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HYDROGEOLOGY OF RED DEER AND VICINITY, ALBERTA

G. M. Gabert

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CONTENTS

Illustrations

Page

Tables

HYDROGEOLOGY OF RED DEER AND VICINITY, ALBERTA

ABSTRACT

The hydrogeology of Red Deer and vicinity was investigated from 1967 to 1969. The total area of study included 533 square miles, but test drilling and pump testing were limited to a 30 square mile area north of Red Deer. The field program comprised the drilling of 17 test holes totalling 7 906 feet, 33 bail tests, 3 long pump tests, the collection of 108 water samples, and the measurement of water levels and water temperatures. Prior to this study, several sites for the development of groundwater supplies were selected by mapping natural phenomena related to groundwater conditions. This method is evaluated by comparison with results obtained from the present investigation. The hydrogeology was described, interpreted, and predicted by the application of regional study techniques. A two-dimensional, quantitative flow net, drawn for a representative hydrogeological cross section in the area, was used as a reference to guide interpretation of hydrogeological data and to calculate the natural yield of a portion of the main aquifer.

The regional hydrogeologic environment generates and controls various groundwater conditions which can be described by a group of parameters that collectively constitute the groundwater regime. The environment for the groundwater regime was described in terms of topography, geology, and climate. The topography is characterized by a broad depression with gentle slopes, bordered on the east and west by uplands and incised at its lowest part by the valley of the Red Deer River which is the principal drainageway. The Tertiary and Quaternary deposits are of particular interest in the study area. The Tertiary sediments consist of a sequence of alternating shales and sandstones of the Paskapoo Formation. Quaternary deposits include Saskatchewan Gravels and Sands in valleys on the bedrock surface and drift deposits of gravel, sand, silt, and clay. Climate is depicted by a mean annual

precipitation ranging from 18 to 20 inches, a mean annual temperature of 53°F, and a mean annual potential evapotranspiration of 20 to 22 inches.

Regime parameters described in detail are the occurrence, movement, and chemistry of groundwater. The main aquifers in the surficial deposits are sands and gravels. In the bedrock the principal aquifers are sandstones but shales also are important locally. Aquifer-performance tests are used primarily to identify and evaluate aquifers suitable for the development of large groundwater supplies. Hydraulic conductivities of aquifers range from less than 1 to 1 000 gallons per day per square foot (gpd/ft^2). Sixty-five percent of the groundwater flow takes place in local and intermediate flow systems at depths up to 600 feet, and the remainder for the most part in high permeability sandstone layers at greater depths. Water quality is generally very good throughout the area and the dominant chemical type of groundwater is sodium bicarbonate. The total dissolved solids content of groundwater is usually less than 1 000 parts per million (ppm) but is as high as 8 000 ppm in small areas. Fluoride content is high in deep aquifers, ranging from 2 to 6 ppm. Groundwater temperatures to depths of 700 feet range from 5 to 10.8°C. Noncommercial quantities of natural gas are present in aquifers below 100 feet in the river valley and at greater depths in other areas.

The principal aquifer investigated during the study is a sandstone layer in the Paskapoo Formation found immediately north of the City of Red Deer. It has a known extent of about 60 square miles, occurs at depths ranging from 134 feet in the river valley to 600 feet in the highlands, ranges in thickness from 10 to 40 feet and in hydraulic conductivity from 186 to 565 gpd/ft^2. The water quality in the aquifer is excellent except for a high fluoride content. Water temperatures range from 4.4 to 5.6°C. A natural yield of 2.3 million gallons per day was calculated for the aquifer by means of a flow net for a 2 by 11.5 mile area north of Red Deer. Of this quantity 900 000 gpd can be obtained in the river valley area from wells designed for capacities of 50 to 100 gallons per minute.

INTRODUCTION

Background Information

The Groundwater Division of the Alberta Research Council, since its inception in 1956, has been continuously involved in detailed evaluations of local groundwater resources. Investigations of this type are presently carried out within the scope of planned groundwater research programs. The City of Red Deer in February 1960 formally requested the Groundwater Division's assistance in a groundwater resource investigation for industrial purposes in an area north of the city. The exploration program was conducted by the City and information obtained was analysed by the Groundwater Division. Results indicated that a potential yield of 1.5 million gallons per day (mgpd) could be obtained by induced infiltration supply from gravels adjacent to and underlying the Red Deer River. To determine the hydrogeologic situation in more detail an additional investigation was recommended and executed by the Groundwater Division in cooperation with the City of Red Deer and the Canadian National Railways. The results of this program showed that the aquifer, a sandy gravel layer averaging about 15 feet in thickness, was restricted to an area about one-half mile in length along the west bank of the river. Based on interpretation of additional pump test data, the potential yield of the aquifer was reduced from 1.5 mgpd to 1.0 mgpd. In 1964 the Groundwater Division had planned to begin a detailed investigation of the groundwater resources in that part of the province that included Red Deer, but the program was postponed due to emergency programs of groundwater resource investigation at Olds and Three Hills, undertaken at the request of other departments of the Government of Alberta. Study of the groundwater resources in the Red Deer region began in 1965 with the mapping of naturally occurring surficial phenomena to determine the occurrence, movement, and chemistry of groundwater. A formal submission in 1966 by Red Deer to the Federal Government for financial assistance in the study, through the agency of Agricultural Rehabilitation and Development (ARDA), was not approved. The City of Red Deer, however, budgeted $50 000 to be spent over a 3-year period beginning in 1967 for detailed groundwater resource investigation in the proximity of the city. This detailed investigation, part of a larger study of the Red Deer area, provided basic data for construction of a hydrogeological model enabling a quantitative estimation of the groundwater resources north of Red Deer. This model was also used as a reference to guide interpretation of basic data available for an area of 533 square miles surrounding and including the city of Red Deer.

Location and Extent of Area

The study area (Fig. 1), located in central Alberta, is bounded by longitudes 113°34′ and 114°18′ west, and latitudes 52°8′ and 52°25′ north, and comprises townships 37 to 39, ranges 26 to 28, west of the fourth meridian, and ranges 1

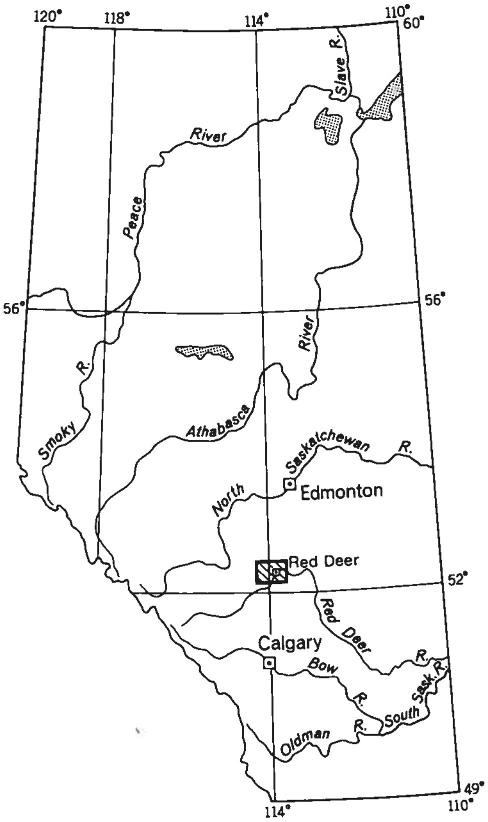


FIGURE 1. Location of the Red Deer area.

and 2 west of the fifth meridian. The detailed investigation was carried out in a 30 square mile area (Fig. 2) north and east of the city in part of township 38, ranges 26 and 27, west of the fourth meridian.

Geographical Setting, Population, and Industry

The Red Deer area is located in the Red Deer River drainage basin in the western Alberta Plains (Govt. and Univ. Alberta, 1969). To the west lie the Rocky Mountain Foothills and eastward the eastern Alberta Plains. The area lies in the fertile black soil zone of Alberta, and the natural vegetation is characterized by aspen parkland to the east and mixed forest to the west of Red Deer.

Population in the area is concentrated in the city of Red Deer, the towns of Blackfalds and Sylvan Lake, and the Canadian Forces Base, Penhold. In 1968 the population of Red Deer was 26 730; Blackfalds, 779; and Sylvan Lake, 1 352. The rural population density in the area ranges from 6.0 to 7.9 persons a square mile (Baker, 1962) which would give a total minimum rural population of 3 198. The population of the study area is, therefore, in the order of at least 32 000.

The principal industry in the area is agriculture. Over 50 percent of the land is cultivated; the main type of activity is mixed farming, but specialization in livestock raising and dairying is also prominent. Oil and natural gas production is the only other economic activity of much significance. Part or whole of major oil and gas fields in the area include: (1) Joffre and Joffre South oil field, east and north of Red Deer; (2) Gilby oil field, northwest of Red Deer; and (3) Prevo and Sylvan Lake gas fields, west of Red Deer.

The city of Red Deer is primarily an important trade center in central Alberta. Industry, by comparison, is of secondary importance but has shown noticeable development in recent years.

Purpose of Investigation

The purpose of the hydrogeological investigation was twofold: (1) to explore the Paskapoo Formation for major aquifers and determine the availability and quality of groundwater present in those aquifers; and (2) to describe the hydrogeology in an area of 533 square miles surrounding and including the city of Red Deer. A secondary objective was to evaluate the mapping of naturally occurring phenomena as a method of selecting sites for the development of groundwater supplies (Appendix A).

Scope of Investigation

A four-stage program of study was executed during the investigation which included: (1) mapping of naturally occurring surficial phenomena to determine the groundwater regime; (2) test drilling, aquifer-performance tests, and well-performance tests to obtain basic hydrogeologic data; (3) construction of a hydrogeological model from basic data to study the hydrogeologic environment, groundwater regime, and groundwater resources by the application of regional study techniques; and (4) a comprehensive description of the hydrogeology incorporating the information from the second and third parts of the program with a large quantity of available basic data. The first part of the program was completed by Clissold (1967, 1968) who mapped, examined, and described natural features occurring on the surface, particularly those related to the presence of groundwater. He also studied the areal distribution of several different chemical types of groundwater as determined from water samples collected on or immediately below the land surface. On the basis of this study the location and areal extent of proposed sites for test drilling for large supplies of groundwater were outlined for investigation. Material from the final three parts of the program comprise almost the entire text of this publication. Basic hydrogeological data were obtained in the area of detailed investigation from 17 test holes totalling 7 906 feet, 33 bail tests, 3 pump tests, 108 water samples, lithologic samples, and many groundwater level and groundwater temperature measurements. A two-dimensional electrical analogue model of groundwater flow distribution was constructed from the basic data along a cross section located in the northern part and west of the area of detailed investigation. A flow net was drawn for calculation of groundwater development yields for a major sandstone aquifer in a strip of land along the cross section. The flow net also defined the groundwater flow systems present along the cross section. This publication represents the summary of all groundwater investigations in the Red Deer area to date and includes a synthesis, interpretation, and description of hydrogeological information obtained from 1 090 water wells and flowing seismic shot hole reports, 221 structure test hole electric logs, 17 exploration test holes, and 14 other publications or reports dealing with some aspect of the hydrogeology or relevant geology of the study area.

Selection of Sites for Investigation

Eight sites for investigation, namely: Red Deer 8-15, Deerhome 1-22, Bickford 8-12, Ireland 12-25, Robinson 13-30, Morrisroe 1-18 No. 1, Morrisroe 1-18 No. 2, and Bickford 13-32 (Fig. 2), were proposed by Clissold (1967, 1968). The remaining nine sites were selected successively and progressively following examination and evaluation of test data from previously investigated sites. These sites were: Spenceley 13-13, Williamson 4-19, Choate 14-28 No. 1, Choate 14-28 No. 2, Choate 13-28, Hermary 2-32, Longacre 5-33, Hermary 7-33, and Viewpoint 2-28 (Fig. 2). Selection of sites also took into consideration planned pump tests and the eventual construction of a two-dimensional cross section that was chosen as a hydrogeological model of the area. The Red Deer Packers 16-28 test hole (Fig. 2) is a private water well that was supervised during drilling by Groundwater Division personnel.

Exploration Methods and Techniques

Investigation of the hydrogeology was carried out mainly by means of a cable-tool drilling rig, but a conventional rotary rig adapted to compressed air drilling was employed to complete observation wells for pump testing purposes. Techniques included the installation of up to four strings of casing in a drill hole in a fashion that enabled the sampling of drill cuttings, measurement of water levels, obtaining of water samples, and bail or pump testing of main aquifers or open hole intervals. Groundwater temperatures were taken for water samples obtained from aquifers after two hours of bailing or at intervals during long pump tests. Lithologic samples were obtained at least every five feet during drilling. Test holes were cleaned and developed by bailing at the end of each day of work and the time interval for recovery of water level until the next work day was noted. Prior to the commencement of work each day, a water sample was taken from the test hole and the water level recorded. Bail testing involved bailing the test holes for a two-hour period at a constant rate. Time-drawdown and time-recovery measurements of water levels were both taken where possible. On occasion, time-drawdown measurements were impossible because of high bailing rates or deep water levels. Three long aquifer-performance tests of 1 600 minutes, 5 days, and 7 days duration were conducted on wells located at the Ireland 12-25, Choate 14-28 No. 2, and Morrisroe 1-18 No. 2 sites (Fig. 2), respectively. The 1 600-minute pump test was conducted without an observation well, whereas seven observation wells were used during the 7-day pump test and eight throughout the 5-day test to record time-drawdown and time-recovery data. Step-drawdown tests as outlined by Jacob (1947) and Rorabaugh (1953) were carried out to analyse factors concerning well performance at the Morrisroe 1-18 No. 2 and the Choate 14-28 No. 2 locations.

Type, Analysis, and Treatment of Data

The location and type of basic data and range of well depths are shown in figure 3. Measured and observed basic data and analyses of basic data are presented graphically in Appendix B for each of the 17 exploration test holes and the Red Deer Packers well. Lithologic samples were described in detail with aid of a binocular microscope. Water samples were analysed for the major ions usually present in groundwater in Alberta, including calcium, magnesium, sodium, potassium, carbonate, bicarbonate, sulfate, and chloride; in addition, analyses were made for total dissolved solids, hardness, fluorides, and iron. The majority of water levels measured represented composite water levels. Coefficients of transmissivity and storage were calculated by the modified nonequilibrium formula (Jacob, 1950) for time-drawdown data, and transmissivity values were also calculated by the Theis (1935) recovery formula for time-recovery data. Step-drawdown test data were analysed with consideration of relevant remarks published by Lennox (1966) and Mogg (1968). All observed, measured, and analysed basic hydrogeologic data have been interpreted and described in a regional context, particularly those in the area of detailed investigation. Only in this context can the hydrogeology of an area be fully comprehended, described, and predicted.

Acknowledgments

Test drilling was financed by the City of Red Deer, and the cooperation of Mr. N. J. Deck, City Engineer, during the study is greatly appreciated. The author would like to express his gratitude to private landowners who generously granted permission to drill test holes on their property. Test drilling and aquifer testing throughout the investigation were effectively carried out by Forrester Water Well Drilling Limited, Red Deer, Alberta. Three test holes used as observation wells were drilled by Hi-Rate Drilling Company Limited, Stettler, Alberta. Structure test hole electric logs were supplied by Chevron Standard Limited. Chemical analyses of the groundwater samples were carried out by the Geology Division of the Alberta Research Council and the Provincial Analyst. Comments, discussions, and technical assistance from members of the Groundwater Division and draftsmen at the Alberta Research Council have been very valuable to the author in the preparation of this bulletin. Mr. W. R. Turner, hydrogeologist, conducted the first year of groundwater exploration in this study and pump-test data then obtained were analysed by D. H. Lennox. Mr. R. Stein constructed electric analogue models of the hydrogeologic cross section and drew groundwater flow patterns for given water table and geologic configurations; Miss B. Annett compiled and plotted a very large quantity of basic data, Mrs. D. Borneuf typed the manuscript, and Mr. H. Weiss drafted the illustrations. J. Tóth, D. A. Hackbarth, Miss A. Badry, and R. Green edited the report and their contribution is gratefully acknowledged.

SUMMARY OF PREVIOUS HYDROGEOLOGICAL AND PERTINENT GEOLOGICAL INVESTIGATIONS

Hydrogeological studies or geological reports containing reference to groundwater in the Red Deer area date back to 1945, and the most recent information was published in 1971. The studies can be grouped into five categories according to their relevant aspects:

(1) Geology
(2) Groundwater availability and quality
(3) Well and aquifer performance
(4) Groundwater mapping and chemistry
(5) Hydrogeology.

The first four deal with particular aspects of hydrogeology and the last one includes comprehensive regional investigations of parameters of the groundwater regime. An index map of these investigations is shown in figure 4. Summary of these investigations will provide an annotated reference to previous hydrogeological studies but the intent is to present important portions of these reports which are not updated or expanded in the present study, so that this publication can be used as a complete, comprehensive description of the hydrogeology in the Red Deer area based on an interpretation of all available data, published and unpublished.

Geological Studies

Allan and Sanderson (1945) published the first hydrogeological observations pertinent to the present study in a detailed report of the geology of the Red Deer and Rosebud map areas which include that part of the study area east of the fifth meridian. They observed that surface water did not seep away on the Edmonton surface but was readily absorbed by Paskapoo rocks and that "at many points along the valley of the Red Deer the contact between the Edmonton and the Paskapoo is marked by the emergence of strong, steady springs." They concluded that "the Edmonton rocks are clayey and impervious and that the Paskapoo rocks act as collectors and reservoirs of the precipitation." This obvious difference in the relative porosities and permeabilities of the Edmonton and Paskapoo Formations is confirmed by subsequent hydrogeological investigations in the Red Deer area and is considered a significant fact in the present study.

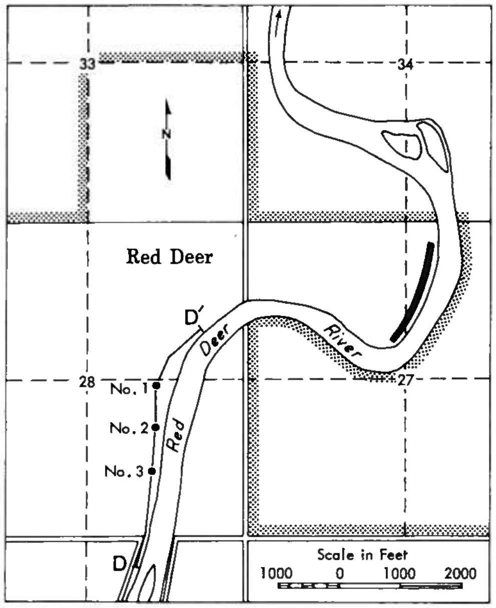
Stalker (1960) mapped the surficial geology of the Red Deer-Stettler area. He describes the groundwater supply of the various types of surficial deposits in general but concludes that the deposits, except for aquifers in buried valleys, are not important for large quantities of groundwater because of slightly permeable materials and poor water quality, particularly in regard to hardness. Figure 5 shows the surficial geology as mapped by Stalker (1960) in that part of the present study area east of the fifth meridian and as mapped by A. N. Boydell (pers. comm.) west of the fifth meridian.

Studies of Groundwater Availability and Quality

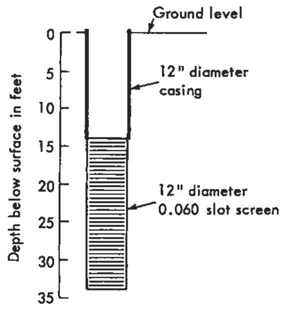
Latour (1947) and Rutherford *et al.* (1948) studied existing groundwater supplies in the study area east of the fifth meridian by interpreting information obtained from a survey of water wells. The locations of a few springs were also noted. The survey showed that sufficient supplies were obtained from aquifers in the surficial deposits and the upper bedrock deposits. Well depths, with few exceptions, were less than 200 feet. The use of groundwater at this time was almost entirely for domestic and stock-watering purposes. Foster and Farvolden (1958) defined very generally the groundwater yielding characteristics and chemistry of groundwater for the Upper Cretaceous bedrock formations in Alberta. They also pointed out the possibility of obtaining large quantities of groundwater from buried gravels of preglacial drainage systems and from gravels underlying and adjacent to present-day rivers. Farvolden (1963a, 1963b) outlined the bedrock topography and explained the erosional history of the Alberta plains since the uplift of the Rocky Mountains in Oligocene time. The purpose of mapping the bedrock topography was to show the locations of major buried valleys which could be explored for aquifers. A major buried valley on the bedrock surface is present along the major topographic depression that trends northeastward across the study area through the city of Red Deer. Le Breton and Jones (1963) studied differences in the chemistry of groundwaters in the settled areas of Alberta, including the Red Deer area, and showed the phenomena on a series of contour maps and "range-of-values" maps. The distribution in parts per million of total solids, hardness, sulfates, and iron for groundwater in bedrock and drift deposits was studied. Important conclusions from the study were that bedrock waters were lower in sulfates, hardness, and iron than drift waters; that the Paskapoo Formation contains the best quality water for human consumption; and that surficial deposits contain groundwater of best quality in areas of high precipitation.

Well- and Aquifer-Performance Studies

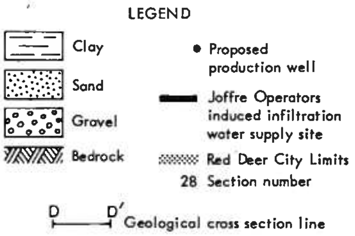
Tóth (1961) investigated the possibility of developing an induced infiltration groundwater supply from gravel aquifers in the surficial deposits along the west bank of the Red Deer River north of the city of Red Deer. Two gravel layers are present at the location most suitable for groundwater supply development (Fig. 6, a and b). The lower gravel (Fig. 6b), on the basis of interpretation of a 48-hour pump test, does not have a direct connection with the river; however, a 36-hour pump test of the upper gravel aquifer (Fig. 6b) showed that water can be induced to flow from the river to wells completed in the upper gravel. Tóth (1961) recommended that three production wells be completed in the upper gravel to

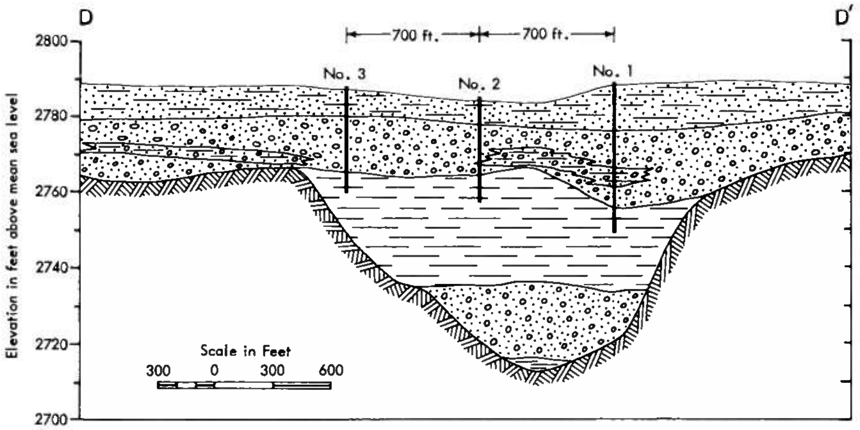


(a) Location of geological cross section and proposed production wells.



(c) Proposed design for Well No. 1





(b) Geological cross section along the west bank of the Red Deer River.

FIGURE 6. Induced infiltration water supply details (after Tóth, 1961).

obtain a minimum total production of one mgpd. The recommended locations of these wells and the proposed design and construction for one of the wells are shown in figure 6a and c. Quality of the groundwater and river water at the location is shown in Appendix C.

In 1957 the (then) California Standard Company and Imperial Oil Limited (pers. comm.) conducted a hydrogeological survey of alluvial deposits along the Red Deer River from Lsd. 8, Sec. 28, Tp. 38, R. 27, W. 4th Mer. to the center of Sec. 30, Tp. 38, R. 26, W. 4th Mer. to determine the feasibility of developing an infiltrated water supply of at least 50 000 barrels (1 750 000 gallons) per day by means of horizontal collectors. The survey showed that the only suitable location along that stretch of the river for development of a large water supply was in the north half of Sec. 27, Tp. 38, R. 27, W. 4th Mer. (Fig. 6a) in a permeable sand and gravel formation which is hydraulically connected with the Red Deer River. The sand and gravel deposits extend to depths of 24 feet below surface. Interpretation of data from pump tests conducted on two wells at the site in section 27 (Fig. 6a) at rates of 166 and 91 gpm, for periods of 96.5 hours and 66 hours, respectively, gave values for hydraulic conductivity of 4 175 gpd/ft^2 and 5 354 gpd/ft^2, respectively. The study also indicated that the quality of the water produced, assuming continuous pumping conditions, will closely approach the average chemical quality of the river (Appendix C), except that it will be free from turbidity and normally free from organic matter and pathogenic bacteria. Groundwater temperatures during the pumping tests ranged from 6.7 to 9.2°C. Seasonal temperature variation for groundwater at the site is estimated to range from 3 to 12°C. Saturated thickness of the aquifer was approximately 18 feet at each pump-test site and drawdown in each pumping well during the tests was less than two feet. Six wells constructed with 13 3/8 inch O.D. casing were completed with 12 feet of slotted casing opposite the lower part of the aquifer. Peak daily water production from four of the wells for the years 1959 to 1961, inclusive, was about 800 000 gallons. Presently, little water is produced from the wells because requirements for water flooding operations have declined.

Groundwater Mapping and Chemistry

Clissold (1967, 1968) mapped naturally occurring surficial phenomena to determine groundwater conditions on or near the land surface in the Red Deer area. Clissold (1967) defines groundwater mapping as the systematic examination of a region for groundwater information. Clissold's approach to mapping deliberately assumed that little or no basic hydrogeological data was available for study prior to field investigation. The practical objective of the studies was to select test drilling sites suitable for the development of groundwater supplies for municipal purposes. The underlying principles of groundwater mapping are based on a theory of groundwater motion in small drainage basins presented in two papers by Tóth (1962, 1963). Subsequently Tóth (1966b) investigated the possibility of mapping and interpretation of field phenomena for groundwater reconnaissance in a prairie environment in central Alberta. Studies important to the development of groundwater mapping were carried out by Meyboom (1966) who related discernible groundwater phenomena of a typical prairie drainage basin in south-central Saskatchewan to a flow system in a particular geological model, called the "Prairie Profile." Meyboom (1967) also studied the role of phreatophytes in the hydrology of the same basin. Clissold (1967, 1968) mapped, investigated, described, and interpreted naturally occurring surficial phenomena which included springs, seepages, damp soil, vegetation, salt precipitates, soap holes, swamps, "less-fertile soil," closed depressions, and gullies and meanders at locations with surface material less resistant to erosion. Figure 7 shows the location and distribution of easily discernible groundwater phenomena (excluding phreatophytic vegetation) mapped by Clissold (1968), distribution of recharge and discharge areas, and areas proposed for the development of large supplies of groundwater. The locations of former flowing seismic shot holes are also plotted on the map. The distribution of recharge and discharge areas has been outlined on the basis of mapped phenomena interpreted in terms of groundwater flow direction relative to the water table. Areas of ascending groundwater movement are considered discharge areas while those of descending direction are recharge areas. Clissold (1968) studied groundwater flow patterns in vertical two-dimensional cross sections by constructing flow nets with an electric analogue. He compared the flow patterns with mapped phenomena and concluded that the most active flow systems are the local systems originating on the uplands and terminating on the adjacent lowlands. He also assumed that the type of natural groundwater movement in the Red Deer area is as if the medium were homogeneous and that the homogeneity extends to a depth of approximately 3 600 feet below surface (top of the Lea Park Formation). He obtained water samples from locations of groundwater discharge on the surface or from shallow depths for chemical analysis to determine the quality of groundwater in the area. He classified the chemical types of groundwater (Fig. 8) and showed their distribution in the area (Fig. 9). Clissold (1968) mapped 53 points where springs, seepages, and swamps can be developed for water supplies up to 10 gallons per minute. The majority of the locations for springs and seepages are shown in figure 7, together with areas where large supplies of groundwater probably can be developed by drilling wells to depths up to 1 000 feet. Clissold (1968) delineated these areas by interpreting field observations and electric analogue cross sections of fluid potential distribution in terms of rates and directions of groundwater movement in the subsurface, areas of recharge, locations of groundwater discharge on the surface, and change in water levels in relation to well depths. Groundwater quality was also a criterion for selection of areas for development of large groundwater supplies. Clissold (1968) also emphasized that terrace gravels hydraulically connected to the Red Deer River were potential sources of large quantities of groundwater. The remaining part of the area studied by Clissold (1967, 1968) was considered to have a groundwater probability of about 5 gpm to depths ranging from 100 to 300 feet, except in the Red Deer River valley bottom where yields of 10 to 25 gpm could probably be obtained from the development of aquifers to a depth of 500 feet. Clissold (1967, 1968) expressed two significant

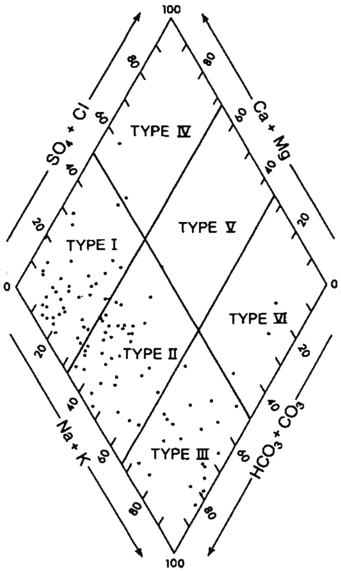


FIGURE 8. Chemical type of groundwater based on analysis of groundwater samples on or near the surface (after Clissold, 1968).

general conclusions: (1) the method is most useful in groundwater hydrology studies in areas where no hydrogeological information is available, and (2) the main shortcoming is the lack of permeability data at greater depths.

