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A HYDROGEOLOGICAL STUDY OF THE THREE HILLS AREA, ALBERTA

by

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A Hydrogeological Study of the Three Hills Area, Alberta

ABSTRACT

A program of groundwater exploration, reconnaissance, and research was carried out in the Three Hills area in 1965 and 1966. The area of study covers 204 square miles of the rolling grass lands of the Central Alberta Plains, 50 miles east of the Rocky Mountain Foothills. Information concerning the geology and groundwater was obtained from geological reports, oil-company records, a water-well survey, and fifteen drilled and tested bore holes, providing an average density of points of various observations of approximately 1.5 per square mile.

The freshwater-bearing rocks consist of cross-bedded, interbedded, and lenticular, Upper Cretaceous argillaceous siltstones and sandstones of river channel and floodplain origin, overlain by a veneer of lacustrine and glacial clays and sands ranging from 0 to 110 feet in thickness. The strata dip westward at 15 ft/mi and hydrogeologic phenomena indicate the sporadic existence of east-west oriented minor faults.

A supply of potable groundwater of 45 gpm from two sites has been located for the Town of Three Hills, with an additional 65 gpm indicated but requiring further testing. The average, renewing potential of groundwater in the area is estimated to be between 20 and 60 gpm per square mile. The total dissolved solids content in the groundwaters ranges from approximately 400 ppm to over 10,000 ppm, the majority being in the range of 1000 to 2000 ppm. The most common type of water is sodium bicarbonate-sulfate. Water-storing and transmitting properties of the rocks are poor, generally permitting the development of only 0 to 5 gpm capacity wells. Development of wells with capacities of 5 to 50 gpm is possible only in isolated and irregularly distributed areas a few square miles in extent at most, while single wells with a sustained production of over 50 gpm can probably not be established.

Due to the heterogeneity of the rock formations, pumping-test data can not be interpreted by known standard methods. However, a combination of type-curve solutions and geological interpretation made possible the estimation of long-term safe yields of proposed permanent production wells. The transmissibility calculated from the early parts of the time-drawdown curves is believed to represent the aquifer into which the well is drilled, while values having transmissibility dimensions may be obtained from late portions of the pumping test, and are used for safe-yield calculations. Such a value is called "equivalent transmissibility", T_e, and is thought to be characteristic of the average water-transmitting properties of the entire rock volume traversed by the front of the cone of depression up to the time the field-data curve is used for calculation. On continued pumping, the successive values of T_e are expected to decrease approaching the average value of the basin transmissibility, thus that calculated from regional flow-system analyses.

In order to facilitate the analysis of regional groundwater flow a two-dimensional electric model has been designed, constructed, and applied. With the use of conducting paper and a multi-electrode arrangement, the distribution and intensity of the natural, hydraulic recharge and discharge become solutions rather than *a priori* imposed constraints of the flow problem. In a homogeneous geologic environment flow lines converge toward regions of steeply sloping water table regardless of whether these occur in areas of recharge or discharge. Abrupt changes of chemical quality of groundwater have been explained by the analysis of the electric cross sections.

The depth of intensive flow in the Three Hills area has been found to be a function of the topography. A correlation between rock permeability and flow intensity is suggested by assuming that a differential internal chemical and physical weathering is brought about by different intensities of groundwater flow. The possibility of reduction in the bentonites' swelling properties by exchanging portions of their sodium ions with the groundwater-transported calcium ions is postulated.

The area of study is divided into two, approximately equal parts: (1) an area of downward groundwater flow; and (2) an area of upward groundwater flow. The natural basin (dynamic reserves) is estimated to be 1.35 inches per year, or 9 per cent of the precipitation. The average velocity of groundwater flow is approximately 0.1 feet per day, and the average rock permeability in the basins is $4.5 \cdot 10^{-2}$ gpd/ft^2, or $3.10 \cdot 10^{-3}$ darcys.

INTRODUCTION

This report describes the results of an investigation for groundwater supplies in the Three Hills area of south-central Alberta. The area is located in the central Alberta Plains, near the western extremity of the Canadian Prairies. It is bounded by longitudes 113° and 113° 24′ west, and latitudes 51° 37′ and 51° 48′ north, comprising most of range 22, and the whole of ranges 23 and 24 west of the fourth meridian, in townships 31 and 32 (Fig. 1). It covers 204 square miles, being situated within a triangular area with three major municipalities (Red Deer, Calgary, and Drumheller) situated at the points. The principal settlement within the area is Three Hills, a farming community, which together with the contiguous Prairie Bible Institute has a population of 2,500.

Purpose of Investigation

The purpose of the study was threefold: (1) to locate additional supplies of groundwater for the town of Three Hills; (2) to produce an evaluation of the groundwater resources in the Three Hills area; and (3) to search for new ways of widening the scope of groundwater investigations, and to advance the knowledge of the hydrogeologic aspects of continental sediments in Alberta.

The finding of new reserves of groundwater had been necessitated by the progressively increasing water use of the town, combined with gradually declining pumping levels at the existing supply wells, and by the fact

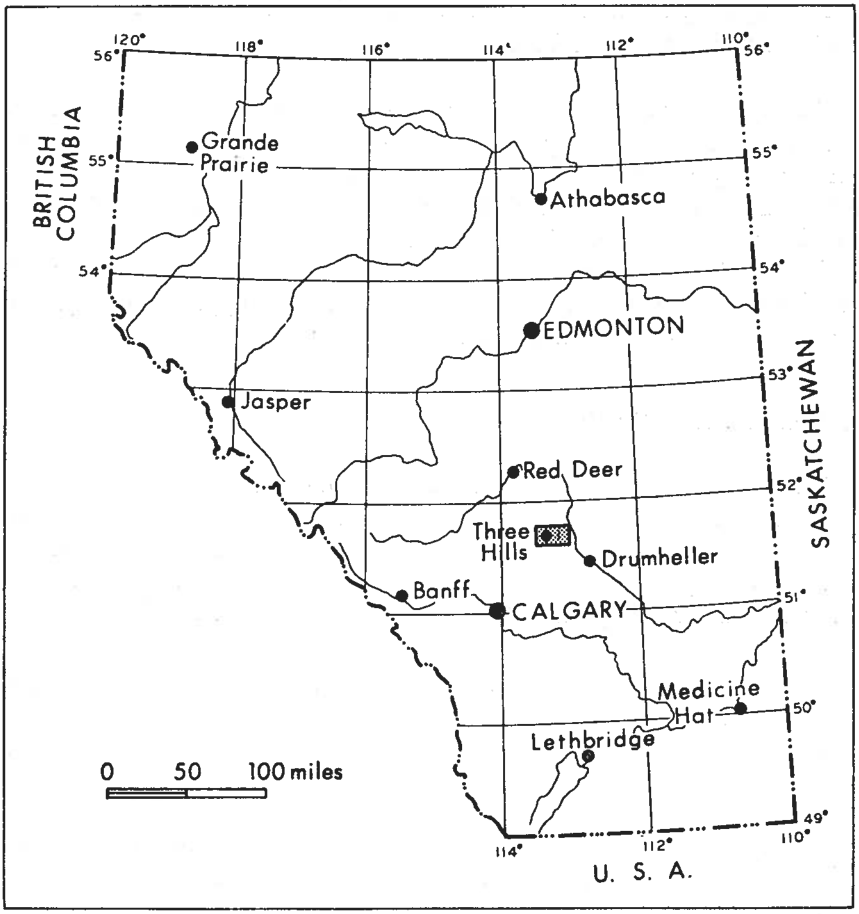


FIGURE 1. Location of the Three Hills area.

that the costs of obtaining water from surface sources would have been prohibitive to the town under the prevailing technical and economic circumstances.

An areal evaluation of the groundwater resources, chiefly consisting of estimates regarding the general distribution of groundwater and its rates of movement and replenishment, is desirable from the point of view of further economic development of the area. Expansion of municipal and private water-withdrawal facilities and future exploration can be made more efficient if they are based on a comprehensive, albeit general, knowledge of the water resources in the area. Also, the general picture obtained for the Three Hills area is intended as a major step towards the completion of an integrated study of the groundwater hydrology of central Alberta, initiated by the writer in 1962.

The third goal of the study was to determine from the results of a detailed drilling and testing program the hydrologic properties associated with typically lensing, detrital strata of the Three Hills area. These or similar strata, long considered to be relatively poor sources of potable groundwater, underlie much of the Alberta Plains, and it was hoped that the detailed investigation of these rocks at Three Hills would lead to the formulation of techniques and principles generally applicable to groundwater investigations elsewhere in central Alberta.

Scope of the Investigation

The Three Hills investigation can be divided into four major phases: (1) compilation and preliminary evaluation of existing information obtained from various sources; (2) procurement of information specifically for the present purposes; (3) development and application of an electrical analog model; and (4) analysis and evaluation of the results.

The type of information referred to under (1) consists of geological reports, lithologic samples and electric logs of deep oil and gas wells, core descriptions and electric logs of shallow structure test holes; and drillers' logs of seismic shot holes. Information oriented specifically to the requirements of the present program comprise the results of a survey of district farm wells including water-level measurements and chemical analyses of well waters; the drilling, sampling, and bail testing of 15 test holes; the results of three major pump tests each of one week duration, and a pump test of one of the town's old wells for four days; records of water levels and discharge for the town's supply wells since 1954; monthly water-level measurements in seven observation wells for certain periods between 1962 and 1966; stream-stage records for Ghostpine Creek and Threehills Creek at four gauging stations between 1962 and 1966; and meteorological information for the area of study. An electrical analog model has been developed and used for the purpose of analyzing the regional flow of groundwater in the area.

Previous Work

A water-well survey was carried out by Stalker (1953) in a portion of central Alberta including the present study area. His report contains valuable information on the regional availability of groundwater for farm supplies and also some interesting remarks and suggestions regarding the regional occurrence of groundwater. Stalker (1956, 1961) has also mapped the surficial geology and the bedrock valleys in that general area.

Among other authors who have studied various aspects of the local geology are Sanderson (1931), Allen and Sanderson (1945), Sternberg (1947), Ower (1960), and Campbell (1962, 1965). With the exception of Stalker's (1953) publication, little or no attention has been paid to the hydrologic aspects of the local geologic formations and to the groundwater resources of the area.

History of Groundwater Investigations in the Three Hills Area

The only systematic investigation of the area's groundwater resources prior to the present program was conducted by Stalker (1953). From a survey of farm wells, with an average density of approximately 0.6 wells per square mile, he gave a summarized description of groundwater availability against a geologic background for each township. This information was provided in terms of reported depths and yields, water quality, and expected construction costs of farm wells.

The only area with a somewhat concentrated withdrawal of groundwater is a narrow strip of land approximately 2.5 mi long between the SE ¼ of Sec. 27, Tp. 31, R. 24, W. 4th Mer., and Three Hills. It stretches along the main water line and water has been produced there since 1948 for the town. In this area seven holes were drilled in 1947, three of which were completed as water wells. Another well was drilled in 1955, and one more production well resulted from the drilling of three test holes in 1960. In 1964 the average combined production of the five wells then in use was 122,500 gpd (85 gpm)*, or approximately 49 gpd per capita.

Although this amount of water satisfied the needs of the town, farsighted municipal officials decided in 1964 upon a major exploration program in order to obtain a comprehensive picture of the area's groundwater potential, as well as to increase the actual production. During the summer of 1965 the Research Council of Alberta carried out a systematic well survey in the area, which was followed by a test-drilling program in the winter of 1965-66. Out of the 15 test holes and observation wells drilled during this program, four may be completed immediately as production wells with a combined yield of 160,000 gpd (110 gpm) for 20 years. In addition, specific areas with good groundwater potential, although with poor water quality locally, have been indicated. Presently (April, 1967), town

*Imperial gallons are used throughout this Bulletin.

officials plan the completion of two of the test holes as permanent production wells. The two new wells are expected to increase the town's water-supply potential by 65,000 gpd (45 gpm), or by approximately 50 per cent of its present potential.

Acknowledgements

The costs of the actual operation, including drilling, testing, and land survey were born by the Town of Three Hills, whereas the Research Council of Alberta provided the professional and technical services, including field and office work, and the preparation of the report.

The author wishes to acknowledge the kind co-operation of the Three Hills town council in providing good records of water consumption for past years, and in helping with test-site arrangements. Chemical analyses of water samples were carried out by the Provincial Laboratory under the direction of the late Mr. E. C. Noble. Mr. R. J. Clissold, geological assistant, carried out the well survey. Mr. R. Forrester, water well contractor, and his drillers (Messrs. E. Kind, R. Loewen, and A. Mottus) are to be complimented for their excellent technical know-how and resourcefulness, and for their usual enthusiasm and ready co-operation. The Drumheller Health Unit kindly helped with the collection of water samples. The design and construction of the power supply, potential divider, and precision voltmeter are by Mr. P. Noel of Research Electronics Co. Ltd., Edmonton.

GEOGRAPHY

Town of Three Hills

The main part of Three Hills is located in the northeast quarter of Sec. 36, Tp. 31, R. 24, W. 4th Mer., at an altitude of 2,939 feet, at longitude 113° 15′ 30″ west and latitude 51° 42′ 30″ north. Subdivisions of the settlement, including the constitutionally independent Prairie Bible Institute, are situated in adjacent quarter sections. The total population was 2,500 in January, 1967. The main livelihood of the people is farming, commerce, and services. Former coal mines in the district have been closed.

Topography

The topography of the general area is dominated by the broad valleys of Threehills ad Ghostpine Creeks, in the wide, flat bottoms of which, narrow, well-defined stream channels meander. The valleys run nearly parallel to each other from northwest to southeast across the west and east thirds of the area (Fig. 2). This parallelism prevails also between other streams situated to the west and east, beyond the boundaries of the study area. Pronounced northwest-southeast striking ridges form the water divides between these valleys. One of the most prominent of these elevated areas comprises the "Three Hills", approximately three miles due north of the town of the same name. This is the region of maximum topographic elevation within the area of study, reaching to approximately 3,180 feet; the lowest altitude of approximately 2,500 feet is found in the south and east where Ghostpine Creek leaves the area. The high and regular hill ranges are subdivided by deeply incised tributaries of both main streams. The general direction of these tributaries is east-west, and they all have well-defined, minor gullies striking at right angles to them. This distinct drainage pattern gives the area a broadly undulating, dynamic appearance.

A general feature of the valleys is that their west-facing flanks are slightly steeper than their east-facing flanks, the slopes, measured between the major divides and valley bottoms, averaging approximately 90 ft/mi (0.017 ft/ft) and 82 ft/mi (0.0155 ft/ft), respectively. Extensive level areas are found locally on the flood plains of the main streams, and on some of the high plateaus between major tributaries. In addition to the locally subvertical stream banks, slopes as steep as 400 ft/mi (0.08 ft/ft) are found on some of the major hills.

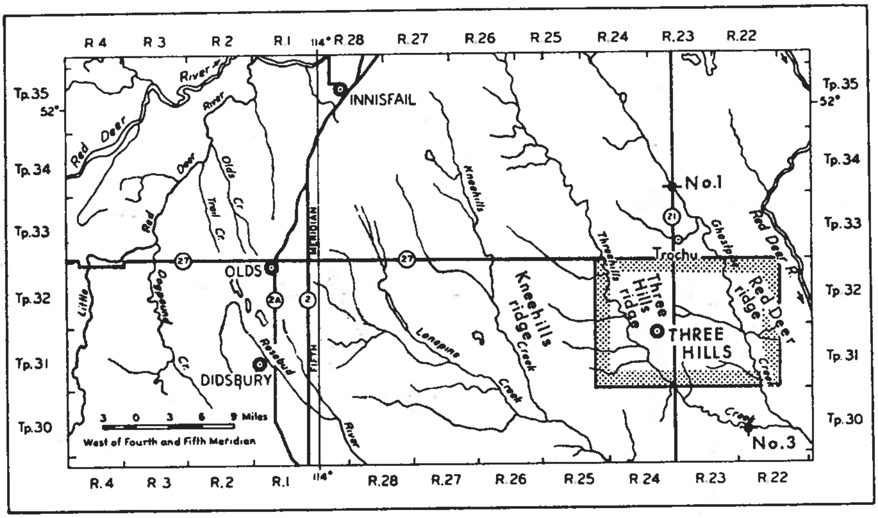


FIGURE 2. Map showing surface drainage and locations of steam-gauge stations.

An important topographic feature, the deeply incised valley of the Red Deer River, the flanks of which drop over 500 ft/mi in places, lies a few miles east of the eastern boundary of the study area (Fig. 2).

Drainage

The area is well drained by the highly developed network of tributaries. No impounded bodies of stagnant surface water are known to occur in the area. The numerous short, steep, and straight gullies, which are dry except during and immediately after rain, quickly collect and convey snow melt and rain water to the two major drainage ways of the area: Ghostpine and Threehills Creeks. Beyond their confluence, a few miles south of the area, the waters of both streams enter the Red Deer River.

The efficiency of the drainage system results in variable discharge in both major creeks. Major summer storms cause flash floods. The estimated maximum value of discharge on both Ghostpine and Threehills Creeks is 3,000 cfs, whereas their flows often reduce to nil for parts of the summers (personal communication from Mr. R. K. Deeprose, Water Resources Division, Department of Agriculture, Government of Alberta). The average yearly discharge of each of the two main creeks is estimated at 7,000 acre-feet. The streams are frozen to the bottom during the winters, except at places where water may collect in deep, natural hollows in the stream beds or at dams made by man or beavers. The fact that during the long periods of frost and drought there is no perceptible flow in the streams strongly suggests that contribution from groundwater to river discharge (base flow) is negligible.

Climate and Vegetation

According to Koeppen's system of classification, the climate in the Three Hills area is designated by Dfb, i.e. a cold, humid, continental region. The meaning of the Koeppen letter-symbols may be summarized as follows: "D" — microthermal climate, average temperature of coldest month below 26.6°F (-3°C), average temperature of warmest month above 50°F (10°C), region characterized by frozen ground and snow cover of several months' duration each year; "f" — no dry season; "b" — cool summer, average temperature of warmest month under 71.6°F (22°C). Further details of the climate may be found in table 1.

Originally the Three Hills area had a typical prairie grassland vegetation. The native vegetation can hardly be recognized now due to the changes brought about by extensive crop farming. A growth of several species of rushes (*Juncus*), sedges (*Scirpus*), and cattails (*Typha*), as well as alkali-tolerant, poorly developed pasture grass are found on the floodplains of the major streams. Patches of spruce, poplar, willow, and flowering shrubs are localized around farms and stream trenches; otherwise the area is treeless. Major crops grown are wheat, rye, and barley.

