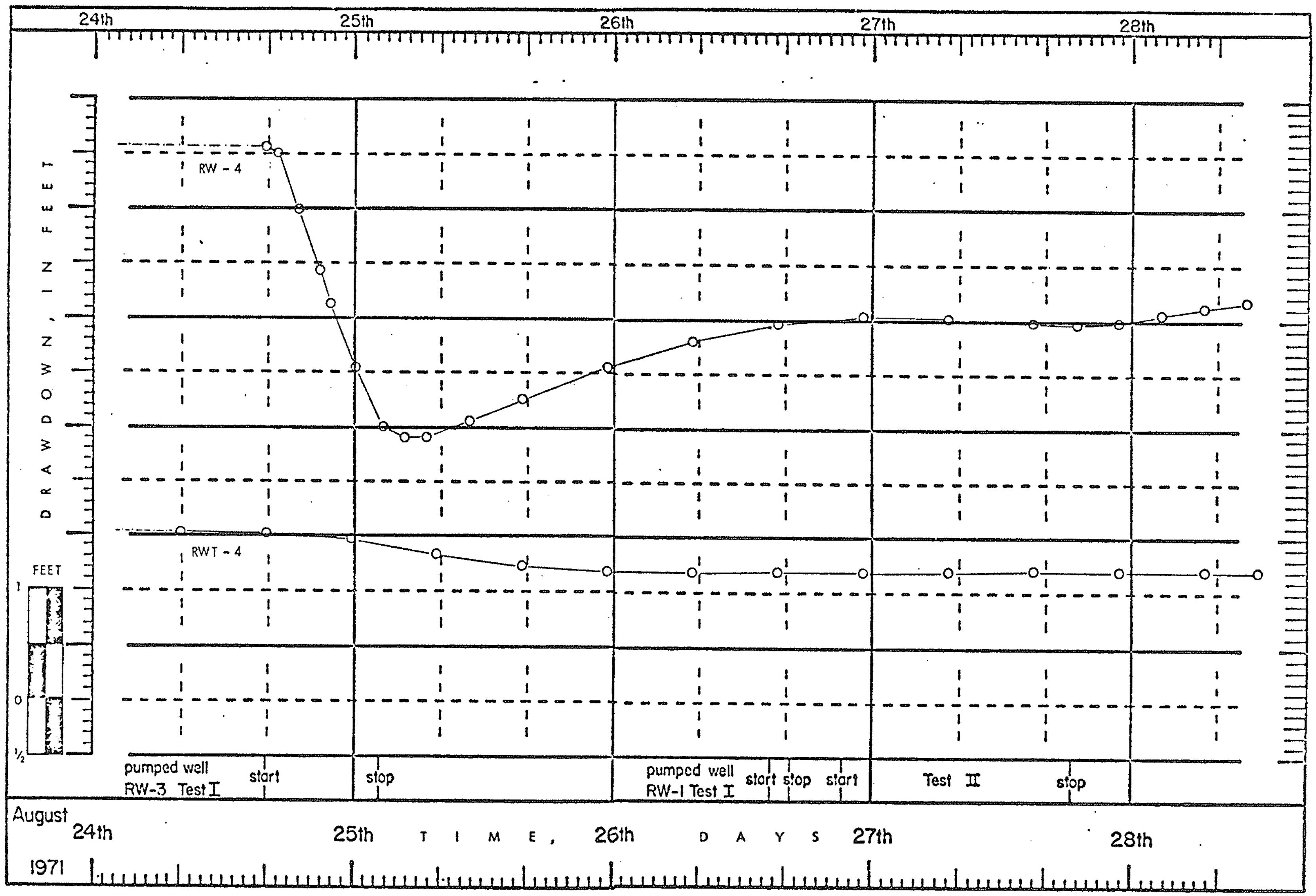


Figure 55. Arithmetic plot of drawdown versus time, RW-4.

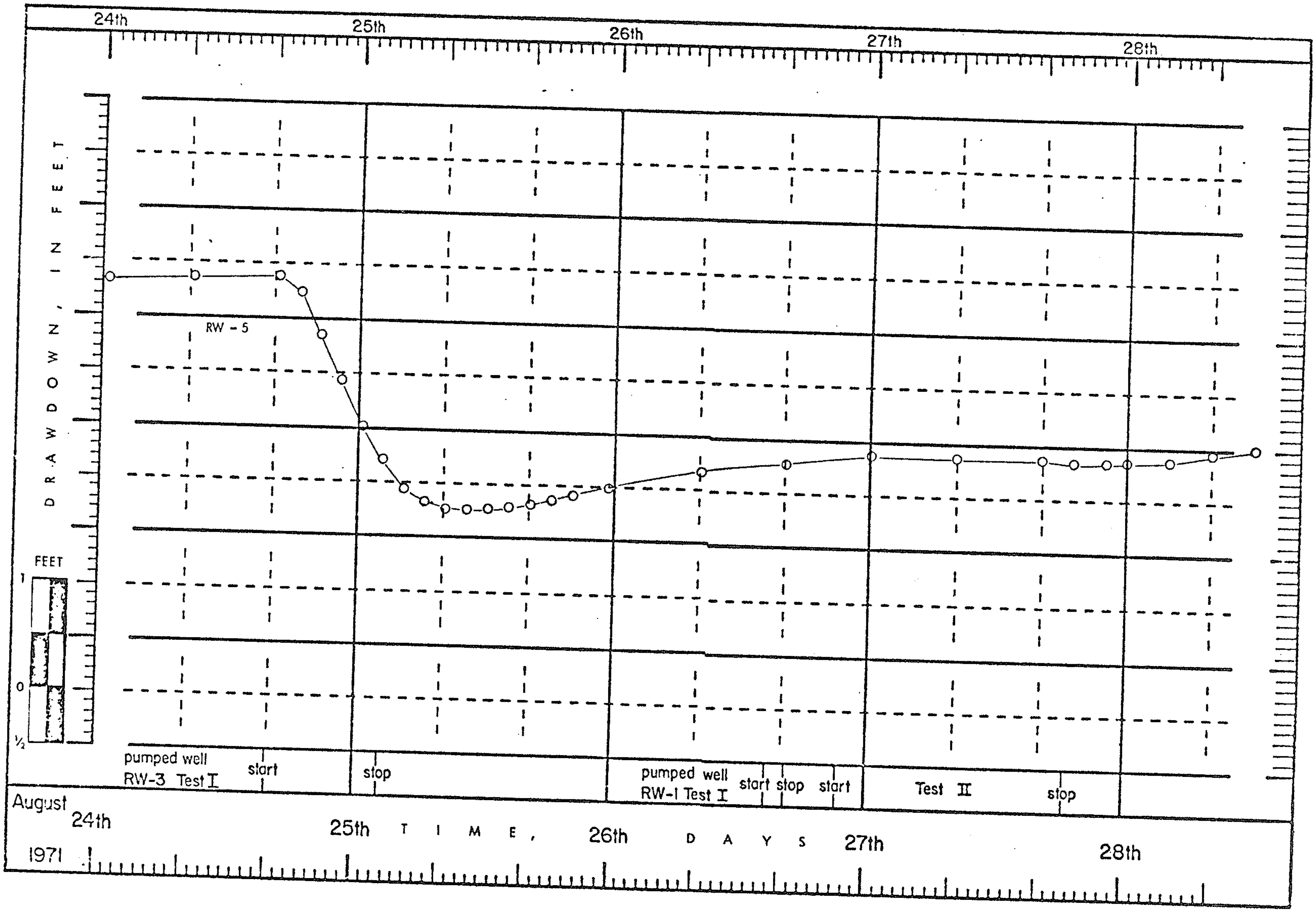


Figure 56. Arithmetic plot of drawdown versus time, RW-5.