Hydrogeological Reports and Maps

Nielsen (1963) investigated the groundwater resources of the Blindman River basin. The southern tip of the basin extends into the northern part of the present study area, mainly in Tp. 39, R. 27 and 28, W. 4th Mer., and Tp. 39, R. 1, W. 5th Mer. (Fig. 4). The hydrologic characteristics of the basin and the hydrogeology of the Paskapoo Formation and surficial deposits are discussed in some detail. Information about existing groundwater supplies and future prospects are outlined for towns, villages, and industrial sites in the basin. Nielsen (1963) concluded that the main aquifers in the Paskapoo Formation were sandstone lenses highly variable in hydrogeologic characteristics. The sandstone lenses were considered economically more important than sand and gravel aquifers in the surficial deposits which, he stated, constituted only a minor source of groundwater in the basin. He determined that yields up to 100 gallons per minute can be obtained from single wells completed in the Paskapoo Formation. The groundwater chemistry was studied in detail and the water was found to be generally of good quality for human consumption and industrial use. One interesting feature of the chemistry of groundwater in the Paskapoo Formation for wells up to 200 feet in depth was that water high in sulfate content is also high in total dissolved solids content.

Quist (1969) studied the groundwater resources in the area of the present study. Most of his basic data was essentially that available now, including some information obtained during the three-year detailed groundwater investigation in the proximity of Red Deer. Detailed information from exploration test holes Robinson 13-30, Morrisroe 1-18 No. 1, Bickford 13-32, and Spenceley 13-13 was made available for use by Quist. Quist (1969) concluded for the area of the four test holes that the aquifers consist of bentonitic sandstone lenses with hydraulic conductivity values ranging between 0.9 to 88.6 igpd/ft^2. Twenty-year "safe yield" values for the four test holes range from 1.9 to 67.3 igpm. The most common chemical type of groundwater in the area is sodium-potassium-bicarbonate-carbonate water. High concentrations of sulfate in percent of total anions and fluoride in parts per million were observed at a few localities. Raw data used in Quist's (1969) work and new information are reinterpreted in the present study in the light of the hydrogeological investigation carried out in the Red Deer vicinity.

In 1968 the Groundwater Division of the Alberta Research Council initiated a program aimed at the systematic and complete reconnaissance of the hydrogeology of the province. The results are being published in a series of maps on a scale of 1:250 000, each map covering the area of a national topographic system (NTS) map sheet (approximately 5 000 square miles). The maps present a reconnaissance degree of detail and are intended to show, to a depth of approximately 1 000 feet: geology, hydrogeologic properties of rocks, distribution of economically significant aquifers, potential yields of individual wells, rates and directions of the movement of groundwater in three dimensions, distribution of fluid potentials, locations and yields of natural springs, flowing wells, distribution of major and minor chemical constituents, water temperatures, and relevant meteorological data. Le Breton (1971) and Tokarsky (1971) have completed hydrogeological maps for the Red Deer and Rocky Mountain House map areas, respectively. The present study area constitutes a small part of the total area of the two hydrogeological maps.

THE HYDROGEOLOGIC ENVIRONMENT

Concept of the Hydrogeologic Environment and the Groundwater Regime

In the last decade increasingly more attention has been paid to the interpretation of various aspects of the groundwater regime in the regional rather than the local context. In particular the concept of regional groundwater flow systems has been developed quantitatively (Tóth, 1962, 1963; Freeze, 1969a). Tóth (1970a) recognized that a working hypothesis or theoretical framework was needed upon which the procedures and interpretation of groundwater investigations could be based. He stated that such a framework must be able to identify, define, and quantify each significant property of the groundwater as well as establish functional relations between these properties and their controlling factors. Tóth (1970a) showed, by means of a conceptual model, that the regional hydrogeology of any geographic area can be described and analysed most clearly, for practical purposes, within a theoretical framework of two systems of physical and chemical parameters: the hydrogeologic environment and the groundwater regime. A cause-and-effect type of relationship exists between the two systems, with the hydrogeologic environment generating and controlling various groundwater conditions which can be described by a group of parameters that collectively constitute the groundwater regime. Table 1 lists the physical and chemical parameters of the hydrogeologic environment and the groundwater regime. Based on the fact that the relationship between the hydrogeologic environment and the groundwater regime is genetic and quantitative, Tóth (1970a) suggests that the parameters of the regime can be identified and quantified from a knowledge of the hydrogeologic environment, the only limitation being the state of present-day knowledge.

There is a total interaction between all the physical and chemical parameters of both the hydrogeologic environment and the groundwater regime. The intricacy of these interactions and the link between the theoretical framework and practical interpretation is demonstrated in the description of the hydrogeology of the Red Deer area, particularly with reference to groundwater movement, groundwater chemistry, and calculation of yield for a major aquifer.

The Hydrogeologic Environment of the Red Deer Area

The topography, geology, and climate of any geographic area are the three main components of the hydrogeologic environment or environment for the groundwater regime. Descriptions of these components are for the entire study area but a summary is given of the characteristics of each component along the cross section A-A′-A″ (Figs. 2 and 10) that was constructed as a representative hydrogeological model through the area in which a major sandstone aquifer is present in the subsurface.

Table 1. Parameters of the Hydrogeologic Environment and Groundwater Regime

Hydrogeologic Environment Parameters		
Component	**Elements**	**Groundwater Regime Parameters**
Topography	Topographic relief	Amount of water present in the saturated zone
Geology	Rock porosity	Pattern of groundwater flow
	Rock permeability	Volume discharge or flow velocity
	Mineralogy	Chemical composition of water
	Subsurface temperature	Water temperature
Climate	Precipitation	Regime variance
	Air temperature	
	Evapotranspiration	

Topography

Topographic relief, which can be defined as the three-dimensional configuration of the land surface, and drainage (referring collectively to all natural surface-water bodies) are the important elements of topography as a component of the hydrogeologic environment. The area of investigation is characterized by a broad, gently sloping, regional topographic low bordered on the east and west by higher land and incised at its lowest part by the valley of the Red Deer River which drains the area (Fig. 11). Local topographic low areas are present at three locations: (1) along the tributary Medicine River valley in the southwest part of the area; (2) along the tributary Blindman River valley in the north-central area; and (3) along the Red Deer River valley in the east-central area. The river flows along the northeast-trending regional topographic low to a position approximately six miles from the city of Red Deer where it turns to the southeast, creating an apparently natural paradox by eroding a canyon over 500 feet deep through the major topographic high area in the eastern part of the study area. This was due to the river being diverted from its former valley by glacial damming early in Pleistocene time and prior to the last glaciation (Stalker, 1960).

Elevations above mean sea level are highest northeast of Sylvan Lake (over 3 350 feet) and southeast of Red Deer (over 3 450 feet). Elevations at the location where the Red Deer River flows eastward out of the study area are less than

2 675 feet. Local topographic divides and associated well-developed, steep slopes are well defined in the area (Fig. 11). Sylvan Lake is the only lake of significant size. The catchment area for the lake is small because the local divides are situated close and parallel to the northeast and southwest sides of the lake. The lake has no major inlet but when water levels are high discharge takes place along a poorly developed outlet through Cygnet Lake and Sylvan Creek to the Red Deer River. Drainage is locally well developed on the steep slopes of uplands, on the face of escarpments, and on the sides of the Red Deer River valley and canyon. Local areas of internal drainage exist along the regional topographic low, the Medicine River valley, and in the southeast corner of the map area. These areas contain either aeolian or hummocky moraine deposits. Drainage is poorly developed in flat areas and in areas of very gentle slopes. The main features of the topography along cross section A-A′-A″ (Figs. 2 and 10) are listed below:

(1) a broad topographic low with gradual slopes rising to prominent high areas with steep slopes at each end of the cross section;

(2) a river valley (Red Deer River valley) with steep sides eroded about 100 feet below the general level of the lower part of the major topographic low;

(3) a deep canyon (Red Deer River canyon) eroded to a depth greater than 500 feet through the uplands in the eastern part of the area.

Geology

Stratigraphy

The present study is concerned mainly with the deposits of two geologic periods, the Tertiary and the Quaternary. The Cretaceous-Tertiary transition takes place within the lower parts of the Paskapoo Formation which constitutes the uppermost bedrock deposits over the area of investigation. The lower boundary of the Paskapoo Formation is taken as the top of the Kneehills Member (Battle Formation) as proposed by Carrigy (1970); the upper boundary is an erosional surface. The base of the Ardley coal zone (Campbell, 1967), which occurs above the Kneehills Member, is the lower boundary for groundwater investigation in this report. The coal zone is widespread and is found at moderate depths ranging from less than 300 feet in the Red Deer River canyon to over 1 200 feet along the Medicine River valley (Fig. 12). The Paskapoo strata above the Ardley coal zone are Paleocene in age (Snead, 1969). Where major valleys are present on the bedrock surface (Fig. 13) the Paskapoo Formation is overlain by Saskatchewan Gravels and Sands that were deposited prior to the first Quaternary glaciation (Stalker, 1968). The Saskatchewan Gravels and Sands and the bedrock surface are overlain by glacial deposits of the Pleistocene. Sediments laid down in present-day streams, rivers, and lakes of the area are of Recent age. A map of the areal distribution of surficial deposits in the study area is shown in figure 5 and figure 14 shows the thickness of these deposits. Hydrogeological cross sections A-A′-A″ (Fig. 10) and B-B′ (Fig. 15) in the area of detailed investigation show the vertical sequence and character of strata of the Tertiary and Quaternary periods.

Lithology

Deposits of the Paskapoo Formation above the Ardley coal zone have been described generally by Allan and Sanderson (1945) as "...consisting chiefly of soft, grey, clayey sandstones, soft shales, and clays slightly indurated. In the lower part of the formation there is a coarse, more or less uncemented sandstone, weathering to a buff color and of uniform character over a large area. The formation is of freshwater deposition and contains freshwater fossil shells, chiefly mollusks." They further state that "...the Paskapoo was deposited on a low and sinking surface and apparently represents a combination of subaerial floodplain and shallow lake conditions." Information obtained from 17 exploration test holes (Fig. 2 and Appendix B) in the area of detailed investigation shows that the lower part of the Paskapoo Formation occurring above the Ardley coal zone is characterized by thick extensive sandstones of fine to medium grain size alternating with thick sections consisting largely of siltstones and shales (Figs. 10 and 15). These sandstones are present in an interval of 400 feet above the coal zone in the eastern part of the study area, and in 500 to 700 feet of sediments above the coal zone in the western part of the area. The cumulative thickness of sandstones is generally greater in the west because of a general increase in the thickness of the Paskapoo sediments in that area. Examination of structure test hole electric logs suggests that, locally, part of the Paskapoo Formation is essentially a shale section. Two such areas are: (1) along the western half of the boundary between townships 38 and 39, range 28, west of the fourth meridian; and (2) north of and adjacent to the boundary between township 38 and 39, range 2, west of the fifth meridian. The upper part of the Paskapoo Formation occurring above the Ardley coal zone in the study area is generally characterized by the presence of a large number of thin sandstone lenses in a shale-siltstone section. The more extensive sandstones may cover several square miles and are often considerably thicker than the smaller lenses. The uplands east of Red Deer, southwest of Sylvan Lake town, and northeast of Sylvan Lake have resisted erosion because sequences of relatively flat-lying, thick sandstones interbedded with shale-siltstone sections cap the topographic highs. These sandstones outcrop in the Red Deer River canyon and are exposed at some locations on the highs in the western part of the area. Well developed scarps, facing generally northeast and rising 50 to 75 feet on the topographic surface, are found trending north-northeast from the center of township 38, range 28, to the northwest part of township 39, range 27, and in the northwest part of township 38, range 28. These scarps are due to thick sandstone layers that dip gently to the southwest in the subsurface. In the area of detailed investigation (Fig. 2) sandstones have a great range in permeability depending primarily on the clay content and the overall grain size. Test drilling and bail test data show that medium-grained, uncemented sandstones have the highest permeability. Siltstones and shales have generally very low permeabilities. Data obtained from test holes suggest that fracture permeability is of minor importance in the Paskapoo strata in the area.

The Saskatchewan Gravels and Sands lack material from the Precambrian Shield, such as granite, gneiss, and schist. Stalker (1968) lists eight criteria that must be fulfilled for definite identification of Saskatchewan Gravels and Sands. Stalker (1960) states that except for fragments of local bedrock, the gravels consist of rock types found in the mountains to the west. These include hard sandstone, quartzite, chert, arkose, and limestone. Owing to the occasional prominence of sand and silt lenses in the presumably Saskatchewan Gravels and Sands, these deposits are often referred to by water-well drilling contractors as "dirty gravels." Nevertheless, permeability of the gravels and sands is high.

The distribution of surficial deposits is shown in figure 5 and discussion of the lithology of the deposits is drawn largely from a study by Stalker (1960). Ground moraine and hummocky moraine are the most extensive surface deposits. These deposits are composed of till which is nonsorted and nonstratified. It was deposited by a glacier and consists mostly of locally derived material with minor constituents from more distant sources. Till overlying the Paskapoo Formation contains much more sand than till above the Edmonton Formation which constitutes the subcrop east of the study area. Although the permeability of till is generally low, it increases somewhat with higher sand content and where joints are common. Hummocky moraine is distinguished by knob-and-kettle topography and includes numerous pockets of sand and gravel. Till deposits, commonly separated by beds of gravel, sand, and silt, underlie other surficial deposits in the area.

Outwash deposits consist of gravel, sand, silt, and clay carried from the ice-sheet by meltwater streams. Areas covered by outwash deposits are classified into three types on the basis of the most prominent material: (1) areas of mainly gravel deposits; (2) areas of mainly sand deposits; and (3) areas of mixed deposits. Outwash materials, especially sand and gravel, have high permeabilities and capacities to absorb precipitation. This is indicated by the disappearance of intermittent streams as they enter the northeastern margin of outwash gravel deposits in township 37, range 2, west of the fifth meridian (Fig. 5).

Pleistocene alluvium in the area of investigation contains large amounts of good quality gravel and a large variety of deposits that owe their origin to strong erosion and deposition by short-lived streams. The gravels consist of sandstone, limestone, quartzite, and chert, with less abundant granite, gneiss, and schist pebbles. The gravel is commonly clean, well sorted, and with prominent bedding and crossbedding.

Glacial lake deposits lie mainly in the major depression trending northeast through the city of Red Deer. The deposits were laid down in Glacial Lake Red Deer which was formed when normal drainage to the northeast was blocked by ice.

The lake was fed partly by the Red Deer River, partly by other streams, and partly by meltwater from the ice to the north. The deposits consist chiefly of sand and silt, but clay was deposited in deeper or less disturbed areas. The coarse deposits of the lake were one source of sand for the dunes formed in postglacial times.

Recent lacustrine deposits are found mainly in the Cygnet Lake area and bordering present-day lakes. The sediments consist predominantly of silt and clay of low permeability.

Aeolian deposits, consisting entirely of sand and coarse silt, are found in the area of glacial lake deposits along the Red Deer River valley and in an area of outwash deposits along the valley of the Medicine River. The coarse materials are very permeable and readily absorb precipitation.

Recent alluvium is found in modern stream and river valleys in which substantial postglacial deposition has taken place. The most common deposits in the area of investigation are gravel and sand that characteristically have a high permeability.

Structure

The study area lies on the eastern limb of the Alberta syncline. The strata are relatively flat-lying or very gently dipping in the eastern part of the area. West of the Red Deer River the dip increases from approximately 15 feet per mile to about 25 feet per mile. The strata in the study area undulate (Allan and Sanderson, 1945), as demonstrated by a structure contour on the Ardley coal seam in figure 12. Allan and Sanderson (1945) observed that the directions of main tributaries of the Red Deer River in the area of Red Deer are partly controlled by structure and suggested that the influence of the underlying gentle folds on stream directions is an important consideration. Robinson (1968) studied the main Cretaceous structural trends of the Plains of southern Alberta by computer analysis of deep test hole data and suggested that in the area surrounding Red Deer, structural movements took place throughout the Cretaceous along old, pre-Cretaceous, northeast-southwest structural trends. He also concluded that the pattern of structural activity is discernible in the morphology of the present surface. Structural control of morphology in Alberta has been examined by Ozoray (1972). After mapping the hydrogeology of the Wabamun Lake area (NTS 83G), Ozoray interpreted the definite geometric pattern of the drainage network in Alberta as a result of structural control. He also stated that recent uplift and revitalization of tectonic control are indicated in the Wabamun Lake map area. No direct evidence of faulting has been discovered in the present study and any effect that tectonic activity might have on the hydrogeology of the area cannot be predicted.

Characteristics of the geology along cross section A-A′-A″ (Fig. 10) are listed below:

(1) a near-horizontal, slightly permeable basement considered to be the base of the Ardley coal zone (stratigraphically over 2 000 feet higher in elevation than the Lea Park boundary chosen by Clissold (1967, 1968));

(2) a series of relatively highly permeable, extensive sandstone layers alternating with thick sections of predominantly shale and siltstone with low permeability in the lower part of Paskapoo strata above the Ardley coal zone;

(3) a large number of permeable sandstone lenses or layers of restricted extent present throughout a shale-siltstone section in the upper part of Paskapoo beds above the Ardley coal zone;

(4) in the area of the main topographic depression, thick surficial deposits with generally low permeability but containing layers of high permeability material, particularly in the bottom of buried valleys on the bedrock surface and in the valley of the present Red Deer River valley;

(5) thin surficial deposits with generally low permeabilities in the uplands.

Climate

The climate in the eastern part of the study area is classified according to the Koeppen system as humid continental (designated Dfb), with cool summers and no dry season: the western part is classified as subarctic (designated Dfc), with cool short summers (Dept. Mines and Tech. Surveys, 1957). The meaning of Koeppen letter symbols is as follows: "D" — humid microthermal climate (rain-snow climate with cold winters) with the mean temperature of the coldest month below 26.6°F and the mean temperature of the warmest month above 50°F; "f" — no dry season; "b" — cool summer; and "c" — cool short summer.

Precipitation

Longley (1968) has prepared climatic maps for Alberta that show precipitation figures calculated from a 30-year record from 1931 to 1960. The mean annual precipitation for the Red Deer area ranges from 18 to 20 inches. Mean precipitation for the period April 1 to September 30 is 12 to 14 inches.

Temperature

The mean annual temperature for the Red Deer area for a 30-year period from 1931 to 1960 is 53°F (Govt. and Univ. Alberta, 1969). Mean temperatures indicative of the four seasons for the same period are: January, 7.5°F; April, 39°F;

July, 62°F; and October, 40°F. The warmest month is July with an average maximum temperature of 74°F; the coldest month is January with an average minimum temperature of -3°F. For the period of record 1951 to 1964, the first fall frost occurs between September 1 to 15; the last spring frost before May 15. The average length of frost-free period is 100 to 120 days.

Potential evapotranspiration

Potential evapotranspiration is defined as the evapotranspiration occurring under adequate soil-moisture supply at all times for given temperature and humidity conditions (Pfannkuch, 1969). Average annual potential evapotranspiration for the study area is 20 to 22 inches (Govt. and Univ. Alberta, 1969).

The characteristics of the climate in the area of cross section A-A'-A" (Fig. 10) are listed below:

(1) mean annual precipitation ranging from 18 to 20 inches;

(2) rain-snow climate with cold winters (the average length of frost-free period is 100 to 120 days);

(3) average annual potential evapotranspiration of 20 to 22 inches.

THE GROUNDWATER REGIME

The Occurrence and Distribution of Groundwater

Hydrostratigraphic units

The occurrence and distribution of groundwater can conveniently be described in the study area within a framework of "hydrostratigraphic units." Maxey (1964) defined hydrostratigraphic units as "bodies of rock with considerable lateral extent that compose a geologic framework for a reasonably distinct hydrologic system." Two hydrostratigraphic units which can be identified over the study area are defined in cross section A-A'-A" (Fig. 10) on a basis of the nature of permeability distribution and contrasts. The boundary between the two units does not coincide with geologically defined rock unit boundaries.

The upper unit, Hydrostratigraphic Unit 1, is distinguished by a permeability generally higher than the underlying shale-siltstone portions of Hydrostratigraphic Unit 2, the contrast being about 4 to 1. This unit extends from the surface to within the upper part of the bedrock and contains two major, very highly permeable layers in the surficial deposits: the buried gravels in the preglacial Red Deer valley, and present-day gravel terraces underlying and adjacent to the Red Deer River. The boundary between Hydrostratigraphic Units 1 and 2 was determined from bail- and pump-test data at the location of test holes drilled during the study and on a basis of the nature of response of the resistivity and spontaneous potential on electric logs of oil company structure test holes over the remaining part of the area. Comparison of electric logs of test holes drilled during the study with those of oil company electric logs provided an objective approach to establishing the boundary. The thickness of Hydrostratigraphic Unit 1 is shown on figure 16. The thickness of the unit is 300 to 400 feet in the uplands, up to 200 feet along the broad topographic depression, and somewhat greater than 100 feet along the Red Deer River valley. The unit is very thick (up to 700 feet) in a local area immediately south of Sylvan Lake town.

The lower unit, Hydrostratigraphic Unit 2, is characterized by thick, extensive layers of highly permeable sandstones alternating with thick layers of predominantly shale and siltstone with low permeability. The maximum magnitude of permeability contrast in this unit is in the order of 1000. Laterally, some of these sandstones are rather consistent in permeability (for example, sandstone No. 1, Fig. 10) but the very thick sandstones (50 to > 100 feet) have noticeable vertical and lateral changes in permeability. Evidence from the test drilling indicates that higher permeabilities in the thick sandstones were present most often in the upper and lower portions. The sandstones with the highest permeabilities consisted mainly of medium-sized, well-sorted quartz grains. The main aquifer, Sandstone No. 1, figure 10, has a higher permeability in the area of the Red Deer River valley than in areas outside the valley. The depth to the top of Hydrostratigraphic Unit 2 in a large part of the study area is indicated in figure 16.

Aquifers in Hydrostratigraphic Unit 1

The main aquifers in Hydrostratigraphic Unit 1 are sand and gravel terraces adjacent to and underlying present-day streams, rivers, and lakes; sand and gravel deposits in buried preglacial valleys; and sandstone lenses and shale beds in the upper bedrock deposits. Other important aquifers are aeolian sands and sand and gravel deposits in glacial drift. With few exceptions, groundwater supplies in the study area are obtained from wells completed in aquifers in Hydrostratigraphic Unit 1.

Coarse alluvium deposits along the Red Deer, Blindman, and Medicine Rivers are important sources of groundwater, particularly where the deposits underlie the present-day streams and rivers to a depth of a few tens of feet. One major groundwater supply has been developed in coarse alluvium deposits in section 27, township 38, range 27, west of the fourth meridian, and a second potentially large supply from similar deposits has been evaluated in section 28 of the same township (Fig. 6).

Buried valley gravels and sands are found mainly in the buried Red Deer River valley. The position of the buried valley is defined by the bedrock topography (Fig. 13) and the isopach map of surficial deposits (Fig. 14). Anomalously low bedrock elevations and great drift thicknesses indicate the approximate position of a deep, narrow channel along the bottom of the preglacial Red Deer valley and Blindman River valley (Figs. 13 and 14). The bedrock depression southeast of Sylvan Lake does not extend out of the study area and buried gravel and sand deposits overlying bedrock appear to be only of minor importance. The valley apparently was formed during the glacial history of the area. Figure 17 shows the thickness of gravel and sand deposits lying on the bedrock surface in buried valleys at elevations lower than 2 900 feet. Within the valleys the thickest deposits are probably associated with deep, narrow channels in the floors of the generally broad valleys. The buried valley gravels and sands are more important as a source of groundwater in the area north of the point where the Red Deer River changes direction and flows to the southeast. South of this point, in the area of study, the Red Deer River has flowed continuously in the old preglacial Red Deer River valley (Stalker, 1968). The buried gravels and sands in this part of the preglacial valley are much thinner and contain more silt and clay because of continuous erosion and redeposition during the glacial period. Today, the Red Deer River has cut through the surficial deposits, and groundwater in buried valley gravels and sands discharges along the river valley sides or river channel banks as contact springs. Along the present-day Red Deer River the most suitable area for the location of wells in buried valley deposits is where the deep channel is present in the floor of the buried valley (Figs. 13 and 14) because deposits in this channel were probably little disturbed and adulterated during the glacial period.

Sandstone aquifers in the bedrock deposits of Unit 1 are lenticular and of limited areal extent. Prominent lenses of sandstone interbedded with shale and siltstone form the regional uplands in the study area. Shale beds are also reported by water-well drillers as aquifers in the bedrock deposits. Based on knowledge gained from test holes drilled in the area of detailed investigation, the writer is of the opinion that the majority of reported shale aquifers are in fact low permeability, fine-grained or very fine-grained sandstones. Nevertheless, the permeability of water-bearing shales present in test holes Morrisroe 1-18 No. 2, Choate 13-28, Viewpoint 2-28, and Hermary 7-33 (Appendix B), is probably due to fracturing. The author also presumptively concludes that areas where only sandstones are reported as aquifers are areas of mainly coarser-grained, more permeable sandstones. Although one or two wells obtain water from thin coal beds, coal beds are not significant as aquifers because the Paskapoo Formation above the Ardley coal zone does not contain significant coal deposits. Figure 18 shows reported aquifer material for bedrock deposits in Hydrostratigraphic Unit 1.

Aeolian deposits consisting of sand contain groundwater in amounts important for small supplies. These aquifers are near the surface and probably do not extend below 40 feet in depth. Areas of aeolian sands are outlined in figure 5.

Sand and gravel aquifers in the drift are found mainly along buried valleys or where the thickness of surficial deposits is great (Fig. 14) and in the areas of Pleistocene alluvium and outwash outlined in figure 5. Fine sand and silt aquifers with low permeabilities exist in the glacial lake sediments but are of little importance for groundwater supplies.

Aquifers in Hydrostratigraphic Unit 2

Hydrostratigraphic Unit 2 is comprised entirely of bedrock with the sandstones being the main aquifers. In the area of detailed investigation the occurrence and distribution of three main sandstone aquifers have been studied from test hole logs, hydraulic conductivity values, and interpretation of structure test hole electric logs along two cross sections (Figs. 10 and 15). Over the remaining part of the study area correlation of these sandstones has been solely from electric logs on a basis of stratigraphic position. The sandstone aquifers are named and referred to informally as Sandstone No. 1, Sandstone No. 2, and Sandstone No. 3. The distribution of these sandstones is shown on figures 19, 20 and 21, respectively. Correlation of the sandstones was difficult west of the fifth meridian because several other thick, extensive sandstones are present in the unit in that area (Fig. 22). Some general observations on sandstones in Hydrostratigraphic Unit 2 are: (1) the most extensive sandstones are found in the lower half of the unit, i.e., the basal Paskapoo; (2) the sandstones are usually thick, ranging from 30 to 150 feet; (3) sandstone layers, some more extensive than others, are more numerous west of the fifth meridian, particularly in the upper part of the unit; (4) the unit is predominantly a shale-siltstone section in some localities (one such locality determined in the study is an area including approximately the northern two thirds of township 38, range 28, and the southern margin of township 39, range 28, west of the fourth meridian); (5) the hydraulic conductivities of sandstones in the unit are unknown except for locations of test holes in the area of detailed investigation (values for particular sandstone aquifers encountered in Hydrostratigraphic Unit 2 in the test holes are shown in Appendix B); (6) the close vertical spacing, inclination, and considerable variation in thickness of sandstones suggest that in some areas sandstone layers probably coalesce.

Natural Movement of Groundwater

Model environment for the groundwater regime

The natural movement of groundwater in response to the hydrogeologic environment can be described by constructing vertical flow nets representing regional groundwater flow. A suitable hydrogeological cross section including one or more groundwater basins is required before a flow net can be drawn. Ideally, the concept of a groundwater basin is explained by Freeze (1969a) as that of a "three-dimensional closed hydrologic unit bounded on the bottom by a horizontal impermeable basement, on the top by the ground surface and on all sides by imaginary, vertical, impermeable boundaries representing the major groundwater divides." In regard to groundwater flow, Freeze and Witherspoon (1967) define a groundwater basin as "a three-dimensional closed system that contains the entire flow paths followed by all the water recharging the basin." They further state that a two-dimensional section through a groundwater basin is representative of the three-dimensional basin if it is taken parallel to the direction of dip of the water table slope. This factor is very important in determining the groundwater resources of an area by means of quantitative flow nets.

Cross section A-A′-A″ (Fig. 10) was constructed such that the requirements outlined in the above paragraph would be fulfilled. The land surface was considered to represent the upper surface of the analogue model, that is, the water table, since Clissold (1967) shows that in the study area the water table closely approximates the land surface. The cross section was drawn parallel to the direction of dip of the topographic slope through the area of test hole control. This in fact means that the cross section is representative of the three-dimensional basin because the slope along the river is negligible as compared with the lateral slopes, that is, those along the cross section. The lower impermeable boundary was taken as the lower boundary of the Ardley coal seam. Allan and Sanderson (1945) noticed that surface (i.e. near the top of the Ardley coal zone) water does not seep away on the Edmonton surface but was readily absorbed by Paskapoo rocks (i.e. rocks above the Ardley coal zone) and that at "many points along the valley of the Red Deer the contact between the Edmonton and the Paskapoo is marked by the emergence of strong, steady springs." Freeze and Witherspoon (1967) also concluded that the lower boundary of the deepest aquifer whose permeability significantly exceeds that of the underlying beds provides a geologic configuration that has the same effect on the potential pattern as an impermeable boundary; that is, the equipotential lines remain vertical below the lowermost aquifer except at the extremities of the flow net. Although, on this basis, the bottom of the lowest widespread sandstone in the hydrogeologic flow system (Fig. 10) is strictly the lower impermeable boundary, it was not so used because it occurs close to the base of the Ardley coal zone which is a convenient mappable boundary. The imaginary, vertical boundaries were assumed to be coincident with the topographic divides and positions of Red Deer River valley and canyon (Figs. 10 and 11).

A refinement in the model construction is attained by the introduction of geologic detail based essentially on consideration of permeability contrasts and their vertical and lateral distribution. Determined hydraulic conductivity values for aquifers are shown on the test hole data diagrams in Appendix B. Actual average values of hydraulic conductivity for different aquifers of the hydrogeological model and relative values of conductivities achieved in the construction of the electric analogue model are shown in table 2 and are indicated on the hydrogeological cross section (Fig. 10).