System of Numbering, Location, and Elevation of Observations Points

Owing to the variety of the sources from which information has been obtained, a master system of observation points had to be adopted. In this report reference is made to any individual observation point by "Three Hills Well No.". This system includes public and private water-supply wells, springs, seismic shot holes, structure test-holes, and oil and gas wells (Fig. 3).

TABLE 1. SUMMARY OF CLIMATOLOGICAL INFORMATION FOR THE THREE HILLS AREA

Monthly and Annual Averages of Temperature for Three Hills, 13 km (8 miles) south of Trochu. (Based on 30-year record between 1931 and 1960).

		Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Year
Mean	F°	5.7	9.4	20.7	38.5	50.4	56.5	62.5	59.0	50.4	39.1	23.2	13.1	35.7
	C°	−14.6	−12.5	−6.3	3.6	10.2	13.6	16.9	15.0	10.2	3.9	−4.9	−10.5	2.1
Mean maximum	F°	17.8	22.1	32.7	52.5	65.9	70.8	78.5	74.9	65.6	54.2	35.4	24.8	49.6
	C°	−7.9	−5.5	+0.4	11.4	18.8	21.6	25.8	23.8	18.7	12.3	1.9	−4.0	9.8
Mean minimum	F°	−6.4	−3.3	8.6	24.5	34.9	42.1	46.4	43.1	35.1	24.0	10.9	1.4	24.8
	C°	−21.4	−19.6	−13.0	−4.2	1.6	5.6	8.0	6.2	1.7	−4.4	−11.7	−17.0	−4.0

Extreme Monthly Temperatures for Trochu-Equity, 5 km (3 miles) south of Trochu, between 1955 and 1963.

		Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
Maximum	F°	48	54	66	82	89	92	96	96	91	84	67	55
	C°	8.8	12.2	18.8	27.7	31.7	33.3	35.5	35.5	32.8	28.8	19.4	12.7
Minimum	F°	−30	−33	−26	1	15	33	36	35	15	−2	−22	−40
	C°	−34.7	−35.0	−32.2	−17.2	−9.4	0.5	2.2	1.6	−9.4	−18.9	−30	−40

Monthly and Annual Averages of Precipitation for Three Hills. (Based on 30 years of records between 1921 and 1950).

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Year
inch	0.34	0.50	0.62	0.85	1.63	3.02	2.16	1.91	1.25	0.86	0.56	0.38	14.35
mm	8.6	12.7	15.7	21.6	41.4	76.7	54.9	48.5	38.6	21.8	14.2	9.6	364

Extreme Lengths of the Frost-Free Period, and of the Period between Last Killing Frost in the Spring and the First Killing Frost in the Fall, for Trochu-Equity, between 1955 and 1963.

	Shortest			Longest		
	Year	Period	Length in days	Year	Period	Length in days
Frost-free	1955	May 31-Sept. 9	100	1958	May 2-Sept. 21	141
Between killing frost	1955	May 7-Sept. 10	125	1963	May 4-Oct. 19	157

Dates of Last Frost and Killing Frost in Spring, and of First Frost and Killing Frost in Fall, for Trochu-Equity, between 1955 and 1963.

		Last, in Spring	First, in Fall
Frost 32°F (0°C)	earliest	May 2	September 3
	latest	May 31	October 9
Killing frost 28°F (−2.2°C)	earliest	April 26	September 8
	latest	May 23	October 19

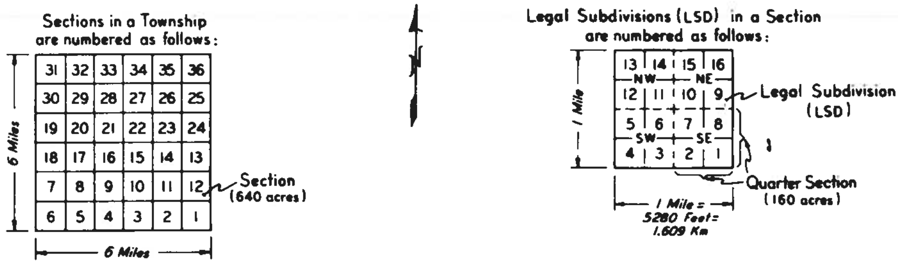


FIGURE 4. System and terminology of the land survey units in Alberta.

Locations of observation points are given either as the smallest land-survey unit of the area within which the point is known to be situated, or with reference to the corner of a land-survey unit. According to the system of land survey in the Province of Alberta, a "Township" (Tp.) is an area of 6 miles square, containing 36 sections, each 1 mile square (Fig. 4). A "Section" (Sec.) is divided into 16 "Legal Subdivisions" (Lsd.). The location of a well is often not known beyond the "quarter section" (¼) level.

Townships are numbered northward from the International Boundary with the United States (forty-ninth parallel). Ranges are numbered westward from each principal meridian (Mer.). The fourth meridian is 110° 00′ longitude west of Greenwich; fifth meridian at 114° 00′; and sixth meridian at 118° 00′.

Topographic elevations are expressed in feet above mean sea level. Elevations for the observation points have either been surveyed or estimated from a base-map with 25-foot contours.

GEOLOGY

Scope and Techniques

The geological investigations in the Three Hills area have been confined to providing the necessary information for: (1) the assessment of the general resources of groundwater (distribution and balance of ground water, locations and depths of high permeability formations, chemical quality); (2) the evaluation of geologic control on groundwater at sites of prospective production wells; and (3) obtaining an insight into those physical and chemical properties of the Upper Cretaceous, Tertiary, Quaternary strata which fundamentally affect the type and nature of groundwater distribution and flow. Information available in the form of reports and raw data has been used to establish the geological background in general. This was supplemented by the results of test drilling conducted specifically to obtain details for the shallow, freshwater-bearing Upper Cretaceous and younger rocks. This drilling was carried out by two "22-W Bucyrus-Erie" cable tool drilling rigs. The depths of the test holes varied between 130 and 735 feet. Drill cuttings, taken at 5-foot intervals, were washed, dried, and described at the test site. The lithologic logs are presented in Appendix C. A more detailed account of the applied sampling technique is given in a previous report on a similar project (Tóth, 1966, p. 19).

Stratigraphy and Lithology

The area of study is located on the broad east flank of the Alberta Syncline, a region underlain by gently dipping strata of late Cretaceous and Tertiary ages. The thickness of strata to the Precambrian crystalline basement here is approximately 10,000 feet (McCrossan and Glaister, 1964).

The lowest geologic unit considered in this report is the combined Lea Park Formation — Colorado Group of late Cretaceous age (Fig. 5). This combination, for present purposes, is justified by the similarity of the lithologies of both formations, with the result that they may be considered uniform with respect to permeability and porosity. The group consists mainly of dark marine shales with some fine-grained, thin siltstone and sandstone beds and lenses, with a total thickness of approximately 2,000 feet. The depth below land surface to the top of the Lea Park Formation varies between 2,400 and 2,700 feet, corresponding to elevations above mean sea level of approximately 380 and 210 feet, respectively.

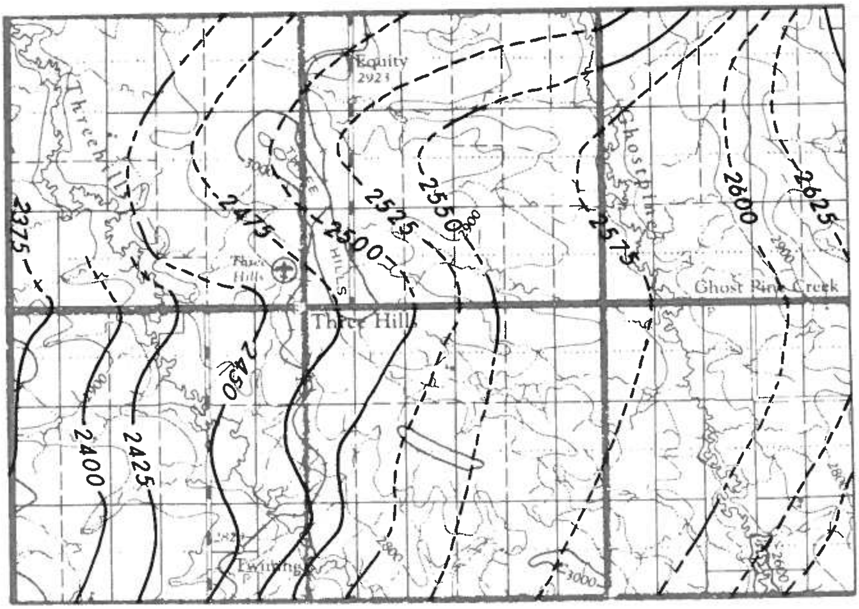
Age	Nomenclature	Formation	Thickness	Description
Recent	Drift	Alluvium	0-110	Unconsolidated glacial, lacustrine and fluvial clays, silts, sands, gravels, and boulders.
Pleistocene		Glacial deposits		
Paleocene	Bed-rock	Paskapoo	0-150	Poorly sorted continental, argillaceous, bentonitic, crossbedded, lenticular, slightly indurated siltstones, and sandstones; coal; volcanic tuff; clay ironstone.
Cretaceous		Edmonton	1000-1500	
		Bearpaw	300-500	Dark grey marine shale with thin bentonite and sandstone beds; ironstone nodules.
		Belly River	700-900	Alternating marine and continental, crossbedded, lenticular sandstones, siltstones; coal; ironstone.
		Lea Park	2000	Light to dark grey, silty marine shales, ironstone concretions, thin sandstone beds.
		Colorado		

FIGURE 5. Generalized stratigraphic section of the Upper Cretaceous and younger deposits in the Three Hills area.

The Lea Park-Colorado unit is overlain by a thick succession of predominantly continental deposits comprising grey, greenish-grey bentonitic siltstones and sandstones, dark grey, carbonaceous claystones, and coals of the Belly River, Bearpaw, Edmonton, and Paskapoo Formations, in ascending order. Intercalated among the coarser-grained, continental strata of the Belly River Formation are beds of dark marine shale and silty shale of brackish environment. However, a distinct marine formation in this succession is the Bearpaw Formation, consisting of dark shale which becomes silty and sandy upward, grading into the Edmonton Formation. The thickness of the Bearpaw Formation varies from 300 to 500 feet in the area.

The total thickness of this series, with the Bearpaw Formation included, is between 2,500 and 3,000 feet. The sandstones and siltstones are cross bedded, laminated, lenticular, and interbedded with shaley layers. Clay nodules, ironstone bands, marls, chert, and abundant coal also are common in these beds. The sandstones form an intricately interwoven network of old stream beds, whereas the shales presumably were interfluve sediments deposited in marshy, deltaic floodplains marginal to the late Cretaceous sea.

The important cementing material in the sandstones and siltstones is montmorillonite, with variable amounts of kaolinite in certain zones. These clay minerals have been derived from volcanic ash deposited simultaneously with non-volcanic detritus in late Cretaceous and early Tertiary times. Volcanic activity gave rise to the only significantly widespread stratigraphic marker bed in the Upper Cretaceous succession, a hard, siliceous, volcanic ash bed associated with a band of brownish-weathering, mauve-colored shale (Kneehills Tuff). Lithologic logs constructed from cores and cable-tool drill-cuttings, and plotted along sections G_1 — G_1' and G_2 —G_2' (Fig. 7) show the position and attitude of the Kneehills Tuff zone, as well as the lithologic character of the Upper Cretaceous continental deposits. More detailed lithologic descriptions of individual test holes are given in Appendix C. Mineable deposits of brown coal are common in the Upper Cretaceous and Paleocene rocks.



LEGEND

Contour on top of Kneehills Tuff Member; definite ———
assumed - - - - - -

FIGURE 6. Contour map of the Kneehills Tuff Member.

Structure contours constructed for the top of the Kneehills Tuff Member (Fig. 6) indicate a simple flexured structure, with a general westward dip of 15 ft/mi in the Upper Cretaceous rocks. The topographic surface, on the other hand, drops to the east, in general, resulting in a rapid decrease of the depth to the top of the Kneehills Tuff from west to east across the area.

Faults are not known to occur in the area. The hypothesis is advanced here, however, that local, east-west faulting may be responsible, at least partly, for the structure observed on the top of the Kneehills Tuff. Highly mineralized, shallow groundwater (Three Hills Well No. 148, with 11,960 ppm total dissolved solids), and steep, southward sloping, local hydraulic gradients (Fig. 10) are associated with the synclinal structure west of the town (Fig. 6). These phenomena could well be caused by the retarding effect of low-permeability, east-striking fault planes on the southward moving groundwater. Also, it is possible that the flowing well conditions found in Secs. 21-22, Tp. 32, R. 23, W. 4th Mer. and Sec. 8, Tp. 31, R. 23, W. 4th Mer. (Fig. 10) are generated by east-striking local faults. The direction and apparent size of the postulated faults are in good agreement with those of a demonstrated hydraulic barrier approximately 30 miles due east of Three Hills (Tóth, 1966, p. 24).

The term "drift", as used in this report, refers to the poorly consolidated deposits of clay, silt, sand, and gravel, or any mixture of these, overlying the bedrock. The material of the drift is composed mainly of Pleistocene till, outwash, lacustrine and morainic deposits, with minor amounts of Recent alluvium. The main lithologic component of the drift is clay, with relatively little sand. Claystone, siltstone, and sandstone derived from the bedrock and reworked by the ice are common and locally predominant in the drift, particularly in those parts close to the bedrock surface. Well-sorted gravels are not known to occur in the study area. In addition to material derived from local bedrock, the drift usually contains fragments of igneous and metamorphic rocks as well as limestones and transported sandstones.

The known thickness of drift within the study area varies between 0 and 110 feet. It is thinnest or absent on the top of the hills and attains the greatest thickness under the floors of Ghostpine and Threehills Creeks. The drift thickness at any location is the difference in elevation of the land surface and bedrock surface (Fig. 8).

The relief on the consolidated, poorly cemented Upper Cretaceous and Tertiary rocks, commonly referred to as "bedrock", closely reflects the present topograhic surface (Fig. 8), having been modified only slightly by Pleistocene glaciation. Both the two major valleys and the tributaries existed before deposition of the veneer of drift, which, being thickest in the valleys, has only served to locally de-accentuate the pre-Pleistocene topography.

Summary

For the purposes of this investigation, it is assumed that the rocks underlying the Three Hills area may be grouped into three comparatively uniform lithologic (and hydrologic) units. The lowest unit is the combined Lea Park-Colorado unit, consisting of approximately 2,000 feet of marine shales with presumably uniformly low porosity and permeability. The second unit consists of the overlying predominantly nonmarine, interbedded sandstones, siltstones, and shales with a total thickness of approximately 2,000 feet (Belly River to Paskapoo Formations). These rocks,

LEGEND

Bedrock contour —2900—

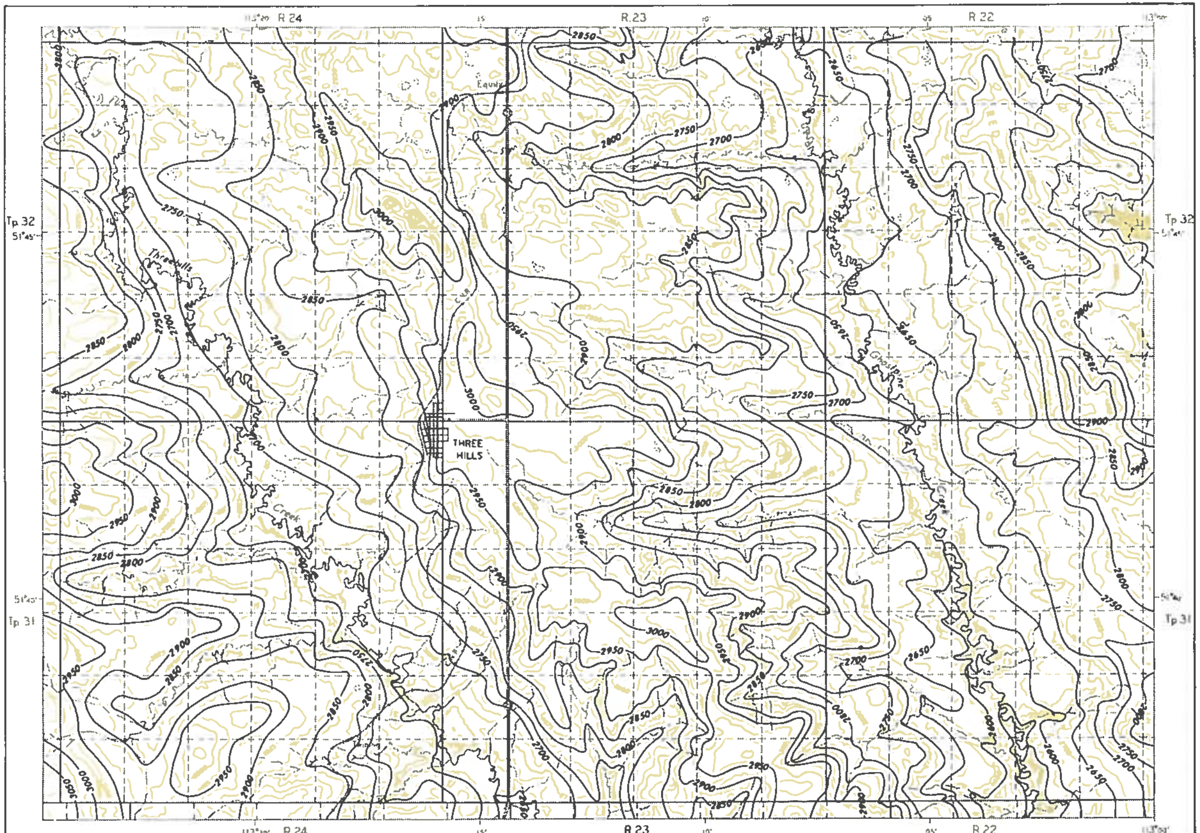


FIGURE 8.
Contour map showing elevations on the top of the bedrock.

although highly bentonitic and locally quite lenticular, show moderate porosities and permeabilities and provide the best potential for groundwater supplies in the Three Hills and adjacent areas. The third unit comprises the thin veneer of unconsolidated Pleistocene and Recent sediments which, owing to its erratic distribution and high clay content, has little potential as a source of groundwater.