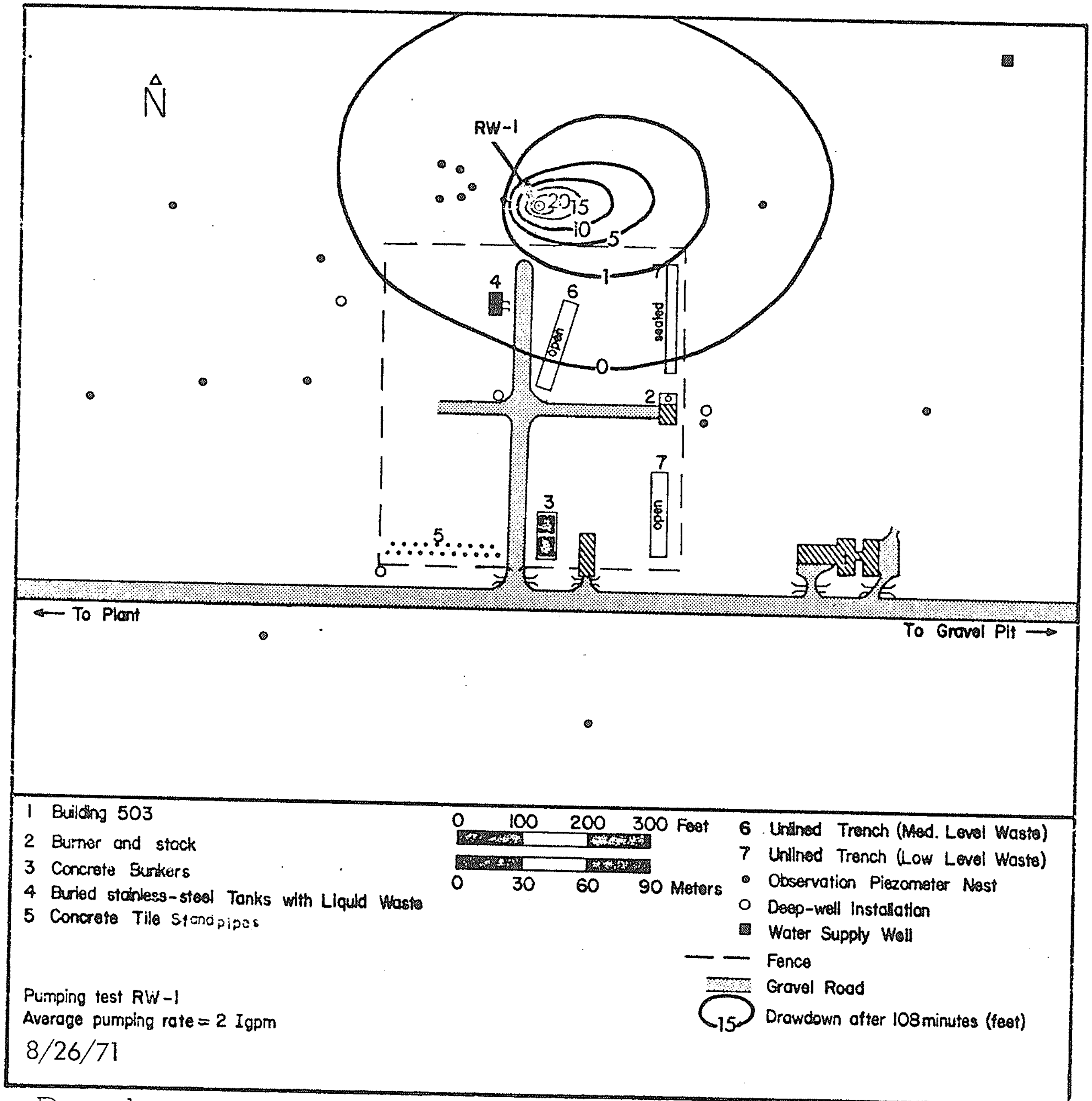


Figure 57. Drawdown cone influence at end of aquifer performance test number 1, pump well RW-1.

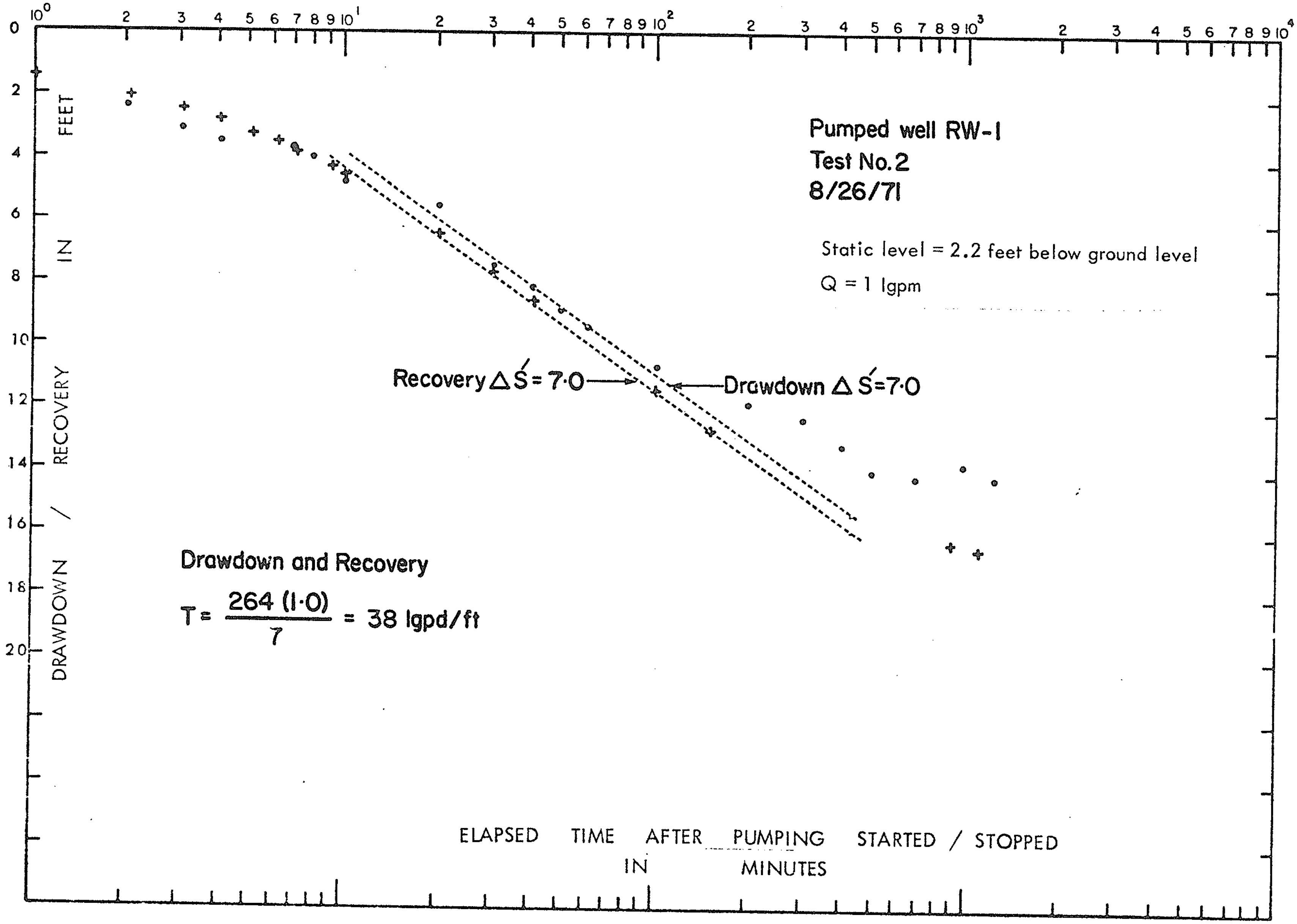


Figure 58. Semi-logarithmic plot of drawdown versus time, test number 2, pump well RW-1.