The hydraulic conductivity of the buried valley gravels was obtained from pump tests carried out by Tóth (1961). The magnitude of hydraulic conductivity values for bedrock aquifers is in close agreement with values calculated from results

Table 2. Hydraulic Conductivities of Aquifers and Representative Conductivities Achieved in the Electric Analogue Model

Hydro-stratigraphic Unit	Aquifer	Average Hydraulic Conductivity of Aquifer (igpd/ft^2)	Relative Conducitivites Achieved in the Analogue Model[1]
1	Buried valley gravel	1000	83 ± 20
	Various sandstone lenses	44	4
2	Sandstone No. 1 (outside river valley)	225	25 ± 4
	Sandstone No. 1 (in river valley area)	561	80[2]
	Sandstone No. 3	6	2
	Other sandstones, siltstones, and shale	0.6 or less	1

[1] With reference to the lowest value

[2] Local variations up to 50 percent

of bail or pump tests carried out at locations in the area of detailed study not in cross section A-A'-A'' (Fig. 10). The relative values of the model's conductivities were intended to be as representative of actual hydraulic conductivities as was possible within the limitations imposed by the conductivity of materials used in construction of the model.

An anisotropy of vertical hydraulic conductivity equal to 1/64th of the horizontal hydraulic conductivity was assumed for all layers in the model. This value is in the order of magnitude (10 to 100) found to be satisfactory for application in similar hydrogeological studies in Western Canada (Freeze, 1969b; Nielsen, 1971). Maasland (1957) showed that the effect of an anisotropy in hydraulic conductivity is equivalent to the effect of shrinkage or expansion of the coordinates of all points in the flow system. Thus, an equivalent isometric system, as drawn in figure 10, is obtained by expanding the coordinates of each point in an anisotropic medium. In a two-dimensional flow problem, transformation of the anisotropic medium into an equivalent isotropic one is achieved by application of the following equations:

$$x' = (k_o/k_x)^{1/2}\ x$$

$$y' = (k_o/k_y)^{1/2}\ y$$

where k_x = hydraulic conductivity of the model in the horizontal direction; k_y = hydraulic conductivity of the model in the vertical direction; x = original coordinate in the horizontal direction; y = original coordinate in the vertical direction; x' = transformed coordinate in the horizontal direction; y' = transformed coordinate in the vertical direction; k_o = an arbitrary constant having the dimensions of k_x and k_y.

If one chooses $k_o = 64$, then $x' = x$, $y' = 8y$, and the vertical dimension is expanded by a factor of 8, as in figure 10. A vertical exaggeration of 8 times was also a convenient scale in which to draw geologic detail. Isotropic flow nets were drawn with an electric analogue for the transformed system in figures 23 and 24. Maasland (1957) provides a proof that the flow through an area of the equivalent isotropic system is equal to the flow through the corresponding area of the real anisotropic system, and that the hydraulic conductivity in the flow direction in a two-dimensional system is not affected by the expansion of the real system. The quantity of groundwater flow through the equivalent model (Fig. 24) can therefore be calculated and will be equivalent to the quantity of groundwater flow in the real system.

Apparatus for drawing fluid potential distributions

Fluid potential distributions were drawn by means of an electric analogue designed and constructed by Tóth (1968, Appendix A) who defined the analogue components, operation, and application. Fluid-flow patterns can be simulated with an electric analogue because of the similarities between the laws governing electric currents and the movement of fluids in permeable media. Instrumental errors can be kept to values not exceeding ± 1 percent by maintaining a close check on potential distribution along the upper boundary of the analogue model and by resetting the values to those originally used if instrumental drift has occurred. Materials used to represent the permeability contrasts consisted of a carbon-impregnated conductive paper and silver paint-carbon mixtures. The silver paint-carbon mixtures were used to simulate high hydraulic conductivities, but construction of mixtures with uniform conductance proved a technical problem and accounts mainly for the estimated variance in achieved hydraulic conductivity values for the mixtures. The conductivity of the mixtures was found to decline gradually with time so that the measurements were effected in as short a time interval as possible to minimize errors due to this phenomenon. The resulting groundwater flow patterns are shown for an anisotropic, homogeneous medium in figure 23 and an anisotropic, nonhomogeneous medium in figure 24.

Terminology to describe patterns of groundwater flow

Definition of three key terms — flow system, recharge area, and discharge area — are necessary prior to detailed discussion of patterns of groundwater flow. Tóth (1963) defines a flow system as "a set of flow lines in which any two flow lines adjacent at one point of the flow region remain adjacent through the whole region and can be intersected anywhere by an uninterrupted surface across which flow takes place in one direction only." Freeze and Witherspoon (1967) define a discharge area as an area where the direction of groundwater flow is towards the water table, and a recharge area as an area where the direction of groundwater flow is away from the water table. Additional and necessary terminology is listed and summarized in table 3, modified from Tóth (1970b).

Observations regarding groundwater flow in the model environment

Several observations regarding prominent features of natural groundwater flow in the model environment can be stated from an examination of figures 23 and 24. The effect of the components of the hydrogeologic environment on the natural flow of groundwater can be exposed by observation of particular aspects of certain regime parameters including: fluid potential distribution, direction and rate of groundwater flow, flow patterns in a homogeneous medium, effect of geology on flow patterns, vertical impermeable boundaries, horizontal distribution of recharge-discharge areas, and total volume discharge of groundwater.

Fluid potential distribution

The natural movement of groundwater is a consequence of fluid-potential differences, the magnitude of which depends on the configuration of the water table. Where the water table closely parallels the land surface, the topographic relief may be used as a first approximation in the determination of the distribution and

Table 3. Terminology of Flow-Pattern Features (modified from Tóth, 1970b)

Item	Type of Item	Code of Item	Characteristic Hydraulic Property
Flow system	Local	L	Recharge and discharge areas are contiguous.
	Intermediate	I	Recharge and discharge areas are separated by those of one or more local systems.
	Regional	R	Recharge and discharge areas are separated by those of one or more local systems and occupy the main divide and main valley, respectively.
Limb of flow system	Descending		Movement is directed away from the water table.
	Lateral		Movement is subparallel to the water table.
	Ascending		Movement is directed toward the water table.
Stagnant zone	Inter-system		Formed at the meeting area of three or four systems in the interior of the flow region.
	Bottom		Formed by the descending or ascending limbs of two systems at lower boundary of the flow region.

magnitude of fluid potential. This is true on a local as well as a regional scale. A survey examination of figures 23 and 24 shows that high fluid potential gradients are associated with steep slopes, for example, the Red Deer River valley and the Red Deer River canyon. Minor hills on the water-table surface and changes in slope distort the fluid potential distribution on a local scale. This phenomenon is most obvious on the slope west of the Red Deer River valley (e.g., flow systems L2, L3, L4, and L5, Fig. 24). Very generally, fluid potential decreases with depth under uplands, is rather constant at midslope positions, and increases with depth under the bottom of the Red Deer River valley and canyon.

Geology, or more strictly, permeability contrasts on a regional scale can strongly influence the natural flow of groundwater because of their effect on the distribution of fluid potential. The highly permeable layers in the model, particularly buried valley gravels and sands and Sandstone No. 1, Hydrostratigraphic Unit 2, have the strongest modifying influence on the distribution of fluid potential, causing near-horizontal movement of water in these layers except in the areas of vertical impermeable boundaries. In the area of the eastern upland, the fluid potential gradient in the nonhomogeneous case, between the base of Hydrostratigraphic Unit 1 and the top of Sandstone No. 1 (flow system R2, Fig. 24), is markedly increased when compared with gradients for the homogeneous case (Fig. 23). This observation is also true for the areas immediately west and east of the Red Deer River valley in flow systems L6 and L7. The increased gradient is a natural consequence of the permeability distribution and is required to maintain continuity of groundwater flow.

Direction and rate of groundwater movement

On a regional scale groundwater movement is from uplands to depressions along an arcuate path (e.g., flow system R2, Fig. 24). Generally, it is downward in topographic high areas, nearly horizontal in midslope areas, and upward in topographic low areas. In high-permeability layers at shallow or moderate depths flow is nearly horizontal as evidenced in Sandstone No. 1 (Fig. 24). At depth, as the lower horizontal impermeable boundary is approached, flow is nearly horizontal. Near regional midslope locations and at moderate depths, high-permeability lenses, consisting of buried valley sands and gravels, influence the potential distribution and cause groundwater to move downward in materials overlying approximately the upslope part of the lenses and upward in the downslope part (e.g., flow system L5, Fig. 24). Similarly lenses located in regionally low areas have the same effect on the direction of groundwater flow except where erosion in the present-day river valley has cut through the lenses. In the latter case, groundwater will move horizontally in the lenses and discharge as contact springs on the river valley sides. In the eastern upland area of the model the direction of groundwater motion is nearly vertical in low-permeability material below Hydrostratigraphic Unit 1 and above Sandstone No. 1, Hydrostratigraphic Unit 2. The direction of groundwater flow immediately west of the eastern topographic divide is westward toward the river valley (flow system R3, Fig. 24). However, it changes direction beneath the base of the steepest slopes and flows eastward toward the Red Deer River canyon.

The velocity of groundwater flow is proportional to the hydraulic conductivity if other properties of the medium and groundwater are constant. This means that the average flow velocity of groundwater in Hydrostratigraphic Unit 1 is higher than flow in Hydrostratigraphic Unit 2, except for high-permeability layers such as Sandstone No. 1. The highest velocities of groundwater flow in the area of the model environment are in Sandstone No. 1 and in buried valley gravels and sands.

Flow patterns in a homogeneous medium (see Fig. 23)

Three groundwater basins, A, B, and C, each consisting of local, intermediate, and regional flow systems are recognized in the model of the study area.

In basin A four local systems (L1, L2, L3, and L4) are concentrated in the upslope portion of the basin where the land surface rises in a somewhat step-like fashion. These systems extend to depths ranging from 50 to nearly 300 feet below ground level. A local system (L5) superimposed on a regional system is also present adjacent to and on the steep west slope of the Red Deer River valley. The recharge area for this local system (L5r) begins about one mile from the valley's edge and the system reaches depths of 200 feet. The upslope local systems are superimposed on two intermediate flow systems (I1 and I2). The lower one (I1) is a very large system spanning almost 5 miles at its extremes and reaching to a maximum depth of 500 feet below surface. The local and intermediate flow systems are superimposed on a regional system (R1) that has a recharge area (R1r) of one-half mile in horizontal extent at the extreme upper end or topographic divide area of basin A, and a discharge area (R1d) of less than one-half mile in the floor of the Red Deer River valley.

In groundwater basin B only two local flow systems (L6 and L7) and one regional flow system (R2) exist. Local system L7 is located about midslope and system L6 is adjacent to the steep east slope of the Red Deer River valley. System L6 has approximately the same lateral and vertical dimensions as its twin system in groundwater basin A. System L7 is similar in lateral extent but is shallower, reaching a depth of slightly over 100 feet. The regional flow system in basin B is smaller but has the same features as the one in basin A.

Groundwater basin C is uniquely characterized by one regional flow system (R3) reaching from the surface of the major divide to the impermeable lower boundary of the basin 1 000 feet below surface, and discharging in the Red Deer River canyon. The obvious reason for the development of a single flow system is the existence of the deep canyon on the major topographic high area proximal to the regional surface divide.

Effect of geology on flow patterns

The most noticeable effects of geology (i.e., of permeability differences) on the flow patterns are (Fig. 24): (1) concentration of local and intermediate flow systems in Hydrostratigraphic Unit 1; (2) a substantial increase in the size of local flow systems relative to those in the homogeneous case (Fig. 23) on and adjacent to the sides of the Red Deer River valley; and (3) restriction of the area of regional groundwater discharge to part of the river valley bottom.

In groundwater basin A concentration of flow systems in Hydrostratigraphic Unit 1 generally results in a decrease in the dimensions of local and intermediate flow systems in the upslope area and the consequential creation of new local and intermediate systems, increasing their number from 5 and 2 to 6 and 3, respectively. In contrast to this effect, the local system (L5, Fig. 23) on and adjacent to the river valley slope is greatly increased in spatial extent (L6, Fig. 24) because of the influence of the major, extensive, highly permeable sandstone aquifer that is present a short distance below or in contact with Hydrostratigraphic Unit 1 in this area of the hydrogeological model. The regional flow system (R1) maintains basically the same general features as it demonstrates in the homogeneous medium, although the configuration of flow channels within the system is more complicated and the discharge (R1d) is concentrated to a greater degree in the valley bottom. Of particular interest are the two recharge areas for flow channels entering Sandstone No. 1 in Hydrostratigraphic Unit 2. One is the entire recharge area of flow system R1 and the second is the upslope half of the recharge area for the large local system (L6r) developed around the western slope of the river valley (Fig. 24). It is noteworthy that one of the recharge areas should be located at a distance of about 4 miles from the nearest extremity of the aquifer.

In groundwater basin B the two local systems L6 and L7 (Fig. 23) of the homogeneous case are replaced by one very large local system (L7, Fig. 24). This system is similar in all respects to its counterpart in basin A. A new, small, rather insignificant local flow system (L8) appears farther upslope in the vicinity of the point where a marked increase in slope occurs. No intermediate flow systems are recognized and the regional flow system has a more restricted recharge area (R2r) on the western slope of the main divide, as well as a more restricted area of discharge in the river valley bottom (R2d) than it had in the homogeneous case. Groundwater basin C remains characterized by one regional flow system (R3).

Lateral basin boundaries

The position of the lateral boundaries between groundwater basins A, B, and C in a homogeneous medium (Fig. 23) are of interest. The boundary between basins A and B is subvertical and is located near the center of the river valley bottom. The boundary between basins B and C originates from a point on the west side of the major topographic divide and is convex to the west. Stagnant zones are present at the bottom of all major vertical boundaries and a well-developed intersystem stagnant zone occurs in the western part of basin A.

The addition of permeability differences in the model (Fig. 24) has only a slight effect on the positions of the lateral basin boundaries. The subvertical boundary between basins A and B is approximately at the same location and the boundary between basins B and C has been shifted only slightly upslope at the surface. However, the boundary has a curvilinear character in Hydrostratigraphic Unit 1 and is subvertical in Hydrostratigraphic Unit 2. This results in the boundary being shifted downslope in the lower unit to a point a horizontal distance of 9/10ths of a mile west of the topographic divide. Bottom stagnant and interstagnant zones are located at approximately the same position as in the homogeneous medium case, demonstrating the controlling influence of the water table configuration on flow patterns.

Horizontal distribution of recharge-discharge areas

For a homogeneous medium the percentage ratio of the horizontal distribution of recharge to discharge areas for the three basins in cross section A-A′ (Fig. 23) is 56 to 44. For basins A, B, and C the ratio is 48 to 51, 64 to 36, and 81 to 19, respectively.

The effect of the introduction of highly permeable layers (Fig. 24) is to increase the area of recharge and to shift or change in some respect the recharge-discharge relationships for individual flow systems. The ratio of recharge-discharge areas for the three basins is 65 to 35 which is an increase compared with the homogeneous case. Groundwater basins A and B have also shown an increase in total recharge area, ratios being 58 to 42 and 78 to 22, respectively. Groundwater basin C showed a decrease in recharge area measured in the horizontal plane with a ratio of 74 to 26.

The most striking feature of the lateral distribution of recharge areas is the presence of extensive areas of recharge adjacent to the sides of the Red Deer River valley in the broad topographic depression of the model environment. This feature, on the basis of present knowledge of the natural flow of groundwater, would not be anticipated. Almost the entire east slope from the river valley edge to the topographic divide is a recharge area.

Total volume discharge of groundwater

Relatively, the amounts of the total volume discharge of groundwater can be determined for groundwater basins A, B, and C, and Sandstone No. 1 from the quantitative flow nets in figures 23 and 24.

For a homogeneous medium (Fig. 23), 8.5 flow channels with a drop in hydraulic head of 25 feet between equipotential surfaces are present in groundwater basin A. Further reference to flow channels will connote the same hydraulic head difference between equipotential surfaces. In basin B, 7.1 flow channels are present. Twelve flow channels are present in groundwater basin C, the number, in comparison to those in basins A and B, indicating the increase in volume discharge of groundwater in this part of the study area.

The effect of geology (essentially an overall increase in the permeability of the model caused by the introduction of layers of higher permeability as shown in Fig. 24) on the total volume discharge of groundwater in the hydrogeological model results in: (1) a fourfold increase in the total volume discharge of groundwater in the three groundwater basins; (2) concentration of 65 percent of the total volume discharge of groundwater in local and intermediate flow systems present predominantly in Hydrostratigraphic Unit 1; and (3) concentration of 31 percent of the total volume discharge of groundwater in Sandstone No. 1 in Hydrostratigraphic Unit 2.

The total number of flow channels with a hydraulic head of 25 feet between equipotential surfaces in the nonhomogeneous case (Fig. 24) in groundwater basins A, B, and C is 50.4, 27.1, and 32.5, respectively. This is a total of 109.9 flow channels which is approximately 4 times the total number (27.6) of flow channels present in the case of a homogeneous medium. Considering the flow systems in the nonhomogeneous case, 3.2 channels in flow system R1, 3.0 in R2, 20.5 in R3, 3.0 in L6, and 4.6 in L7 enter Sandstone No. 1, Hydrostratigraphic Unit 2. The total number of flow channels entering the sandstone represents 31 percent of the total volume discharge of groundwater in the hydrogeological model.

Groundwater Chemistry, Temperature, and Suitability for Consumption

The hydrochemistry of the study area is described in the context of the hydrostratigraphic units. A sufficient density of hydrochemical information was available for Hydrostratigraphic Unit 1 to enable the mapping of the distribution of the chemical types of groundwater and chemical constituents; however, this was not possible for Hydrostratigraphic Unit 2 due to the scarcity of data for that unit. Description of the hydrochemistry of Hydrostratigraphic Unit 2 is based on information obtained from test holes drilled in the area of detailed investigation.

Chemical types of groundwater in Hydrostratigraphic Unit 1

The chemical types of groundwater are classified by a graphical method proposed by Piper (1944). Boundaries for the types of hydrochemical facies are placed at the 60 percent value in equivalents per million for $Na^+ + K^+$ and $HCO_3^- + CO_3^{--}$.The chemical type of groundwater is determined by the dominant cation(s) and anion(s) in the water.

The chemical types of groundwater in Hydrostratigraphic Unit 1 are shown in figure 25. Almost all existing water wells in the area obtain water from aquifers in Hydrostratigraphic Unit 1, and chemical analyses of approximately 400 water samples were available for typing the groundwater. The water was placed into four classes, numbered in order of apparent abundance of occurrence. Type I is a sodium-bicarbonate water; Type II, a magnesium-calcium-bicarbonate water; Type III, a sodium-sulfate-bicarbonate water; and Type IV, a magnesium-calcium-sulfate-bicarbonate water.

Distribution of the chemical types of groundwater in Hydrostratigraphic Unit 1

The areal distribution of the chemical types of water in Hydrostratigraphic Unit 1 is shown in figure 26. The vertical distribution of the chemical types of groundwater is illustrated only along cross section A-A′ (Fig. 27). Type IV water is not present along this cross section.

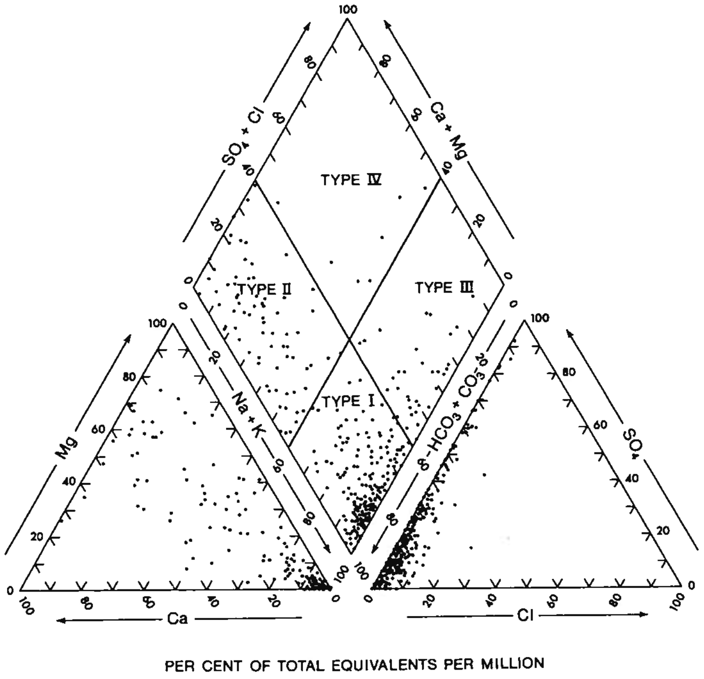


FIGURE 25. Piper diagram, showing the chemical types of groundwater in Hydrostratigraphic Unit 1.

Type I (sodium-bicarbonate) water is the most frequently encountered type in the study area and is the only water present in deep aquifers.

Type II (magnesium-calcium-bicarbonate) water occurs over a large region in the uplands of the western part of the study area, and occurs in smaller, discontinuous areas closely associated with the uplands east of Red Deer. Other areas of Type II water occur in the lower portion of the major topographic low area adjacent to the Red Deer River valley. Type II water is most commonly obtained from depths less than 100 feet.

Type III (sodium-sulfate-bicarbonate) water occurs in fairly large areas along the fifth meridian south of Cygnet Lake and southeast of Red Deer on the upper part of the gentler regional slopes between the city and the eastern topographic upland. Smaller areas of Type III water occur at positions lower on the regional slopes. Type III water is most commonly obtained from depths of 100 to 200 feet.

Type IV (magnesium-calcium-sulfate-bicarbonate) water occurs locally in small areas surrounding the city of Red Deer. This water is most often obtained from depths of 100 to 200 feet.

Areal distribution of chemical constituents in Hydrostratigraphic Unit 1

The areal distribution of chemical constituents is shown on maps in parts per million for total solids, iron, and fluoride (Figs. 28, 29, 30, respectively); and as percent of total cations or anions for sodium plus potassium, bicarbonate plus carbonate, and sulfate (Figs. 31, 32, 33, respectively). The calcium to magnesium and the sulfate to chloride ratios are also shown (Figs. 34, 35, respectively). The purpose of the maps is to obtain a regional picture of the distribution of chemical constituents in the study area. Isolated, anomalous values are considered to be a reflection of strong local conditions.

Total solids

Total dissolved solids content for groundwater (Fig. 28) represents all the major salts in solution. Figure 28 shows that groundwater contains less than 1 000 ppm in the greater part of the study area. Large areas in the western upland and north of the junction of the Blindman River and Red Deer River contain less than 500 ppm. Other small areas containing groundwater with less than 500 ppm are found on the topographic high areas east of Red Deer or at locations proximal to the Red Deer River. Anomalously high concentrations, ranging from 1 000 to over 8 000 ppm, are found in a north-south oriented area lying between the north-east corners of Tps. 38 and 37, R. 27. Other smaller areas of high mineralization ranging from 1 000 to 2 000 ppm are located on gentle slopes in the west-central part of the area.

Iron

Iron content in groundwater (Fig. 29) is less than 1 ppm in most of the study area. Values up to 5 ppm are found in waters at some locations on the gentle regional slopes between uplands and the Red Deer River, particularly in the area east of Red Deer.

Fluorides

The fluoride content of groundwater in Hydrostratigraphic Unit 1 (Fig. 30) is generally less than 2 ppm. Higher values ranging up to 4 ppm are present in regional depressions along the Red Deer River. During test drilling groundwater with high fluoride content was obtained only from aquifers in Hydrostratigraphic Unit 2 which is found at moderate depths in the vicinity of the river valley. At such locations water with a high fluoride content might be a result of the mixture of water in wells open to both hydrogeological units.

Sodium plus potassium

The areal distribution of $Na^+ + K^+$ is shown in figure 31. $Na^+ + K^+$ content is greater than 80 percent of total cations except in the following main topographic areas: the western uplands, the eastern uplands, and the major depression paralleling and adjacent to the Red Deer River valley. A local area extending westward from the northeast corner of Tp. 37, R. 27, is also low in $Na^+ + K^+$ content. $Na^+ + K^+$ content ranges from less than 20 to 80 percent of total cations in these areas. Groundwater from wells drilled in the river valley commonly contains greater than 80 percent $Na^+ + K^+$ content in percent of total cations.

Bicarbonate plus carbonate

Groundwater contains more than 60 percent of the total anions as $HCO_3^- + CO_3^{--}$ in most of the study area, as shown in figure 32. HCO_3^- is the main ion present, the CO_3^{--} content being minor by comparison. Well defined areas of low $HCO_3^- + CO_3^{--}$ content (ranging from less than 20 to 60 percent) are located south of Cygnet Lake along the fifth meridian, and on the gentle slopes centered roughly in Sec. 36, Tp. 37, R. 27, W.4th Mer. These areas of low $HCO_3^- + CO_3^{--}$ content are coincident with areas of occurrence of Type III waters (Fig. 27).

Sulfate

The distribution of SO_4^{--} in percentage of total anions is shown in figure 33. Groundwater in the area is generally characterized by SO_4^{--} content of less than 20 percent. Concentrations of SO_4^{--} in excess of 20 percent are found at locations on the gentle regional slopes in the topographically lower areas. The highest SO_4^{--} content (from 60 to 80 percent) occurs in an area centered in Sec. 36, Tp. 37, R. 27, W. 4th Mer. This area is also characterized by high total dissolved solids content and low $HCO_3^- + CO_3^{--}$ content in percentage of total anions.

Calcium to magnesium ratio

The areal distribution of the Ca^{++} to Mg^{++} ratio is shown in figure 34. The ratio values have been contoured up to 3.0 and the occurrence of higher values ranging from 3.0 to 6.0 are indicated as greater than 3.0. No clear pattern of distribution for this ratio exists. An interesting feature, however, is the presence of high Ca^{++} to Mg^{++} ratios, mainly in the major topographic depressions.

Sulfate to chloride ratio

The map of the SO_4^{--} to Cl^- ratio for groundwater in Hydrostratigraphic Unit 1 (Fig. 35) generally shows values of less than 10 in the western upland, the lowlands parallel and adjacent to the Red Deer River valley, and the highest area east of Red Deer. SO_4^{--} to Cl^- ratios greater than 10 are located in an extensive area paralleling the base of steep slopes rising to topographic divides east and west of Red Deer. Small areas of SO_4^{--} to Cl^- ratio greater than 10 are present at locations along the lowland near the Red Deer River valley. Groundwater for some areas contains no Cl^-. The maximum Cl^- content in groundwater in Hydrostratigraphic Unit 1 is less than 12 percent of the total anions.

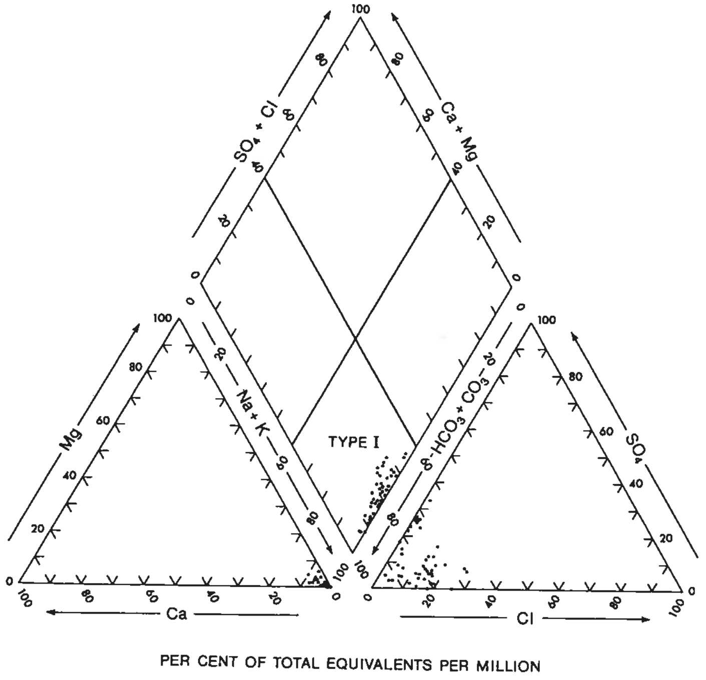


FIGURE 36. Piper diagram, showing the chemical types of groundwater in Hydrostratigraphic Unit 2.

Temperature of groundwater in Hydrostratigraphic Unit 1

The temperature of groundwater in Hydrostratigraphic Unit 1 ranges from 4.4 to 5.6°C (average 5.0°C). The temperature of water produced from terrace gravels along the Red Deer River north of Red Deer increased gradually from 5.6 to 9.2°C during pump tests up to four days in duration. The temperature of water produced during the tests was dependent largely on the temperature of the river water induced to flow through the gravels to the wells.

Chemical types of groundwater in Hydrostratigraphic Unit 2

The classification of the chemical types of groundwater in Hydrostratigraphic Unit 2 is shown in the Piper diagram in figure 36. Only chemical analyses of water samples obtained from aquifers in Hydrostratigraphic Unit 2 at the locations of the 17 test holes in the area of detailed investigation (Fig. 2) have been used in this classification. Type I (sodium-bicarbonate) water is the only type of water present in Hydrostratigraphic Unit 2 based on interpretation of the test hole data; however, minor amounts of Types II and III may be present (Fig. 27).

Features of the groundwater chemistry in Hydrostratigraphic Unit 2

Total dissolved solids

It is primarily regional groundwater flow that moves through the deposits of Hydrostratigraphic Unit 2 (Fig. 24). Two large local systems (L6 and L7, Fig. 24) surrounding the sides of the Red Deer River valley are the only exceptions. The flow of groundwater in these local systems enters the upper part of Sandstone No. 1, Hydrostratigraphic Unit 2. The vertical and lateral distribution of total solids content in parts per million do not display the expected increase in the direction of regional groundwater flow. In fact, the groundwater in Sandstone No. 1 in the river valley area has one of the lowest total dissolved solids content in parts per million (<600 ppm) of all test holes drilled in the area of detailed investigation (Appendix B). Chemical analyses of water samples from the main aquifer at test hole locations indicate a decrease in total dissolved solids content from upslope areas to the river valley area. Probably, this is a result of two factors:

(1) Under natural fluid potential gradients (Fig. 24), 55 percent of the total volume discharge of groundwater through Sandstone No. 1 is from the two large local flow systems (L6 and L7, Fig. 24). The influence of several years of water withdrawal at the location of the Red Deer Packers well has increased the relative contribution of groundwater to the aquifer from the local flow systems.