The bedrock formations dip approximately 15 ft/mi to the west. The presence of moderate structure is evidenced by the contours of the top of the only reliable marker bed, the Kneehills Tuff. The possibility of local faulting within a depth of 200 feet is suggested by certain groundwater phenomena namely steep, local potential gradients, associated with flowing wells, and highly mineralized groundwater, the groundwater movement presumably being slowed down or blocked by the fault planes.

DISTRIBUTION AND NATURAL MOVEMENT OF GROUNDWATER

The Groundwater Regime and the Hydrogeologic Environment

Concepts

The groundwater regime is that aspect of a given geographic region which pertains to groundwater and related phenomena. It comprises the phenomena and the combined processes of distribution, chemistry, and motion of groundwater. Quantitatively, it is described by the amount in storage, rate of volume discharge, velocity and direction of movement, chemical quality, and temperature of groundwater at discrete locations, and by changes in these properties in time and space.

The groundwater regime is simultaneously controlled by three other aspects of the region, namely topography, geology, and climate. Together, these three aspects constitute the *hydrogeologic environment* of an area, or briefly, the environment for the groundwater regime. Owing to the fact that the environment and the groundwater regime have a unique and quantitative cause-and-effect relationship, a knowledge of the environment affords the construction of a realistic model of the groundwater regime, provided that the functional relation between the environment and regime is known. The three components of the environment may be stated in terms of: topographic relief (e.g. length and steepness of slopes; size and shape of depressions and prominences; distribution of valleys and ridges), physical and chemical properties of the rocks (e.g. type, magnitude, and distribution of porosity and permeability; degree of anisotropy; soluble mineral content), and climatic characteristics (e.g. amount, type, and seasonal apportionment of precipitation, potential evapotranspiration). Depending on the details to which the environment is known, a more or less accurate picture of the groundwater regime may be produced. However, even if only a qualitative analysis of the environment is feasible, information on the groundwater regime, useful for both practical and scientific purposes, may be procured (Popov, 1965; Sharov, 1965).

A general procedure for deducing the groudwater regime of a given area from the environment may be outlined as follows:

(1) information available on the actual environment is compiled for the purposes of a working hypothesis, and a model environment is constructed mathematically, electrically, mechanically, or by some other means;

(2) fluid present in the environment is represented and introduced into the model in the form of digits, electrical current, or some type of fluid;

(3) properties of the model fluid (controlled by the model environment) characterizing the fluid movement are calculated and measured;

(4) the degree of correctness of the obtained flow distribution is established by comparing the model solution with actual field data. It is important to realize that the validity of the model solution cannot be demonstrated with any greater degree of accuracy than that permitted by the actual field data.

Hydrogeologic Environment of the Three Hills Area

The three components of the hydrogeologic environment in the Three Hills area may be characterized as follows:

(1) topography (Figs. 2, 3, and 7):

(a) the land surface has a pronounced relief which is dominated by the valleys of three major subsequent streams and numerous minor tributaries, all having undulating flanks;

(b) the ratio of the slopes of the thalwegs to those of the valley flanks is generally low;

(c) the main tributaries strike at near right angles to the main stream valleys;

(d) the main streams and ridges are nearly parallel to each other;

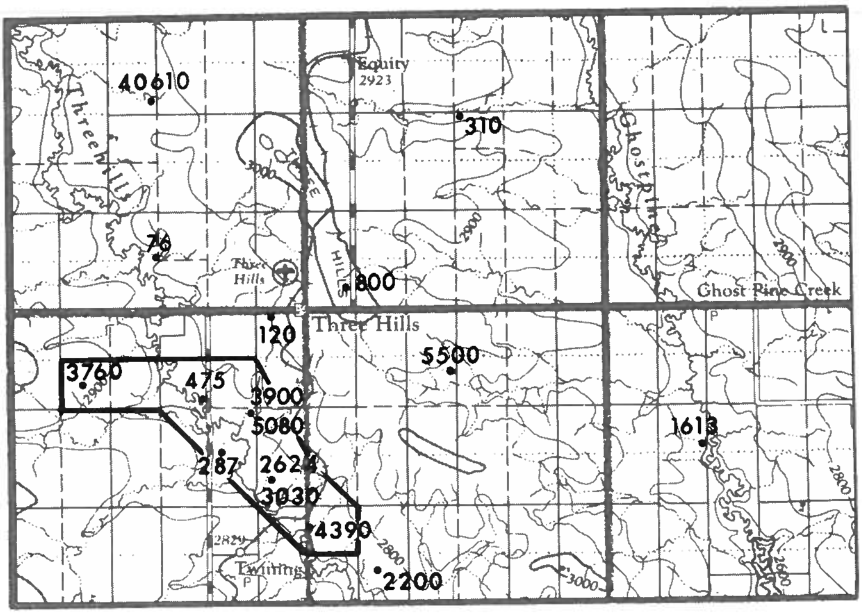
(e) the Red Deer River valley is several hundred feet deeper and lower than the other valleys;

(2) geology (Figs. 5, 7, 9, and Appendix B):

(a) the permeability of the rocks, at least to a depth of approximately 400 feet, is generally high enough to permit pumping at rates up to 100 gpm, and to maintain sustained yields up to 30 gpm;

(b) permeability and transmissibility of the rocks vary abruptly; values of high permeability are restricted to channel sands, sandstone lenses, drift-bedrock contact, and coal seams;

(c) below the top of the Lea Park-Colorado unit the permeability is generally lower than in the overlying formations;



LEGEND

Estimated value of transmissibility in gpd/ft 5500

Boundary of area to be reserved for town water-supply.....................

FIGURE 9. Map showing values of transmissibilities at test sites and area recommended to be reserved for town supply.

(d) the top soil and drift cover is sufficiently permeable for infiltration;

(e) the thick succession of Paleozoic and younger sediments is underlain at considerable depths by an impervious crystalline basement;

(3) climate (Table 1):

(a) there is enough precipitation to maintain the water table near the land surface (Fig. 10);

(b) the ground is frozen for a period of at least 5 months, from November through March.

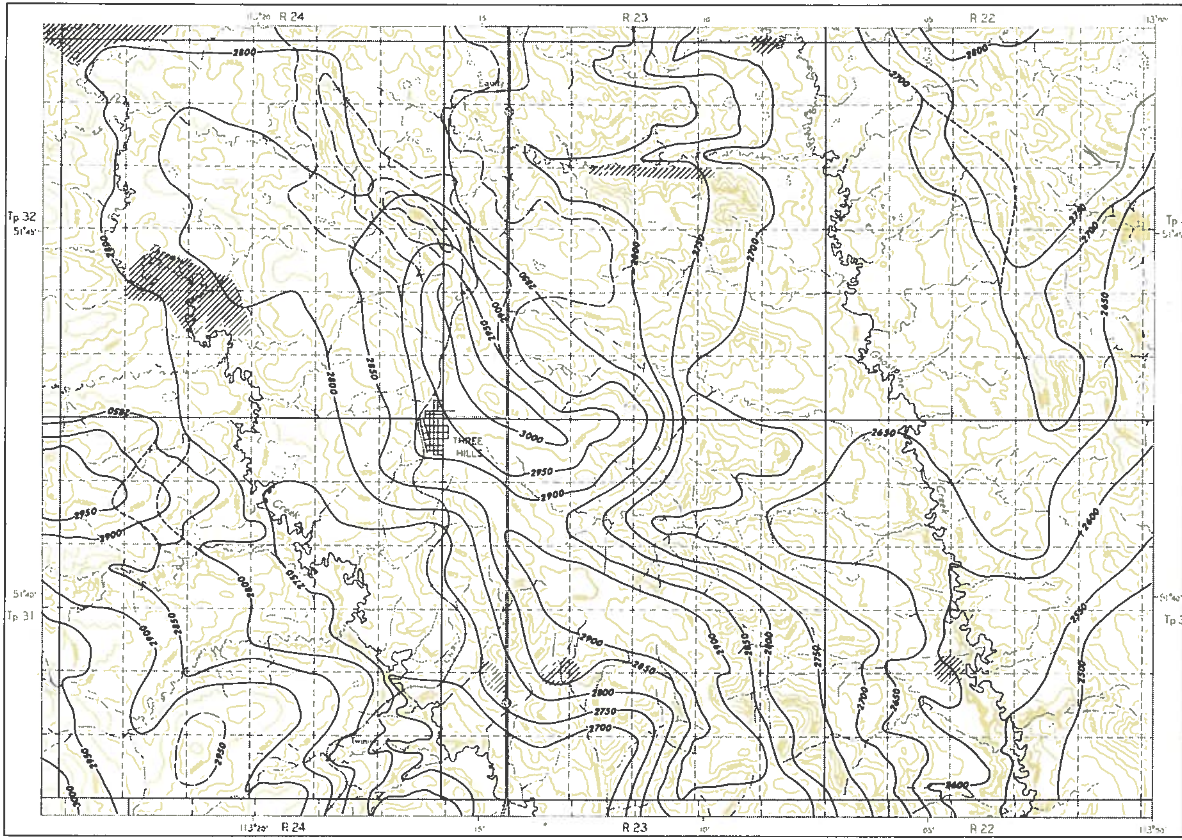


FIGURE 10.
Map showing non-pumping water levels.

Occurrence of Groundwater

The term "occurrence of groundwater" is used in this report to mean the physical presence of water in the rock pores, without giving consideration to the economy of its withdrawal for water-supply purposes.

Verbal reports and field observations indicate that water generally occurs to within 10 feet of the land surface. Figure 11 shows that water in economic quantities may be obtained to depths of 400 feet in the area. The occurrence of groundwater in economic quantities does not appear to be related to any regionally significant geologic feature; instead, it seems to be localized to limited regions of high permeability (Fig. 7).

Direct evidence is lacking regarding the distribution of water in areas where it cannot be obtained in economic quantities, i.e. between producing localities, and below the deepest known producing zones. However, from the following considerations it may be inferred that water does occur at such places:

(1) well yields from producing zones are sustained, which phenomenon is possible only if recharge takes place through surrounding, nonproductive zones;

(2) the fact that fresh water occurs under nonproductive zones indicates that this water is refreshed by meteoric water percolating through lateral and overlying nonproductive zones;

(3) distribution of gas (see logs of Wells Nos. 144, 145, Appendix C) proves the existence of open pore space below the maximum depths of known freshwater producing zones;

(4) recovering water levels (Fig. 12, Well No. 144) during drilling of test holes, and the fact that water, in amounts sufficient for drilling by the cable-tool method, collects from low permeability formations, supply strong evidence for mobile water being present at depths below economic yield;

(5) virgin fluid pressures obtained from drillstem tests in oil wells indicate that the fluid-potential distribution is influenced by the overlying topography to depths of several thousands of feet, suggesting hydraulic continuity between deep seated formation fluids and the land surface (B. Hitchon, pers. comm.).

LEGEND

Most common well-depth range, in feet . . . 0-200

Boundary of range area . . . .

Area recommended for further exploration 2

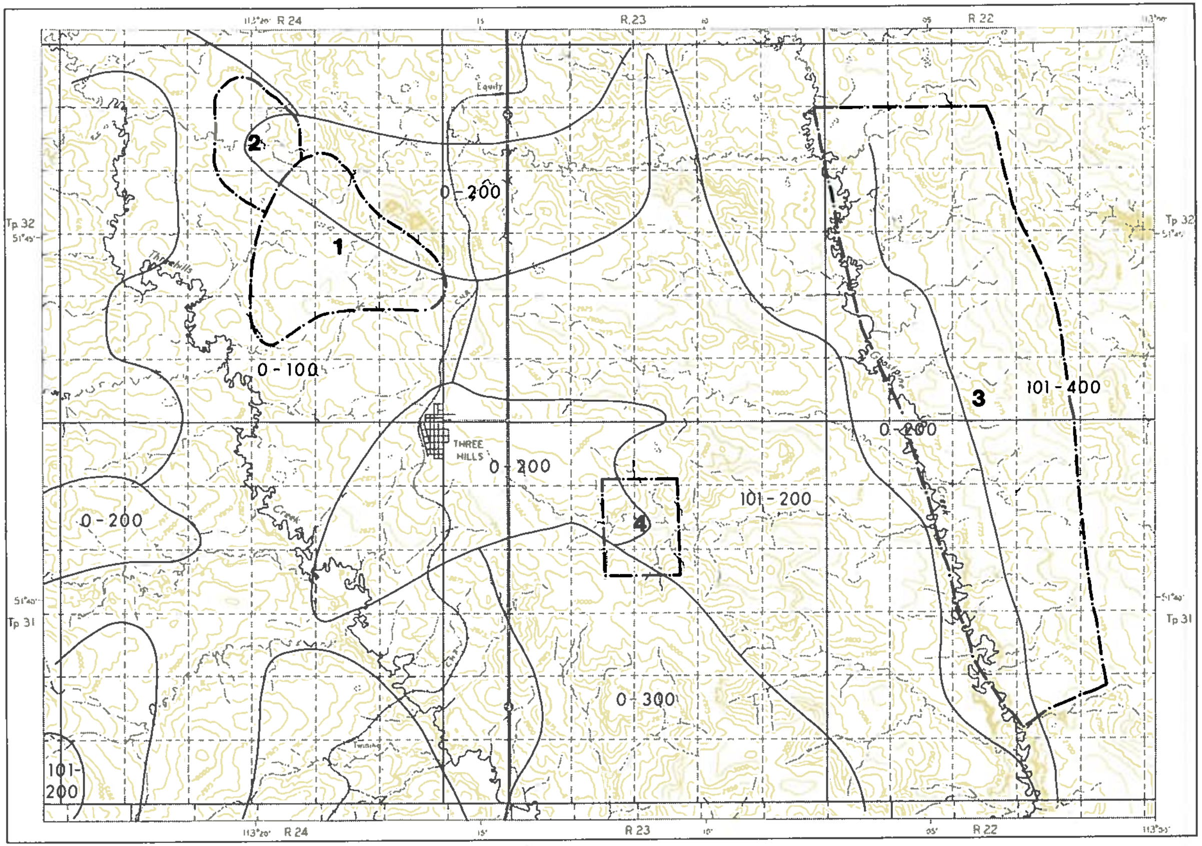


FIGURE 11. Map showing areal distribution of the most common well-depth ranges and areas recommended for further exploration.

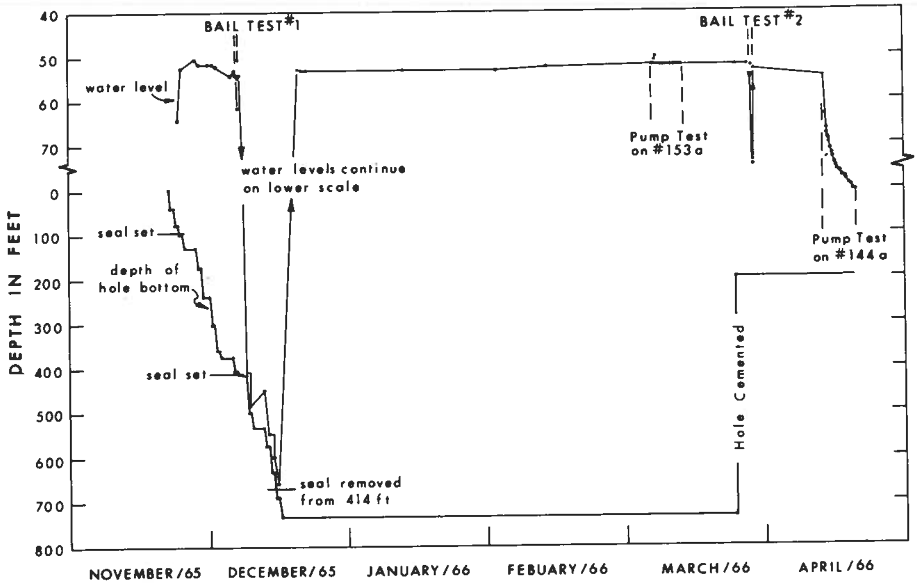


FIGURE 12. Relation between non-pumping water levels and well depth in Three Hills Well No. 144.

Movement of Groundwater

Model Environment for the Groundwater Regime

On the basis of the information presented above, a rather simple model for the hydrogeologic environment may be formulated. It consists of a hydraulically continuous medium with the lower boundary being an extended horizontal, or nearly horizontal, impermeable stratum located at some depth, whereas the upper boundary is a close, somewhat subdued replica of the land surface. In the course of previous investigations it has been established that in this type of environment the natural flow of groundwater does not cross the vertical, imaginary planes coinciding with major valleys and water divides (Tóth, 1963, p. 4808; Freeze, 1966, p. 177). These planes, therefore, represent lateral, impermeable boundaries of natural flow regions. The permeability varies within the medium but, depending on the scale of investigation, certain areas and groups of formations may be regarded homogeneous. Groundwater flow in this environment is generated by the differences in fluid potential at the land surface, and its distribution is modified by the permeability distribution in the geologic formations.

Although general solutions for groudwater flow-distribution in similar environments are available (*op. cit.*), an attempt has been made to obtain solutions specifically for the Three Hills area. For this purpose an electric analog was designed and constructed (Appendix A).

Conclusions Regarding Regional Groundwater Flow

Certain conclusions may be derived from an analysis of the models of fluid-potential distribution (Appendix A, Fig. 13) regarding the geometry, intensity, direction, and direct or indirect manifestations of groundwater movement in the Three Hills area.

(1) Topographic control

The natural movement of groundwater is controlled by the local topography to depths corresponding to at least the top of the Lea Park-Colorado unit. As a result, no lateral flow occurs under the three major surface-water divides: Kneehills ridge, Three Hills ridge, and Red Deer ridge (Fig. 3). Also, flow does not cross the vertical plane under the Red Deer River. Under natural conditions and above the Lea Park-Colorado unit, therefore, each basin has its own groundwater regime, with the direction of movement, balance and chemical quality of groundwater being determined by the hydrogeologic environment of the individual basin. Because the hydrogeologic environments in the three basins are similar in every respect, except for topographic and geologic details which are small compared to the extents of the basins, the groundwater regime will also be uniform over the entire area, with minor local differences only.

(2) Direction of movement

Groundwater in each basin moves in two, oppositely directed regional flow systems from the major surface-water divides towards the main valleys, and in several intermediate and local flow systems, superimposed on the regional systems, from local topographic highs to local lows. Flow velocities generally decrease with depth, although lateral variations in velocity are locally more important than vertical changes.