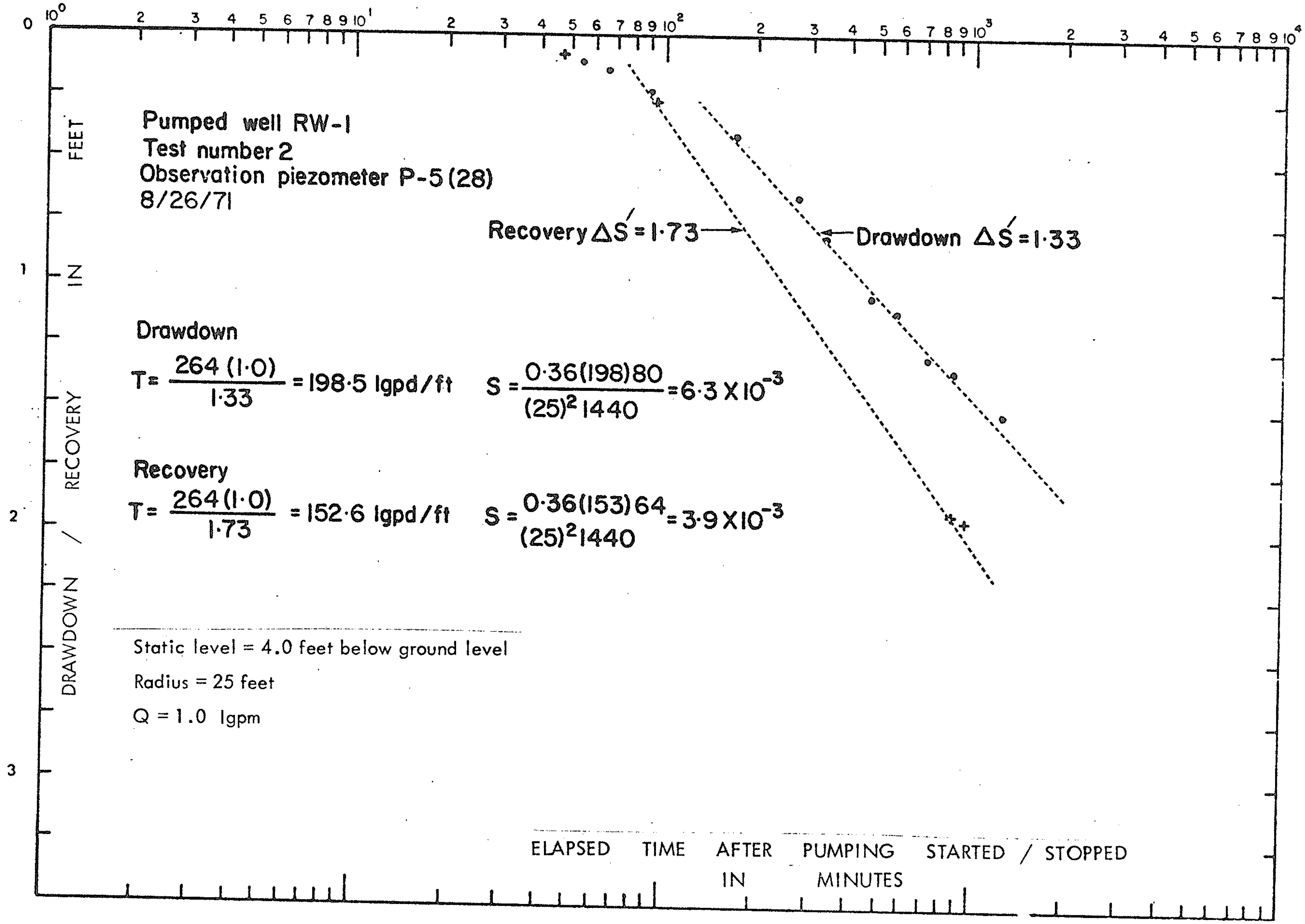


Figure 59. Semi-logarithmic plot of drawdown versus time, test number 2, observation piezometer P-5(28).

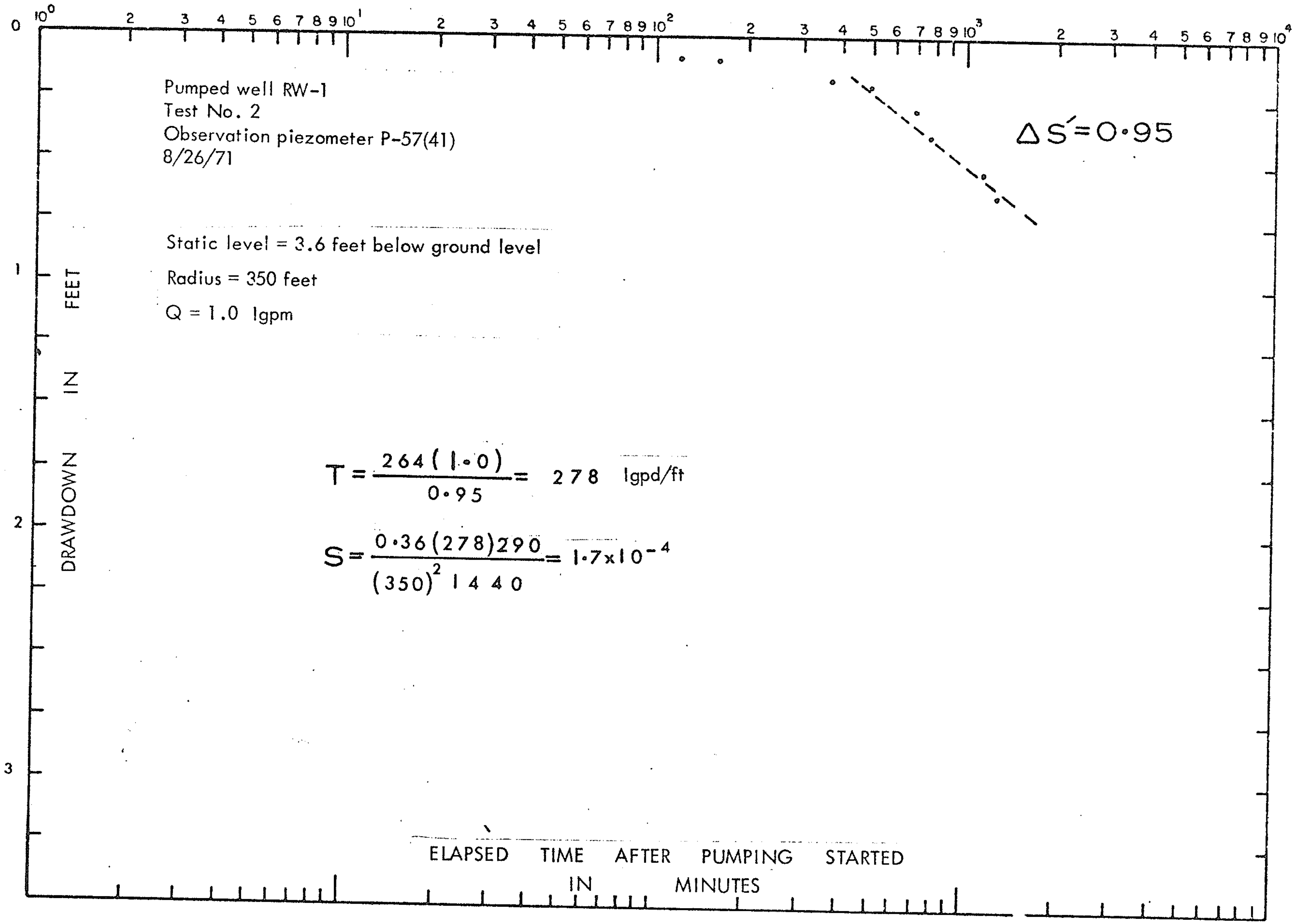


Figure 60. Semi-logarithmic plot of drawdown versus time, test number 2, observation piezometer P-57(41).