(2) The high permeabilities and consequent rapid movement of water in the aquifer results in a low residence time, one of the dominant factors in determining the mineralization of groundwater. Study of the chemical analyses of water samples from Hydrostratigraphic Unit 2 also indicates that groundwater with low dissolved solids content is confined primarily to the more permeable intervals in the hydrogeologic section. Total dissolved solids content for the entire unit is, with few exceptions, less than 1 000 ppm.

Hydrochemical facies

The groundwater chemistry in Hydrostratigraphic Unit 2 is distinguished by the anion facies. Except for water in Sandstone No. 1, the SO_4^{--} to Cl^- ratio displays a regular decrease with increasing depth and in the direction of regional topographic depressions (Appendix B). In light of the Chebotarev sequence (Chebotarev, 1955) this is probably a good indicator of the direction of groundwater flow. Cl^- content in percent of total anions increases with depth and in the direction of groundwater flow at the expense of the SO_4^{--} and HCO_3^- content. With increasing depth the SO_4^{--} content approaches zero (see diagrams for Morrisroe 1-18 No. 2, Spenceley 13-13, and Choate 14-28 No. 1, Appendix B). The anion facies of water in Sandstone No. 1 undergoes a transition from $HCO_3^- + SO_4^{--}$ in the upslope area (Ireland 12-25, Appendix B) to

$HCO_3^- + SO_4^{--} + Cl^-$ in the downslope area (Choate 13-28, Red Deer Packers 16-28, Appendix B) with similar and relatively low concentrations (5 to 20 percent) of total anions of $SO_4^{--} + Cl^-$. The concentration of SO_4^{--} or Cl^-, individually, is less than 40 percent of total anions for all analyses of other samples of water from Hydrostratigraphic Unit 2.

Na^+ is the predominate cation in Hydrostratigraphic Unit 2, constituting more than 95 percent of the total cations. The total Ca^{++}, Mg^{++}, and K^+ content is less than 5 percent.

Fluoride content

All groundwater samples from the seventeen test holes in the area of detailed investigation contain fluorides. Highest values are found for groundwater in the more permeable sandstones in Hydrostratigraphic Unit 2 with values of up to 4 parts per million for water in Sandstone No. 1 and 2 to 6 parts per million for groundwater in deposits below the main aquifer.

Temperature of groundwater

The ranges and averages of representative temperatures measured for the upper, middle, and lower part of Hydrostratigraphic Unit 2 are: 5.0 to 6.7°C (average 5.6°C), 5.6 to 7.8°C (average 6.2°C), and 6.7 to 10.8°C (average 9.0°C), respectively. Values obtained for water samples from Sandstone No. 1 are not included. That aquifer contains water with temperatures ranging from 3.0 to 6.1°C (average 5.1°C). Most temperature measurements were for water samples obtained after periods of bailing. One water sample obtained from Sandstone No. 1 after 2 days of pumping at 69 igpm at the location of Choate 14-28 No. 2 (Fig. 2) had a temperature of 8.4°C. This value is in the range of the maximum values recorded for the lower part of Hydrostratigraphic Unit 2. The evidence suggests a noticeable increase in groundwater temperature in Hydrostratigraphic Unit 2 as compared to temperatures of 4.4 to 5.6°C (average 5.0°C) for groundwater in Hydrostratigraphic Unit 1.

Interpretation of the groundwater chemistry

Groundwater chemistry in the study area is interpreted within a framework of the topographic and geologic components of the hydrogeologic environment and with respect to other parameters of the groundwater regime, particularly the geometry of flow systems and velocity of flow of groundwater. Tóth (1966a, 1966b, 1968) showed a distinct interrelationship between hydrodynamic flow systems and the hydrochemistry of groundwater in the Olds, Trochu, and Three Hills areas located near Red Deer in south-central Alberta. Tóth (1970a) listed the following as the main factors that determine the chemical composition of water at any subsurface point:

(1) types of soluble minerals

(2) amounts of soluble minerals

(3) solubility of minerals

(4) temperature of rock

(5) area of contact between rock (a function of porosity)

(6) antecedent composition of water

(7) antecedent temperature of water

(8) fluid pressure

(9) flow velocity and flow geometry.

The influence of a number of these factors can be demonstrated in the Red Deer area.

The distribution of the chemical types of groundwater (Figs. 26 and 27), total dissolved solids (Fig. 28), sodium and potassium ions (Fig. 31), bicarbonate and carbonate ions (Fig. 32), and sulfate ions (Fig. 33) show that the groundwater chemistry in the Red Deer area is intricately linked with topography, geology, and the geometry of flow systems. If Type I is the only water occurring in Hydrostratigraphic Unit 2, as suggested by the study of the water chemistry in this unit in the area of detailed investigation, then the entire area of study is characterized by sodium-bicarbonate water with superimposed hydrochemical systems of groundwater Types II, III, and IV (Fig. 27). This phenomenon can be observed in the diagrams of basic data for test holes Robinson 13-30, Bickford 8-12, Bickford 13-32, and Spencely 13-13 (Appendix B). On the basis of the flow system geometry (Fig. 24) in the electric analogue model and the features displayed by the groundwater chemistry, the study area can be divided into five general regions of predominantly downward-moving (recharge area) or upward-moving (discharge area) groundwater, which are: (1) the western divide, (2) the depression parallel and adjacent to the Red Deer River valley, (3) the eastern divide, (4) the gentle slopes situated between uplands and depressions, and (5) an area centered roughly on the northeast corner of township 37, range 27, west of the fourth meridian. The first three divisions are predominantly recharge areas and the last two are discharge areas. Strong regional discharge is indicated by the model to take place in the bottom of the Red Deer River valley in the area where Sandstone No. 1, Hydrostratigraphic Unit 2 is present in the subsurface (Fig. 27).

The hydrochemical facies and ratios of certain chemical constituents for groundwater in the five topographic regions are summarized in Table 4. The similarity of features of the groundwater chemistry in the areas of downward-moving groundwater is apparent. The groundwater chemistry, particularly low total

Table 4. Summary of Major Chemical Constituents in Groundwater in Five Topographic Regions

Chemical Constituent of Groundwater		Regional Topographic Area				
		Eastern Divide Area	Area Centered on NE Corner of Tp 37, R 27, W 4 Mer	Depression Parallel and Adjacent to River Valley	Western Divide Area	Slopes Situated between Uplands and Lowlands
Expressed as percentage of total anions or total cations	$Na^+ + K^+$	40-80 (moderate to high)	40-80 (moderate to high)	20-80 (low to high)	20-80 (low to high)	>80 (high)
	$HCO_3^- + CO_3^{--}$	>80 (high)	20-60 (low to moderate)	60->80 (moderate to high)	>80 (high)	60->80 (moderate to high)
	SO_4^{--}	<20 (low)	40-80 (moderate to high)	<20 (low)	<20 (low)	<20-40 (low to moderate)
Expressed as parts per million	Total dissolved solids	<500-1000 (low)	1000->8000 (moderate to very high)	<500-1000 (low)	<500 (very low)	500-1000 (low)
	Iron	<1	0-2	<1	<1	<1
	Fluorides	<1-2	1-2	<1-4	<1	<1-2
Expressed as a ratio	Ca^+ to Mg^{++}	0.5-2.0	0.5-1.0	0.5-3.0	1.0-3.0	0-2.0
	SO_4^{--} to Cl^-	<10 (low)	>10 (high)	<10 (low)	<10 (low)	>10 and <10 (low to high)
Type of groundwater present		I and II	III and IV	I and II	I and II	I
Position in groundwater flow system		Regional recharge	Local discharge	Local recharge	Regional recharge	Recharge-discharge area

dissolved solids (Fig. 28), areas of low $Na^+ + K^+$ content (Fig. 31), areas of high $HCO_3^- + CO_3^{--}$ content (Fig. 32) and high SO_4^{--} to Cl^- ratio (Fig. 35), confirms the presence of extensive local recharge areas on and adjacent to the sides of the Red Deer River valley (Fig. 27). The recharge areas are characterized by both sodium-bicarbonate water (Type I) and magnesium-calcium-bicarbonate water (Type II). The intermediate slope areas are characterized by mainly sodium-bicarbonate water (Type I). Type I water is representative of areas of both downward and upward flow, but in Hydrostratigraphic Unit 2, excepting Sandstone No. 1, the groundwater is distinguished by the presence of Cl^- and in Hydrostratigraphic Unit 1 by the SO_4^{--} content. Types I and II waters, because of their dominant occurrence throughout the study area, must be associated with both local, intermediate, and regional flow systems (Fig. 27). The behavior of chemical constituents within any flow system, however, can only be understood if the geometry of each system is known.

The most interesting and obvious feature of the groundwater chemistry in the study area is the strong local flow system with a recharge area on the topographic divide southeast of Red Deer, and a well-defined discharge area on the upper part of the gentle slopes in the vicinity of the northeast corner, township 37, range 27, west of the fourth meridian. Types III and IV waters characterize the discharge area and are, as previously mentioned, superimposed on Type I water. The recharge area of this flow system contains Type I and Type II waters. The topographic divide is located in a semicircle around the discharge area; thus the flow from the divide area converges radially and upward on the discharge area. Examination of test hole data (Appendix B) for Morrisroe 1-18 No. 1 and No. 2 (located at the lower edge of the recharge area of this flow system), and Bickford 13-32 (located in the discharge area of this flow system) show that the flow system extends at least to a depth of 200 feet, contains from 20 to 40 percent SO_4^{--} expressed as a percentage of total anions in the recharge area, and SO_4^{--} content ranging from 40 to 65 percent in the discharge area. Analyses of groundwater from wells located on the highest part of the recharge area show Mg^{++} content ranging from 20 to 65 percent as percentage of total cations. Maximum values for Mg^{++} content in the discharge area are about 50 percent of total cations. Groundwater in the flow system (similar to L8, Fig. 24) is interpreted as flowing mainly through glacial drift deposits containing abundant magnesium and sulfur compounds. Pawluk and Bayrock (1969) studied the composition of salts in water extracted from till for northern and central Alberta and found that sodium sulfate and magnesium sulfate are the two most abundant compounds in solution. They concluded: (1) that there is no close relationship between bedrock formations and salt content of till, and (2) that high salt concentration in the till is related to groundwater discharge; it does not reflect the original composition of till but is a characteristic acquired by the sediment after deposition. The high total dissolved solids (1 000 to>4 000 ppm, Fig. 28) in the discharge areas of the flow system can be explained by the large amounts of very soluble magnesium sulfate and calcium sulfate in the glacial drift and the fact that chemically large amounts of magnesium can be held in solution in equilibrium with sulfate.

Similar flow systems probably occur in township 37, range 1, west of the fifth meridian, but only Type III water is present in the discharge areas (Fig. 26) and total solids do not exceed about 2 000 ppm (Fig. 28). The chemistry of the groundwater suggests that the degree of mineralization of groundwater in Hydrostratigraphic Unit 1 is closely related to the type, amount, and solubility of minerals in the geologic deposits and to the geometry of flow systems. Local flow systems with Type III water in their discharge areas grade into and merge with local flow systems characterized by Type I or sodium-bicarbonate water in their discharge areas (Fig. 27). However, the $Na^+ + K^+$ content in percentage of total cations is greater in discharge areas than in recharge areas (Fig. 31). The more extensive discharge areas are indicated by a sulfate to chloride ratio greater than 10 (Fig. 35).

The generally low degree of mineralization throughout the study area suggests a rather short residence time for groundwater flowing through the geologic deposits. The analogue model shows that 65 percent of the total volume discharge of groundwater takes place in Hydrostratigraphic Unit 1 and 31 percent takes place through Sandstone No. 1 in Hydrostratigraphic Unit 2. The main types of flow systems present in Hydrostratigraphic Unit 1 are local and intermediate and the flow paths are relatively short. In addition, the general permeability of this unit is higher by several orders of magnitude than the lowest permeability determined for deposits in Hydrostratigraphic Unit 2. The flow paths are longer in Hydrostratigraphic Unit 2, but the residence time is shortened by the rapid movement of water along highly permeable layers which appear to be only slightly interconnected in the vertical direction.

Suitability of groundwater for human consumption

Groundwater in Hydrostratigraphic Units 1 and 2 is generally suitable for human consumption except for areas of excessive dissolved solids content (Fig. 28) and high iron content (Fig. 29). These areas are generally coincident with areas of Types III and IV water and groundwater from either hydrostratigraphic unit at depths greater than 200 feet in these areas will probably have a mineralization of not more than 1 000 ppm. In Hydrostratigraphic Unit 1 fluoride contents vary from less than 1 to 2 ppm and so in places may be higher than the upper limit of 1.5 ppm recommended by Alberta Health and Social Development.

Groundwater in Sandstone No. 1, Hydrostratigraphic Unit 2, is suitable for human consumption except that the fluoride content ranges up to 4 ppm. The high temperature, low total dissolved solids, and low hardness of the water in this aquifer are very desirable for municipal water supply. The concentrations of the main anion and cation constituents of the groundwater are well within the limits set by health authorities for water for human consumption.

Other aquifers in Hydrostratigraphic Unit 2 in the area of detailed study generally contain water of good quality, the exception again being the fluoride content.

THE GROUNDWATER RESOURCES

Aquifer-Performance Tests and their Interpretation

During the course of test drilling in the area of detailed investigation, 33 short and 3 long aquifer-performance tests were conducted on test wells. In addition, information was available for 2 short and 6 long tests conducted on private wells in or near the area of detailed investigation.

Time-drawdown and time-recovery data were plotted on semilog graph paper and values of transmissivity were calculated by the modified nonequilibrium formula (Jacob, 1950) and the Theis (1935) recovery formula. The two formulae are, respectively, $T = 264Q/\Delta s$ and $T = 264Q/\Delta s'$, where T = transmissivity in igpd/ft; Q = production rate in igpm; Δs = the difference in drawdown per log cycle, in feet; and $\Delta s'$ = the difference in recovery per log cycle, in feet (recovery plotted as residual drawdown).

The hydraulic conductivities of water-yielding beds were calculated from the equation $K = T/b$, where K = hydraulic conductivity in igpd/ft^2; T = transmissivity in igpd/ft; and b = thickness of water-yielding beds in feet.

For optimum conditions, the maximum yield of a single well, pumping water from an aquifer continuously at a constant production rate for a 20-year period, is calculated with the appropriate form of the modified nonequilibrium formula $Q_{20} = TH/2110$, where Q_{20} = maximum continuous rate of production in igpm for a 20-year period; T = transmissivity in igpd/ft; and H = available drawdown in feet.

The graphs of time-drawdown and time-recovery data for the short and long aquifer-performance tests are shown in figures 37 and 38, respectively, and the results of the tests are summarized in table 5 and table 6, respectively.

Discussion of Short Aquifer-Performance Test Results

The main purpose of the short aquifer-performance tests was to identify those aquifers with the best potential for the development of large supplies of groundwater. The values for 20-year single well yields as listed in table 5 must be viewed in the same context as they represent to some degree a theoretical, ideal situation. Other factors influencing drawdown in a well, including the effect of the type of well completion, interference of other wells, and effects due to natural conditions in the hydrogeologic environment, must be considered in specifying a maximum yield for an individual production well operating on a sustained basis.

The short aquifer-performance tests clearly show that Sandstone No. 1, Hydrostratigraphic Unit 2 is the most important aquifer in Paskapoo strata above the Ardley coal zone in the area of detailed investigation. At locations where this aquifer was bail or pump tested several other aquifers also yielded water to test holes. However, transmissivity values calculated from test data are considered to be representative of Sandstone No. 1 because of its high permeability and the fact that independent tests of aquifers above and below the main aquifer indicate water-bearing beds to have considerably lower or very low transmissivity values. Transmissivity values calculated for Sandstone No. 1 average 7 298 igpd/ft and range from 2 539 igpd/ft to 11 978 igpd/ft. The highest value was found for the location of Hermary 7-33 test hole (Fig. 2) in the river valley and the lowest value for the Viewpoint 2-28 test hole also in the river valley. The Viewpoint 2-28 test hole is located near the known southern boundary of Sandstone No. 1 which was not encountered during the drilling of test holes Red Deer 8-15, Deerhome 1-22, Spenceley 13-13, and Williamson 4-19 (Fig. 2). Also, the main aquifer was not encountered at the location of two test holes drilled in Lsd. 11 and Lsd. 14 of Sec. 22, Tp. 38, R. 27, W. 4th Mer., between one half to one mile in distance from Viewpoint 2-28 test hole. Bail test No. 2 at the location of Choate 13-28 was conducted for a predominantly shale-siltstone interval below Sandstone No. 1. One thin water-bearing bed occurred from 357 to 364 feet below surface with a transmissivity value of 4.4 igpd/ft. At the location of Red Deer Packers 16-28 well (Fig. 2) a transmissivity value of 15 igpd/ft was determined for a very fine, clayey sandstone (Sandstone No. 2) present from 264 to 329 feet below surface. A total of six values of transmissivity were determined for Sandstone No. 2 and only two values, 564 and 291 igpd/ft, were determined for Sandstone No. 3. The transmissivity values for Sandstone No. 2 averaged 281 igpd/ft and ranged from 15 to 768 igpd/ft. Thirteen transmissivity values for aquifers in Hydrostratigraphic Unit 1 averaged 641 igpd/ft and ranged from 12 to 3 687 igpd/ft. Transmissivity values at three locations for aquifers in the lower part of Hydrostratigraphic Unit 1 and upper part of Hydrostratigraphic Unit 2 (above or stratigraphically about the same position as Sandstone No. 1) averaged 844 igpd/ft and ranged from 574 to 1 292 igpd/ft. Natural gas was observed in all aquifers in Hydrostratigraphic Unit 2 and in some aquifers in the lower part of Hydrostratigraphic Unit 1. At the Ireland 12-25 test hole location (Fig. 2) a very strong flow of gas was encountered in a porous sandstone at a depth of 775 feet (Appendix B). A continuous record of water level for the Sandstone No. 1 aquifer at the Choate 14-28 No. 1 test hole location (Fig. 2) showed that the water level at that location was definitely affected by cyclic pumping at the Red Deer Packers well location (Fig. 2). Information obtained from test holes Hermary 7-33 and Viewpoint 2-28 showed that aquifers were more numerous throughout the deposits in the river valley bottom, suggesting a generally higher vertical permeability for the sequence of deposits overlying Sandstone No. 1 in the valley than for the vertical sequence of deposits at locations out of the valley (Fig. 2 and Appendix B).

Discussion of Long Aquifer-Performance Test Results

Water levels in wells completed in Sandstone No. 1 at the time of pump test No. 1 were continuously affected by declining or rising water levels in the cone of depression established by years of cyclic pumping at the location of three wells owned by Red Deer Packers, Ltd., a meat processing plant. The main well is the Red Deer Packers 16-28 well (Appendix B); the two other wells are nearby. Pump testing at Choate 14-28 No. 2 (Test No. 1) and Ireland 12-18 (Test No. 4) therefore resulted in cones of depression which were superimposed on an existing cone of depression. To obtain time-drawdown data or a portion of time-drawdown data that would reflect a minimum influence due to pumping of the Red Deer Packers wells, their weekly pumping schedule was taken into consideration. The plant operates approximately 16 hours a day, Monday to Friday. During weekends and holidays it is not in operation. Heavy pumping begins about 7.00 a.m. and continues until approximately 11.30 p.m. daily, except for Fridays when pumping stops about 6.00 p.m. Prior to the beginning of long aquifer-performance test 1, automatic water level recorders were placed on eight observation wells to establish the trend of nonpumping water levels. Six of the eight observation wells (Table 6) were completed in Sandstone No. 1, Hydrostratigraphic Unit 2, and responded to pumping of the production well, Choate 14-28 No. 2. The test (test No. 1) was begun at 1.30 p.m., Saturday, so that recovery of water levels due to the weekend stoppage of pumping at the Red Deer Packers plant would approach a steady-state condition. This enabled more accurate extrapolation of recovering water levels in observation wells for determination of drawdown due to the pumping of Choate 14-28 No. 2. Records of water levels taken before, throughout, and after test No. 1 for six observation wells are shown in figure 39. Two observation wells located in Lsd. 5, Sec. 28 and Lsd. 8, Sec. 29 of Tp. 38, R. 27, W. 4th Mer. did not respond to pumping during test No. 1 at Choate 14-28 No. 2 or to pumping of the Red Deer Packers wells. These wells were completed in bedrock aquifers above Sandstone No. 1, Hydrostratigraphic Unit 2, and are located about 1/2 mile southwest of Choate 14-28 No. 2 test hole. The arrival times of the cone of depression from the pumping of Choate 14-28 No. 2 (Fig. 40a) were determined from the hydrographs (Fig. 39). The initial drawdowns for observation wells Choate 14-28 No. 1 and Choate 13-28 were considered due almost entirely to the pumping well. The arrival time for the cone of depression caused by pumping at Choate 14-28 No. 2 was easily determined on the hydrographs for observation wells Hermary 2-32, Longacres 5-33, Hermary 7-33 and Viewpoint 2-28, but drawdown was calculated by subtracting the observed water level in the well from the extrapolated water level representing recovery from pumping at the Red Deer Packers wells (Fig. 39). Drawdowns caused by Choate 14-28 No. 2 were indeterminable after the cone of depression from the Packers wells reached the observation well locations following the beginning of pumping at the packing plant on Monday morning. The arrival time of the cone of depression established after pumping started at the Red Deer Packers plant is shown for the locations of observation wells in figure 40b. The effect of cyclic pumping of the Red Deer Packers wells is apparent on the hydrographs for all six observation wells measured during pump test No. 1 (Fig. 39). The effect was extreme at the location of Hermary 7-33 observation well, giving support to the previously stated conclusion of a higher transmissivity in the Red Deer River valley area. Viewpoint 2-28 and Longacre 5-33 were also noticeably

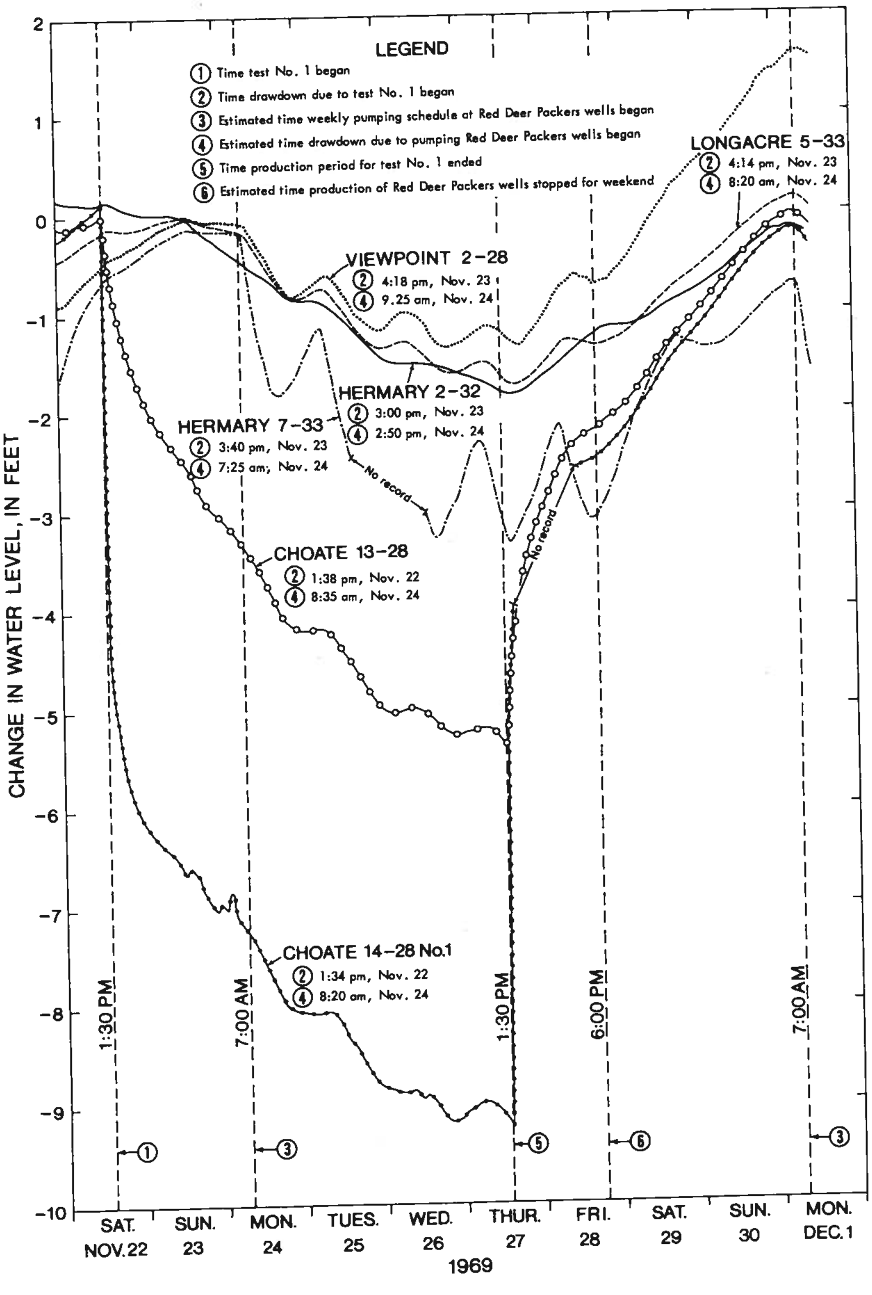
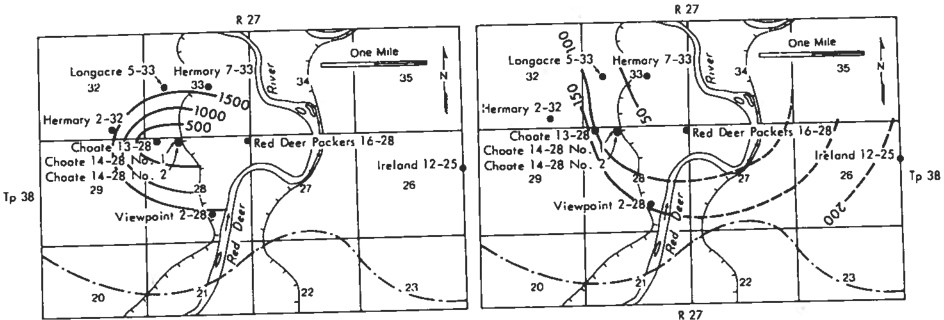
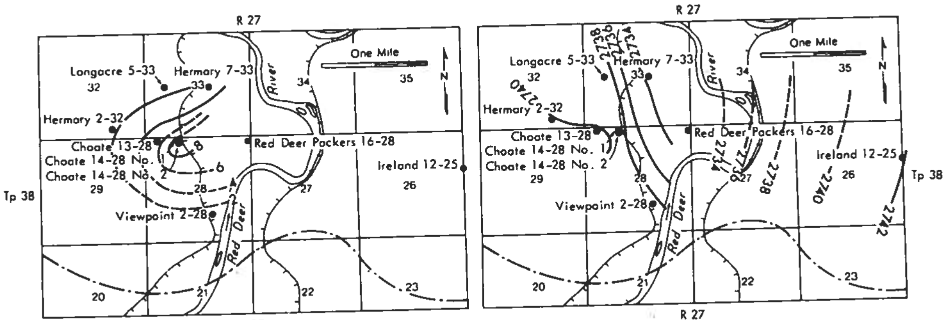


FIGURE 39. Hydrographs of water levels in observation wells, test No. 1.



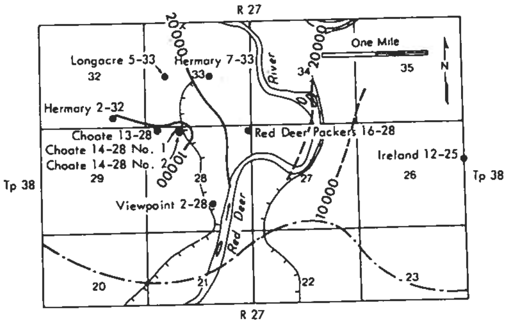
(a) Arrival time in minutes of cone of depression after pumping started at Choate 14-28 No. 2; long test No. 1.

(b) Estimated arrival time in minutes of cone of depression after pumping started at Red Deer Packers 16-28; long test No. 1.



(c) Maximum drawdown in feet caused by pumping of Choate 14-28 No. 2 and Red Deer Packers 16-28 after 5 days; long test No. 1.

(d) Surveyed elevations of water level in feet above sea level; Sandstone No. 1 aquifer (March, 1969).



(e) Transmissivity in igpd/ft.