(3) Recharge and discharge areas

Inasmuch as the ratio of the lengths of downward-flow sections to the lengths of upward-flow sections along the upper boundary of the model may be considered to be proportional to the ratio of the areas of downward flow to the areas of upward flow in the three dimensional actual basin, the Three Hills area is divided according to a 1:1 (50 per cent to 50 per cent) ratio into areas of hydraulic recharge and hydraulic discharge.

Areas of downward flow are characterized in the field by a decrease in fluid potential (lowering of water levels) with increasing well depth, whereas, depending on the local slope of the land surface, water levels may drop, remain constant, or rise with increasing depth in areas of upward flow (Tóth, 1966, p. 33 and Fig. 13. *op. cit.*).

In areas where flow is directed upward, the fluid potential may increase to such a degree that water levels rise above the land surface in bore holes. On the potential cross section shown in figure 13b, deduced from the electrical model, this phenomenon may be expected between miles 6.75 and 8.75, with the center of this theoretical flowing well area being shifted approximately 1 mile to the east of the channel of Threehills Creek. Drilling of seismic shot holes, approximately ½ mi south of the cross section, reveals that flowing conditions exist over a large area (Fig. 10). The known extremities of this area are at miles 6 and 8 of the cross section (Figs. 10 and 13). Another area of flowing wells occurs in the northwest corner of the map-area, the position of which in the natural systems of groundwater flow is similar to that of the one mentioned above.

Based on this and other agreements (discussed in the section on chemistry) between features of the flow model and actual observations, it is concluded that the 1:1 ratio of discharge and recharge "areas" indicated by the model represents the actual field situation with good approximation. This ratio, however, may change from basin to basin as their slope characteristics vary. Due to the relative steepness of the high divide on the east flank of the Threehills basin, for example, the areas of downward flow are reduced, resulting in a recharge to discharge area ratio of 2:3 (40% to 60%). On the other hand, the broad, relatively flat water divide contrasting the steep-sided flanks of the deeply incised valley of the Red Deer River, results in a 2.2:1 (69% to 31%) ratio, indicating widely spread areas of downward flow with flow converging in the discharge areas.

(4) Contribution to base flow

From the pattern of flow distribution in the electric cross section, it is seen that the channel proper of a creek is not a preferred place for regional groundwater discharge; instead, groundwater approaches the land surface over an area of approximately 50 per cent of the drainage basin. This type of flow distribution means that groundwater contribution to the area's streams is small compared to the total amount of groundwater discharge. Thus, the streams receive base flow from the total groundwater discharge in proportion to the ratio of their channel area to the area of upward-moving groundwater.

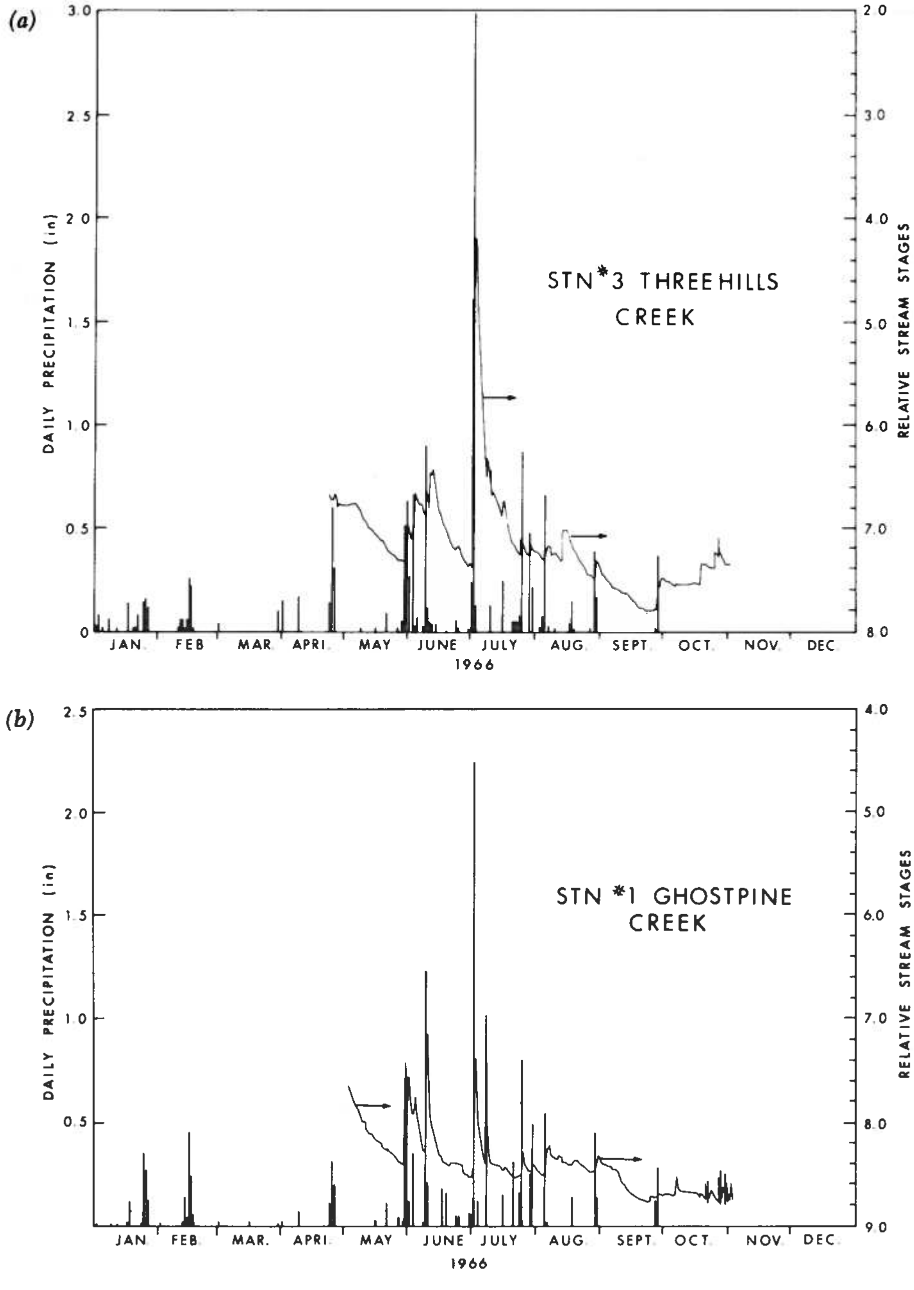


FIGURE 14. Precipitation and stream stages for 1966: (a) Station No. 3, Three Hills Creek, (b) Station No. 1, Ghostpine Creek.

This conclusion, concerning base flow, is corroborated by the high degree of correlation between the stages of Threehills and Ghostpine Creeks and the amounts of local precipitation (Figs. 14a, b). From the hydrographs it is seen that stream stages rise in response to each rain within a few hours and drop to their pre-storm level within two or three days, i.e. as soon as channel storage in the basin is depleted. The lack of permanent rise in the river stages after major storms, plus the fact that these streams dry or freeze up completely during periods of drought of several weeks duration and in the winter, indicate that in the Three Hills area subsurface flow does not contribute any significant quantities of water to stream flow.

In addition to the above observations, the amount of stream flow in the contiguous basins of Kneehills Creek and Rosebud River was found to be 0.5 per cent of the precipitation (Canada, Water Resources Branch, 1965, p. 8). These basins have hydrogeologic environments similar to the Ghostpine and Threehills basins. Since these creeks have similar flow characteristics as well, it is certain also that the major part of the discharges of Ghostpine and Threehills Creeks is derived from precipitation, indicating again the subdued importance of groundwater contribution.

(5) Influence of Red Deer River Valley

Cross sections derived from the electrical model indicate that the subsurface draining effect of the deep valley of the Red Deer River is strong, resulting in a marked decrease in fluid potential with depth under the areas of downward flow between Ghostpine Creek and the Red Deer River (Fig. 13a). A similar effect in the actual flow distribution is indicated by (1) the necessity of drilling wells up to 400 feet in depth to secure a sufficient height of the water column in domestic wells (Fig. 11); (2) the low nonpumping water levels (Fig. 10); and (3) the westward shift of the groundwater divide at depth, which is particularly noticeable in the southeast corner of the map-area (Fig. 10). The low water levels and the consequent necessity of deep wells, which may be inferred from and explained by the electrical cross section, were attributed by Stalker (1953, p. 15) to draining by the Red Deer River.

(6) Influence on porosity and permeability

According to the results of test drilling and well surveys, economically significant quantities of water are generally restricted to depths of 300 feet or less from the surface, except in the Red Deer basin, where production wells deeper than 300 feet have been completed. Since there is no correlation between bedrock lithology and the present land surface, the development of a relatively shallow region of increased permeability appears to be related to topography. Thus, based on the demonstrable influence of land forms on the distribution of groundwater flow-systems, the hypothesis is advanced here, that if rock types and chemical conditions are suitable, a type of internal erosion takes place within the rock framework resulting in an increase in the original permeability in areas of relatively intense groundwater flow-systems.

The basic assumptions in the suggested process are that the rocks contain fine particles that can be transported by moving groundwater, and that chemical reactions between groundwater and the rocks result in permeability-increasing volumetric changes of some of the rock-forming minerals. In the Three Hills area both the mechanical and the chemical processes may be operative. The cement materials in the siltstones and sandstones of the Upper Cretaceous-Tertiary bedrock consist mainly of soft, unconsolidated clays, mainly montmorillonite and kaolinite. Conceivably, moving groundwater may rearrange the colloidal particles by dislodging and shifting them from places of high velocity flow to low velocity embayments and to the leeward side of protruding grains in the intricate system of rock interstices. This mechanical process would result in a decrease in the degree of tortuosity and in a reduction of the length of the passageways, both effects tending to augment permeability. Concurrently with this process, an exchange of cations may occur between the Ca-Mg type shallow recharge waters and Na-bearing montmorillonite, producing Na-type groundwater and Ca-type montmorillonite. Both the dry volume of Ca montmorillonites and their swelling on wetting is less than those of Na montmorillonites. For this reason this type of cation exchange also would increase the cross-sectional area of the passageways. The suggested increase in permeability would allow increased rates of groundwater flow in regions where it is already active, thereby progressively accentuating the original differences in flow intensity and also the generated differences in permeability along preferred depth intervals of the basin.

Obviously, this process will result in a flow distribution that is different from the configuration of flow lines obtained by the electrical analog. Yet, as a qualitative conclusion, it is suggested that the differentiation in flow intensity will be such that the intensity increases where it is initially high in a homogeneous medium, and it decreases in regions from which water is diverted towards high permeability zones.

The above-average depth of economically significant water supplies in the Red Deer basin also supports the hypothesis on the permeability--increasing effect of active flow systems, in which, according to the electrical model high intensity, deeply penetrating systems, and steep gradients are associated with the deeply incised valley. Also in favor of the above hypothesis is the fact that economically significant water quantities are known to occur only at shallow depths (less than 150 ft) in areas where gradients of the fluid potential are low (Well Nos. 144 and 150, Fig. 7), and at greater depths (to 300 or 400 ft) where deeper penetration of intense flow can be expected, for instance under topographic highs, and midline areas (Fig. 7).

(7) Depth of active flow

According to the potential distribution derived from the electrical model, most of the land surface is underlain by local flow systems. If this observation is combined with those of the preceding discussion, according to which shallow, active flow is restricted to a depth of less than 300 feet, then the conclusion is that most groundwater circulation occurs within 300 feet from the land surface in local flow systems. Water-level fluctuations in shallow observation wells (less than 300 feet), therefore, must be indicative of the dynamics of shallow, local systems. It is this conclusion, upon which estimates of groundwater balance, flow rates, and average hydraulic conductivity of the rocks in the Three Hills area are based.

(8) Influence of possible faults

Configuration of water levels at three different localities, high mineralization of groundwater at one of these localities, and structural contours on the Kneehills Tuff indicate the possibility of local, east-west faulting in the Three Hills area. The direction and type of the suggested faults are consistent with a hydraulic barrier demonstrated in the Olds area (Tóth, 1966, p. 24 and 45). The apparently low-permeability planes of the postulated faults will impede both natural and induced movement of water across them.

Groundwater Balance

Theoretical Background

"The quantity of flow through an undeveloped basin under natural conditions . . ." was defined as the "natural basin yield" by Freeze (1966, p. 185). It is the lower limit of the "basin safe yield", since water withdrawal will divert a portion of that water toward points of artificial discharge which would not enter the systems of saturated flow under natural conditions. A corresponding concept in Russian literature is the "dynamic reserves of groundwater".

A similar concept was developed and called "artesian water circulation" by Szebényi (1965) in an attempt to determine the "quantity of water crossing a unit surface of the artesian aquifer boundaries in unit length of time under the influence of natural potential gradients" (quotation translated by author), from fluctuations of water levels in observation wells during periods of frost in the Hungarian Plains.

A relation between the saturated flow of groundwater and the fluctuations of the water table during periods of frost, in general, and between saturated flow in local flow systems, specifically, and phreatic fluctuation during periods of frost was pointed out by Tóth (1962, p. 4383; 1966a, p. 264).

Concepts based on conclusions of these works and on the limited amount of information available from precipitation records, observation wells, and the electrical model suggest that it is possible to estimate the order of magnitude of the average natural basin yield in the Three Hills area. In the following paragraphs the principles of the calculations are summarized.

The natural yield ($Q_{i,t}$) of any flow system (i) during a given time interval (t) equals the amount of water passing through and at right angles to its cross section at the boundary between the area of downward flow and area of upward flow. This quantity is equal to the product of the average specific yield of the rocks ($\overline{Sy}$) multiplied by the average drop of water levels ($\overline{f}_{d,t}$) taken over the surface of the flow system's area of downward flow ($A_{i,d}$) during the time interval t, or the average rise of water levels ($\overline{f}_{u,t}$) over the surface of the flow system's area of upward flow ($A_{i,u}$) for t, provided that the water-level fluctuations are due solely to the exchange of water between the system's areas of downward flow and upward flow. This condition is closely approximated during periods of ground frost, when recharge by precipitation and discharge by evaporation are negligible. The natural yield of the flow system i for the time interval t, therefore, may be expressed as:

$$Q_{i,t} = \overline{Sy} \cdot \overline{f}_{d,t} \cdot A_{i,d} = \overline{Sy} \cdot \overline{f}_{u,t} \cdot A_{i,u} \qquad (1a)$$

or, as:

$$q_{i,t,d} = \frac{Q_{i,t}}{A_{i,d}} = \overline{Sy} \cdot \overline{f}_{d,t}; \text{ and } q_{i,t,u} = \frac{Q_{i,t}}{A_{i,u}} = \overline{Sy} \cdot \overline{f}_{u,t} \qquad (1b)$$

as the depths of the recharged or discharged water over the areas of downward flow, or upward flow, respectively, during a length of time t. For a flow system whose areas of upward flow and downward flow are equal, equation 1a may be written as:

$$Q_{i,t} = \overline{Sy} \cdot \overline{f}_t \cdot \frac{A_i}{2} \qquad (1c)$$

where A_i is the total land area of the flow system, and $\overline{f}_t$ is the average change of water level in either the downward flow or upward flow areas.

If the seasonal changes of the hydraulic gradients in the flow system are small compared to the average gradient, the total yield of the system ($Q_{i,T}$) during the time of a complete phreatic cycle (T) is:

$$Q_{i,T} = Q_{i,t} \cdot \frac{T}{t} = \overline{Sy} \cdot \overline{f}_t \cdot \frac{A_i}{2} \cdot \frac{T}{t} \qquad (1d)$$

In a drainage basin containing only one flow system, the above equations will represent the natural basin yield. In a basin containing several flow systems, however, the basin yield will be:

$$Q_T = \sum_{i=1}^{n} Q_{1T} + Q_{2T} + \ldots Q_{uT} \qquad (1e)$$

Ideally, Q_T is the consequence of a dynamic equilibrium determined by the existing hydraulic gradients, specific yield, and permeability of the rocks, and is recharged in areas of downward flow by a certain portion of the total precipitation. It is discharged hydraulically in the areas of upward flow during a phreatic cycle. The local needs of evapotranspiration then may be considered to be supplied from an additional portion of the precipitation in both the areas of downward flow and upward flow.

If, however, this need should be satisfied from part of Q_T in the area of upward flow, then a quantity corresponding to this need must be rejected from the precipitation there. Thus, whether the local natural water use in the area of upward flow is obtained from the regional flow of groundwater or from local precipitation, a quantity of Q_T seems to be recoverable without adversely effecting the moisture supplies for crops or causing a permanent depletion of stored groundwater.

Strictly speaking, Q_T is available for artificial withdrawal in the area of upward flow only. Lowering the water levels by pumping in areas of downward flow, however, will promote the recharge from rainwater. For this reason it is believed that a minimum, or safe rate of water production per unit surficial area is possible by distributing Q_T over the entire surface of a flow system according to:

$$q_{l,\,T,\,safe} = \frac{Q_{l,T}}{A_l} = \frac{q_{l,T}}{2} \qquad (2a)$$

or for the entire drainage basin:

$$q_{T\ safe} = \frac{Q_T}{A} = \frac{q_T}{2} \qquad (2b)$$

Considering $Q_{l,t}$ as defined above, and estimating the cross-sectional area of the flow system between the areas of downward flow and upward flow, velocities of groundwater flow and average permeabilities of the rocks may be calculated. If the ratio of areas of downward flow to areas of upward flow in a drainage basin containing numerous flow systems is similar to that ratio of an individual flow system, then the above method of calculating velocities and permeabilities in the flow system should be valid for the entire basin. The following calculations for the Three Hills area are based upon the above considerations.