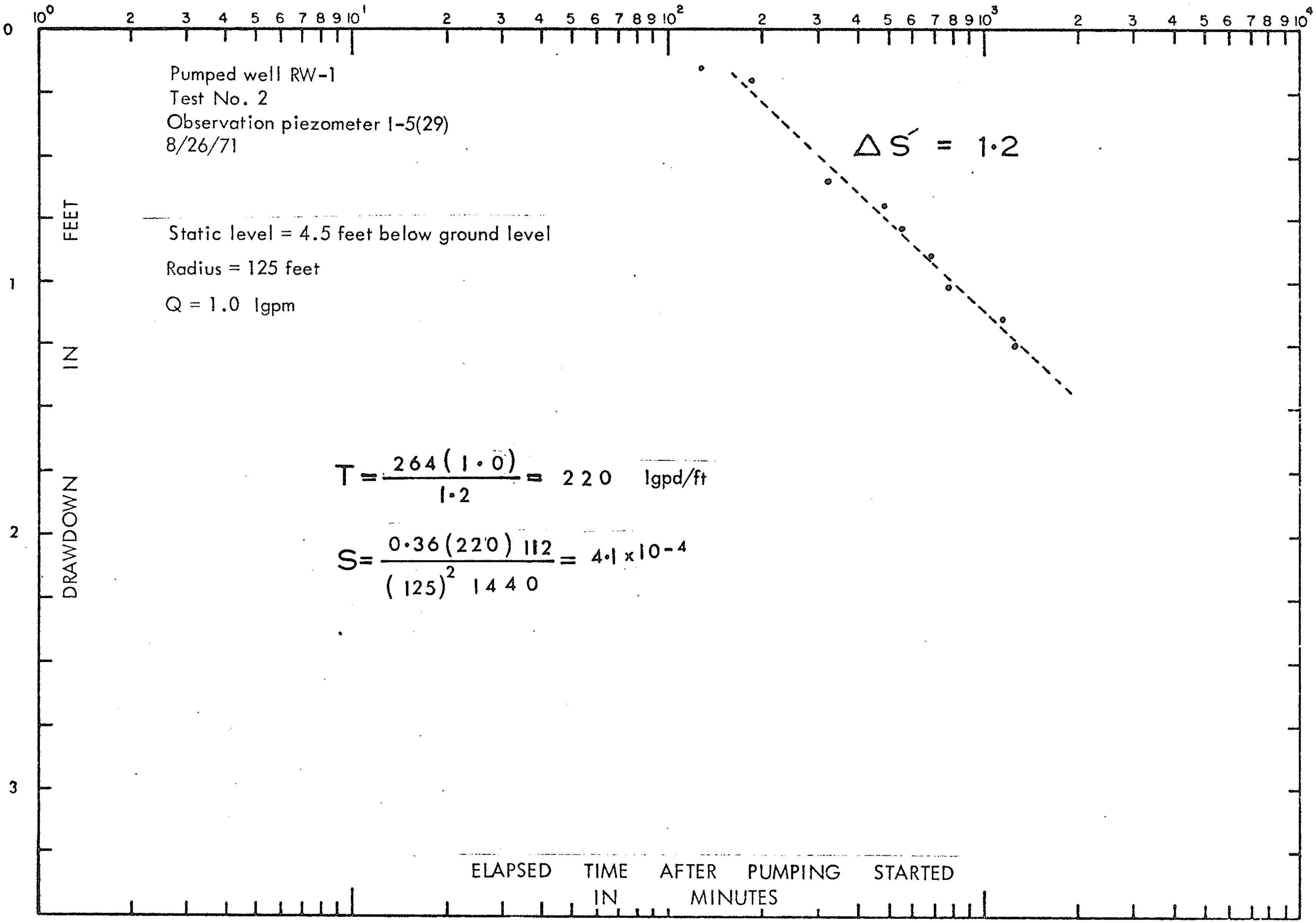


Figure 61. Semi-logarithmic plot of drawdown versus time, test number 2, observation piezometer I-5(29).