LEGEND

Edge of river valley .... ⊥⊥⊥

Southern boundary of Sandstone No. 1 aquifer .... —·—

Point of control .... ●

Section number 23

FIGURE 40. Maps showing hydrogeological features of Sandstone No. 1, Hydrostratigraphic Unit 2, north of Red Deer.

affected but drawdown and recovery in Hermary 2-32, the observation well most distant from the Red Deer Packers wells, was least affected by pumping of those wells. The early drawdown and recovery at Choate 14-28 No. 1 and Choate 13-28 was considered caused mainly by pumping of Choate 14-28 No. 2 because of their close location (100 feet and 1 000 feet, respectively) to the pumping well. For these reasons time-recovery for calculation of transmissivity was interpreted only for wells Choate 14-28 No. 1, Choate 13-28, and Hermary 2-32 (Fig. 38). The initial, more rapid time rate of drawdown in pumping well Choate 14-28 No. 2, and the closest observation well, Choate 14-28 No. 1, is interpreted as being a result of three factors: (1) the expected response of water levels to the period of early pumping; (2) an apparent lower permeability caused by the release of natural gas to form bubbles in the formation surrounding the pumping well; and (3) the type of well completion. Hydrographs for some observation wells used to measure water levels during pumping test No. 3 are plotted with the inverse of barometric pressure change in figure 41. The hydrographs show clearly that water levels in Ireland 12-25 responded to cyclic pumping at the Red Deer Packers plant. Departure of the trend of water level in Robinson 13-30 from that of the barometric pressure change (such as water levels in Spenceley 13-13 demonstrated in Fig. 41) to follow more closely the change in water level in Ireland 12-25 suggests that pumping of the Red Deer Packers wells might affect water levels in wells completed in Sandstone No. 1 at distances of at least three miles radially. Test No. 4 (Fig. 38) conducted on the main Red Deer Packers well was begun on a holiday Monday. The recovery period prior to this test was therefore greater than two days and the high transmissivity value calculated for the Red Deer Sandstone at this location is considered reliable. The value for transmissivity calculated for Ireland 12-25 (Test No. 2, Fig. 38) is also considered reliable because the well was completed as an open hole and fully penetrated the aquifer. Furthermore, natural gas was not noticeable in Sandstone No. 1 at this location. Total drawdowns at the location of observation wells used in long aquifer-performance test 1 for a five-day period of pumping of wells at both the Choate 14-28 No. 2 and Red Deer Packers location are shown on figure 40c. Elevations of nonpumping water levels for wells completed in Sandstone No. 1 are shown on figure 40d. Water level in observation well Choate 14-28 No. 1, used during test No. 1 (Table 6), was relatively constant during a one-month period of measurement during the study. The water level at Ireland 12-25 (Fig. 2) was first surveyed in June 1967, and in March 1969 was found to be approximately the same, suggesting rather stable conditions at that location despite several years of heavy pumping at the Red Deer Packers plant. A map of transmissivity values in Sandstone No. 1, Hydrostratigraphic Unit 2 for several square miles north of Red Deer is shown in figure 40e. Transmissivity values for Sandstone No. 1 averaged 9 015 igpd/ft outside the river valley, except for the Longacre 5-33 test hole, and averaged 20 200 igpd/ft in the river valley. A transmissivity of 16 264 igpd/ft was determined for the aquifer at the location of Longacre 5-33 (Fig. 2). This value was the highest obtained for the aquifer outside the river valley. The range of transmissivity values is from 7 435 to 26 966 igpd/ft. The average of two coefficients of storage calculated for the Choate 14-28 No. 1 and Choate 13-28

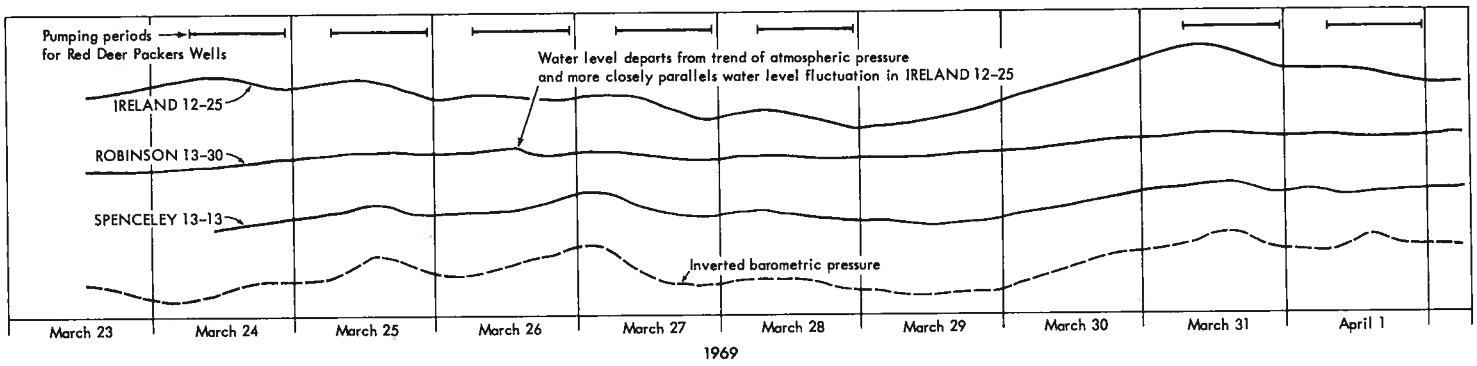


FIGURE 41. Hydrographs of water levels in three observation wells and the inverted barometric pressure, test No. 3.

observation wells during test 1 is 1.6×10^{-4}. Transmissivity values for sandstone aquifers in Hydrostratigraphic Unit 1 ranged from 238 to 3 043 igpd/ft. The long aquifer-performance tests demonstrated that the short aquifer-performance tests also gave the correct range of transmissivity values. The only exception was that the transmissivity determined for Sandstone No. 1 by short tests was lower than the actual value. The discrepancy was probably due to the interference caused by the pumping of the Red Deer Packers wells during the short tests at Hermary 7-33 and Viewpoint 2-28 test hole locations.

Test No. 3 (Fig. 38) at the location of Morrisroe 1-18 No. 2 was difficult to interpret. Only one observation well out of seven responded, but this was not surprising for the production rate for the test was only 10 igpm and the closest observation well that did not respond was located approximately 1.3 miles away. The sudden rise in water level in the pumping well remains unexplained. Transmissivity values determined for Sandstone No. 2 in Morrisroe 1-18 No. 1 are very different for the short aquifer-performance test (Table 5) and the long aquifer-performance test (Table 6). The difference in transmissivity values calculated from time-drawdown and time-recovery is suspected to be partly due to the influence of natural gas on permeability of the aquifer surrounding the pumping well. Difficulty with an electrical measuring device installed on observation well Morrisroe 1-18 No. 1 was experienced during the test and it is uncertain whether the sudden drop in the observation well during the last part of the pumping test (Fig. 38) is real or due to instrument error.

Long aquifer-performance tests Nos. 5 to 8 are for sandstone aquifers in Hydrostratigraphic Unit 1 south of the city of Red Deer, and No. 9 is for a sandstone aquifer in Hydrostratigraphic Unit 1 north of Red Deer and just outside the north boundary of the area of study. These long tests indicate the existence of some excellent aquifers in Hydrostratigraphic Unit 1 south of the city area.

Well-Performance Tests and their Interpretation

Step-drawdown tests, as proposed by Jacob (1947), have since been considered a means of testing the performance of a well. Several modifications and improvements in the technique and analysis of step-drawdown tests have taken place over the years but Mogg (1968) concluded that many of the interpretations made from analysis of step-drawdown data are wrong or misleading and that a critical review of the test method is needed. Mogg (1968) suggested that a simple plot of specific capacity (Q/s) *versus* pumping rate (Q) can be useful to predict an optimum pumping rate for a well, or it may be extrapolated to provide a specific capacity at some rate not used during the test.

Two step-drawdown tests were carried out on Choate 14-28 No. 2; one with open hole completion and one with slotted casing completion. The graphs of time

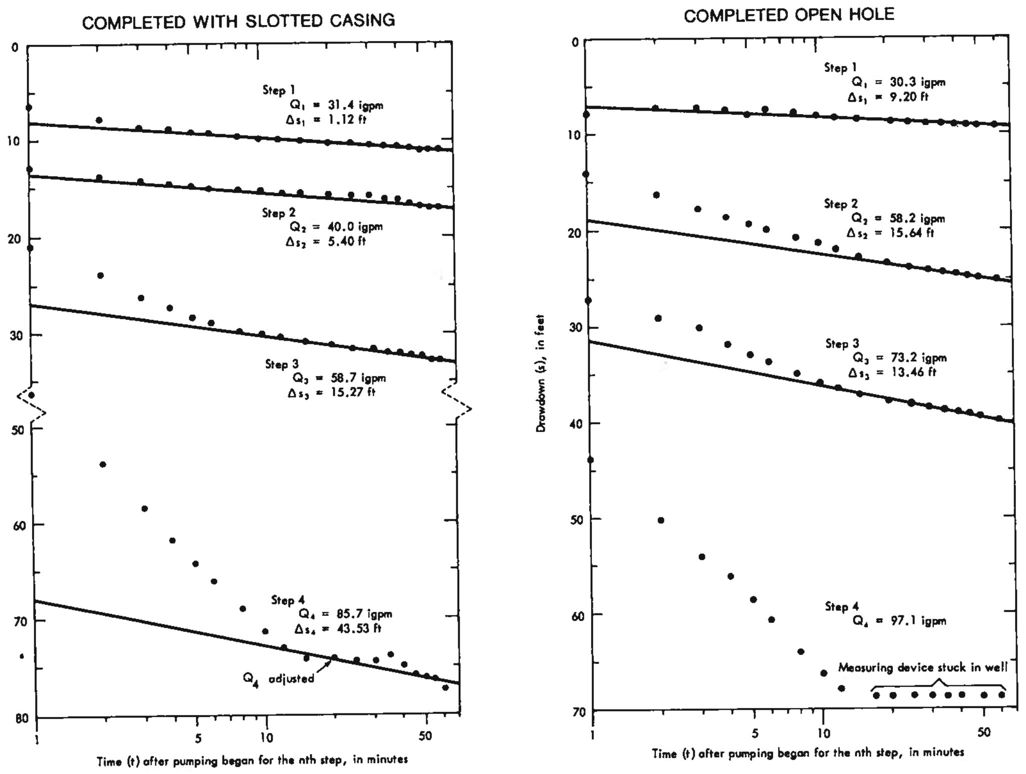


FIGURE 42. Graphs of time-drawdown of water level in Choate 14-28 No. 2 well during well-performance tests.

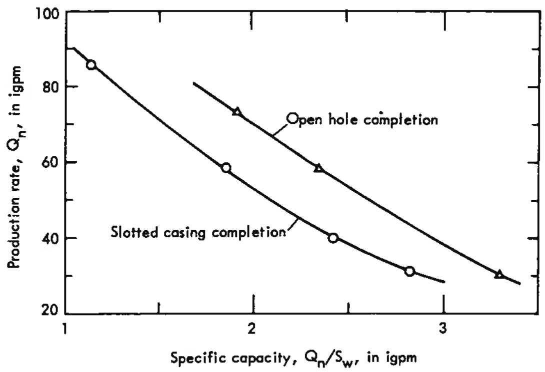


FIGURE 43. Graph of specific capacity versus *production rate for well-performance tests conducted on Choate 14-28 No. 2 well (60-minute production period).*

drawdown for different pumping rates for each test are shown in figure 42. Specific capacities are calculated by dividing the production rate (Q_n) during the nth step of the step-drawdown test by s_w, the sum of incremental drawdowns determined for each step after a pumping period of 60 minutes. Values of specific capacity for each step of the two tests are plotted *versus* the corresponding production rate in figure 43.

The time-drawdown plots for pumping wells used in long aquifer-performance tests can also be used as well-performance tests. A sustainable 20-year pumping rate for the pumping wells can be calculated with the equation $Q_{20} = HQ/s_{20}$, where Q_{20} = sustainable 20-year pumping rate in igpm; H = available drawdown in feet; Q = test rate of well in igpm; and s_{20} = total projected drawdown in feet over 7 log cycles (about 20 years) plus the drawdown after one minute of pumping at the test rate.

The values of drawdown per log cycle used to calculate s_{20} are determined from the latter part of time-drawdown graphs for production wells completed in Sandstone No. 1 (Fig. 38). The steep slopes on the graphs are due mainly to the effect of interference drawdown caused by the pumping of wells at the Red Deer Packers Ltd. plant. Effects of cyclic pumping probably due to wells other than the Red Deer Packers wells are clearly evident on the hydrograph for Hermary 7-33 observation well (Fig. 39).

Table 7 shows the values of H, Q, s_{20}, and Q_{20} for the production wells used in long aquifer-performance tests.

Table 7. Calculated Values of Sustainable 20-year Pumping Rate (Q_{20}) for Production Wells

Well Name or Location	Aquifer	H (ft)	Q (igpm)	S_{20} (ft)	Q_{20} (igpm)
Choate 14-28 No. 2	Sandstone No. 1	97	69	302	22
Ireland 12-15	Sandstone No. 1	87	220	68	282
Morrisroe 1-18 No. 2	Sandstone No. 2	173	10	296	6
Red Deer Packers Well 16-28	Sandstone No. 1	86	143	61	202
SE 29-37-27 W4M	Sandstone in Hydrostratigraphic Unit 1	98	37	185	20
SE 29-37-27 W4M	Sandstone in Hydrostratigraphic Unit 1	93	100	121	75
Lsd 4-33-37-27 W4M	Sandstone in Hydrostratigraphic Unit 1	205	63	163	80
SW 33-37-27 W4M	Sandstone in Hydrostratigraphic Unit 1	88	38	26	42
NE 4-40-27 W4M	Sandstone in Hydrostratigraphic Unit 1	109	10	87	38

Discussion of Well-Performance Tests

The values of sustainable 20-year pumping rates for wells completed in Sandstone No. 1 (Table 7) indicate that wells of high yields can be developed in that aquifer. The low value calculated for Choate 14-28 No. 2 is considered due largely to the effect of natural gas in the aquifer and the type of well completion. The effect of natural gas on the transmissivity of the aquifer cannot be separated from the effect of the type of well completion, but the graph in figure 43 shows that a considerable improvement in production can be attained with open hole completion. The graph in figure 44 shows the relative increase in specific capacity for various production rates for open hole compared to slotted casing completion. The graph indicates that the specific capacity increases with the production rate, and that the probable maximum increase in specific capacity at 100 igpm with open hole completion instead of slotted casing is about 40 percent. The increased specific capacity of the well with open hole completion is primarily due to the increase in open area of aquifer yielding water to the well. The open area could also be increased by increasing the diameter of a well. For a given production rate, the entrance velocity of water entering a large-diameter well completed open hole will

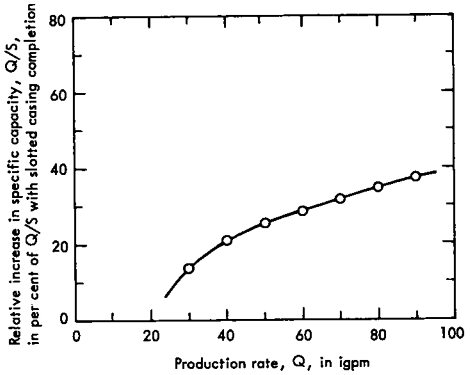


FIGURE 44. Graph of relative increase in specific capacity for open hole compared to slotted casing completion, Choate 14-28 No. 2 well (60-minute production period).

be lower than for other types of completions and will probably greatly reduce the effects of natural gas on the permeability of strata surrounding a production well. The end result will be an increase in the available drawdown for long, sustained production periods.

Natural Yield of a Portion of Sandstone No. 1, Hydrostratigraphic Unit 2

One of the main purposes of the present study was to determine the availability of water in Sandstone No. 1 on a regional basis. Conventional solutions based on interpretation of local aquifer-performance tests would be difficult because of the existing intricate interplay between the hydrogeologic environment, the groundwater regime, and effects imposed on the regime by the withdrawal of groundwater from the aquifers. If, therefore, a more meaningful answer is desired, the overall potential of the aquifer must be interpreted in a regional context. This can be accomplished by a method which requires the construction of vertical quantitative flow nets representing regional groundwater flow, the application of Darcy's Law, and consideration of the concept of "natural basin yield" (Freeze, 1969a). A suitable hydrogeological model is required before a flow net can be drawn. The required model is described in an earlier part of this report and is shown in figure 10. A two-dimensional, quantitative flow net drawn from the fluid potential pattern for the equivalent isotropic, nonhomogeneous model is shown in figure 24. The quantity of flow in Sandstone No. 1 in this model is equal to the quantity of flow in the real aquifer. The discharge in each flow channel can be calculated by Darcy's Law as presented by Freeze (1969a) in the form $Q = K \cdot (\Delta\phi/\Delta s)\Delta m \cdot w$ where Q = discharge through a flow tube; K = hydraulic conductivity; $\Delta\phi$ = drop in hydraulic head between equipotential surfaces; Δs = length in the flow tube; Δm = width of flow tube perpendicular to direction of flow; and w = thickness of the flow system perpendicular to the plane of the diagram.

For any square in the flow net where $K = 1, \Delta s = \Delta m$; and considering a unit thickness of the system, $w = 1$, then $Q = K \cdot \Delta\phi$.

The discharge in each flow tube remains constant throughout the tube's length and it is equal in all flow channels. The total quantity of groundwater flow through an aquifer is equal to the number of flow channels entering the aquifer multiplied by the discharge through a segment of the flow net. For the regional flow net $\Delta\phi = 25$ feet, and a K value of 0.25 igpd/ft^2 was assumed a representative value for the material of lowest permeability (the square portion of the flow net where $K = 1$) because a value of 0.6 igpd/ft^2 was determined for a 7 foot thick, slightly more permeable zone in a 149-foot interval of low hydraulic conductivity material at the location of Choate 13-28 (Appendix B) and a second value of 0.6 igpd/ft^2 was calculated for a 25-foot interval of very low permeability, clayey sandstone in the Red Deer Packers 16-28 well (Appendix B). This gives a flow channel discharge of $Q = K \cdot \Delta\phi = (0.25) \cdot 25 = 6.25$ igpd per foot of thickness perpendicular to the two-dimensional flow net.

It is necessary now to introduce the concept of "natural basin yield," defined by Freeze (1969a) as the quantity of flow through an undeveloped basin with a given water-table configuration and geologic configuration. The natural basin yield is, therefore, a consequence of the existing potential field which is a function of the configuration of the water table and the geology. It is a unique property of a groundwater basin which can be considered as a measure of the quantity of water that a given basin can accept, and is, therefore, a measure of the potential groundwater recharge to the basin. Assuming a steady-state water table, the natural basin yield will represent constant discharge which does not change with time and is relatively independent of local rainfall fluctuations. That portion of the natural basin yield or quantity of flow entering the aquifer is equal to the natural yield of the aquifer.

Yields for aquifers are often stated with respect to a definite time period, but if yields are related to the natural basin yield, the period of withdrawal is of little importance because natural basin yield is independent of time. Considering the three groundwater basins defined in the flow net (Fig. 24) and the distribution of the aquifer in the subsurface (Fig. 19), the natural yield of the aquifer can be calculated for a strip of land two miles wide and 11.5 miles long with cross section A-A' as the longitudinal axis (Fig. 2). The results of these calculations are shown on page 60.

The natural yield of the aquifer is equal to 13.8 percent of the available precipitation, based on a mean annual precipitation of 18 inches over the area considered. The natural yield for the aquifer in groundwater basins A and B is 5.6 percent of the available precipitation. The expected response to production of large quantities of water with time is a lowering of the water table, but the time from the beginning of heavy pumping to noticeable lowering of the water table is

Groundwater Basin	Number of flow channels entering aquifer	Natural yield of Sandstone No. 1 (igpd)
A	6.2	409 200
B	7.6	501 600
C	20.5	1 353 000
Total	34.3	2 263 800

unpredictable and in fact might be in the order of years. Presently there is no evidence of lowering of the water table in the area where the Red Deer Packers plant has been producing a large quantity of water (250 000 gpd, 5 days per week) for several years.

Recommendations for Location of Well Fields and Type of Well Completion for Development of Sandstone No. 1, Hydrostratigraphic Unit 2

Well fields

The river valley north of the city of Red Deer in the study area is the best location for a well field to withdraw water from Sandstone No. 1, Hydrostratigraphic Unit 2. Several hydrogeologic and economic advantages are gained in this area:

(1) Two major groundwater basins (A and B, Fig. 24) can be developed for water supply by means of a well field.

(2) A yield of at least 900 000 gallons per day can be obtained from the aquifer during initial development.

(3) The aquifer is closest to the surface in this area, thus requiring the least drilling to complete wells.

(4) Several aquifers present in the deposits above the main aquifer tend to increase the effective vertical permeability of the deposits overlying the aquifer.

(5) Pumping water levels in wells would be close to the surface and therefore the cost of lifting water would be reduced.

(6) The water quality is excellent with the exception of fluoride content.

(7) The area is situated near the city of Red Deer.

The location for a second well field is about one-half mile upslope from the Ireland 12-25 test hole (Fig. 2). In this area part of the large total volume discharge of groundwater in the aquifer in groundwater basin C (Fig. 24 and table on p. 60), as well as that in groundwater basin B, can be developed. Initial development yield for this area can be in the order of one million gallons a day. A performance study of the withdrawal of water from Sandstone No. 1 in the river valley prior to the development of a second well field would be a wise approach to development of the groundwater resources at Red Deer.

Well completion

Interpretation of data to date shows the most successful type of well completion to be large-diameter wells (about 10 to 12 inches) fully penetrating the aquifer, and constructed open hole across the aquifer. Where hydrogeologic conditions indicate that the aquifer material in a well requires stabilization, continuous-slot wire screens of proper size should be installed in the wells. The installation of sand packs around screens might also improve the performance of a well completed in the main aquifer, but no specific information is available to substantiate this possibility. Wells drilled in the river valley area can also be completed so that aquifers overlying the main aquifers are also developed. Initial production rates of 100 igpm are recommended for individual wells located in the river valley and completed in Sandstone No. 1, Hydrostratigraphic Unit 2. Elsewhere, initial production rates ranging from 50 to 100 igpm, depending on hydrogeologic conditions, are recommended.

Groundwater Probability Map

A groundwater probability map for the area of study is shown in figure 45. The map is for the most part a reproduction of portions of groundwater probability maps published by Le Breton (1971) and Tokarsky (1971). The map is revised in the area of detailed investigation, where aquifer-performance tests conducted during the present study gave results that do not agree with the existing groundwater probability maps.

SUMMARY OF THE HYDROGEOLOGY OF RED DEER AND VICINITY

The Hydrogeologic Environment

The hydrogeologic environment of the Red Deer area has a generating and controlling influence on various groundwater conditions which are the result of total interaction between components of the hydrogeologic environment and parameters of the groundwater regime. The three main components of the environment for the groundwater regime are topography, geology, and climate.

The regional topography is characterized by a broad depression with gentle slopes, bordered on the east and west by uplands and incised at its lowest part by the valley of the Red Deer River which is the principal drainageway. The Red Deer River has eroded a canyon deeper than 500 feet through the major upland in the eastern part of the area.

Deposits of the Tertiary and Quaternary are of particular interest in the study area. The Tertiary consists mainly of bedrock deposits of the Paskapoo Formation that occur above the Ardley coal zone. These sediments constitute the uppermost bedrock deposits and range in thickness from 300 feet in the Red Deer canyon to over 1 200 feet in the southwest part of the area. The lower part of Paskapoo strata above the Ardley coal zone is characterized by a series of relatively thick, high-permeability, extensive sandstones alternating with thick shale-siltstone sections with low permeability. A large number of permeable sandstone lenses or layers of restricted extent are present throughout a shale-siltstone section in the upper part of Paskapoo sediments above the coal zone. Sandstones are commonly fine to medium in grain size and contain various amounts of clay. The attitude of bedrock strata ranges from near horizontal to a dip of 25 feet a mile to the southwest. The strata undulate over much of the area. In major valleys on the bedrock surface the Paskapoo Formation is overlain by Saskatchewan Gravels and Sands of pre-first Quaternary glaciation age. The gravels and sands consist of rock types found in the mountains to the west and local bedrock fragments. Sand and silt lenses and beds are prominent in these sediments which commonly range up to 40 feet in thickness. Glacial deposits, overlying both bedrock and Saskatchewan Gravels and Sands, are composed largely of till which is the main constituent of extensive ground and hummocky moraine in the area. Other important glacial materials that overlie till in topographically low areas include outwash gravel, sand, silt, and clay; Pleistocene alluvial gravel; and glacial lake sand, silt, and clay. Recent lacustrine silt and clay, aeolian sand and coarse silt, and recent alluvial gravel and sand are the youngest sediments in the area. The thickness of surficial deposits ranges from less than 50 feet on regional topographic highs to over 200 feet at locations of major buried valleys on the bedrock surface.

Climate in the area is characterized by a mean annual precipitation ranging from 18 to 20 inches, a mean annual temperature of 53°F, and a mean annual potential evapotranspiration of 20 to 22 inches. Winters are cold and summers cool, with the average length of the frost-free period ranging from 100 to 120 days.

The Groundwater Regime

Parameters of the groundwater regime, including the occurrence and distribution of groundwater, the natural movement of groundwater, groundwater chemistry, and groundwater temperature, can conveniently be described within a framework of two hydrogeological units defined on a basis of the nature of permeability distribution and contrasts in the subsurface.

The upper unit, Hydrostratigraphic Unit 1, is distinguished by a permeability generally higher than the underlying shale-siltstone portions of Hydrostratigraphic Unit 2, the contrast being about 4 to 1. The unit includes the upper part of the bedrock and the surficial deposits. Generally, thickness of the unit ranges from 100 feet along the Red Deer River valley to 400 feet in upland areas. The main aquifers are sandstone lenses and shale beds in the bedrock deposits. Other important aquifers are gravel and sand deposits in buried preglacial valleys, sand and gravel deposits in the glacial drift, aeolian sands, and alluvial sands and gravels along present-day streams, rivers, and lakes. Most water wells in the area obtain water from bedrock deposits in Hydrostratigraphic Unit 1. High permeability layers in the unit, particularly buried valley gravels and sands, have a strong modifying influence on the distribution of fluid potential. North of Red Deer near-horizontal movement of groundwater is characteristic of highly permeable layers and, at the other extreme, the flow of groundwater is near-vertical in slightly permeable materials, particularly those overlying high permeability layers. The natural flow of groundwater takes place mainly in local and intermediate flow systems in which is concentrated 65 percent of the total volume discharge of groundwater in the area north of Red Deer. Regional recharge is restricted to the topographic divide areas and regional discharge to part of the Red Deer River valley bottom. The large local flow systems on and adjacent to the sides of the Red Deer River valley are the most striking feature of the natural movement of groundwater in Hydrostratigraphic Unit 1. Sodium-bicarbonate water (Type I) is the dominant chemical type of water in the unit. Other types present in order of abundance of occurrence are: magnesium-calcium-bicarbonate water (Type II), sodium-sulfate-bicarbonate water (Type III), and magnesium-calcium-sulfate-bicarbonate water (Type IV). Large areas of Types I and II water are associated with recharge areas in the regional uplands and the area adjacent to the Red Deer River valley. Type I water is also common in the recharge-discharge areas on slopes intermediate to uplands and lowlands. Types III and IV water occur in discharge areas surrounding the base of steep slopes which rise to the topographic divide. Type IV water also occurs locally in small areas surrounding Red Deer. Total dissolved solids content in groundwater is generally less than 1 000 ppm except for areas of Types III and IV water where the total dissolved solids content ranges from 1 000 to 8 000 ppm. The content of chemical constituents in groundwater in Hydrostratigraphic Unit 1 can be expressed in percentage of total anions or cations and described for particular regions.

Groundwater contains 20 to 80 percent $Na^+ + K^+$, 60 to greater than 80 percent $HCO_3^- + CO_3^{--}$, and 20 percent SO_4^{--} in regional uplands and areas adjacent to the Red Deer River valley; and 80 percent $Na^+ + K^+$, 60 to greater than 80 percent $HCO_3^- + CO_3^{--}$, and less than 20 to 40 percent SO_4^{--} in the Red Deer River valley and areas intermediate to regional uplands and lowlands. Areas characterized by groundwater with very high total dissolved solids content contain 40 to 80 percent $Na^+ + K^+$, 20 to 60 percent $HCO_3^- + CO_3^{--}$, and 40 to 80 percent SO_4^{--}. Iron content is generally less than 1 ppm and fluoride content less than 2 ppm. Groundwater temperatures range from 4.4 to 5.6°C. Features of the groundwater chemistry confirm the presence of extensive local recharge areas on and adjacent to the sides of the Red Deer River valley. Areas of high total dissolved solids content are the result of local flow systems in drift deposits containing abundant Mg^{++} and SO_4^{--}. Study of the chemistry suggests a rather short residence time for groundwater flowing through the rocks, as a result of rapid movement along high permeability layers, particularly in Hydrostratigraphic Unit 2, or short flow paths in local and intermediate flow systems. The large local systems on and adjacent to the sides of the Red Deer River valley result from the influence on fluid potential distribution of the steep water table slope on the sides of the valley and high permeability of Sandstone No. 1, Hydrostratigraphic Unit 2, in the subsurface.

The lower unit, Hydrostratigraphic Unit 2, is characterized by thick, extensive layers of highly permeable sandstones alternating with thick layers of predominantly shale and siltstone with low permeability. The maximum permeability contrast in this unit is in the order of 1 000. In the eastern part of the study area three extensive sandstone aquifers are present, although at any one location all three are not always represented. The middle and lowermost sandstones, Sandstone No. 2 and Sandstone No. 3, respectively, range up to greater than 100 feet in thickness and have noticeable differences in permeability, both vertically and laterally. The uppermost sandstone, Sandstone No. 1, is found in the subsurface north of the city of Red Deer with a known areal extent of about 60 square miles. The permeability of this aquifer is higher in the area of the Red Deer River valley than elsewhere. The aquifer ranges from 10 to 40 feet in thickness and occurs at depths of 134 feet in the Red Deer River valley area and up to 600 feet below surface at the major topograhic divide east of the city. In the western part of the study area several other thick, extensive sandstones are present in the unit. In the area where Sandstone No. 1 is present in the subsurface, Hydrostratigraphic Unit 2 is a medium for mainly regional groundwater flow systems with downward flow in uplands, lateral flow under regional slopes, and upward flow in depressions. In high permeability layers the movement of groundwater is nearly horizontal. Vertical flow-system boundaries are present in the subsurface at the location of regional uplands and depressions, but east of Red Deer the boundary is not coincident with the topographic divide but is shifted westward due to the influence of the Red Deer River canyon. Thirty-one percent of the total volume discharge of groundwater is concentrated in Sandstone No. 1 where it occurs in the subsurface north of Red Deer. Recharge areas for the sandstone aquifer are those of regional groundwater flow systems in topographic divide areas and recharge areas of large local flow systems adjacent to and upslope from the steep sides of the Red Deer River valley. The only chemical type of groundwater in Unit 2 is a sodium-bicarbonate water characterized by a total dissolved solids content of less than 1 000 ppm. Fluoride content ranges from 2 to 6 ppm with values up to 4 ppm for water in Sandstone No. 1. Temperatures of groundwater in Hydrostratigraphic Unit 2 range from 5°C in the upper part of the unit to 10.8°C in the lower part. Natural gas is present in noticeable but noneconomic quantities in aquifers throughout the unit.