Practical Calculations

(1) Groundwater coefficient of precipitation (K_p)

From monthly measurements in seven widely scattered observation wells in both recharge and discharge areas (Fig. 3), the average change of water levels for two five month-long periods of ground frost was found to be (Fig. 15):

$$\bar{f}_{t=5\,months} = 0.47 \text{ feet}$$

This fluctuation, with an assumed specific yield of 0.1 for the local rocks,

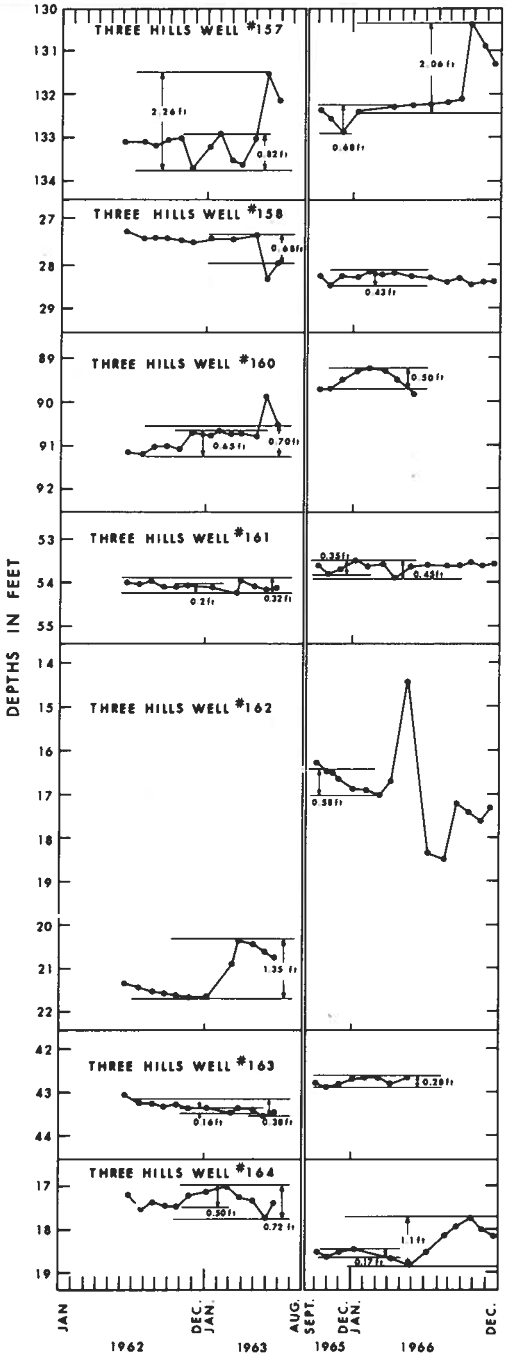


FIGURE 15. Monthly readings of water levels in seven observation wells.

represents an average depth of water exchange for a period of 5 months of

$$q_{t=5} = \overline{Sy} \cdot \overline{f}_t = 0.1 \cdot 0.47 = 0.56 \text{ in./5 months}$$

or

$$q_T = \frac{Q_{d,T}}{A_d} = \frac{Q_{u,T}}{A_u} = 1.35 \text{ in./year.}$$

The groundwater coefficient of precipitation will then be:

$$K_p = \frac{q_T}{p} 100\% = \frac{1.35}{14.35} 100\%$$

$$K_p = 9\%$$

where p is the amount of annual precipitation.

(2) Natural basin yield

Since, according to the electrical model the average ratio of the areas of downward flow to the areas of upward flow is approximately one, and since in the water-level fluctuations both types of areas are equally represented, it follows that the 9 per cent must be equivalent to the quantity of water moving annually from areas of downward flow to areas of upward flow in the Three Hills area. This further means that an average depth of water of

$$q_T = 1.35 \text{ in./year} \sim 72 \text{ acre-feet/sq mi/year} \sim 38 \text{ gpm/sq mi} \sim 65 \text{ l/min/km}^2$$

replenishes the zone of saturated flow in the areas of downward flow during the specified time intervals.

(3) Areal, or safe rate of production

According to equation 2b, if the natural basin yield, Q_T, is to be withdrawn over both areas of recharge and discharge, the evenly distributed, safe production rate is:

$$q_{T\,safe} = \frac{q_T}{2} = 19 \text{ gpm/sq mi} \sim 33 \text{ l/min/km}^2$$

(4) Flow velocity

The same amount of water that enters the flow systems at the areas of downward flow, at a rate of 38 gpm/sq mi, will have to be transmitted to the areas of upward flow across a 1 mile-wide vertical cross-sectional area, the "mid-line" area of the flow system, which can be assumed to be approximately 300 feet deep [point (7) on page 00]. The contraction of

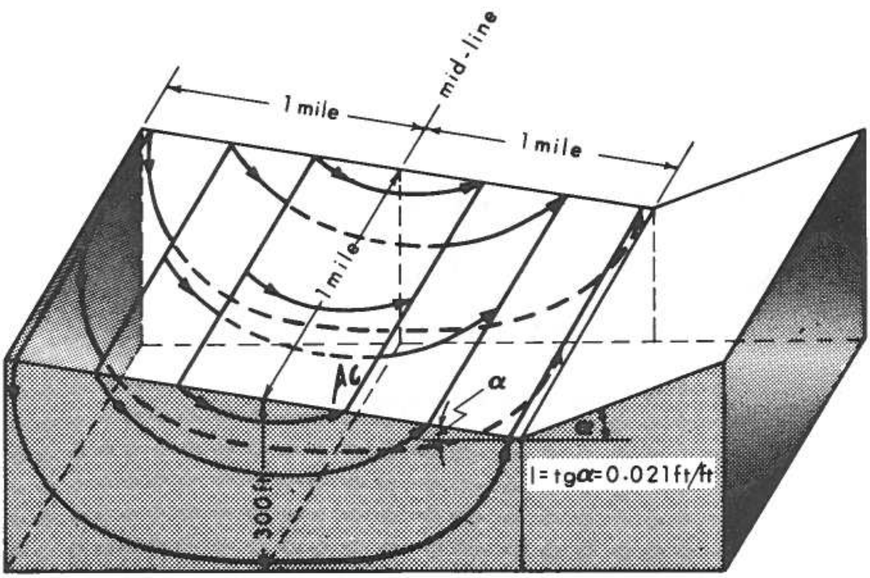


FIGURE 16. Diagram illustrating the calculation of flow velocity.

the cross-sectional area of the "typical" flow system (Fig. 16) from 1 sq mi at the intake to $A_c = 5280 \cdot 300$ ft² at the mid-line requires an increase in the flow rate by a factor of 17.6, resulting in an average discharge of

$$Q_c = 658 \text{ gpm} = 10.5 \text{ ft}^3/\text{min}$$

through a section 1 mile wide by 300 feet deep of the mid-line regions. The rate of volume discharge per unit cross-sectional area is then:

$$q_c = \frac{5280 \cdot 300}{Q_c} = 9.56 \cdot 10^{-3} \frac{\text{ft}^3}{\text{day} \cdot \text{ft}^2} = 2.91 \cdot 10^{-3} \frac{\text{m}^3}{\text{day} \cdot \text{m}^2}$$

which, when divided by the assumed specific yield of 0.1 for the local rocks, yields for actual flow velocity at the mid-line regions:

$$v_c = \frac{q_c}{\overline{S}y} = 95.6 \cdot 10^{-3} \text{ ft/day} = 2.91 \cdot 10^{-2} \text{ m/day}$$

or, approximately

$$v_c \sim 0.1 \text{ ft/day} \sim 3 \text{ cm/day}.$$

(5) Average field permeability of the rocks

Measurements of the slopes of the water levels in figure 10 along 13 cross sections yield an average gradient of

$$I = 0.0212 \text{ ft/ft.}$$

With the previously obtained figures for A_c and Q_c, the equation

$$Q = PAI$$

yields a value for the average permeability of

$$P = \frac{Q_c}{A_c\,I} = 4.5 \cdot 10^{-2} \text{ gpd/ft}^2 \sim 3 \cdot 10^{-3} \text{ darcy.}$$

Discussion of the Practical Results

Due to various uncertainties involved in the above calculations, the results at best can be regarded correct within the order of magnitude. However, in an area for which no information whatsoever is available for the water balance, even the first, rudimentary estimates may be of value in future development of the water resources.

If it is accepted that approximately 0.5 per cent of the total precipitation runs off from the area as stream flow, and that no groundwater moves out of the drainage basins, then 99.5 per cent of precipitation is available for evapotranspiration. Of this amount, 90.5 per cent must evaporate and transpire without participating in the groundwater circulation, whereas 9 per cent of precipitation completes the subsurface portion of the hydrologic cycle. The high rate of evapotranspiration obtained from stream-flow measurements is in good qualitative agreement with the results obtained from the Thornthwaite method, which show that the Three Hills area is characterized by a year-round deficit of precipitation compared to the potential evapotranspiration.

Owing to a scarcity of published data, the range of values expected for average basin yields is uncertain. It was calculated to be 9 per cent of the precipitation in the present case. Estimates of K_p for several places in the United States range between 5 and 18 per cent (Farvolden *et al*, 1963, p. 104), whereas for a small drainage basin in Alberta it was calculated by Farvolden (*op. cit.*) to be 2 per cent. The writer feels that groundwater flow has been underestimated in the latter case because only that part of the groundwater flow was taken into consideration which discharged at a spring, the spring being accepted as the only point sink of the basin.

Another indication that the estimated average basin yield in the Three Hills area is of the correct order of magnitude is found in the values for flow velocity (3 cm/day) and permeability ($3 \cdot 10^{-3}$ darcy), calculated using the average basin yield figure of 9 per cent. The flow velocity and permeability values so derived are in good agreement with the range of values suggested by Todd (1959, p. 53) for rocks of the type that underlie the Three Hills area.

Summary

The hydrogeologic environment of the Three Hills area is characterized by rolling topography with prominent water divides and broad, flat floodplains, underlain by fine grained, argillaceous, continental clastic sedimentary rocks, with sufficient precipitation to keep the water table near the land surface. In this environment groundwater forms a hydraulically continuous body moving from areas of higher head to areas of lower head, coinciding with topographic uplands and depressions, respectively. Movement of the groundwater under the presently prevailing natural distribution of fluid potential occurs in groundwater flow systems of different orders. Flow is active in the shallow, local systems and sluggish in deeper systems. The areal average depth of the active flow is approximately 300 feet. Permeability of the rocks to this depth seems to be higher than below it. This is attributed to the mutually reinforcing interaction between the intense flow of groundwater and its permeability-increasing effect by physical and chemical weathering inside the granular framework of the rocks at shallow depths. The depth within which these processes take place is a function of the topographic relief.

Generally, 50 per cent of the Three Hills area is underlain by areas of downward flow, and 50 per cent by areas of upward flow of groundwater. This ratio of 1:1 varies from basin to basin according to the local topography. It is 2:3, 1.13:1, and 2.2:1 for the Threehills, Ghostpine, and Red Deer basins, respectively.

The natural basin yield, which is the amount of water exchanged between areas of downward flow and areas of upward flow during a specified time interval is approximately 9 per cent of the precipitation, or 1.35 in./year $\sim$ 38 gpm/sq mi. Since groundwater contribution to stream discharge is negligible, 9 per cent of precipitation is regarded to be the minimum amount of water that may be withdrawn in each square mile of upward flow area without depleting groundwater storage. Distributed over the entire area, the safe natural yield is approximately 10 gpm/sq mi.

The average lateral velocity of groundwater flow in the upper 300-foot zone underlying the Three Hills area is estimated to be approximately 0.1 feet/day. Calculated with a value of 0.1 for porosity (specific yield), the average lateral permeability of the rocks within the above-mentioned zone is $4.5 \cdot 10^{-2}$ gpd/ft^2 $\sim$ $3 \cdot 10^{-3}$ darcy.

Although it is realized that these results are preliminary and gross estimates of the groundwater conditions in the Three Hills area, there are indications that their general order of magnitude is correct.

GROUNDWATER CHEMISTRY

Areal Distribution of Chemical Constituents

Figures 17 through 23 present the areal distribution of the total dissolved solids (TDS) content and the most important chemical constituents of groundwater in the Three Hills area by means of contour maps. The maps have been constructed on the basis of well-water analyses. Owing to the limited number and wide spacing of the sampled wells, changes in chemical quality, possibly occurring within short distances (2 miles on the average) and in the vertical direction, could be observed in a few places only. In certain parts of the area, no water samples could be secured over several square miles due to an absence of water wells.

The maps are self-explanatory, and those aspects of groundwater chemistry which are important from a practical or water-supply point of view will be discussed only briefly.

The areas for good potable water are outlined by the 1500 ppm contour line on the map of the total dissolved solids (Fig. 17). An extended area of low total solids (less than 1500 ppm) covers the ridges and valley slopes east of and parallel to Ghostpine Creek. The TDS content increases slightly but rather uniformly west of this creek as far as the relatively high plateaus in the centre of the map-area. On the plateaus, particularly in the north half of the map-area, water quality is poor, reaching values of 5000 ppm. This area of high mineralization has the shape of an equilateral triangle with the town located approximately in the middle of its northwest-southeast oriented side. Two other areas of low total solids are situated on the west slopes of and within three miles of Three Hills ridge and along Threehills Creek valley, and on the adjacent hills south of the town. Along the west boundary of the map-area, the total dissolved solids content is generally above 1500 ppm.

For the purposes of human and stock consumption, SO_4^{--} is the least desirable major anion in water because of the laxative nature of the main SO_4^{--} compounds, namely Na_2SO_4 (Glauber salts) and $MgSO_4$ (Epsom salts). For this reason it is important to note that the areas of low total dissolved solids are also areas of relatively low SO_4^{--} (less than 50 per cent of total anions), thus becoming strongly preferable for the development of water supplies. The areas of high total solids, on the other hand, are also high in SO_4^{--}, which correlation renders these areas unsuitable for development of public water supplies.

LEGEND

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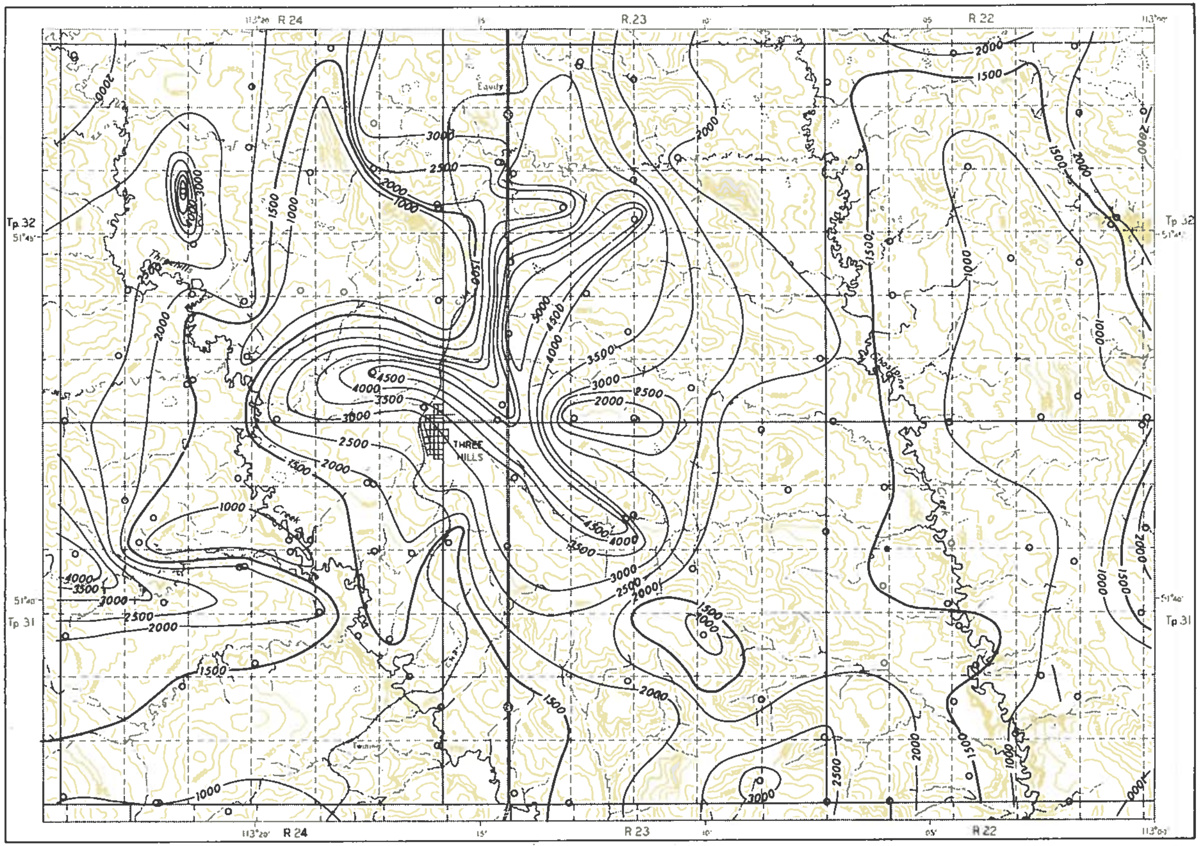

FIGURE 17.
Areal distribution of total solids, in ppm.

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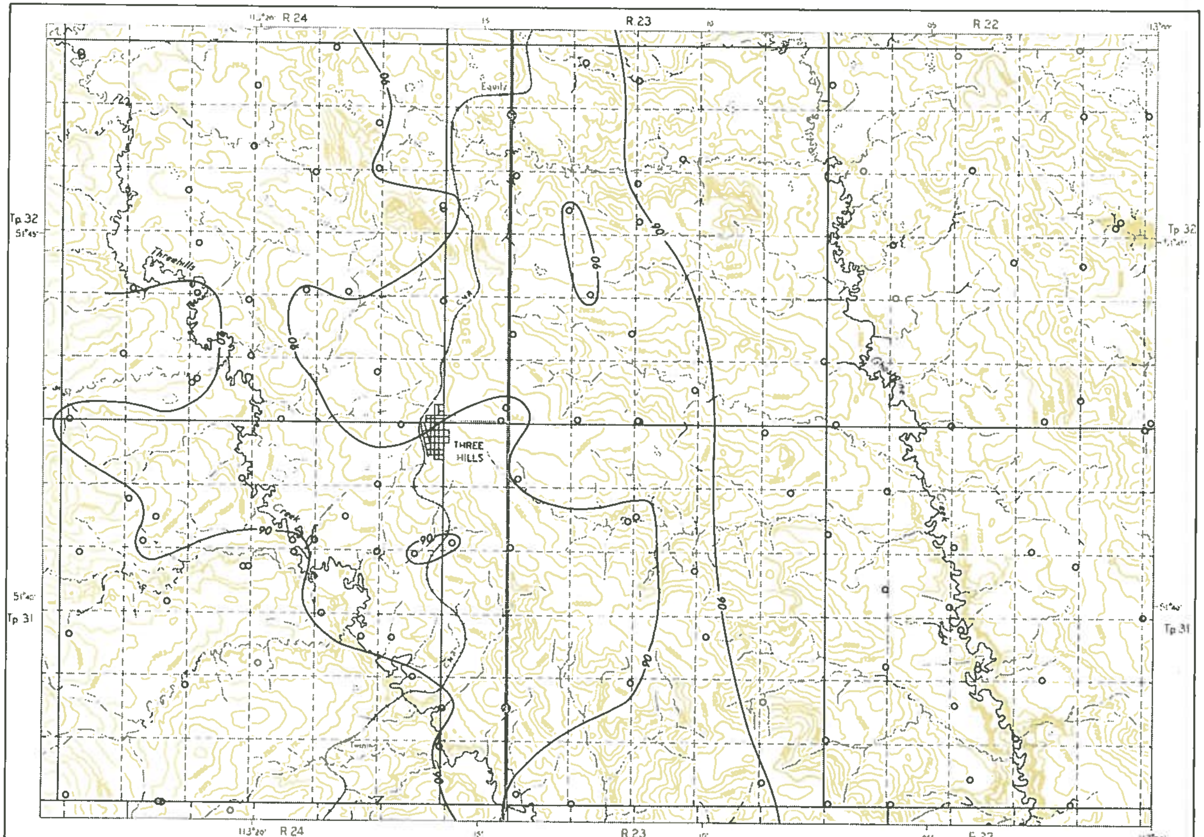

FIGURE 18.
Areal distribution of sodium + potassium ions, in percentage of total cations.