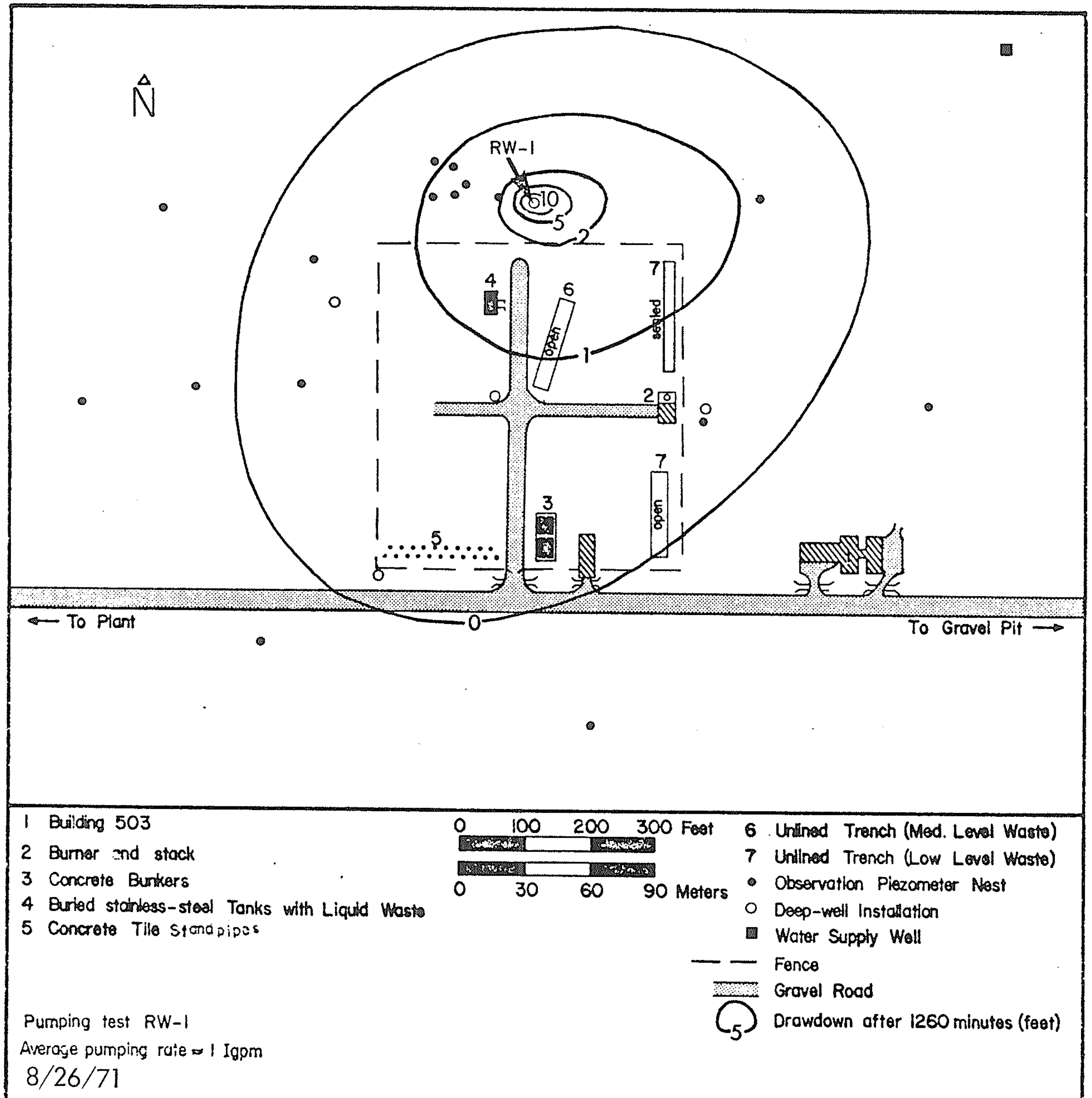


Figure 62. Drawdown cone influence at end of aquifer performance test number 2, pump well RW-1.

GEOLOGIC LOGS OF WELL

AND PIEZOMETER INSTALLATIONS

1971

Piezometers Installed

before 1971 see

Beswick, 1971

A P P E N D I X A

PUMP WELL PW 1-71 (RW-1)

Interval in feet b.g.l.*	Description	Stratigraphic unit
0 - 2	Top soil, fill	---------------
2 - 8	Clay, very silty, silty clay-till appearance in part, colour 2.5 Y 5/2	Lacustrine Clay
8 - 23	Till, carbonate pebbles, silty, colour 2.5 Y 3.5/2	Clay-loam Till
23 - 24	Boulder pavement	---------------
24 - 25	Sand, very coarse, angular granitic pebbles, med. to poorly sorted	Basal Sandy Drift
25 - 26	Transition, very coarse sand and gravel	Basal Sandy Drift
26 - 27	Sand, coarse, med. to well sorted, silty	Basal Sandy Drift
27 - 28	Sand, fine grained, well sorted, silty	Basal Sandy Drift
28 - 28.7	Sand, coarse, disturbed	Basal Sandy Drift

* b. g. l. "below ground level"

PUMP WELL PW 1-71 (cont'd)

Interval in feet b.g.l.	Description	Stratigraphic unit
28.7 - 29	Sand, coarse, gravel, poorly sorted, sub-rounded, 5% silt	Basal Sandy Drift
29 - 29.3	Till-like interbed, bound	Basal Sandy Drift
29.3 - 29.7	Sand, coarse, gravel, poorly sorted, sub-round, 5% silt	Basal Sandy Drift
29.7 - 30	Sand, very fine, well-sorted, 10 to 20% silt, colour 2.5 Y 3.5/2	Basal Sandy Drift
30 - 31.5	Sand, fine to coarse, med. to poorly sorted, slightly silty	Basal Sandy Drift
31.5 - 32	Sand, very fine, silty, colour 2.5 Y 4/2	Basal Sandy Drift
32 - 35	No samples taken, drilling indicated fine silty sand	Basal Sandy Drift
35 - 37	Sand, very fine, silty, slight clay, till-like in part	Basal Sandy Drift
37±	Sand, very fine, silty, colour 2.5 Y 3.5/2	Basal Sandy Drift
37±	Hole ended	---------------

PUMP WELL PW 1-71 (cont'd)

SCREEN SET: Johnson Stainless Steel

SCREENED INTERVAL: 26.7 feet b.g.l. to 31.7 feet b.g.l.

SLOT SIZE: #30

SCREEN SIZE: 4-inch diameter

PUMP WELL PW 2-71 (RW-2)

Interval in feet b.g.l.	Description	Stratigraphic unit
0 - 3	Topsoil, fill	---------------
3 - 9	Clay, laminated, silty, pebbly near interval base, colour 10 YR 3/1	Lacustrine Clay
9 - 23	Till, carbonate pebbles, colour 3.75 Y 4/2.5	Clay-loam Till
23 - 26	Boulders and cobbles, pavement zone	---------------
26 - 30	Sand, very silty, poorly sorted, slight clay	Basal Sandy Drift
30 - 32	Sand, coarse, gravel, sub-round to sub-angular, 20% silt, colour 5 Y 4/1	Basal Sandy Drift
32 - 34	Sand, very fine, 10 to 20% silt, colour 5 Y 4/1	Basal Sandy Drift
34 - 34.8	No samples, drill "slipped" through	---------------

PUMP WELL PW 2-71 (cont'd)

Interval in feet b.g.l.	Description	Stratigraphic unit
34.8 - 40	Sand, very fine, very silty, thin silt and clay layers, colour 5 Y 5/1	Basal Sandy Drift
40 - 41	Sand, med. to coarse, slight silt, med. to well-sorted, sub-rounded grains	Basal Sandy Drift
41	Hole ended, apparent bedrock contact	----------------

SCREEN SET: Brass-jacketed Sand Point; Upper 2.17 ft. burlap-wrapped

SCREENED INTERVAL: 38 feet b.g.l. to 41 feet b.g.l.

SLOT SIZE: #40

SCREEN SIZE: 2-inch diameter

PUMP WELL PW 3-71 (RW-3)

Interval in feet b.g.l.	Description	Stratigraphic unit
0 - 3	Top soil, fill	---------------
3 - 10	Clay, laminated, silt balls, colour 10 YR 3/1	Lacustrine Clay
10 - 19	Till, carbonate pebbles, colour 2.5 Y 4.5/3	Clay-loam Till
19 - 21	Boulder pavement	---------------
21 - 24.3	Sand, coarse to very coarse, some gravel, sub-round, med. sorted, slight silt	Basal Sandy Drift
24.3 - 24.5	Till-like interbed, bound	Basal Sandy Drift
24.5 - 26.2	Sand, med. to coarse, some gravel and cobble sizes, well-sorted sub-round sand at base of interval, initially poorly sorted and silty	Basal Sandy Drift
26.2 - 26.5	Sand, med. to coarse, clay and silt bound, till-like	Basal Sandy Drift
26.5 - 26.9	Sand, coarse, poorly sorted, gravel and pebble sizes, silty	Basal Sandy Drift

PUMP WELL PW 3-71 (cont'd)

Interval in feet b.g.l.	Description	Stratigraphic unit
26.9 - 28	Lost interval, disturbed, (assumed-fine grained sand)	Basal Sandy Drift
28 - 29.5	Sand, fine to medium, round to sub-round, well-sorted, trace silt	Basal Sandy Drift
29.5 - 30	Sand, med. to coarse, med.-sorted, silt bound	Basal Sandy Drift
30 - 31.8	Sand, very fine, silty	Basal Sandy Drift
31.8 - 32.6	Sand, coarse to very coarse, poorly sorted, sub-round, silty	Basal Sandy Drift
32.6 - 34	Sand, very fine, very silty, colour 10 YR 4/1	Basal Sandy Drift
34	Hole ended	

SCREEN SET: Johnson Stainless Steel

SCREENED INTERVAL: 19 feet b.g.l. to 29 feet b.g.l.