The Groundwater Resources

Aquifer-performance tests clearly show that Sandstone No. 1 in Hydrostratigraphic Unit 2 is the most important aquifer in the Paskapoo Formation north of Red Deer. Transmissivity values for the aquifer average 9 015 igpd/ft outside the river valley and 20 200 igpd/ft in the river valley. The natural aquifer yield for a portion of the sandstone was calculated in a regional context by means of a quantitative flow net drawn for a representative hydrogeological cross section where the aquifer is present. Relative values of average hydraulic conductivities for the geologic deposits were used in the construction of the flow net. The natural yield of the aquifer, assuming a hydraulic conductivity of 0.25 igpd/ft^2, is in the order of 2 migpd.

The best location for a well field is in the river valley north of Red Deer where 900 000 igpd can be produced from Sandstone No. 1. Performance tests for wells completed in the aquifer suggest that a large-diameter well, fully penetrating the aquifer and constructed open hole across the aquifer, is the best type of well completion. An initial production rate of 100 igpm is recommended for each well completed in the Sandstone No. 1 aquifer in the river valley and 50 to 100 igpm, depending on hydrogeologic conditions, for wells located elsewhere.

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APPENDIX A

AN EVALUATION OF THE MAPPING OF NATURAL PHENOMENA AS A METHOD OF SELECTING SITES FOR THE DEVELOPMENT OF GROUNDWATER SUPPLIES

CONTENTS

INTRODUCTION

This evaluation is attained by comparison and discussion of hydrogeological interpretations and predictions determined from the mapping of naturally occurring surficial phenomena with knowledge of the hydrogeology gained from analysis and interpretation of detailed subsurface data, particularly for the area of detailed investigation (Fig. 2). Reference to the principles and methods of groundwater mapping or to features mapped is avoided except where such reference adds clarity. Clissold (1968) emphasizes that the mapping of naturally occurring surficial phenomena is most useful in groundwater studies in areas where no hydrogeological information is available. Clissold (1967) also states that as the method is evaluated for areas with different hydrogeologic conditions, as in the present manner, interpretations of basic data and predictions regarding groundwater resource development will become more definite. Results obtained by Clissold (1967, 1968) either during, or interpreted from, the mapping program are listed below:

(1) a general knowledge of the groundwater quality;

(2) distribution of groundwater quality over the area;

(3) the distribution of particular features associated with the presence or absence of groundwater near the land surface, for example, springs, dry depressions, phreatophytes, and so on;

(4) actual flow rates where groundwater discharges onto the land surface;

(5) water-table map;

(6) distribution of recharge and discharge areas;

(7) an interpretation of groundwater movement;

(8) conclusions regarding the properties of the geologic medium.

From this knowledge Clissold established a ranking of selected areas with respect to inferred suitability for the development of large supplies of groundwater.

The evaluation of Clissold's method will be developed in a manner consistent to the style of this publication; that is, the hydrogeologic environment, the groundwater regime, and the groundwater resources will be discussed consecutively. Measurements and observations included in points (3) and (4) above are accepted as entirely factual and are not discussed.

THE HYDROGEOLOGIC ENVIRONMENT

Geology

The only component of the hydrogeologic environment about which interpretive inference is made from naturally occurring surficial phenomena that reflect groundwater conditions is geology, or, more specifically, subsurface permeability contrasts and distribution. For the Red Deer region, Clissold (1967, 1968) assumed that the geologic medium could be considered homogeneous and that the top of the Lea Park Formation (3 600 feet below surface) could be considered the base for describing groundwater flow. In the light of the detailed subsurface investigation of the present study neither conclusion is strictly appropriate: extensive high-permeability layers are present in the subsurface, and the base of the Ardley coal zone, which is present at depths ranging from 600 to 1 100 feet in the area, is a convenient and suitable base for describing groundwater flow. Buried valley gravels and sands with high permeability are present in the subsurface along the major topographic low (Fig. 17), and north of Red Deer the highly permeable Sandstone No. 1 is present (Fig. 19). South of Red Deer other high permeability layers are present (Table 7). The influence of these high permeability layers on fluid potential distribution (Fig. 24) results in the downward flow of groundwater along the major depression in an area paralleling the Red Deer River valley. Clissold (1968) has mapped this area as largely one of groundwater recharge, which is in agreement with the findings of this study. In addition to mapping groundwater features, Clissold constructed three cross sections showing the distribution of natural fluid potential for homogeneous mediums. Study of the cross sections in addition to the interpretation of mapped groundwater phenomena led Clissold (1968) to conclude that the major flow systems originate on the regional uplands and terminate in part of the adjacent lowlands. However, the analogue for groundwater flow in a homogeneous medium (Fig. 23) does not show the actual extent or significance of the large local systems as revealed by the flow patterns for a nonhomogeneous medium (Fig. 24); that is, a medium that takes into account the very important influence of the subsurface permeability contrasts and distributions. The large recharge area paralleling and adjacent to the Red Deer River (Fig. 7) as mapped by Clissold (1968) is in agreement with and confirmed by the flow pattern for a nonhomogeneous medium (Fig. 24) and by the chemistry of groundwater as described and interpreted in this study. One hydraulic cross section drawn by Clissold from the western uplands to the Red Deer River south of the city of Red Deer shows a prominent discharge area adjacent to the river where mapping of surficial groundwater phenomena indicated a recharge area. Clissold noted this discrepancy. The present study suggests that such significant discrepancies should be carefully examined as they provide strong insight into permeability of the flow medium, in the above case indicating high permeability in the subsurface.

In the western uplands Clissold (1967, 1968) observed thick, permeable sandstone outcrops discharging large quantities of water, and spring lines surrounding the uplands (Fig. 7). Clissold (1967, 1968) concluded that this evidence suggested the presence of high permeability layers in the subsurface in the western uplands. This conclusion is valid because private water wells drilled in this area penetrate thick layers of permeable sandstones which yield substantial quantities of water. Clissold (1968) pointed out that springs along steep slopes at approximately the same elevation could also be explained by the geometry of groundwater flow systems in a homogeneous situation.

Groundwater can also be observed discharging from thick sandstones which outcrop on the sides of the eastern upland (Fig. 11) or in the Red Deer River canyon. At depth, the shale-siltstone intervals between sandstone layers do not discharge observable quantities of groundwater and are considered to be of low permeability.

THE GROUNDWATER REGIME

The Occurrence and Natural Movement of Groundwater

Clissold (1967, 1968) concluded the following in regard to the occurrence and natural movement of groundwater in the Red Deer area from mapped groundwater phenomena and study of cross sections of fluid potential distributions for an assumed homogeneous, geologic medium.

(1) Representative two-dimensional cross sections showing natural fluid potential distribution could be constructed assuming a homogeneous, geologic medium.

(2) The water table indicates that the general direction of groundwater movement is from high areas to low areas.

(3) Flow rates are high downslope from the hingeline at the base of steep slopes.

(4) Regional, intermediate, and local flow systems are present in the area. The only regional flow system present in the area extends from the eastern divide to the Red Deer River. The most active flow systems are local systems that originate on uplands and terminate in part on adjacent broad lowlands and the Red Deer River valley. These flow systems extend in depth to the top of the Lea Park Formation. Other numerous, smaller local systems range considerably in length, depth, and intensity of flow. Local flow systems adjacent to and on the sides of the Red Deer River valley are minor.

(5) The vertical impermeable boundaries coincide with surface water divides, and the horizontal impermeable boundary can be placed at the top of the Lea Park Formation.

(6) The main areas of recharge are regional uplands, and discharge takes place across most of the expanse of gentle sloping lowlands. Concentrated discharge occurs in areas immediately below steep regional

slopes. Areas of minor recharge are local topographic highs and the area adjacent to the river valley. The discharge areas for local recharge are local topographic lows.

(7) The total volume discharge of groundwater is mainly in flow systems originating on uplands and terminating on part of adjacent lowlands.

Clissold constructed a water-table map based on water levels observed in shallow auger holes, at points of groundwater discharge, and inferred from groundwater phenomena. Observations at test hole locations in the area of detailed investigation (Appendix B) supports Clissold's (1967, 1968) interpretation that the water table closely approximates the land surface.

Clissold (1967, 1968) stated several *a priori* conclusions describing the natural movement of groundwater; conclusions based on up-to-date knowledge of fluid potential distribution, groundwater flow patterns, the general direction of groundwater flow, the position of flow system boundaries, and location of recharge and discharge areas. Cross sections of natural fluid potential distribution drawn for an assumed homogeneous medium can be useful tools for assistance in interpretation of mapped groundwater features but emphasis must be placed on a simultaneous interpretation with mapped phenomena. The usefulness of the hydraulic cross sections lies in the fact that the water-table configuration (determined from field mapping) has a controlling effect on the natural fluid potential. Hydraulic cross sections can, therefore, provide insight into patterns and rates of groundwater flow, distribution of recharge and discharge areas, and the total volume discharge of groundwater.

The inference regarding the rate and direction of fluid potential changes with depth based on delineated recharge and discharge areas determined from mapped groundwater phenomena is the most objective and positive conclusion that can be reached with respect to fluid potential distribution. It is gratifying that such inference based on Clissold's work (1967, 1968) is correct when considered on a regional basis. However, consideration of the hydraulic cross sections by Clissold (1968) resulted in a conclusion that the generally broad area of noticeable recharge adjacent and parallel to the Red Deer River (Fig. 7) is a conglomeration of small local recharge areas rather than a large local recharge area resulting from the influence of the river valley and high permeability layers in the subsurface on the fluid potential distribution (Fig. 24). The choice of the top of the Lea Park Formation for the lower impermeable boundary to groundwater flow and the assumed homogeneity of the medium resulted in some local flow systems being extended to the lower impermeable boundary (3 600 feet at a maximum), and the projected presence of only one regional flow system in the area. In light of the results of the present study, the local and intermediate flow systems are superimposed on regional systems and are distributed entirely in the upper few hundred feet of geologic deposits. Results of Clissold's studies and the present study both show that the greatest percentage of the total volume discharge of groundwater in the area takes place in local and intermediate flow systems. The large, local flow systems adjacent to and on the sides of the Red Deer River valley and the regional flow system associated with the Red Deer River canyon are the most active flow systems in the area in respect to the volume of groundwater flow. This is somewhat at variance with Clissold's conclusion (1967, 1968) that the most active flow systems are local systems originating on highlands and terminating in part on adjacent lowlands. However, Clissold did not study the Red Deer canyon area nor the effects of high permeability layers in the subsurface. Vertical boundaries to groundwater flow are nearly coincident with topographic highs and river valley bottoms where valleys and divides parallel one another and valley flanks are near-symmetrical. Exceptions exist where the configuration of the water table is somewhat anomalous, as in the case where the Red Deer River has eroded a canyon across a major topographic high. The depth of the canyon at such a location markedly influences the natural fluid potential distribution, resulting in very steep fluid potential gradients and a large volume of groundwater discharge in the regional flow system associated with the canyon. Clissold's conclusion (1967, 1968) that concentrated groundwater discharges immediately below steep regional slopes is borne out by the present study except that such areas are probably more limited in areal extent than indicated by Clissold.

Groundwater Chemistry

Clissold (1967, 1968) interpreted groundwater chemistry from evidence collected in the field and interpretations of groundwater movement. The chemical types of groundwater (Fig. 8) and their areal distribution (Fig. 9) in the Red Deer area as described by Clissold (1968) are remarkably accurate in respect to the groundwater chemistry based on subsurface information described in the present report. Boundaries for defining chemical types of groundwater as used by Clissold (1968, Fig. 8) are different to those used in the present study (Figs. 25 and 36), but the similarity of classification is apparent if the present study boundaries (Figs. 25 and 36) are applied to Clissold's diagram (1968, Fig. 8) for classification of the chemical types of groundwater. The obvious difference is the more abundant $(Ca^{++} + Mg^{++})$ $(HCO_3^- + CO_3^{--})$ type water indicated from groundwater samples obtained from points of groundwater discharge at the surface or shallow auger holes. This difference would be expected because of the large number of near-surface sources of water sampled by Clissold (1967, 1968).

Areas of $(Na^+ + K^+)(SO_4^{--} + Cl^-)$ are more restricted than indicated by Clissold (1968) but he mentioned that in some cases boundaries for the distribution of the chemical types of groundwater might not be exact because of limited control data. Misconceptions about some aspects of hydrochemical flow systems have resulted because conclusions were based on wrong or misleading conditions describing the natural flow of groundwater. Clissold (1967, 1968) interpreted areas of $(Ca^{++} + Mg^{++})(SO_4^{--} + Cl^-)$ water with high total dissolved solids and high sulfate content as a result of a long duration of flow in the geologic deposits of water that passes through a medium high in calcium and magnesium ions near the end of the flow path. According to the present study, groundwater at the end of regional flow systems and the majority of groundwater in the Paskapoo Formation at depth contains sodium-bicarbonate type water with low total dissolved solids content (<1 000 ppm). The very high total dissolved solids is actually a result of short flow paths through geologic deposits with abundant amounts of very soluble calcium-magnesium-sulfate.

THE GROUNDWATER RESOURCES

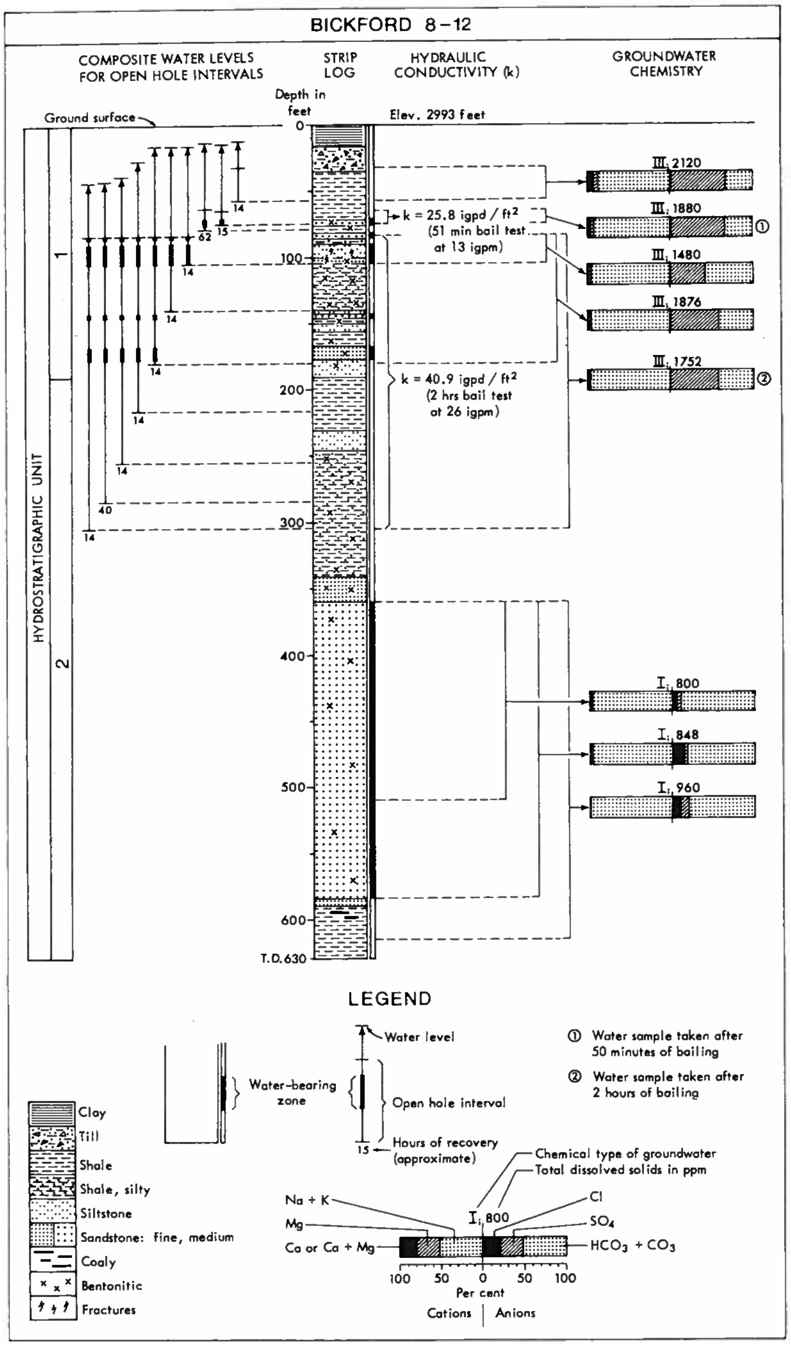
The selection of sites for the development of large supplies of groundwater (Fig. 7) as outlined by Clissold (1967, 1968) was based partly on the availability and quality of groundwater as inferred from the results of the mapping program, but theoretical considerations, particularly of fluid potential distribution, were heavily depended upon. Clissold's conclusions that groundwater quality is excellent, that high permeability layers are present in the subsurface, and that high rates of natural outflow of groundwater at the surface reflect groundwater conditions in the western topographic high area (Fig. 7) are valid. Based on these facts, interpreted from mapped groundwater phenomena, Clissold selected this area as potentially the best in the area for the development of large supplies of groundwater. In the area east of the city of Red Deer greater emphasis was given to direction and rates of groundwater flow, change in hydraulic head with well depth, and recharge areas as determined in part from cross sections of fluid potential distributions. Predictions about groundwater supplies based on these considerations are not acceptable because the present study shows that the basic premises for constructing the analogue models were not correct. Areas of high total dissolved solids content and high sulfate content were correctly considered unsuitable for development of groundwater supplies. Clissold (1968) wrongly concluded that less favorable conditions are present in the river valley because only small amounts of circulating groundwater reach the valley. Well depths recommended on information about thickness of different geologic deposits, evidence of depths to highly permeable layers, and consideration of the change in hydraulic head in wells with reference to mapped recharge and discharge areas are justifiable. Predictions for depths greater than the upper 200 or 300 feet of geologic deposits are highly speculative when judged in the light of the results of the detailed subsurface investigation. In fact, the excellent yields predicted by Clissold (1967) and consequently obtained at the Ireland 12-25 site (Figs. 2 and 7) could be argued as being fortuitous.

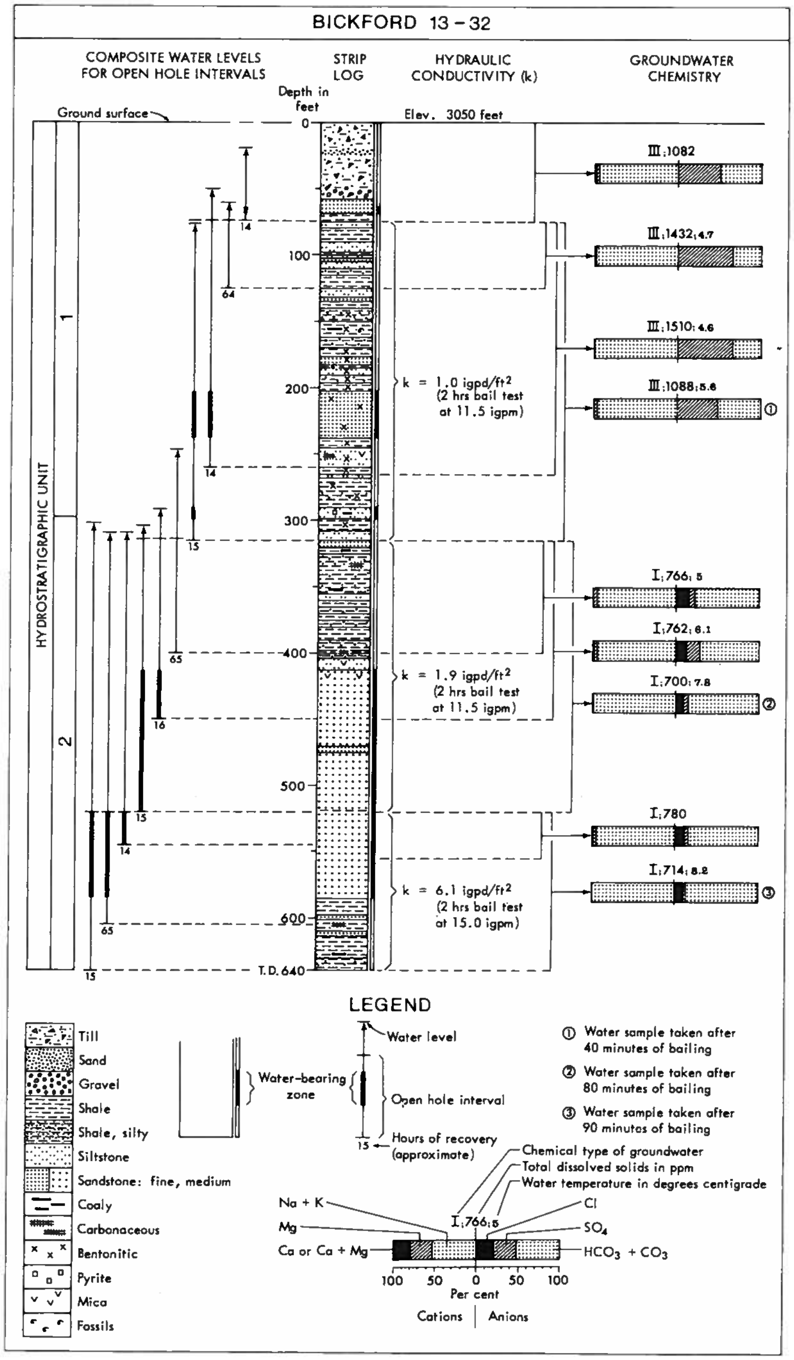
CONCLUSIONS AND RECOMMENDATIONS

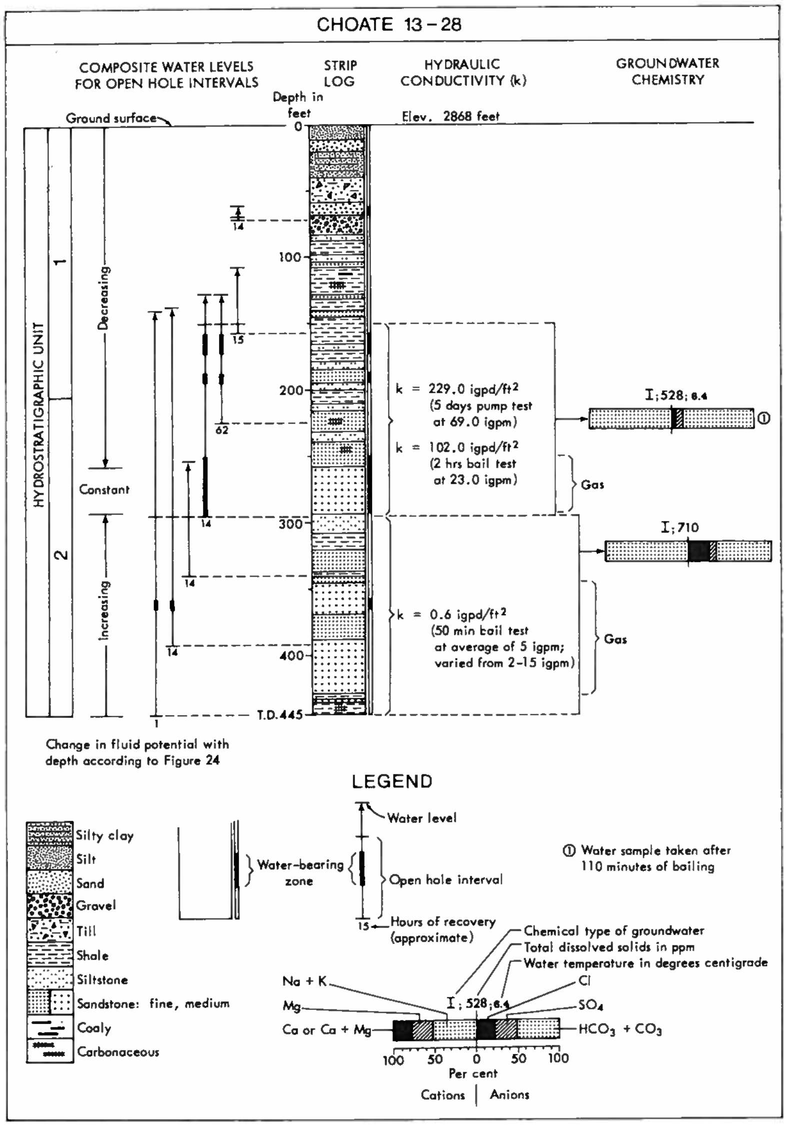
In areas where little, if any, prior hydrogeological information is available, the choice of sites for the development of large supplies of groundwater, based on the mapping of naturally occurring surficial phenomena, offers a feasible approach to initial development of groundwater resources. Discernment of permeability contrasts and distributions in the subsurface is difficult but possible if based on careful comparisons between field observations and flow models. The presence of high permeability layers in the subsurface adjacent to the Red Deer River valley is indicated by discrepancy between areas mapped as recharge areas but occurring as discharge areas in cross sections of fluid potential distribution assuming a homogeneous geologic medium. Insight to guide interpretation of components of the groundwater regime can be gained from study of cross sections of potential distributions for assumed homogeneous mediums. However, stress must be placed on interpretations and descriptions derived from mapped groundwater phenomena and not theoretical considerations. The horizontal impermeable boundary necessary in any model in order to simulate fluid potential distribution must be the base of deposits whose permeability is significantly higher than underlying deposits. Where such geologic information is not available and cannot be obtained from field studies, the greatest percentage of the total volume discharge of groundwater should be considered to take place in local and intermediate flow systems in the upper few hundred feet of geologic deposits and the horizontal boundary to groundwater flow should not be placed at great depths for construction of models used to assist in interpretation of mapped groundwater phenomena. An alternative at any location is to place the horizontal boundary at several positions, draw fluid potential distributions, and choose the one which best agrees with mapped groundwater conditions. An accurate knowledge of the chemical types of groundwater and their distribution can be gained from the interpretation of groundwater samples obtained from points of groundwater discharge at the surface or from shallow auger holes. Sites for development of large supplies of groundwater must be selected primarily from simple, objective interpretations of the hydrogeology based on mapped groundwater phenomena and observations of geology.