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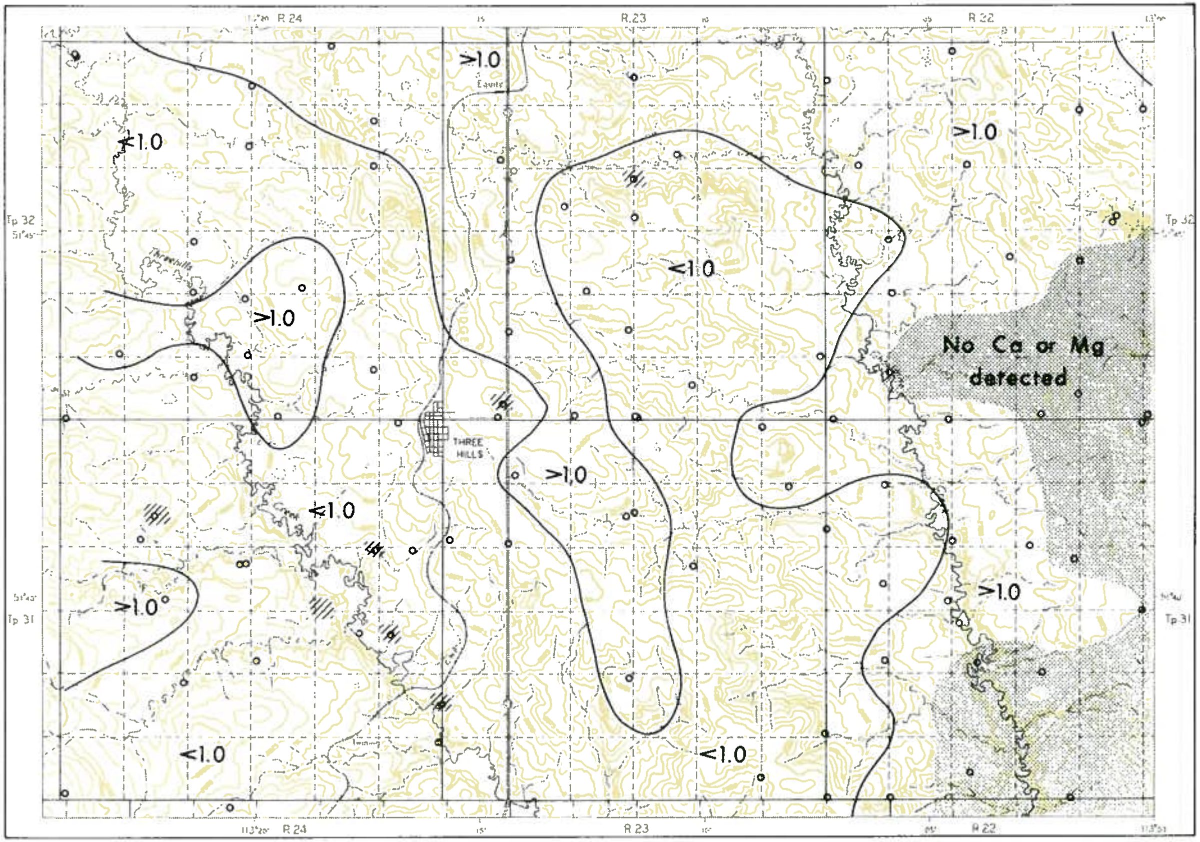

FIGURE 19.
Areal variation in the calcium : magnesium ratio.

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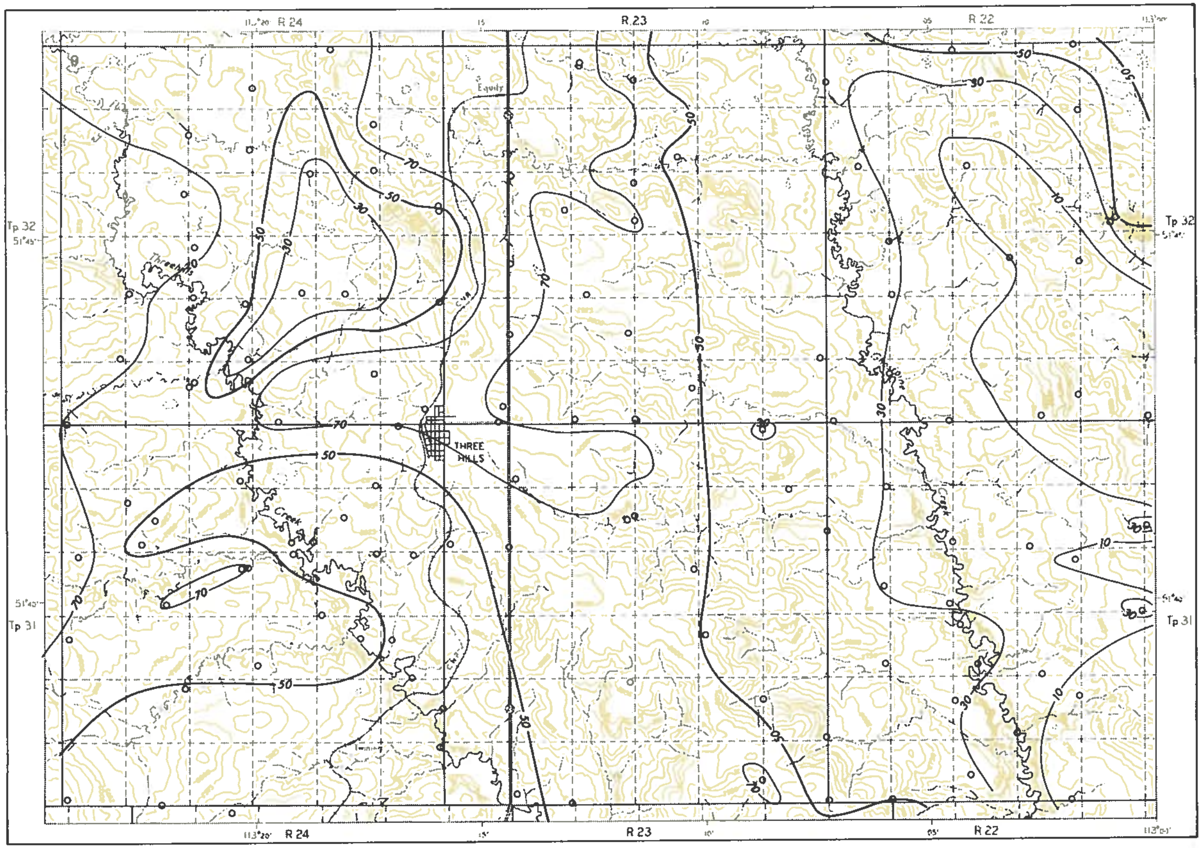

FIGURE 20.
Areal distribution of sulfate ions, in percentage of total anions.

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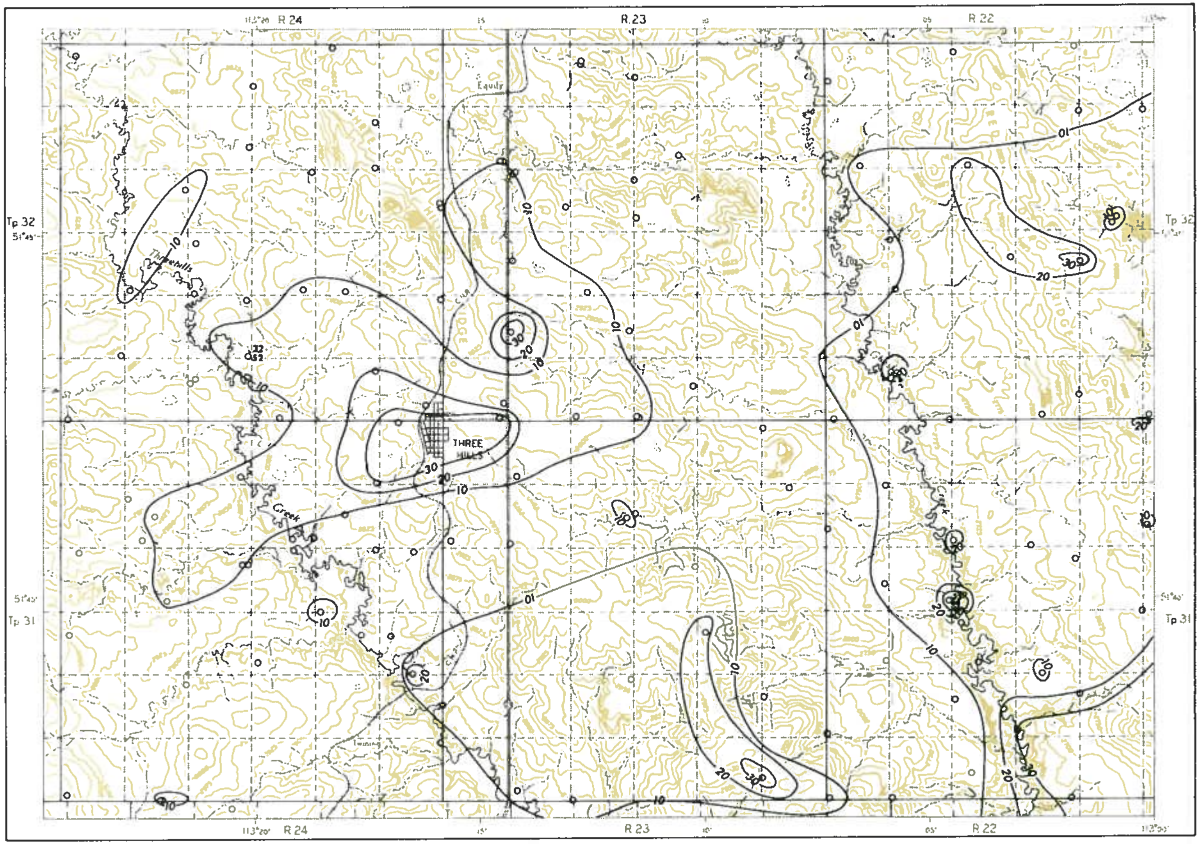

FIGURE 21.
Areal distribution of chloride ions, in ppm.

LEGEND

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Assumed contour

Anomalous value

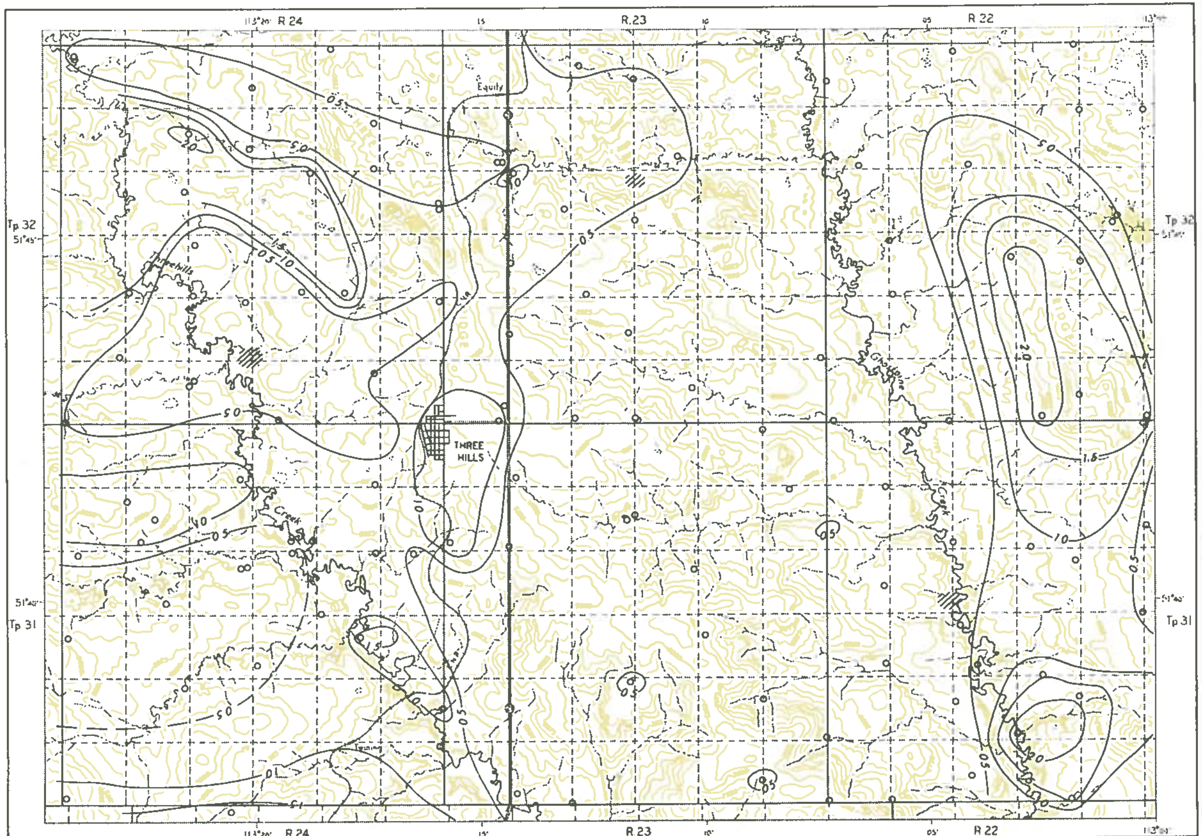

FIGURE 22.
Areal distribution of fluoride ions, in ppm.

LEGEND

Control point . . . . o

Anomalous value ////

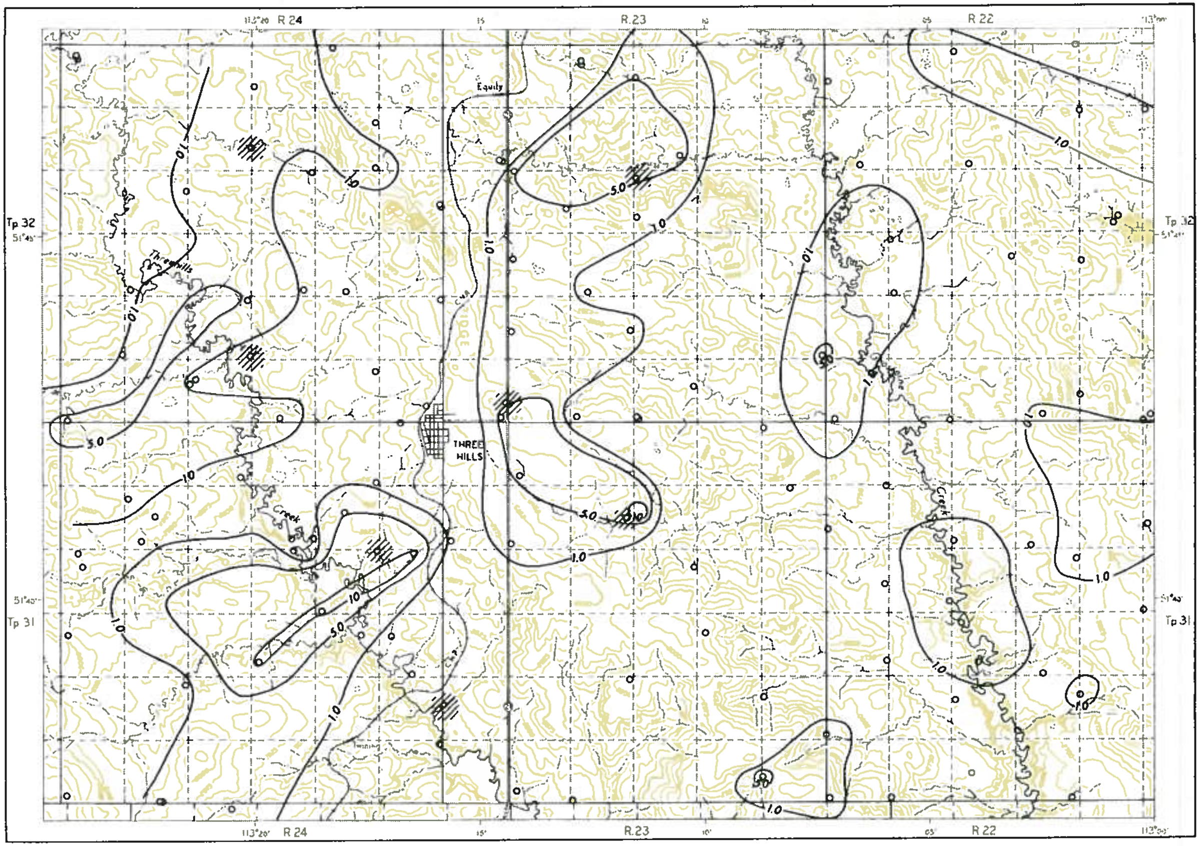

FIGURE 23.
Areal distribution of iron, in ppm.

The SO_4^{--} content of the water is given as per cent SO_4^{--} of the total anions, calculated as equivalents per million (epm). The remaining anions, consist largely of HCO_3^- and some CO_3^{--}, although Cl^- is present in various quantities (Fig. 21). The Cl^- content varies from 0 to 60 ppm and its distribution appears to be related to those of the TDS and SO_4^{--}. Due to the general low amounts, however, Cl^- does not impair the use of groundwater for human consumption in the Three Hills area.