SLOT SIZE: #25

SCREEN SIZE: 4-inch diameter

PUMP WELL PW 4-71 (RW-4)

Interval in feet b.g.l.	Description	Stratigraphic unit
0 - 3	Fill	---------------
3 - 8	Clay, laminated, colour 10 YR 3/1	Lacustrine Clay
8 - 21	Till, carbonate pebbles, normal appearance	Clay-loam Till
21 - 24.5	Sand, very coarse, gravel to pebble sizes, angular granitic grains and sub-round pebbles, slight silt	Basal Sandy Drift
24.5 - 30.4	Sand, very fine, well-sorted, massive, slight silt, colour 5 Y 4.5/1 (occasional pebble)	Basal Sandy Drift
30.4 - 31.9	Lost interval, assumed sand as immediately above	Basal Sandy Drift
31.9 - 37.9	Sand, very fine, massive, silty, silt and clay layering, colour 5 Y 4.5/1	Basal Sandy Drift
37.9 - 39	Sand, coarse, angular, granitic, some gravel sizes, silty, colour 5 Y 4.5/1	Basal Sandy Drift

PUMP WELL PW 4-71 (cont'd)

Interval in feet b.g.l.	Description	Stratigraphic unit
39 - 39.5	Disturbed sample, clay fragments and coarse sand and gravel, angular	Basal Sandy Drift
39.5	Hole ended	---------------

SCREEN SET: Johnson Stainless Steel

SCREENED INTERVAL: 38.1 feet b.g.l. to 39.1 feet b.g.l.

SLOT SIZE: #30

SCREEN SIZE: 4-inch diameter

PUMP WELL PW 5-71 (RW-5)

Interval in feet b.g.l.	Description	Stratigraphic unit
0 - 1	Top soil	---------------
1 - 9	Silt, clayey, silt balls, precipitate streaks, colour 3.75 Y 4/2.5 to 10 YR 3/1	Lacustrine Silt / Lacustrine Clay transition
9 - 21.2	Till, carbonate pebbles, very clayey, silty, slight sand, colour 2.5 Y 5/2	Clay-loam Till
21.2 - 21.7	Silt, coarse granitic sand, sub-angular gravel, clay bound, colour 2.5 Y 5/2	Clay-loam Till
21.7 - 22.3	Sand, very fine, well-sorted, silty, slight clay, 5 Y 4.5/1	Basal Sandy Drift
22.3 - 24.3	Clay and silt layering, very fine sand, well sorted, some gravel sizes, colour 5 Y 4.5/1	Basal Sandy Drift
24.3 - 24.6	Boulder pavement	---------------
24.6 - 25.9	Sand, fine to coarse, med. to poorly sorted, slight silt, some gravel and pebble sizes, colour 5 Y 5/1	Basal Sandy Drift

PUMP WELL PW 5-71 (cont'd)

Interval in feet b.g.l.	Description	Stratigraphic unit
25.9 - 27.4	Gravel, sub-round to angular, granitic, silt/clay bound	Basal Sandy Drift
27.4 - 34.6	Gravel, granitic, sub-round, 20% silt, coarse sand, colour 5 Y 5/1	Basal Sandy Drift
34.6 - 35.3	Sand, sub-round, some gravel sizes, high silt, granitic	Basal Sandy Drift
35.3 - 37.3	Gravel, sub-angular to round, silty, some pebble sizes, granitic, colour 5 Y 5/1	Basal Sandy Drift
37.3 - 38.3	Sand, fine to coarse, sub-round, med. sorted, slight silt	Basal Sandy Drift
38.3 - 40.6	Gravel, sub-angular to sub-round, granitic, med. to coarse sand, silt/clay bound	Basal Sandy Drift
40.6 - 42.5	Sand and gravel, med. to very coarse sands, med. to poorly sorted, slight silt, sub-round	Basal Sandy Drift

PUMP WELL PW 5-71 (cont'd)

Interval in feet b.g.l.	Description	Stratigraphic unit
42.5 - 45	Gravel, coarse sand, clay/silt bound, colour 5 Y 4.5/1	Basal Sandy Drift
45	Hole ended, apparent bedrock contact	---------------

SCREEN SET: Johnson Stainless Steel

SCREENED INTERVAL: 24.6 ft. b.g.l. to 42.0 ft. b.g.l.

SLOT SIZE: 2.58 feet #30 -24.6 feet b.g.l.

1.12 feet blank

5.04 feet #12

0.33 foot coupling

5.08 feet #15

1.75 feet blank

1.50 feet #30 -42.0 feet b.g.l.

SCREEN SIZE: 4-inch diameter

TEST HOLE P - 61

Interval in feet b.g.l.*	Description	Stratigraphic unit
0 - 1	Top soil	---------------
1 - 5	Clay, laminated, silt balls, precipitate streaks, plastic, colour 2.5 Y 4.5/2	Lacustrine Clay
5 - 30	Till, carbonate pebbles, very silty/sandy, clay banding, colour 10 YR 4/1 grading downward to 2.5 Y 3.5/2	Clay-loam Till
30±	Boulder pavement	---------------
30 - 36	Till, as above	Clay-loam Till
36 - 46	Sand, fine grained, med. sorted silty, greater % quartz grains	Basal Sandy Drift
46	Hole ended, probable bedrock contact	

* b.g.l. "below ground level"

TEST HOLE P - 62

Interval in feet b.g.l.	Description	Stratigraphic unit
0 - 1	Top soil	----------------
1 - 3	Clay, laminated, silt balls, plastic, colour 2.5 Y 3.5/2	Lacustrine Clay
3 - 32	Till, carbonate pebbles, silt balls to 12 feet, sandy silt-till appearance to 20 feet, more clayey to 32 feet, colour 10 YR 4/1	Clay-loam Till
32±	Boulder pavement	----------------
32 - 37	Sand, fine grained, well sorted, silty, greater % quartz grains	Basal Sandy Drift
37	Hole ended	

TEST HOLE P - 63

Interval in feet b.g.l.	Description	Stratigraphic unit
0 - 1	Top soil	---------------
1 - 9	Clay, laminated, silt balls, precipitate streaks, till-like and pebbly in part, colour 2.5 Y 3.5/2	Lacustrine Clay
9 - 25	Till, carbonate pebbles, silt streaks, sandy silt-till appearance	Clay-loam Till
25	Hole ended, boulder pavement	---------------

TEST HOLE P - 64

0 - 1	Top soil	---------------
1 - 6½	Clay, silt balls, precipitate streaks, thin sand lenses, colour 10 YR 3/1 at lamination planes -- 2.5 Y 3/2 at broken surfaces	Lacustrine Clay
6½ - 22	Till, carbonate pebbles and gravel near clay/till contact, silty, colour 2.5 Y 3/2	Clay-loam Till
22 - 25	Boulders and sandy till	Clay-loam Till
25	Hole ended, boulder pavement	---------------

TEST HOLE P - 65

Interval in feet b.g.l.	Description	Stratigraphic unit
0 - 1	Top soil	---------------
1 - 7	Clay, silt balls, precipitate streaks, plastic, grades to plastic and massive, colour 2.5 Y 4.5/2	Lacustrine Clay
7 - 24	Till, carbonate pebbles, clay layering, fine sand lenses, plastic, colour 2.5 Y 4.5/2 grading downward to 2.5 Y 4/2	Clay-loam Till
24 - 25	Boulder pavement	---------------
25	Hole ended	---------------