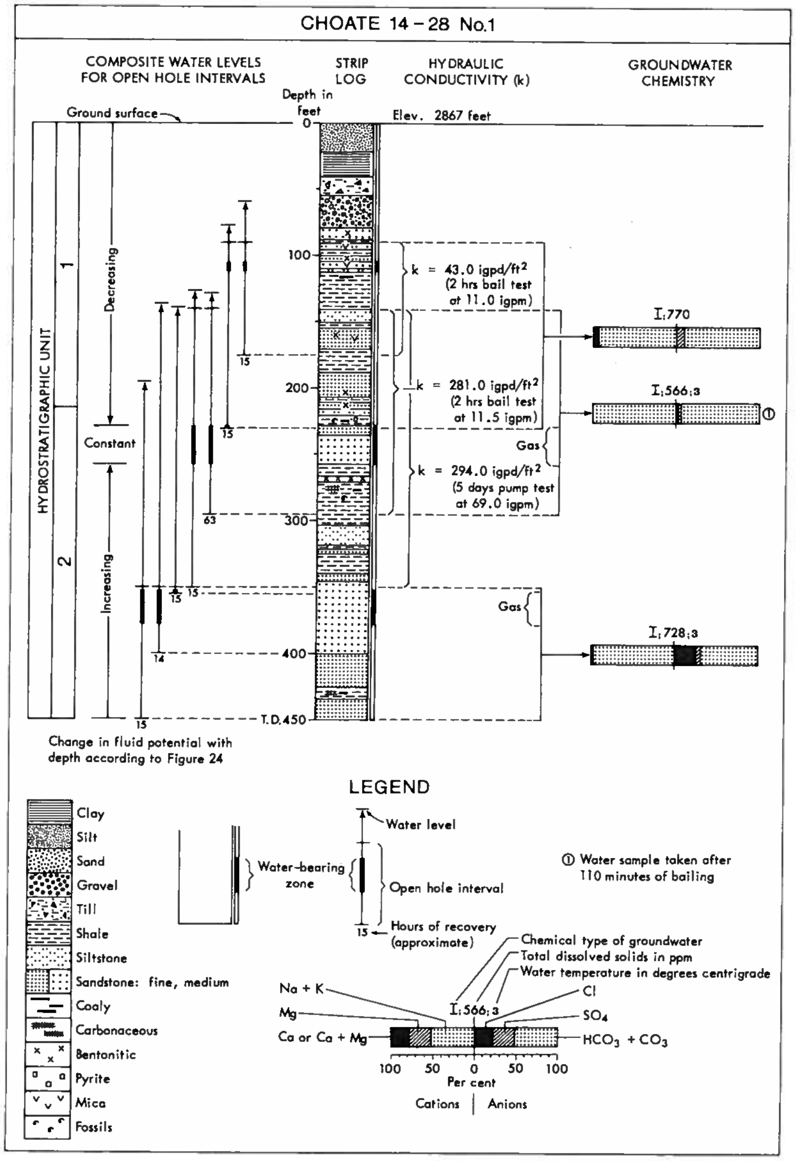
APPENDIX B

DIAGRAMMATIC PRESENTATION OF BASIC DATA FOR TEST HOLES DRILLED IN THE AREA OF DETAILED INVESTIGATION AND FOR RED DEER PACKERS 16-28 WELL

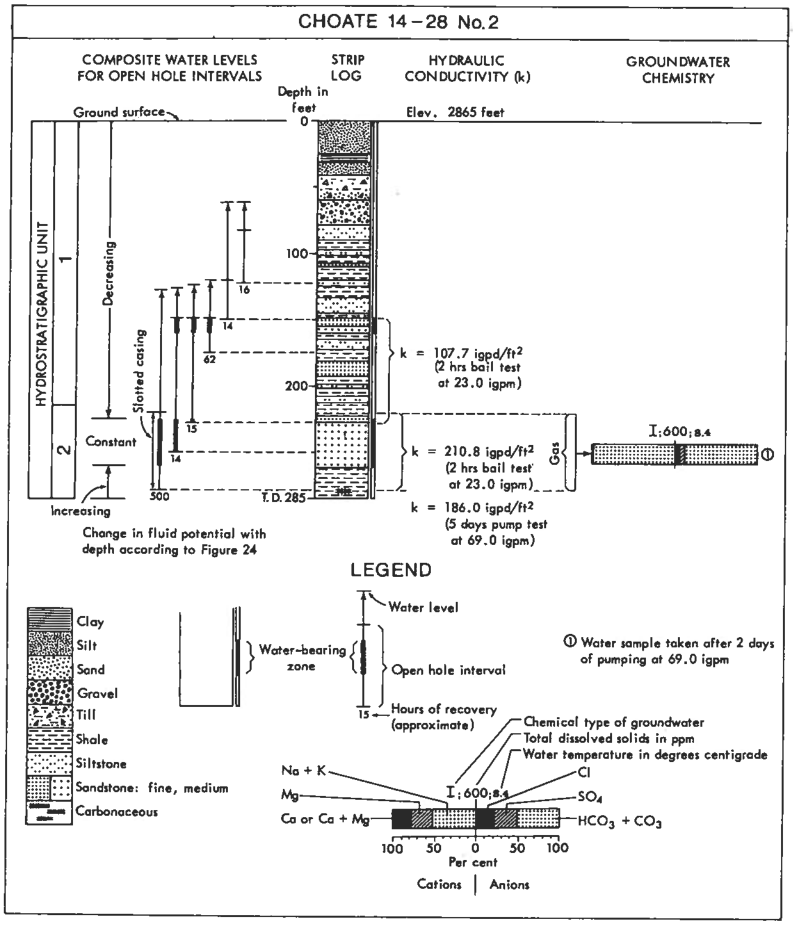

BICKFORD 8-12
COMPOSITE WATER LEVELS FOR OPEN HOLE INTERVALS
STRIP LOG
HYDRAULIC CONDUCTIVITY (k)
GROUNDWATER CHEMISTRY
Depth in feet
Ground surface
Elev. 2993 feet
0
100
200
300
400
500
600
T.D. 630
HYDROSTRATIGRAPHIC UNIT
1
2
14
62
15
14
14
14
14
14
14
40
14
k = 25.8 igpd / ft²
(51 min bail test at 13 igpm)
k = 40.9 igpd / ft²
(2 hrs bail test at 26 igpm)
III, 2120
III, 1880 ①
III, 1480
III, 1876
III, 1752 ②
I, 800
I, 848
I, 960
LEGEND
Water level
Water-bearing zone
Open hole interval
15 Hours of recovery (approximate)
① Water sample taken after 50 minutes of bailing
② Water sample taken after 2 hours of bailing
Clay
Till
Shale
Shale, silty
Siltstone
Sandstone: fine, medium
Coaly
Bentonitic
Fractures
Chemical type of groundwater
Total dissolved solids in ppm
Na + K
Mg
Ca or Ca + Mg
I, 800
Cl
SO₄
HCO₃ + CO₃
100 50 0 50 100
Per cent
Cations
Anions

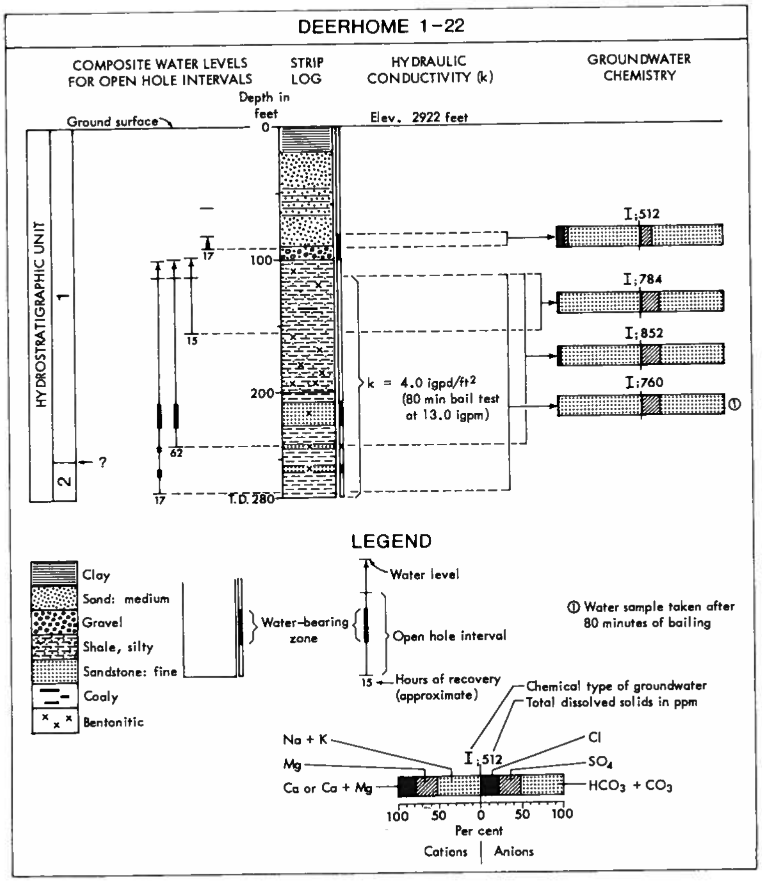

BICKFORD 13 – 32
COMPOSITE WATER LEVELS FOR OPEN HOLE INTERVALS
STRIP LOG
HYDRAULIC CONDUCTIVITY (k)
GROUNDWATER CHEMISTRY
Depth in feet
Ground surface
Elev. 3050 feet
0
100
200
300
400
500
600
T.D. 640
HYDROSTRATIGRAPHIC UNIT
1
2
14
64
14
15
65
16
15
14
65
15
k = 1.0 igpd/ft²
(2 hrs bail test at 11.5 igpm)
k = 1.9 igpd/ft²
(2 hrs bail test at 11.5 igpm)
k = 6.1 igpd/ft²
(2 hrs bail test at 15.0 igpm)
III;1082
III;1432;4.7
III;1510;4.6
III;1088;5.6 ①
I;766;5
I;762;6.1
I;700;7.8 ②
I;780
I;714;8.2 ③
LEGEND
Till
Sand
Gravel
Shale
Shale, silty
Siltstone
Sandstone: fine, medium
Coaly
Carbonaceous
Bentonitic
Pyrite
Mica
Fossils
Water-bearing zone
Water level
Open hole interval
Hours of recovery (approximate)
15
① Water sample taken after 40 minutes of bailing
② Water sample taken after 80 minutes of bailing
③ Water sample taken after 90 minutes of bailing
Chemical type of groundwater
Total dissolved solids in ppm
Water temperature in degrees centigrade
I;766;5
Na + K
Mg
Ca or Ca + Mg
Cl
SO₄
HCO₃ + CO₃
100 50 0 50 100
Per cent
Cations
Anions

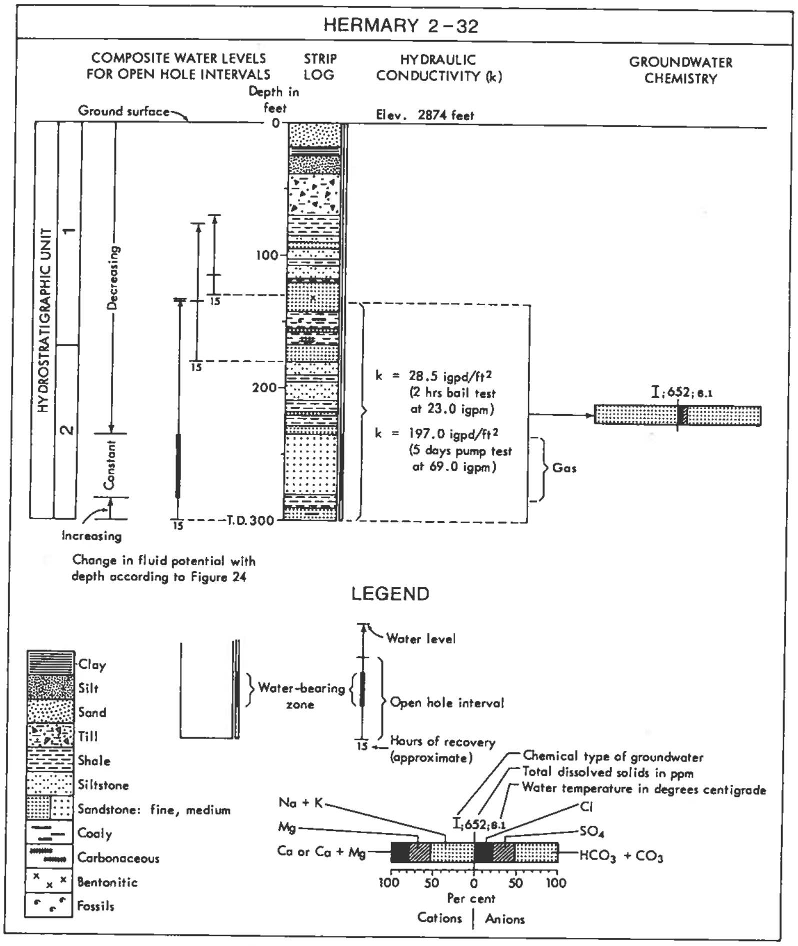

CHOATE 13 – 28
COMPOSITE WATER LEVELS FOR OPEN HOLE INTERVALS
STRIP LOG
HYDRAULIC CONDUCTIVITY (k)
GROUNDWATER CHEMISTRY
Depth in feet
Ground surface
Elev. 2868 feet
HYDROSTRATIGRAPHIC UNIT
1
2
Decreasing
Constant
Increasing
0
100
200
300
400
T.D.445
14
15
62
14
14
14
1
k = 229.0 igpd/ft²
(5 days pump test at 69.0 igpm)
k = 102.0 igpd/ft²
(2 hrs bail test at 23.0 igpm)
Gas
k = 0.6 igpd/ft²
(50 min bail test at average of 5 igpm; varied from 2-15 igpm)
Gas
I; 528; 6.4
①
I; 710
Change in fluid potential with depth according to Figure 24
LEGEND
Silty clay
Silt
Sand
Gravel
Till
Shale
Siltstone
Sandstone: fine, medium
Coaly
Carbonaceous
Water-bearing zone
Water level
Open hole interval
15 Hours of recovery (approximate)
① Water sample taken after 110 minutes of bailing
Chemical type of groundwater
Total dissolved solids in ppm
Water temperature in degrees centigrade
Na + K
Mg
Ca or Ca + Mg
I; 528; 6.4
Cl
SO₄
HCO₃ + CO₃
100 50 0 50 100
Per cent
Cations
Anions

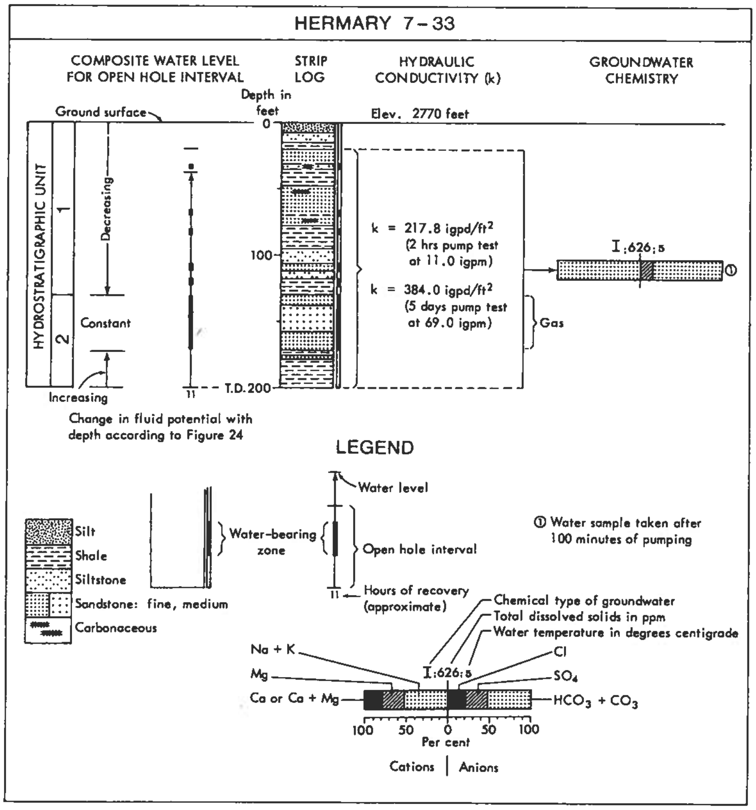

CHOATE 14 - 28 No.1
COMPOSITE WATER LEVELS FOR OPEN HOLE INTERVALS
STRIP LOG
HYDRAULIC CONDUCTIVITY (k)
GROUNDWATER CHEMISTRY
Depth in feet
Ground surface
Elev. 2867 feet
0
100
200
300
400
T.D.450
HYDROSTRATIGRAPHIC UNIT
1
2
Decreasing
Constant
Increasing
15
15
63
15
15
14
15
k = 43.0 igpd/ft²
(2 hrs bail test at 11.0 igpm)
k = 281.0 igpd/ft²
(2 hrs bail test at 11.5 igpm)
Gas
k = 294.0 igpd/ft²
(5 days pump test at 69.0 igpm)
Gas
I;770
I;566;3
①
I;728;3
Change in fluid potential with depth according to Figure 24
LEGEND
Clay
Silt
Sand
Gravel
Till
Shale
Siltstone
Sandstone: fine, medium
Coaly
Carbonaceous
Bentonitic
Pyrite
Mica
Fossils
Water-bearing zone
Water level
Open hole interval
Hours of recovery (approximate)
15
① Water sample taken after 110 minutes of bailing
Chemical type of groundwater
Total dissolved solids in ppm
Water temperature in degrees centrigrade
Na + K
Mg
Ca or Ca + Mg
I;566;3
Cl
SO₄
HCO₃ + CO₃
100 50 0 50 100
Per cent
Cations
Anions

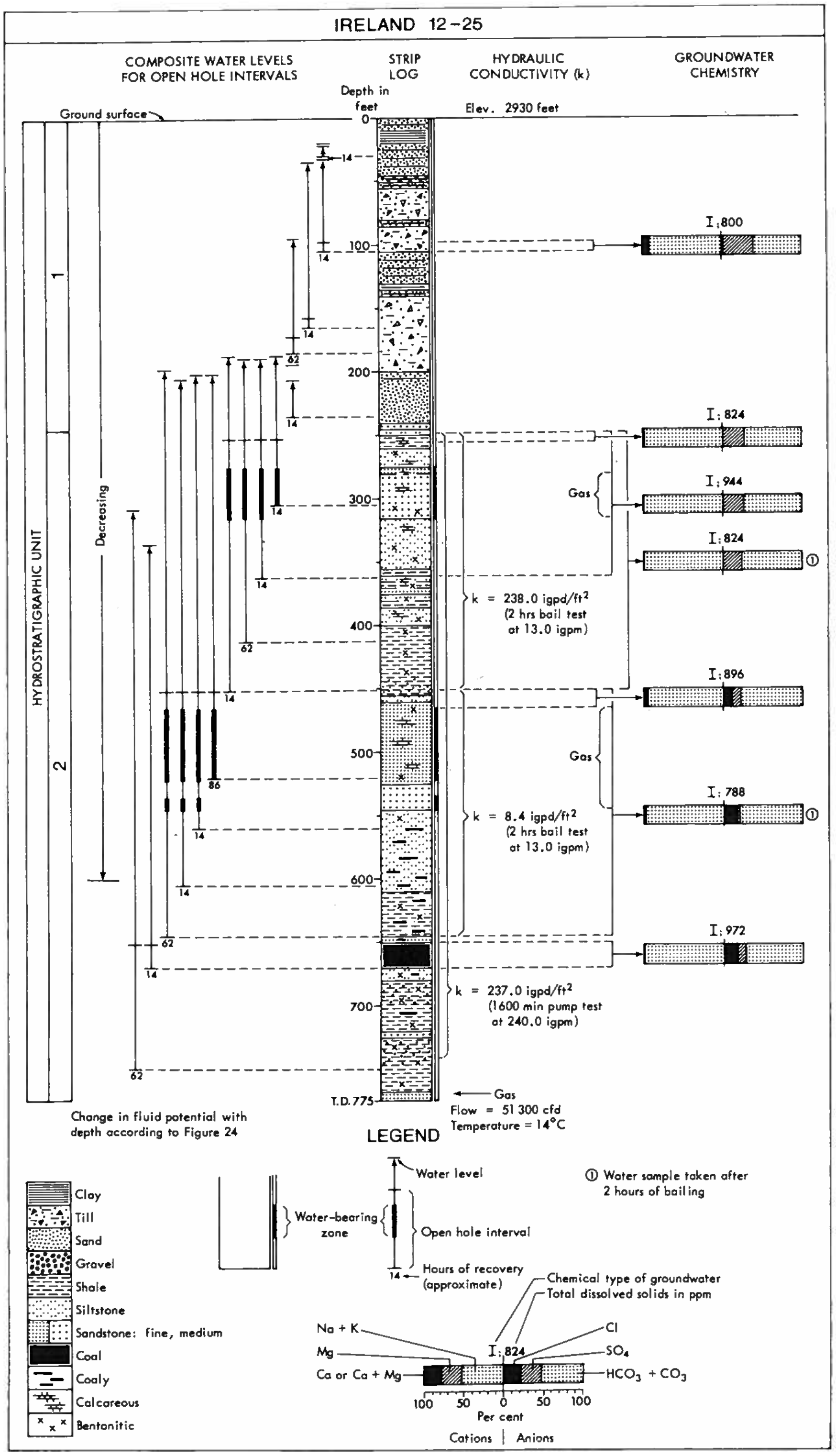
CHOATE 14-28 No.2

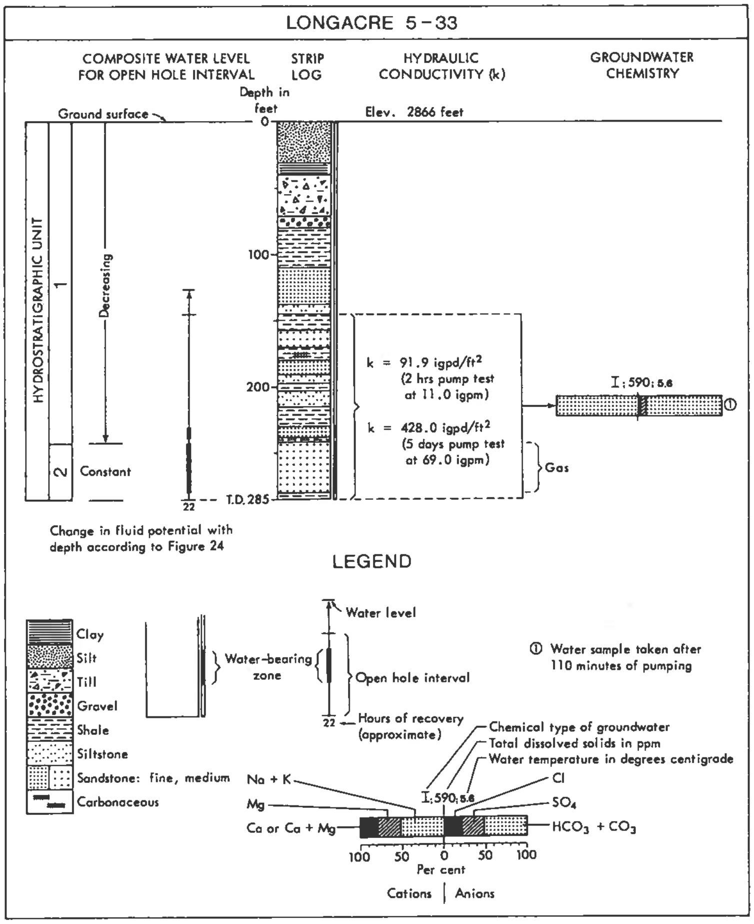


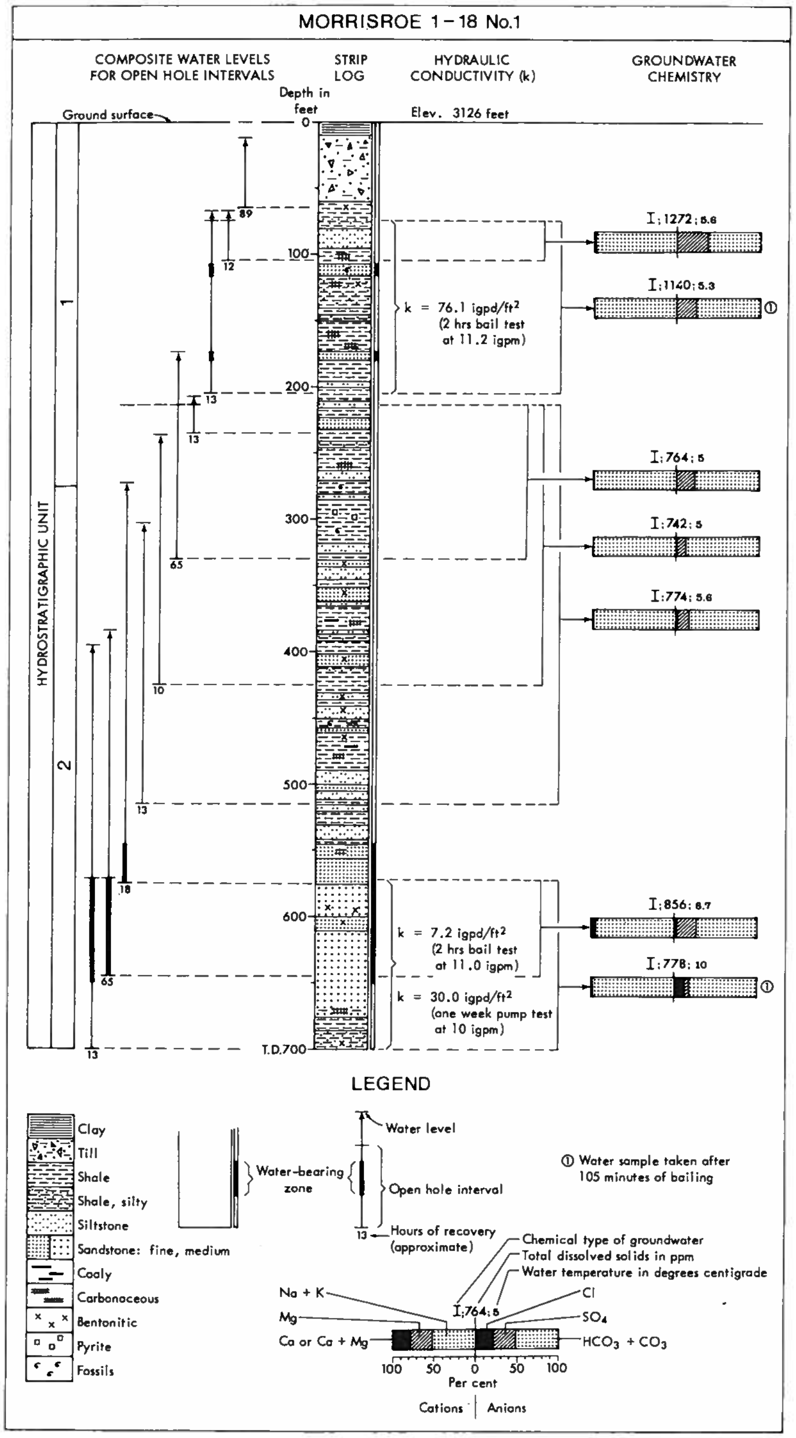

DEERHOME 1-22
COMPOSITE WATER LEVELS FOR OPEN HOLE INTERVALS
STRIP LOG
HYDRAULIC CONDUCTIVITY (k)
GROUNDWATER CHEMISTRY
Depth in feet
Ground surface
Elev. 2922 feet
0
100
200
T.D. 280
HYDROSTRATIGRAPHIC UNIT
1
2
?
17
15
62
17
k = 4.0 igpd/ft²
(80 min bail test at 13.0 igpm)
I;512
I;784
I;852
I;760
①
LEGEND
Clay
Sand: medium
Gravel
Shale, silty
Sandstone: fine
Coaly
Bentonitic
Water-bearing zone
Water level
Open hole interval
15
Hours of recovery (approximate)
① Water sample taken after 80 minutes of bailing
Chemical type of groundwater
Total dissolved solids in ppm
Na + K
Mg
Ca or Ca + Mg
I;512
Cl
SO₄
HCO₃ + CO₃
100
50
0
50
100
Per cent
Cations
Anions

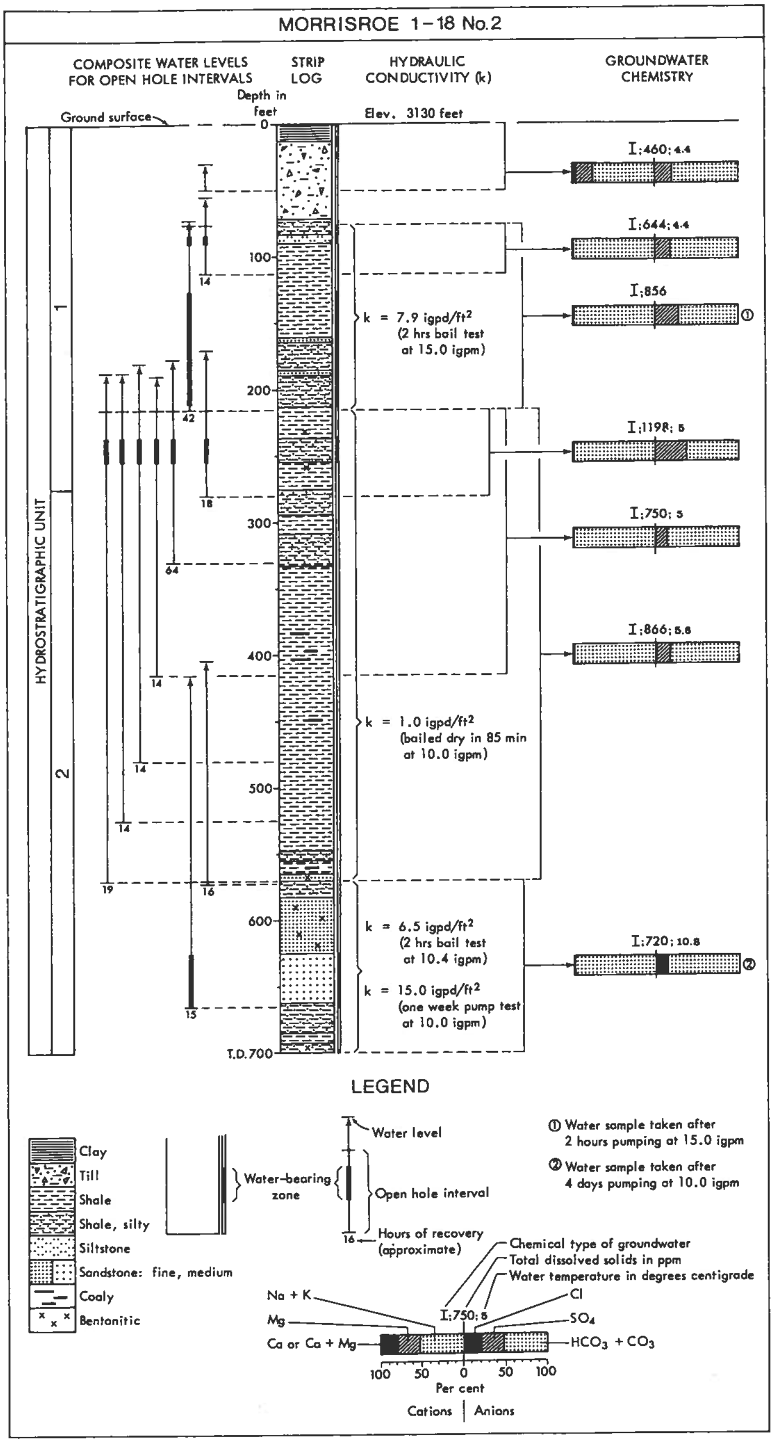

HERMARY 2-32
COMPOSITE WATER LEVELS FOR OPEN HOLE INTERVALS
STRIP LOG
HYDRAULIC CONDUCTIVITY (k)
GROUNDWATER CHEMISTRY
Depth in feet
Ground surface
0
100
200
T.D. 300
Elev. 2874 feet
HYDROSTRATIGRAPHIC UNIT
1
2
Decreasing
Constant
Increasing
15
15
15
Change in fluid potential with depth according to Figure 24
k = 28.5 igpd/ft²
(2 hrs bail test at 23.0 igpm)
k = 197.0 igpd/ft²
(5 days pump test at 69.0 igpm)
Gas
I;652;6.1
LEGEND
Clay
Silt
Sand
Till
Shale
Siltstone
Sandstone: fine, medium
Coaly
Carbonaceous
Bentonitic
Fossils
Water-bearing zone
Water level
Open hole interval
15
Hours of recovery (approximate)
Chemical type of groundwater
Total dissolved solids in ppm
Water temperature in degrees centigrade
Na + K
Mg
Ca or Ca + Mg
I;652;8.1
Cl
SO₄
HCO₃ + CO₃
100
50
0
50
100
Per cent
Cations
Anions