Among the cations, Na^+ is by far the most important. Together with minor amounts of K^+ it constitutes over 90 per cent of the total cations over approximately 60 per cent of the area. The balance is made up of Ca^{++} and Mg^{++}, which, except in a few isolated places, rarely exceeds 30 per cent (Fig. 18). The areas of relatively high $Ca^{++} + Mg^{++}$ content more or less coincide with the areas where SO_4^{--} constitutes 50 per cent or more of the anions. This is particularly true in the eastern part of the area, where, within the region of low total solids, SO_4^{--} is below 50 per cent and $Na^+ + K^+$ more than 90 per cent without exception. In the western half of the area, the correlation is less definite, although there, too, the broad relation between high $Na^+ + K^+$ and low SO_4^{--} is unmistakable. The ratio of Ca^{++} to Mg^{++} is variable over the area. A denser grid of observation would be needed to establish a reliable pattern of distribution, nevertheless, a distinct north to south lineation of the distribution of this ratio seems to exist (Fig. 19).

Little can be added to the distribution patterns of fluoride and iron (Figs. 22 and 23) except to point out that, owing to the possibility of iron being taken into solution from pumps and casings, the distribution pattern presented in figure 23 may not represent the natural ion content of groundwater in the Three Hills area.

Chemical Types of Groundwater in the Three Hills Area

The central part of the Piper diagram (Fig. 24) shows the chemical types of groundwater in the area of study. Groups of points have been isolated by arbitrary boundaries, thereby defining four chemical facies of groundwater.

Although the employed principle of establishing hydrochemical facies is the same as that used by other authors (Back, 1960), the quality ranges have been chosen for the present purposes so as to contain those points which concentrate around apparent centers. It seems that in this way a grouping has been provided on the basis of which the chemistry of the local groundwaters may be conveniently investigated.

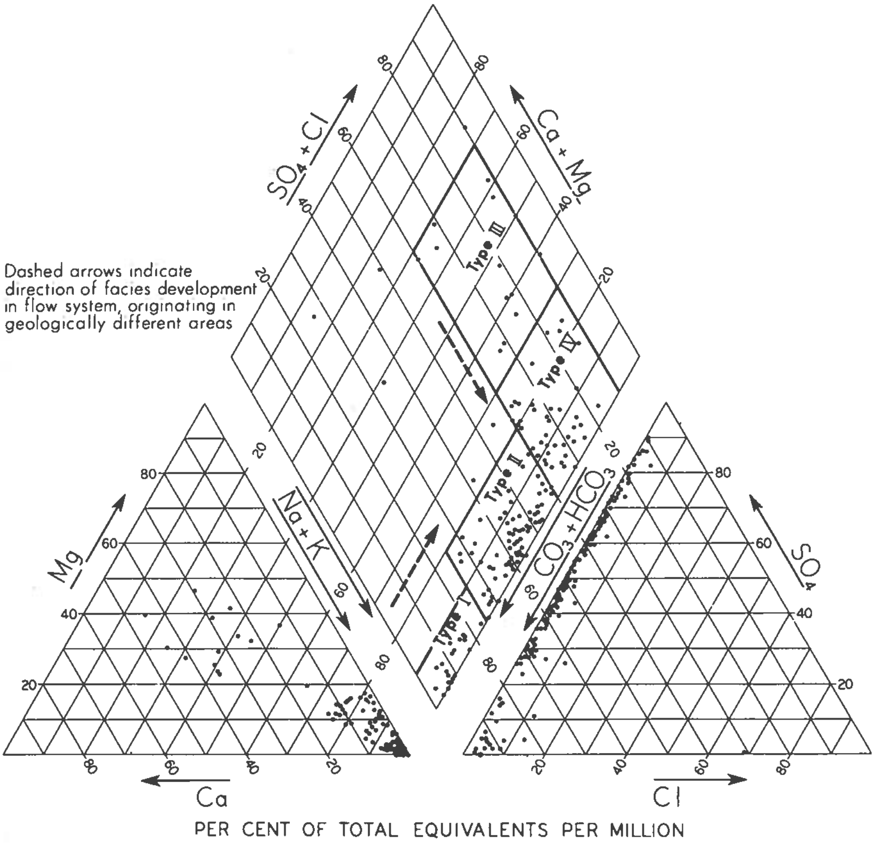

FIGURE 24. Piper diagram, showing the chemical types of groundwater in the Three Hills area.

The designations, ranges, and average compositions of the four groups are given in table 2, and the areal distribution of water types is shown in figure 5.

Table 2. Summary of the Hydrochemical Facies of Groundwaters in the Three Hills Area

Number and designation of Hydrochemical facies	Range of constituents	Number of water samples	Unit	Group averages of main constituents						
				$Na^{+} + K^{+}$	Ca^{++}	Mg^{++}	$HCO_3^{-} + CO_3^{--}$	SO_4^{--}	Cl^{-}	TDS (ppm)
I sodium bicarbonate	Na: 90 to 100% $HCO_3 + CO_3$: 75 to 100%	16	epm %	13.31 97	0.13 1	0.11 1	13.22 90	1.00 7	0.62 4	871
II sodium bicarbonate-sulfate	Na: 80 to 100% $HCO_3 + CO_3$: 40 to 74%	53	epm %	25.40 93	0.75 2	0.86 3	14.69 57	11.59 42	0.36 1	1679
III sodium-calcium sulfate-bicarbonate	Na: 30 to 69% $HCO_3 + CO_3$: 10 to 39%	10	epm %	19.63 48	10.41 28	9.88 28	9.61 26	30.48 73	0.38 1	2711
IV sodium sulfate-bicarbonate	Na: 70 to 100% $HCO_3 + CO_3$: 10 to 39%	38	epm %	42.14 87	2.63 6	3.19 7	14.06 30	34.41 69	0.43 1	3274

Interpretation of Groundwater Chemistry

General Principles

The basic principles and the specific factors determining the evolution of the chemical types of groundwater moving through both single aquifers and whole drainage basins have been studied by various authors, e.g. Chebotarev (1955), Back (1960), and Schoeller (1962). Observations and interpretation of groundwater chemistry in hydrogeologic environments similar to that of the Three Hills area have been made by several workers in Alberta: Meyboom (1960, p. 57), LeBreton and Jones (1963, p. 207-245), and Tóth (1966, p. 49; 1966b). Relevant details may be found in these studies. For the present purposes only two of the most important and well established conclusions regarding the evolution of groundwater chemistry are reiterated: (1) the concentration of dissolved mineral matter is directly proportional to the length of the flow path and to the underground residence time of the water; (2) the chemical type of groundwater at each point in the flow system is a function of the chemical composition of the rocks at that point and of the antecedent water quality.

Interpretation of the groundwater chemistry in the Three Hills area is made difficult by various factors. One of these is that in most parts of the area the distances between adjacent observation points exceed the full lengths of local flow systems, thereby precluding the possibility of establishing the areally characteristic, basic types of chemical changes along completed and simple trajectories. Another point of difficulty arises from the relatively complex chemical and mineral composition of the local rocks. As a result of this complexity, the chemical changes in water quality due to rock composition possibly obscure the changes due to length of flow path and travel time. It is therefore very difficult to separate and determine the relative importance of factors controlling the chemical evolution of the water. However, from the concept of groundwater flow systems and their inferred distribution in the Three Hills area, a comprehensive interpretation of the groundwater chemistry can be obtained, albeit on an areal rather than local scale.

Some characteristic relations, namely those between the contents of major anions and the total dissolved solids, are shown in the scatter diagrams of figure 26. Here, it is seen that above a TDS content of approximately 1000 ppm, the average amount of HCO_3^- + CO_3^{--} ions remains nearly constant. The interpretation of this phenomenon is that the HCO_3^- ions, which are far more important than CO_3^{--} ions in the sampled waters, form immediately after fresh rainwater infiltrates into the ground, i.e. in the soil zone and in zone of plant roots where the supply of free CO_2 derived from the atmosphere, decaying vegetation, and live processes of plants is copious. As the waters percolate to greater depths, where no free CO_2 is commonly available, a further addition of HCO_3^- ions is not possible, resulting in a "fossilized" quantity of HCO_3^- ions for the rest of that water's underground journey, i.e. for the remainder of the flow system in question. According to figure 26, however, both the relative and absolute amounts of the SO_4^{--} + Cl^- ions — SO_4^{--} being usually more important — have a definite tendency to increase with increasing total solids content, indicating that sulfates and chlorides are being added to the water as long as the water resides underground.

These relations combined with observations concerning the cation facies will be of assistance in the following interpretation of the different chemical types.

Chemical Types of Groundwater in the Three Hills Area

Type I. (Figs. 24, 25, and Table 2)

Type I water commonly occurs in areas of downward flow, and in short (few hundred yards to less than a mile), active flow systems on the water divide east of Ghostpine Creek (Fig. 13). The rocks in these areas are commonly devoid of gypsum and are high in sodium due to the nearness of the Kneehills Tuff Member. The other area of occurrence of type I water is in the steep-walled, bowl-shaped depression on and adjacent to the southwest slopes of the Three Hills ridge. Within a distance of approximately three miles of the ridge crest, the quality of water alternates between types I and II, probably as a result of the high to medium intensity local and intermediate systems with alternating areas of downward and upward flow. For unknown reasons the rocks do not seem to contain much gypsum on this side of the ridge.

Type I water is, therefore, interpreted as the "young" waters of areas of downward flow, or of a short, active flow system in regions where the main cation is Na^+ and the supply of SO_4^{--} is limited.

Type II. (Figs. 24, 25, and Table 2)

This is the most common type of water in the Three Hills area. It occurs generally along the bottom of Ghostpine Creek valley; in Threehills Creek valley south of its intersection with the east-west road, three miles west of the town; on the steep hills east of Three Hills ridge, i.e. on the west flank of the Ghostpine valley; and at various places in the bottoms of tributary valleys.

LEGEND

Facies I: sodium bicarbonate . . . . △

Facies II: sodium bicarbonate-sulfate . . . . ▲

Facies III: sodium-calcium sulfate-bicarbonate . . . . . ○

Facies IV: sodium sulfate-bicarbonate . . . . ●

Approximate boundary between different hydrochemical facies . . . . ———

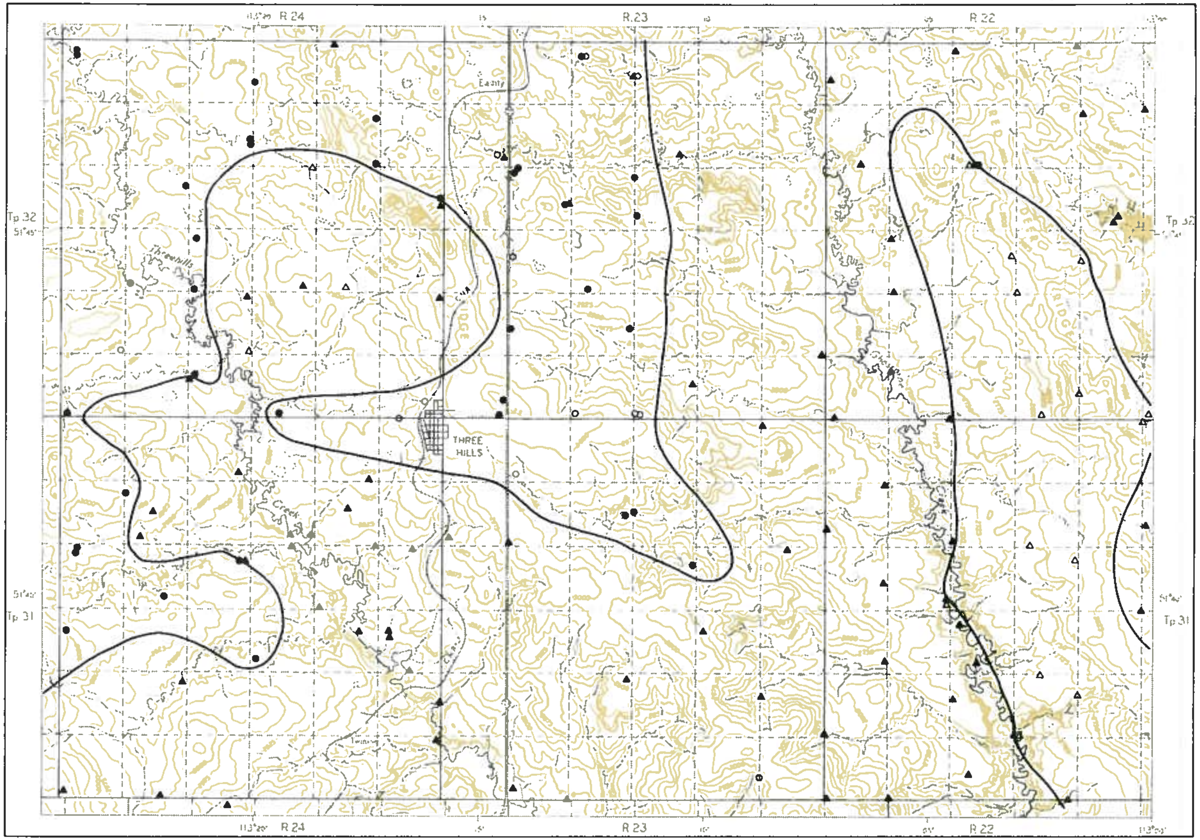

FIGURE 25.
Areal distribution of the chemical facies of groundwater.

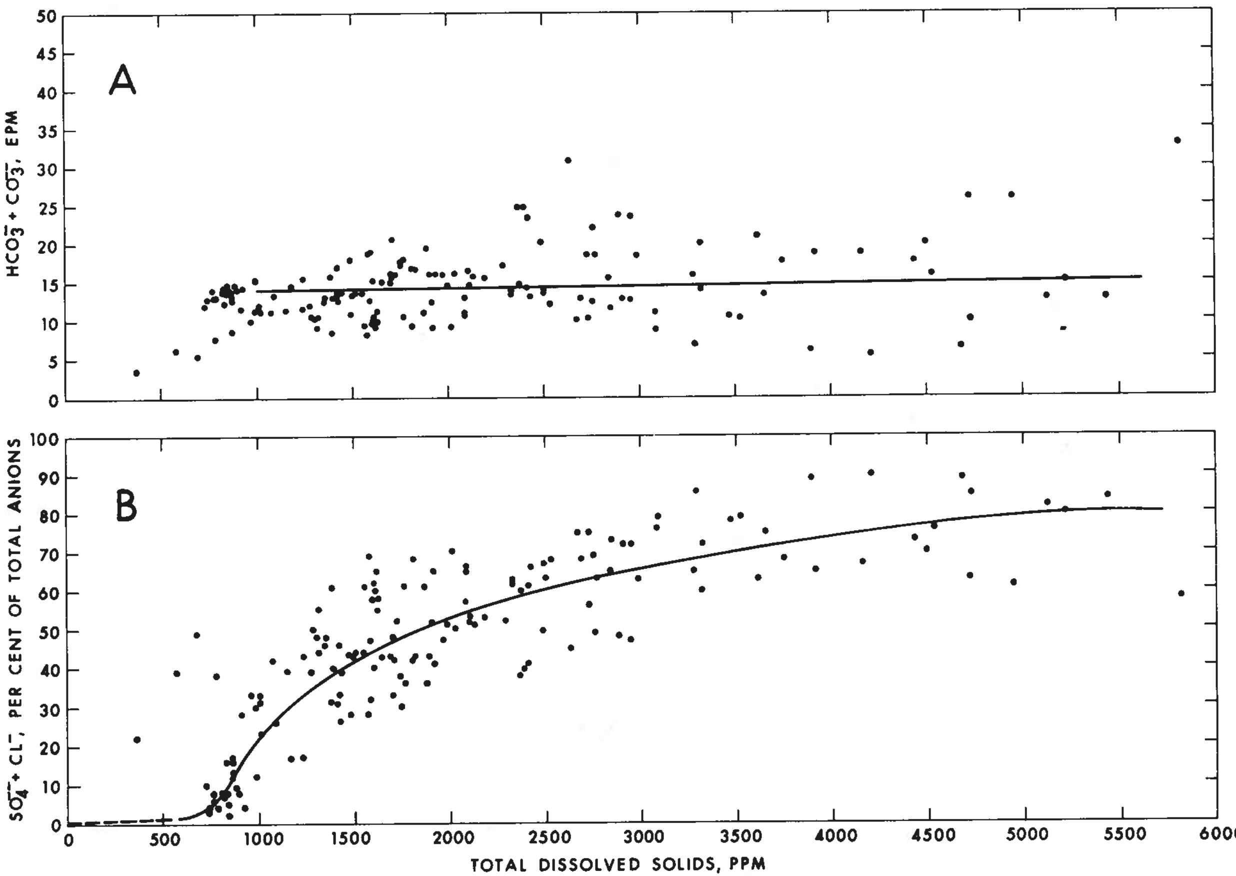

FIGURE 26. Scatter diagrams showing (a) absolute concentration of bicarbonate + carbonate ions versus total dissolved solids, and (b) relative concentration of sulfate + chloride ions.

The moderately high sulfate content together with the associated, moderately high mineralization suggests two possibilities for the origin of this facies: (1) areas of downward flow with a good supply of soluble sulfate, which in the Three Hills area only gypsum, a near-surface alteration product of glacial and bedrock deposits, can be, or (2) mid-line or upward flow areas of moderately long systems. The relative predominance of sodium over calcium suggests, however, that flow systems containing type II waters do not originate in gypsiferous rocks. Thus, the water must have travelled moderate distances to collect the sulfate, whereas the main cation remains sodium supplied by the clays in the bedrock.

The conclusion is that type II waters develop mostly from type I in intermediate, and moderately intense flow systems (e.g. on the east flank of Ghostpine Creek; Threehills Creek, south of the above mentioned intersection; and local gullies) and are found in mid-line and upward flow areas of such systems, or, that they occur in intense, short flow systems moving through rocks containing readily soluble sulfate compounds. This latter is considered to be the case throughout the approximately three-mile wide zone west of Ghostpine Creek, where the steep drop of the land surface from the plateaus east of Three Hills ridge generates active local flow systems (Fig. 13). The proximity of the plateaus, known to contain gypsum in the near-surface strata, may be the reason for the water becoming type II before having reached the mid-line or upward flow areas.
Type III. (Figs. 24, 25, and Table 2)

The few known occurrences of this type of water are concentrated in the triangular high plateau northeast of the town and in adjacent major tributaries. Two further occurrences do not warrant discussion owing to the paucity of data.