TEST HOLE P - 66

Interval in feet b.g.l.	Description	Stratigraphic unit
0 - 1	Top soil	---------------
1 - 8	Silt, carbonate pebbles, clayey, not plastic, colour 10 YR 3/2 to 2.5 Y 3/2	Lacustrine Silt
8 - 29	Clay, laminated, massive and plastic, colour 3.75 Y 3/2 grading downward to 5 Y 2.5/1	Lacustrine Clay
29±	Boulder pavement	---------------
29 - 31	Sand, fine grained, silty	Basal Sandy Drift
31	Hole ended, probable boulder pavement	---------------

TEST HOLE P - 67

Interval in feet b.g.l.	Description	Stratigraphic unit
0 - 1	Top soil	---------------
1 - 7	Silt, possible carbonate streaks, clayey, plastic, colour 2.5 Y 3.5/2	Lacustrine Silt
7 - 21	Clay, laminated, silt balls, plastic, colour 2.5 Y 3/2 grading downward to 3.75 Y 3.5/1.5	Lacustrine Clay
21±	Boulder pavement	---------------
21 - 37	Till, clayey sand-till appearance, plastic, colour 2.5 Y 3.5/2	Clay-loam Till
37	Hole ended	---------------

SHALLOW WELL RWT - 1 (Recording Water Table)

0 - 1	Top soil	---------------
1 - 8	Clay, precipitate streaks, silty, plastic, colour 10 YR 3/1.5 grading downward to 2.5 Y 5/2	Lacustrine Clay
8 - 12½	Till, silty, carbonate pebbles	Clay-loam Till
12½	Hole ended	---------------

SHALLOW WELL RWT - 2

Interval in feet b.g.l.	Description	Stratigraphic unit
0 - 1	Top soil	---------------
1 - 6	Clay, silty, plastic, colour 10 YR 3/1	Lacustrine Clay
6 - 12	Till, clay streaks, carbonate pebbles	Clay-loam Till
12	Hole ended	---------------

SHALLOW WELL RWT - 3

Interval in feet b.g.l.	Description	Stratigraphic unit
0 - 2	Fill	---------------
2 - 10	Clay, laminated, plastic, colour 10 YR 3/1 to 10 YR 3/2	Lacustrine Clay
10 - 12½	Till, carbonate pebbles, silty	Clay-loam Till
12½	Hole ended	---------------

SHALLOW WELL RWT - 4

Interval in feet b.g.l.	Description	Stratigraphic unit
0 - 1	Top soil	---------------
1 - 6	Clay, silt balls, precipitate streaks, colour 10 YR 3/1	Lacustrine Clay
6 - 12½	Till, carbonate pebbles, clay and silt streaks	Clay-loam Till
12½	Hole ended	---------------

SHALLOW WELL RWT - 5

Interval in feet b.g.l.	Description	Stratigraphic unit
0 - 1	Top soil	---------------
1 - 9	Silt, silt balls and streaks, precipitate streaks, colour 10 YR 3/1 (very clayey)	Lacustrine Silt / Lacustrine Clay transition
9 - 12½	Till, carbonate pebbles, colour 2.5 Y 5/2	Clay-loam Till
12½	Hole ended	---------------

A THEORETICAL HYDROCHEMICAL EVOLUTION SEQUENCE

A P P E N D I X B

THEORETICAL HYDROCHEMICAL EVOLUTION SEQUENCE, WNRE STUDY AREA

The correlation of major ion distributions and total dissolved solids to the groundwater flow pattern was shown along geologic cross sections A - A' and B - B'. The flow system effects of concentrating the major ions in the water table of the central discharge zone were discussed. The following is a theoretical sequence of groundwater chemistry changes that may occur as water moves from the uplands recharge zone to the water table near the WM Area along cross section B - B'.

<u>Phase I</u> Recharge to groundwater flow system in southern uplands, cross section B - B'. Precipitation infiltrates surficial sands. Partial pressure of CO_2 is $10^{-1.5}$ atmosphere. Groundwater temperature is 5°C. Dissolution of dolomite will occur until system is at equilibrium. System is at near-saturation with calcite.

<u>Phase II</u> Cation exchange occurs in the lacustrine clay of the southern uplands recharge area. Na^+-montmorillonite assumed to be present in sufficient quantities to enable long-term ion-exchange effects; Ca^{++} and Mg^{++} are lost from the groundwater flow with the Ca^{++} ions having the greater exchange potential.

Phase III — Dissolution of available gypsum $CaSO_4 \cdot 2HOH$ from the clay-loam till. System does not attain equilibrium.

Phase IV — Dissolution of epsomite $MgSO_4 \cdot 7HOH$ from the clay-loam till. Phase IV occurs either in immediate succession or simultaneously with Phase III.

Phase V — Dissolution of sylvite KCl from clay-loam till. Any contribution of sylvite from the basal sandy drift is assumed to be negligible.

Phase VI — Higher flow velocities and low evaporite and carbonate content of basal sandy drift permit only slight chemical change, assumed negligible. Groundwater enters central lowlands discharge zone from basal sandy drift aquifer. Epsomite $MgSO_4 \cdot 7HOH$ is further dissolved from the clay-loam till.

Phase VII — Further dissolution of available gypsum from the clay-loam till. Oversaturation with respect to dolomite and calcite; undersaturation with respect to gypsum.

Phase VIII — Cation exchange in the surficial lacustrine clay of the central lowlands. Na^+-montmorillonite assumed to be present but with ever-decreasing exchange potential. No Mg^{++} lost.

Phase IX Groundwater reaches the water-table zone of the central discharge area. The system adjusts to CO_2 partial pressures of approximately $10^{-3.5}$ atmosphere. No precipitation of calcite or dolomite.

Phase X The ionic strength and total dissolved solids of the groundwater are doubled in that portion of the water-table zone immediate to the zone of aeration. Evaporation in the unsaturated zone and capillary fringe affects a two-fold increase over the initial concentrations

Phase XI Precipitation in the lacustrine clay/silt surficial units. Calcite precipitates formed; position varies with water-table fluctuations. System supersaturated with respect to gypsum.

Phase XII Precipitation of gypsum in capillary fringe of central lowlands discharge area. All available Ca^{++} removed from solution.

Garrels and Christ (1965) and Rozkowski (1967) describe the influence of saturation index and CO_2 partial pressures in a groundwater flow system. Major ion distributions, pH, and total dissolved solids were calculated in the manner of Cherry (1971 and 1972).

The following table shows the change in chemistry of the groundwater as it moves through the stratigraphic units of the area.

PHASE	MAJOR IONS (ppm)								pH	P_{CO_2} atm.	Saturation Index			Ionic Strength	Total Dissolved Solids (ppm)
	Ca^{++}	Mg^{++}	$SO_4^{=}$	$CO_3^{=}$	HCO_3^{-}	Na^{+}	K^{+}	Cl^{-}			dolo	cal	gyp		
I	106	63	—	0.24	508	—	—	—	7.07	$10^{-1.5}$	1.0	0.93	0	0.015	677
II	2	53	—			69	—	—			0.01	0.02	0	0.010	632
III	192	↓	456				—	—			0.83	1.3	0.3	0.029	1278
IV		78	552				—	—			1.2	1.3	0.34	0.033	1398
V		↓	↓				6	6			Slight Reduction			0.033	1410
VI	↓	179	955								1.4	0.93	0.46	0.050	1914
VII	292		1055			↓					2.0	1.4	0.72	0.057	2114
VIII	172			↓	↓	129			↓	↓	1.3	8.3	0.45	0.053	2054
IX	↓	↓	↓	18.6	396	↓	↓	↓	8.90	$10^{-3.5}$	6460	58.9	0.45	0.052	1962
X	344	358	2110	37	792	258	12	12	↓		2950	37.2	0.28	0.104	3924
XI	83		↓	1.02	86				8.20		7.9	1.0	2.2	0.084	2922
XII	0	↓	1911	↓	↓	↓	↓	↓	↓	↓	0	0	0	0.076	2640