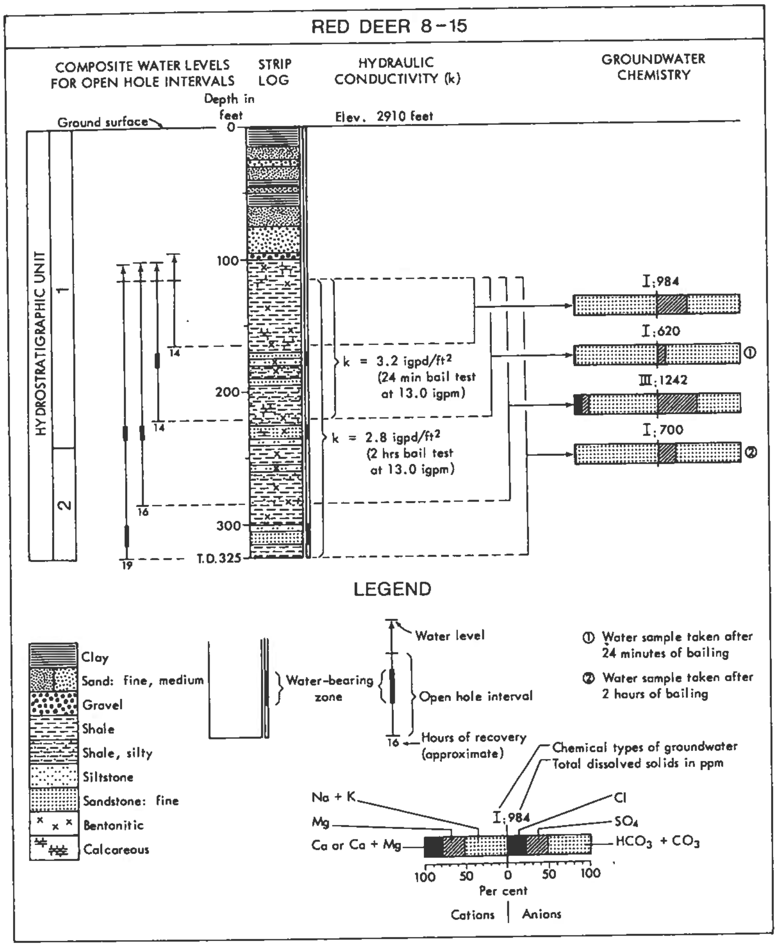

HERMARY 7-33
COMPOSITE WATER LEVEL FOR OPEN HOLE INTERVAL
STRIP LOG
HYDRAULIC CONDUCTIVITY (k)
GROUNDWATER CHEMISTRY
Depth in feet
Ground surface
0
Elev. 2770 feet
100
T.D. 200
HYDROSTRATIGRAPHIC UNIT
1
2
Decreasing
Constant
Increasing
11
Change in fluid potential with depth according to Figure 24
k = 217.8 igpd/ft²
(2 hrs pump test at 11.0 igpm)
k = 384.0 igpd/ft²
(5 days pump test at 69.0 igpm)
Gas
I;626;5
①
LEGEND
Silt
Shale
Siltstone
Sandstone: fine, medium
Carbonaceous
Water-bearing zone
Water level
Open hole interval
Hours of recovery (approximate)
① Water sample taken after 100 minutes of pumping
Chemical type of groundwater
Total dissolved solids in ppm
Water temperature in degrees centigrade
Na + K
Mg
Ca or Ca + Mg
I:626:5
Cl
SO₄
HCO₃ + CO₃
100
50
0
50
100
Per cent
Cations
Anions

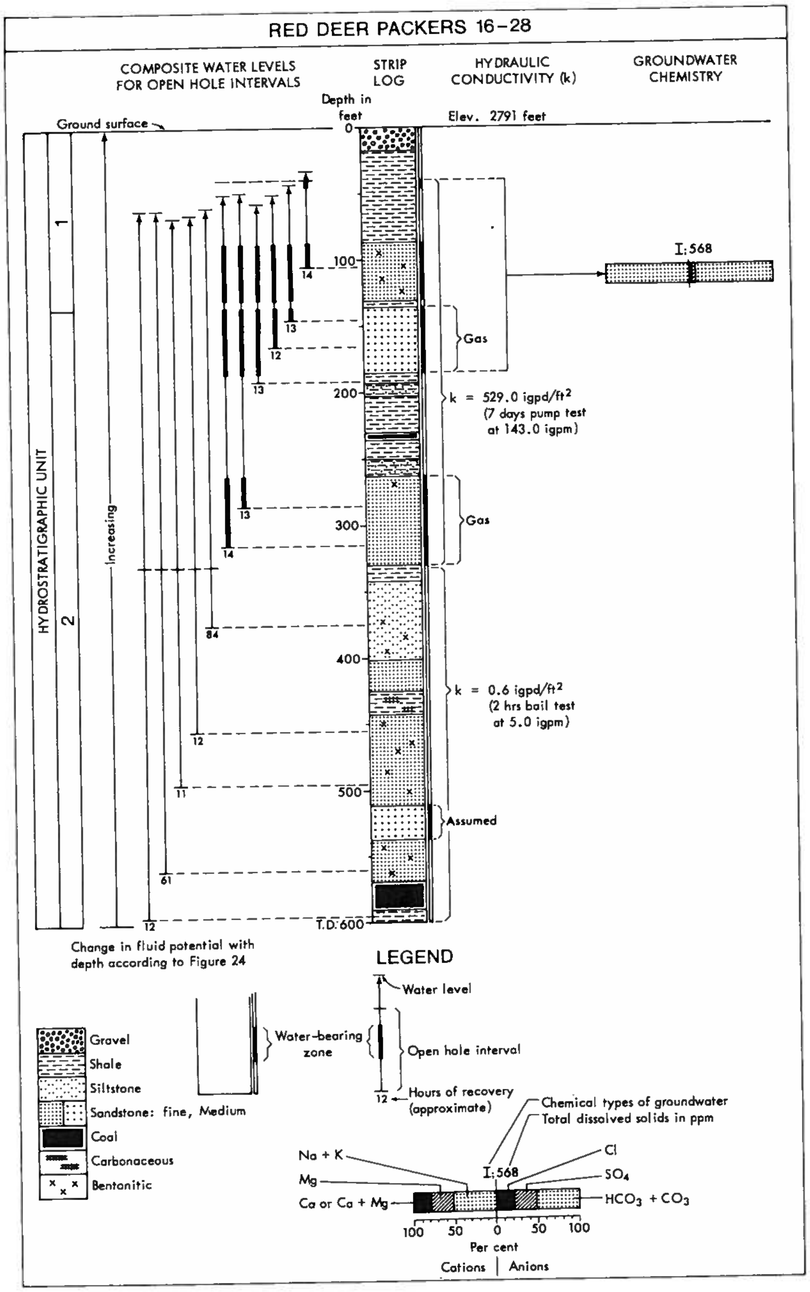

IRELAND 12-25
COMPOSITE WATER LEVELS FOR OPEN HOLE INTERVALS
STRIP LOG
HYDRAULIC CONDUCTIVITY (k)
GROUNDWATER CHEMISTRY
Depth in feet
Ground surface
Elev. 2930 feet
0
100
200
300
400
500
600
700
T.D. 775
HYDROSTRATIGRAPHIC UNIT
1
2
Decreasing
14
62
86
I; 800
I; 824
I; 944
I; 824 ①
I; 896
I; 788 ①
I; 972
Gas
k = 238.0 igpd/ft²
(2 hrs bail test at 13.0 igpm)
k = 8.4 igpd/ft²
(2 hrs bail test at 13.0 igpm)
k = 237.0 igpd/ft²
(1600 min pump test at 240.0 igpm)
Gas
Flow = 51 300 cfd
Temperature = 14°C
Change in fluid potential with depth according to Figure 24
LEGEND
Clay
Till
Sand
Gravel
Shale
Siltstone
Sandstone: fine, medium
Coal
Coaly
Calcareous
Bentonitic
Water-bearing zone
Water level
Open hole interval
Hours of recovery (approximate)
① Water sample taken after 2 hours of bailing
Chemical type of groundwater
Total dissolved solids in ppm
Na + K
Mg
Ca or Ca + Mg
I; 824
Cl
SO₄
HCO₃ + CO₃
100
50
0
50
100
Per cent
Cations | Anions

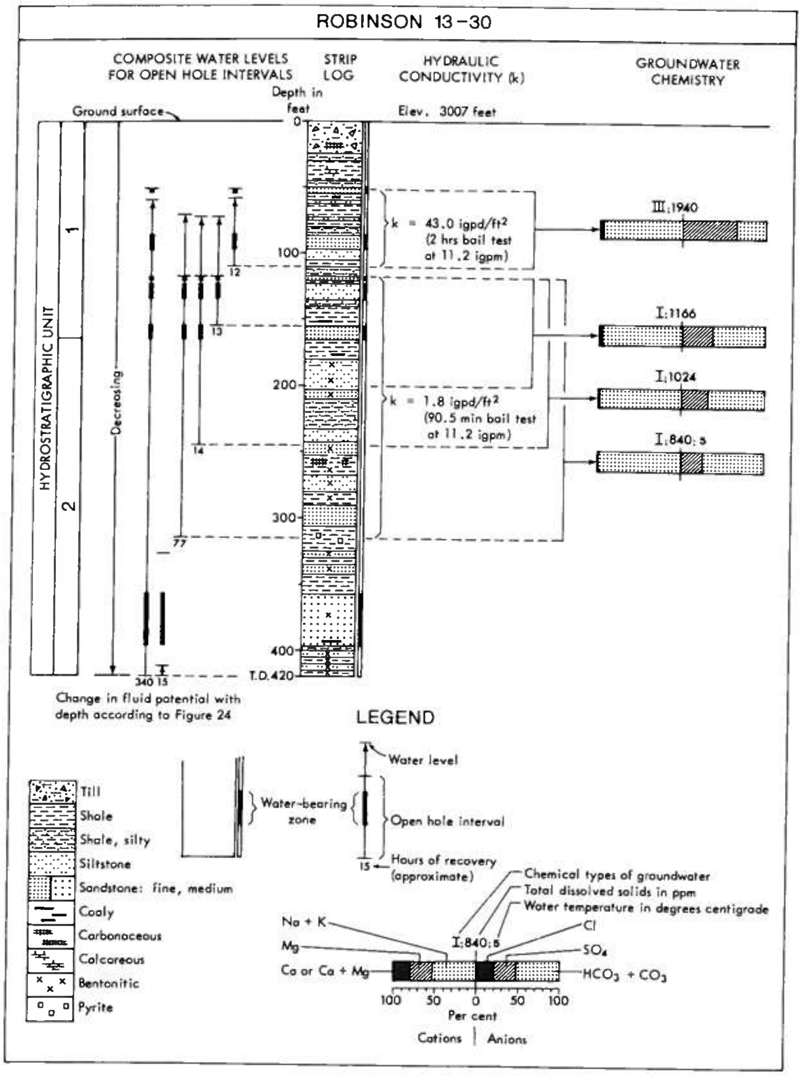

LONGACRE 5-33
COMPOSITE WATER LEVEL FOR OPEN HOLE INTERVAL
STRIP LOG
HYDRAULIC CONDUCTIVITY (k)
GROUNDWATER CHEMISTRY
Depth in feet
Ground surface
Elev. 2866 feet
0
100
200
T.D. 285
HYDROSTRATIGRAPHIC UNIT
1
2
Decreasing
Constant
22
k = 91.9 igpd/ft²
(2 hrs pump test at 11.0 igpm)
k = 428.0 igpd/ft²
(5 days pump test at 69.0 igpm)
Gas
I; 590; 5.6
①
Change in fluid potential with depth according to Figure 24
LEGEND
Clay
Silt
Till
Gravel
Shale
Siltstone
Sandstone: fine, medium
Carbonaceous
Water-bearing zone
Water level
Open hole interval
Hours of recovery (approximate)
22
① Water sample taken after 110 minutes of pumping
Chemical type of groundwater
Total dissolved solids in ppm
Water temperature in degrees centigrade
Na + K
Mg
Ca or Ca + Mg
I; 590; 5.6
Cl
SO₄
HCO₃ + CO₃
100
50
0
50
100
Per cent
Cations
Anions

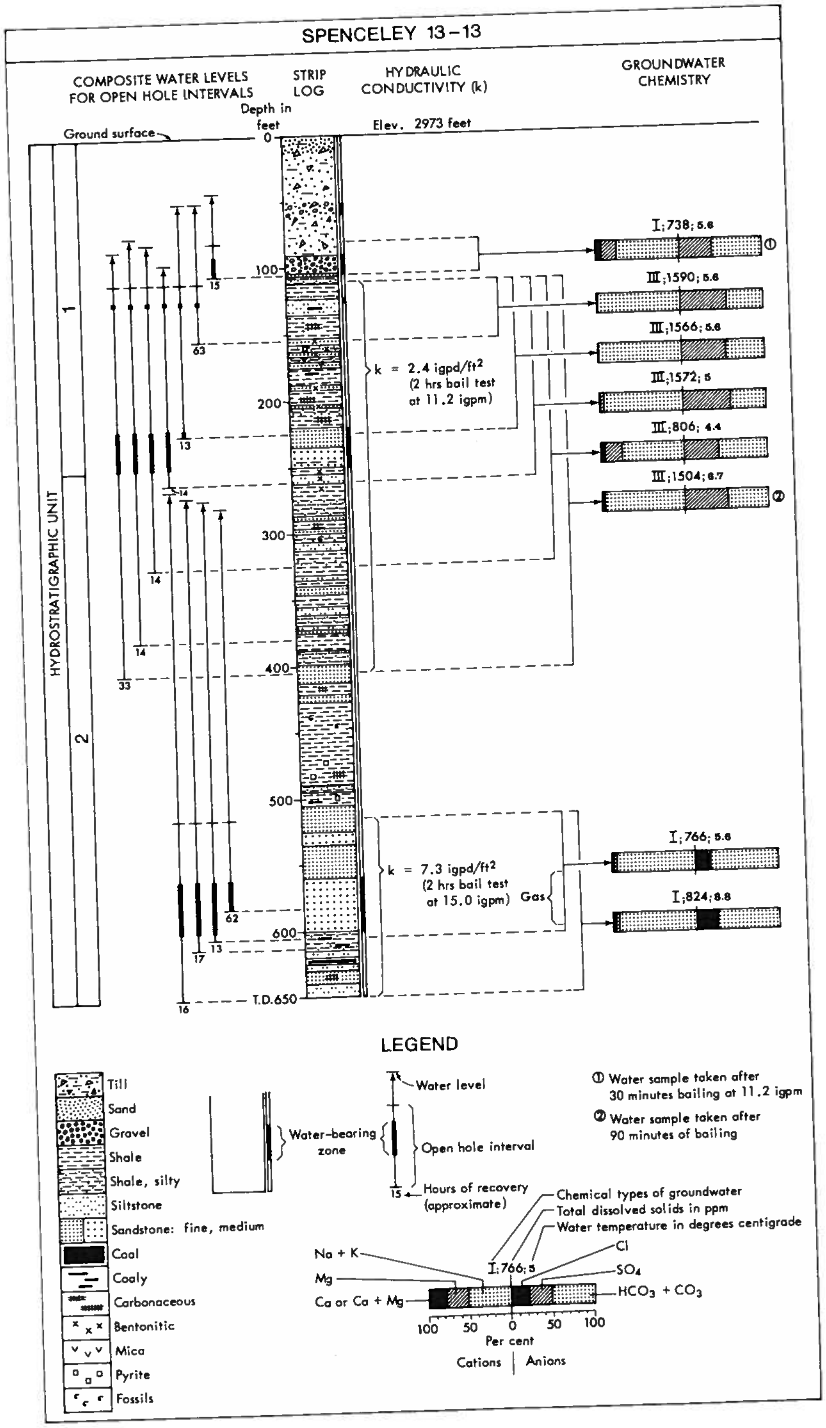

MORRISROE 1-18 No.1
COMPOSITE WATER LEVELS FOR OPEN HOLE INTERVALS
STRIP LOG
HYDRAULIC CONDUCTIVITY (k)
GROUNDWATER CHEMISTRY
Depth in feet
Ground surface
Elev. 3126 feet
0
100
200
300
400
500
600
T.D.700
HYDROSTRATIGRAPHIC UNIT
1
2
89
12
13
13
65
10
13
18
65
13
k = 76.1 igpd/ft²
(2 hrs bail test at 11.2 igpm)
k = 7.2 igpd/ft²
(2 hrs bail test at 11.0 igpm)
k = 30.0 igpd/ft²
(one week pump test at 10 igpm)
I; 1272; 5.6
I; 1140; 5.3 ①
I; 764; 5
I; 742; 5
I: 774; 5.6
I; 856; 6.7
I: 778; 10 ①
LEGEND
Clay
Till
Shale
Shale, silty
Siltstone
Sandstone: fine, medium
Coaly
Carbonaceous
Bentonitic
Pyrite
Fossils
Water-bearing zone
Water level
Open hole interval
13 Hours of recovery (approximate)
① Water sample taken after 105 minutes of bailing
Chemical type of groundwater
Total dissolved solids in ppm
Water temperature in degrees centigrade
Na + K
Mg
Ca or Ca + Mg
I; 764; 5
Cl
SO₄
HCO₃ + CO₃
100
50
0
50
100
Per cent
Cations
Anions

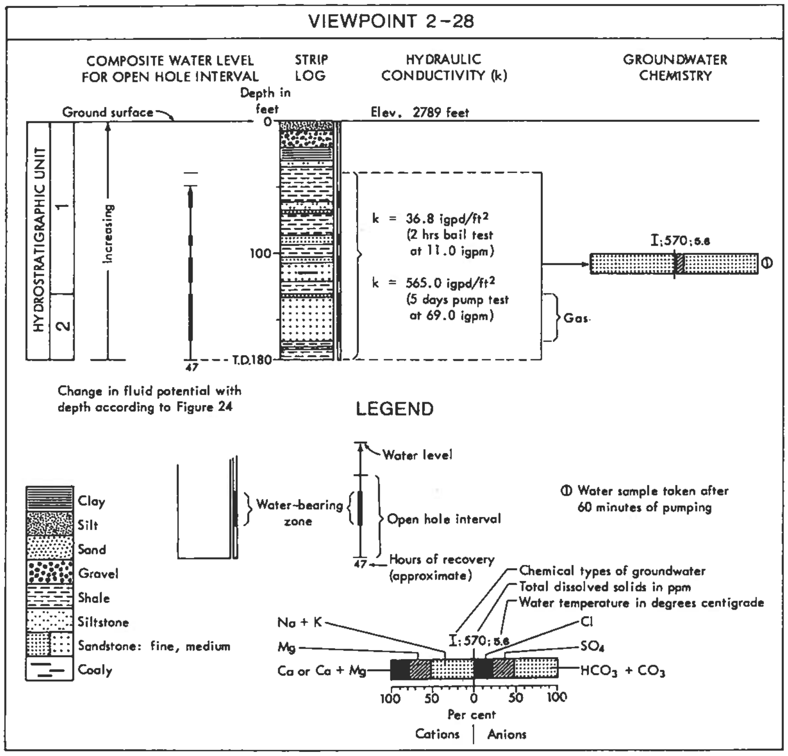

MORRISROE 1-18 No.2
COMPOSITE WATER LEVELS FOR OPEN HOLE INTERVALS
STRIP LOG
HYDRAULIC CONDUCTIVITY (k)
GROUNDWATER CHEMISTRY
Depth in feet
Ground surface
Elev. 3130 feet
0
100
200
300
400
500
600
T.D. 700
HYDROSTRATIGRAPHIC UNIT
1
2
14
42
18
64
14
14
14
19
16
15
k = 7.9 igpd/ft²
(2 hrs bail test at 15.0 igpm)
k = 1.0 igpd/ft²
(bailed dry in 85 min at 10.0 igpm)
k = 6.5 igpd/ft²
(2 hrs bail test at 10.4 igpm)
k = 15.0 igpd/ft²
(one week pump test at 10.0 igpm)
I;460;4.4
I;644;4.4
I;856 ①
I;1198;5
I;750;5
I;866;5.8
I;720;10.8 ②
LEGEND
Clay
Till
Shale
Shale, silty
Siltstone
Sandstone: fine, medium
Coaly
Bentonitic
Water-bearing zone
Water level
Open hole interval
Hours of recovery (approximate)
16
① Water sample taken after 2 hours pumping at 15.0 igpm
② Water sample taken after 4 days pumping at 10.0 igpm
Chemical type of groundwater
Total dissolved solids in ppm
Water temperature in degrees centigrade
I;750;5
Na + K
Mg
Ca or Ca + Mg
Cl
SO₄
HCO₃ + CO₃
100 50 0 50 100
Per cent
Cations | Anions

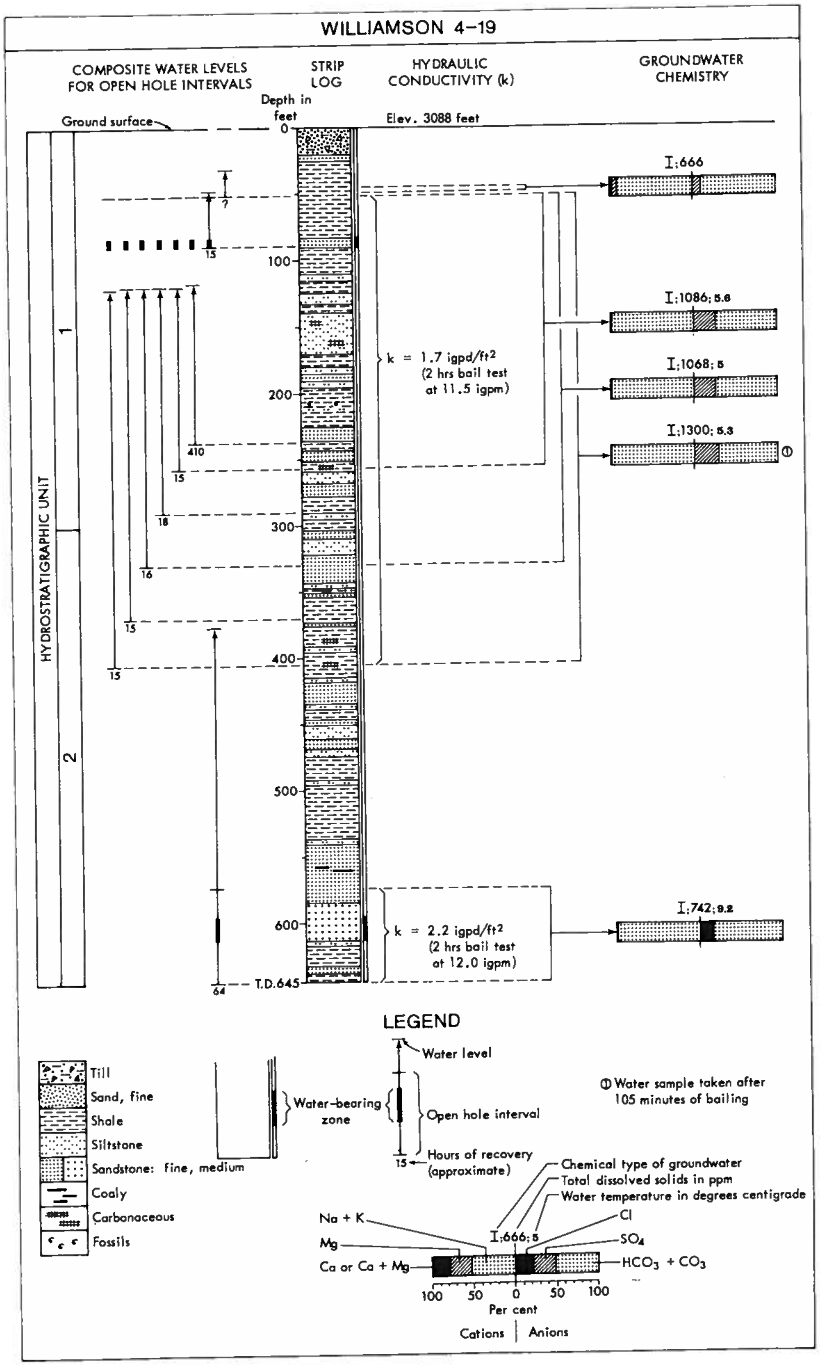

RED DEER 8-15
COMPOSITE WATER LEVELS FOR OPEN HOLE INTERVALS
STRIP LOG
HYDRAULIC CONDUCTIVITY (k)
GROUNDWATER CHEMISTRY
Depth in feet
Ground surface
Elev. 2910 feet
0
100
200
300
T.D. 325
HYDROSTRATIGRAPHIC UNIT
1
2
14
14
16
19
k = 3.2 igpd/ft²
(24 min bail test at 13.0 igpm)
k = 2.8 igpd/ft²
(2 hrs bail test at 13.0 igpm)
I:984
I:620 ①
III:1242
I:700 ②
LEGEND
Clay
Sand: fine, medium
Gravel
Shale
Shale, silty
Siltstone
Sandstone: fine
Bentonitic
Calcareous
Water-bearing zone
Water level
Open hole interval
16
Hours of recovery (approximate)
① Water sample taken after 24 minutes of bailing
② Water sample taken after 2 hours of bailing
Chemical types of groundwater
Total dissolved solids in ppm
Na + K
Mg
Ca or Ca + Mg
I:984
Cl
SO4
HCO3 + CO3
100
50
0
50
100
Per cent
Cations
Anions


RED DEER PACKERS 16-28
COMPOSITE WATER LEVELS FOR OPEN HOLE INTERVALS
STRIP LOG
HYDRAULIC CONDUCTIVITY (k)
GROUNDWATER CHEMISTRY
Depth in feet
Ground surface
Elev. 2791 feet
0
100
200
300
400
500
T.D. 600
HYDROSTRATIGRAPHIC UNIT
1
2
Increasing
14
13
12
13
13
14
84
12
11
61
12
I; 568
Gas
k = 529.0 igpd/ft²
(7 days pump test at 143.0 igpm)
Gas
k = 0.6 igpd/ft²
(2 hrs bail test at 5.0 igpm)
Assumed
Change in fluid potential with depth according to Figure 24
LEGEND
Water level
Water-bearing zone
Open hole interval
12
Hours of recovery (approximate)
Gravel
Shale
Siltstone
Sandstone: fine, Medium
Coal
Carbonaceous
Bentonitic
Chemical types of groundwater
Total dissolved solids in ppm
Na + K
Mg
Ca or Ca + Mg
I; 568
Cl
SO₄
HCO₃ + CO₃
100
50
0
50
100
Per cent
Cations
Anions


ROBINSON 13-30
COMPOSITE WATER LEVELS FOR OPEN HOLE INTERVALS
STRIP LOG
HYDRAULIC CONDUCTIVITY (k)
GROUNDWATER CHEMISTRY
Depth in feet
Ground surface
Elev. 3007 feet
0
100
200
300
400
T.D. 420
HYDROSTRATIGRAPHIC UNIT
1
2
Decreasing
12
13
14
77
340
15
k = 43.0 igpd/ft²
(2 hrs bail test at 11.2 igpm)
k = 1.8 igpd/ft²
(90.5 min bail test at 11.2 igpm)
III;1940
I;1166
I;1024
I;840;5
Change in fluid potential with depth according to Figure 24
LEGEND
Till
Shale
Shale, silty
Siltstone
Sandstone: fine, medium
Coaly
Carbonaceous
Calcareous
Bentonitic
Pyrite
Water-bearing zone
Water level
Open hole interval
Hours of recovery (approximate)
15
Chemical types of groundwater
Total dissolved solids in ppm
Water temperature in degrees centigrade
Na + K
Mg
Ca or Ca + Mg
I;840;5
Cl
SO₄
HCO₃ + CO₃
100
50
0
50
100
Per cent
Cations
Anions


SPENCELEY 13-13
COMPOSITE WATER LEVELS FOR OPEN HOLE INTERVALS
STRIP LOG
HYDRAULIC CONDUCTIVITY (k)
GROUNDWATER CHEMISTRY
Depth in feet
Ground surface
Elev. 2973 feet
0
100
200
300
400
500
600
T.D.650
HYDROSTRATIGRAPHIC UNIT
1
2
15
63
13
14
14
14
33
62
13
17
16
k = 2.4 igpd/ft²
(2 hrs bail test at 11.2 igpm)
k = 7.3 igpd/ft²
(2 hrs bail test at 15.0 igpm)
Gas
I;738;5.6 ①
III;1590;5.6
III;1566;5.6
III;1572;5
III;806;4.4
III;1504;6.7 ②
I;766;5.6
I;824;8.8
LEGEND
Till
Sand
Gravel
Shale
Shale, silty
Siltstone
Sandstone: fine, medium
Coal
Coaly
Carbonaceous
Bentonitic
Mica
Pyrite
Fossils
Water-bearing zone
Water level
Open hole interval
Hours of recovery (approximate)
15
① Water sample taken after 30 minutes bailing at 11.2 igpm
② Water sample taken after 90 minutes of bailing
Chemical types of groundwater
Total dissolved solids in ppm
Water temperature in degrees centigrade
I;766;5
Na + K
Mg
Ca or Ca + Mg
Cl
SO₄
HCO₃ + CO₃
100
50
0
50
100
Per cent
Cations
Anions


VIEWPOINT 2-28
COMPOSITE WATER LEVEL FOR OPEN HOLE INTERVAL
STRIP LOG
HYDRAULIC CONDUCTIVITY (k)
GROUNDWATER CHEMISTRY
Depth in feet
Ground surface
0
Elev. 2789 feet
HYDROSTRATIGRAPHIC UNIT
1
2
Increasing
100
47
T.D.180
k = 36.8 igpd/ft²
(2 hrs bail test at 11.0 igpm)
k = 565.0 igpd/ft²
(5 days pump test at 69.0 igpm)
Gas
I;570;5.6
①
Change in fluid potential with depth according to Figure 24
LEGEND
Clay
Silt
Sand
Gravel
Shale
Siltstone
Sandstone: fine, medium
Coaly
Water-bearing zone
Water level
Open hole interval
47
Hours of recovery (approximate)
① Water sample taken after 60 minutes of pumping
Chemical types of groundwater
Total dissolved solids in ppm
Water temperature in degrees centigrade
I;570;5.6
Na + K
Mg
Ca or Ca + Mg
Cl
SO₄
HCO₃ + CO₃
100 50 0 50 100
Per cent
Cations
Anions


WILLIAMSON 4–19
COMPOSITE WATER LEVELS FOR OPEN HOLE INTERVALS
STRIP LOG
HYDRAULIC CONDUCTIVITY (k)
GROUNDWATER CHEMISTRY
Depth in feet
Ground surface
Elev. 3088 feet
0
100
200
300
400
500
600
T.D.645
HYDROSTRATIGRAPHIC UNIT
1
2
?
15
410
15
18
16
15
15
64
k = 1.7 igpd/ft²
(2 hrs bail test at 11.5 igpm)
k = 2.2 igpd/ft²
(2 hrs bail test at 12.0 igpm)
I;666
I;1086; 5.6
I;1068; 5
I;1300; 5.3 ①
I;742; 9.2
LEGEND
Till
Sand, fine
Shale
Siltstone
Sandstone: fine, medium
Coaly
Carbonaceous
Fossils
Water-bearing zone
Water level
Open hole interval
Hours of recovery (approximate)
15
① Water sample taken after 105 minutes of bailing
Chemical type of groundwater
Total dissolved solids in ppm
Water temperature in degrees centigrade
I;666; 5
Na + K
Mg
Ca or Ca + Mg
Cl
SO₄
HCO₃ + CO₃
100
50
0
50
100
Per cent
Cations
Anions