HVORSLEV WATER-LEVEL DRAWDOWN METHOD

FOR CALCULATING HYDRAULIC CONDUCTIVITY

APPENDIX C

THE HVORSLEV RESPONSE TECHNIQUE IN THE CALCULATION OF HYDRAULIC CONDUCTIVITY

Derivation of the Hvorslev Equation

The variable head formula for calculating hydraulic conductivity is a result of modifying Hvorslev's basic equation for determining hydrostatic time lag "T". Basic time lag is defined as the time required for equalization of the head difference between the water table or piezometric level and the head "H" in the piezometer when the corresponding discharge

/4/ $$Q = FK_h H$$

is maintained." "H" in eqn. /4/ is the active head at a time "t". Fig. 39 demonstrates that H = z - y where "z" is a function of time; i.e., $Z = H_o$ at t = 0. "F" is defined as a shape factor dependent upon the dimensions and configuration of the well-point diameter "d", piezometer diameter "D", and length of well-point intake area "L".

Relating discharge "Q" to "A", the cross-sectional area of the piezometer,

/5/ $$\frac{Q}{A} = \frac{dy}{dt}$$

the discharge per unit area is proportional to the change in active hydraulic head with respect to time. By substituting eqn. /4/

for "Q" in eqn. [5],

[6] $$\frac{FK_hH}{A} = \frac{dy}{dt}$$

and combining with eqn. [7],

[7] $$V = AH$$

where "V" = the total volume of flow required for equalization of the drawdown "H", the basic time lag may be expressed as

[8] $$T = \frac{V}{Q} = \frac{AH}{FK_hH} = \frac{A}{FK_h}$$

By exchanging eqn. [8] for "A" in eqn. [6],

[9] $$\frac{FK_hH}{TFK_h} = \frac{dy}{dt}$$

eqn. [10], a final differential equation for determination of the hydrostatic time lag, can be developed.

[10] $$\frac{H}{T} = \frac{z - y}{T} = \frac{dy}{dt}$$

At a constant piezometric pressure and a "t" of zero, integration of eqn. [11]

[11] $$\frac{H_o}{T} = \frac{dy}{dt}$$

yields a natural logarithmic relation between initial drawdown head and active hydraulic head at time "t".

[12] $$\frac{t}{T} = \ln \frac{H_o}{H}$$

Calculation of the basic time lag is from a semi-logarithmic plot of head ratio H/H_o versus time "t" (Fig. 40).

The Hvorslev Method as Applied in the General Study Area

The Hvorslev equation for determining hydraulic conductivity via the time lag constant "T" is given as

$$K = \frac{A}{FT} \qquad [3]$$

However, eqn. [3] was not used in the WNRE studies but was replaced by eqn. [2]. The latter method can be easily modified to include the basic time lag as shown by eqn. [4].

$$K_h = \frac{d^2 \cdot \ln \left[mL/D + \sqrt{1 + (mL/D)^2} \right]}{8 \cdot L \cdot T} \qquad [4]$$

In this case, "T" is determined through use of the previously mentioned semi-logarithmic plot of head ratio and time.

Eqn. [2] was chosen for its independence of the time lag factor. Thus, one source of departure from the straight line graph, an initial fast response not reflective of actual permeability, was clearly isolated; i.e., the initial steep slope of the graph can be neglected provided the value of H_o is large enough to compensate for the initial head response.

Equally important is the actual head ratio at which the slope abruptly changes. If a sharp decrease in slope does occur, it will be prior to a head ratio of 0.37 (Fig. 40). Lawson (1968) has chosen to calculate basic time lag by considering only those straight-line segments below a head ratio of 0.65. This allows for possible initial deviations. Lawson (1968) suggested that the "mean value [of T] be calculated from an equal number of corresponding straight-line segments covering the entire range of permissable head ratios [0.65 - 0.0]".

Neverthcless, if the slope breaks after 90% equalization has occurred, it will require twice the amount of time to attain 99% equalization as it did to attain 90% (Fig. 40). Thus, in determining external influence upon the piezometric response, the point of departure from the straight line must be considered with respect to the equalization ratio at that point. That is, if deviation occurs after y/H_o = 90%, then the response may be unreliable in that portion of the graph.

Validity of the Hvorslev Procedure with Respect to the Shape Factor and Transformation Ratio

The effectiveness of the Hvorslev technique can be examined in light of the shape factors inherent in the piezometer construction and the stratigraphy involved. The tests in the study area involved the general shape factors d, D, and L. The piezometer intake diameter "D" ranged from 0.067 to 0.50 foot while the actual piezometer diameter "d" ranged from 0.067 to 0.20 foot. Where the sand pack about the well-point filter is lithologically dissimilar to the surrounding hydrostratigraphic unit, the value of "D" is assumed to equal the total diameter of the well-point filter; i.e., a piezometer with d = 0.067 whose well-point filter lies in a clay unit will have a "D", not of 0.067, but of the width of the borehole. With a well-point filter in a sand unit, "D" equals "d" the diameter of of the piezometer.

The length of well intake "L" varied from 1.5 to 2.0 feet with a very few values of 3 to 5 feet. The water-table wells and piezometers were treated, as were the large majority of piezometers tested, in this 1.5 to 2.0 foot range. Using the actual water-table piezometer intake length of approximately 10 feet would decrease the horizontal hydraulic conductivity K_h by a maximum factor of three where L = 2.0 for the water table piezometer in the original test. By varying d or D, changes up to factors of two were recorded for the values of K_h.

The relation of these general shape factors in a uniform, sandy soil (d = D) is seen to be an approximation of the Dachler formula. In this case, the formula is applied to a cylindrical intake or well point instead of the normal application based on semi-ellipsoidal, equipotential surfaces. The flowlines are symmetrical with respect to a horizontal plane through the center of the well point with eqn. [15]

$$[15] \qquad q = \frac{2\pi L \cdot KH}{\ln \left[L/D + \sqrt{1 + (L/D)^2} \right]}$$

applied to both halves of the well intake.

The accuracy of this equation will decrease with the decreasing ratio L/D. For increasingly large values of L/D, eqn. [16] is sufficient.

$$[16] \qquad q = \frac{2\pi L \cdot KH}{\ln (2L/D)}$$

This adjustment for L/D is reflected in the variation of eqn. [2] to adjust for values of mL/D that are greater than 4.

$$[17] \qquad K_h = \frac{d^2 \cdot \ln (2mL/D)}{8 \cdot L \cdot (t_2 - t_1)} \ln \frac{H}{H_o}$$

The transformation ratio "m" was set at a unit value of one.

[18]
$$m = (K_h/K_v = 1)^{\frac{1}{2}}$$

A significantly larger value of "m" would require a horizontal hydraulic conductivity "K_h" that is impossibly greater than the vertical conductivity.

In an experimental case the transformation ratio in Equation 18 was allowed to equal 10; i.e., the horizontal conductivity was considered 100 times greater than the vertical conductivity. The result was a doubling of the horizontal conductivity calculated using "m" equals one. Where the value of "m" was increased to 100, the horizontal conductivity increased threefold.

The secondary permeability of an overlying clay or till unit would considerably decrease this ratio through an increased vertical conductivity (Williams and Farvolden, 1967). Thus the choice of m = 1 is based on a decision that it would be impractical to assign a more exact value to the K_h/K_v ratio.