The plateau is underlain by fine-grained rocks containing abundant carbonaceous material (coal, carbonaceous shale), fragments of gastropod and pelecypod shells, and gypsum crystals (Well No. 147, Appendix C) within 50 feet of the land surface. This material constitutes a ready source of calcium, magnesium, and sulfate to the recharging fresh rainwater.

Type III water is, therefore, thought to occur in flow systems originating in rocks containing large amounts of readily soluble calcium, magnesium, and sulfate. The total solids content will increase in each individual case proportionally with the length of time the water spends underground.

Type IV. (Figs. 24, 25, and Table 2)

The main areas of occurrence of type IV water are: the triangular plateau east of Three Hills ridge; the area north of Three Hills ridge; a two-mile wide strip along the north half of the western boundary of the map-area; and some slopes and tributary bottoms along the south half of the western border of the area.

The production of type IV water is possible along two basically independent lines. First, when water spends a long time underground due to either great length or sluggish motion of the flow system, or both, it will partly or wholly exchange its calcium and magnesium for the sodium of the clays (mainly montmorillonite), thereby changing its original calcium or sodium-calcium content to sodium. At the same time it will dissolve other soluble matter, increasing its mineral content above that of the original type III water. The direction of this process is represented by the arrow parallel to the equal anion lines in figure 24. The second possible way of development does not involve exchanges of cations but a direct increase in the concentration of mineral matter along a long flow path, by a gradual evolution through types I and II. The process is represented by the arrow parallel to the equal cation lines in figure 24.

The first process postulated is believed to be largely responsible for the poor quality of water in the region northeast of the town of Three Hills. In addition to geologic conditions presumed associated with type III water in this area, groundwater movement itself is sluggish owing to the low hydraulic gradients, particularly in the area between miles 12.5 and 14.5 (Fig. 13).

A good example of the second way in which type IV water may be formed presents itself in an area northwest of Three Hills. A well-defined, north-south oriented boundary approximately 3¼ mi west of Three Hills ridge separates this area from the bowl-shaped depression characterized by types I and II water (Fig. 25). This boundary of chemical facies coincides exactly with the dividing line between the local and intermediate flow systems originating on the west slopes of Three Hills ridge, and the regional system with area of downward flow on the top of the ridge. Although the geologic conditions that cause the high mineralization and sulfate content on the east slopes of the ridge are apparently absent on the crest and west side, the great length and sluggishness of the westward moving regional system transforms the recharging type I water into highly mineralized, type IV water in the areas of upward flow. Also, the abrupt change in the total dissolved solids content between the two sides of this boundary, with intermediate values of 1000 and 2500 ppm virtually lacking, is adequately explained by the difference in hydrodynamic conditions in flow areas.

Suitability of Groundwater for Human Consumption

Standards of water quality for human consumption are generally flexible all over the world and are adjusted to the quality of waters locally available. Table 3 gives the upper limits of the more important chemical constituents in drinking water recommended by Alberta Public Health Units. On the basis of these standards, groundwater is deemed unsuitable for human consumption over a large portion of the Three Hills area due to high total dissolved solids content. These areas occupy mainly the ridges and plateaus of the divide areas between Ghostpine and Threehills Creeks (Fig. 17), with particularly poor water north and northeast of the town. Water is also highly mineralized along the west margins of the map area. The single constituent responsible for the poor water quality is sulfate, mainly in the form of Na_2SO_4 (Glauber salts) and $MgSO_4$ (Epsom salts), both of which have laxative qualities. All other constituents are generally below the accepted limits.

Table 3. Chemical Quality Standards of the Alberta Public Health Units

	ppm	
Total solids	1600	to 2000
Sulfates	400	for municipal supply
	800	for private supply
Chlorides	435	
Sodium	700	
Nitrates	10	
Iron	0.3	

The areas of good quality water are outlined by the 1500 ppm contour of the total dissolved solids content. Water is particularly good on the eastern flank of the Ghostpine basin and on its eastern water divide. Water quality is excellent in the bowl-shaped depression southwest of Three Hills ridge and good in Threehills Creek valley south of town.

The most common types of water in the Three Hills area are sodium bicarbonate-sulfate and sodium sulfate-bicarbonate. Due to the generally low amounts of calcium and magnesium, waters are soft except in regions characterized by type IV waters and in some areas with type III waters (Fig. 25) where they are hard. Due to the high concentrations of sodium, the water generally tastes flat.

Regarding both the chemical type and the areal extent of potable water, Ghostpine Creek basin is definitely superior to that of Threehills Creek. A limited area, the bowl-shaped depression southwest of Three Hills ridge, seems to contain good quality water in Threehills Creek basin. Groundwater quality is marginal or unsuitable for human consumption over most other parts of the Three Hills area.

The suitability of groundwater in the Three Hills area for purposes other than human consumption, such as irrigation, brewery, boilers, stock and so on, is not discussed. Using the basic information presented on water quality and its distribution, however, experts in these fields will be able to tackle individual requirements.

EXPLORATION AND EVALUATION OF GROUNDWATER RESOURCES

Planning and Exploration

The present exploration program was aimed at locating areas within the economic reach of the Town of Three Hills which contained adequate quantities of potable water, and at assessing the groundwater potential in an area of slightly less than six townships (204 sq mi) in the vicinity of Three Hills. The dual purpose required a dual approach in the exploration and testing program, namely detailed investigations and relatively closely spaced drilling in areas with prospects for immediate development of groundwater on the one hand, and a more general areal or reconnaissance approach involving field observations, theoretical considerations, and a few strategically located test holes on the other.

The locations for the first few test holes were decided upon after the preliminary evaluation of existing information on water levels, water quality, well depths, production rates, geology, and so forth, compiled from previous reports and supplemented by a survey carried out by the Research Council of Alberta. Further test sites were located with due consideration given to newly obtained data as work progressed.

Test drilling started in areas of inferred upward flow of groundwater, in order to secure a favorable combination of high water levels with large well depths. Subsequent drilling was carried out in areas where these features were expected to coincide with extensions of the newly discovered, promising aquifers.

The location and elevation of each test hole was surveyed, and drilling was carried out by two truck-mounted "22-W Bucyrus-Erie" cable-tool drilling rigs. Lithologic samples were taken at 5-foot intervals and processed at the test sites in order to keep the developing picture up to date and make plans accordingly. One or more bail tests, consisting of accurate water-level measurements during a two-hour period of bailing at 20 gpm and a subsequent 2-hour recovery, were conducted in each test hole, or at each major aquifer. Major pump tests, preceded by trial pump tests, were carried out at appropriate pumping rates in each of the wells which had been selected on the basis of the bail tests as prospective permanent production wells for immediate use by the town (Table 4). Water samples for chemical analysis were taken regularly from each test hole and at different stages of the pump tests. Non-pumping water levels were measured before and after each day's drilling in order to determine the variation of fluid potential with depth.

The above outlined methods and techniques have been successful in other hydrogeologically similar parts of central Alberta. Since their detailed description is available elsewhere (Tóth, 1966, p. 70-88), the present discussion is limited to a summary of the interpretation and results of the testing, and to the recommendations for development and further exploration of the area's groundwater resources.

Production Tests and Their Interpretation

Bail Tests and Selection of the Test Sites

Figure 27 shows the time-drawdown and recovery curves obtained in the test holes during bail tests. Both the drawdown and the recovery portion of the curves have been utilized to calculate the transmissibility (T) of the formations in the test holes. According to the Jacob, or straight line method (Todd, 1959, p. 94):

$$T = \frac{264 \cdot Q}{s}$$

where T = coefficient of transmissibility in gpd/ft; Q = rate of water withdrawal in gpm; and s = difference in drawdown in feet per log cycle.

On the basis of the transmissibilities calculated from bail-test results, available drawdown, distance from the town's existing water lines, and water quality, test sites Nos. 144 and 153 have been selected as the best localities for the drilling of wells for immediate additions to the town's water-supply system (Fig. 2). Additional considerations in this decision are: (1) if on the basis of further and more accurate production tests these sites are tied into the town's water system, then test hole No. 150, also with a good potential and good quality water, would be within a mile of the supply line; therefore, this well represents an ever-ready possibility for a subsequent relatively inexpensive expansion of the supply system; (2) if the town should require even further supplies of water in the future, a well at site 149 may be a good prospect. The pipe lines collecting the water from the proposed wells would run more or less parallel to the strike of the main aquifers, allowing future development of several wells between the existing ones with a minimum of expense.

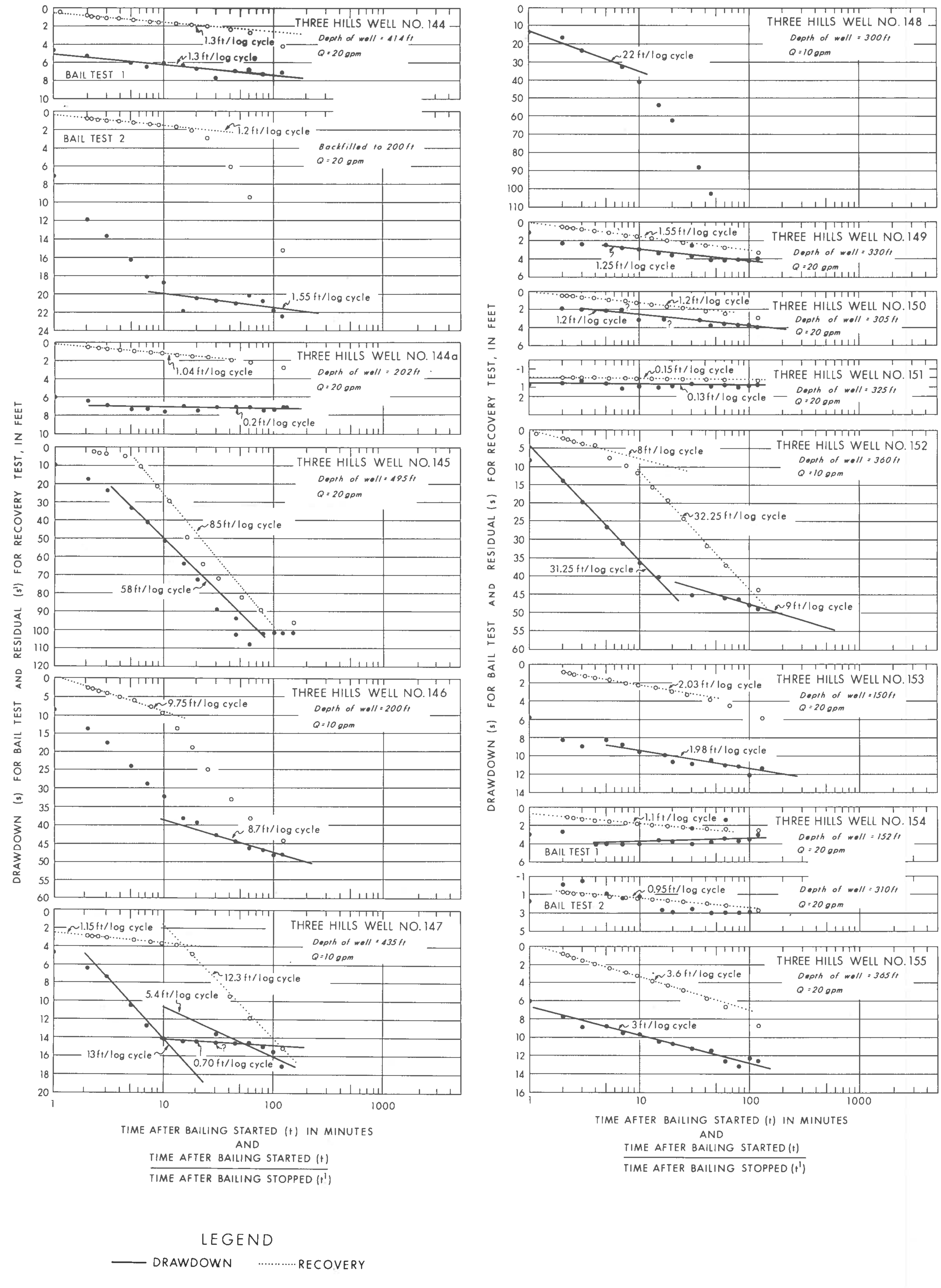

FIGURE 27.
Drawdown and recovery of water levels in test holes during bail tests.

In addition to the pump tests at sites Nos. 144 and 153, a test was conducted at site No. 151, although both its distance from the town and the poor quality of the water precluded the possibility of completing a supply well at this site. It was felt, however, that for the general area, exceptionally high transmissibilities found from the bail tests might allow the development of large quantities of water suitable for some industrial purposes with less demanding quality requirements. Also, the very presence of an area underlain by saturated rocks of high permeability is an important indication of possible occurrences of large quantities of groundwater in storage. Recognition of these factors was considered to be of sufficient value both for the general knowledge of the hydrogeologic properties of the central Alberta Upper Cretaceous rocks and for the over-all water resources of the Three Hills area to have warranted a major pump test at site No. 151.

Finally, a four-day pump test was conducted on Well No. 7. A former town supply-well, this well had been out of use for several years because its reduced production did not justify operating and maintenance expenses. The purpose of this test was to establish the well's potential value as a standby for the town.

FIGURE 28. Pump test on Three Hills Well No. 153a.

Each pump test at sites Nos. 144, 151, and 153 (Table 4) was carried out in test wells drilled 25 feet from the original test holes (Fig. 28) to depths several tens of feet below the major aquifers. These test wells are referred to as Well Nos. 144a, 151a, and 153a, respectively. Casing of 10⅝ in. outside diameter was tightly driven to the top of the aquifers in these holes, and the holes were left open against the water-bearing strata. Thus, in case of satisfactory results, the supply wells would be partially completed. In this way the same expenditures would cover part of the testing and part of the development programs.

Some technical details of the production tests and certain aspects of the interpretation are discussed below.

Pump Tests

Pump test 1, Three Hills Well No. 153a

Time of start and finish of pumping: March 7, 9:00 a.m., March 13, 9:50 p.m. Duration of pumping: 156.8 hrs. Depth of well: 135 feet. Diameter of well: from 0 to 25 feet — 13 in.; from 25 to 65 feet — 10 in.; from 65 to 135 feet — 8½ in. Casing: from 0 to 67.2 feet — 10⅝ in. O.D.; open hole from 67.2 feet to bottom. Pump set at 100 feet. Non-pumping water level: 15 feet. Maximum depth to water during pump test: 62.5 feet. Maximum drawdown reached during test: 47.5 feet. Average pumping rate: 67 gpm. Depth to the top of the first important water occurrence in the bedrock: 100 feet. Water levels observed in pumping well and seven observation wells, one of which was equipped with automatic water-level recorder.

The detailed water-level measurements of this test are included with Appendix D.

Apart from the pumped well and well No. 153, measurable drawdowns attributable to the test pumping could only be observed in wells Nos. 153b and 153c which, however, were intermittently pumped by their owners. Quantitative interpretation of the test, therefore, is based on the time-drawdown curves obtained in the pumped well and at the observation well with the automatic water-level recorder (Fig. 29). Transmissibility values have been calculated by the straight line method for the pumped well, and by Theis' method for the observation well. However, the interpretation of the pump-test data did not consist of a simple application of the above-mentioned methods, or some other published technique, because no available, and geologically realistic theoretical model would yield time-drawdown relations such as those observed during the pump test.

For the initial 100 minutes of pumping, the Theis plot of the drawdown values follows the nonleaky artesian type curve, and water levels fall on a straight line on Jacob's semi-logarithmic plot. After the initial period, however, the rate of drawdown increases relative to that required by the straight line or artesian type curve. After a period of deviation from the theoretical, not attributable to a finite number of discharge boundaries or to any other clearcut cause, the time-drawdown curves, for a second time, follow the artesian type curve and the straight line, in the observation and pumping wells, respectively. Values of transmissibility calculated from the two curves are in fair agreement for both portions of good fit. The average of the two curves obtained for the first 100 minutes is $T = 3030$ gpm/day foot, and for the period after the first day of pumping $T_e = 1301$ gpm/day foot.

The same phenomenon was observed and reported in detail by the author for pump tests in other parts of central Alberta (Tóth, 1966). The explanation was summarized in the following statement (*ibid.* p 78): "The general conclusion from the analysis of the time-drawdown curves is that the wells are located in formations of relatively high permeability which are adjacent to areas of lower-permeability material, and that the line of contact does not follow a simple pattern". The applicability of this conclusion to pump tests conducted at site 153 in the Three Hills area is corroborated by the following, independent observations of geology and hydraulics:

(1) the presence of a lithologically continuous, channel-shaped body of medium- to coarse-grained, relatively clean sandstone, established from drill cuttings;

(2) the relative uniformity of the transmissibilities of different points in this sandstone, exceeding by at least an order of magnitude the transmissibilities measured in adjacent rocks — this is based on bail tests results (Fig. 9);

(3) the irregular nature of the cone of depression inferred from water level observations in surrounding wells, during the pump test at site 153 (Appendix D).

On the strength of these observations, the above explanation of the Olds situation is thus accepted to be valid for the Three Hills area. The transmissibility value calculated from the early parts of the time-drawdown curves is thought to represent the actual T of the aquifer at the test site.

That portion of the time-drawdown curves during which the rate of drawdown is higher than theoretically expected (i.e. the transition period from the early to the late stabilized portions) is attributed to the cone of depression reaching the producing but relatively low permeability rocks along the sandstone channel, and its points of intersection migrating away from the pumping well and along the irregular boundaries of contact as pumping continues. After the cone of depression has extended over an area which is large compared to the dimensions of the high permeability rocks in the pumped well's immediate surroundings, the time-rate of drawdown will be determined by the average permeability of all the rocks sampled by the cone, including the sandy, silty, and shaly phases of the rocks. This new, large volume of water-bearing and transmitting rock will act as a large aquifer contributing at different rates from its different areas to the pumping well. *Non-homogeneities which were important on a local scale become insignificant*, and the rate of time-drawdown will conform again to that expected theoretically in a homogeneous, infinite aquifer, as long, at least, as other major (formational or group) boundaries are not intersected by the continuously expanding cone of depression. A theoretical, "equivalent aquifer" with specified physical characteristics can be postulated, the transmissibility of which would be the same as that resulting from the cone of depression sampling a large volume of heterogeneous rocks, and which can be calculated from the late part of the field-data curve. This "equivalent transmissibility", T_e, which in a previous report was called "apparent transmissibility", is used in estimating safe yield.

With available drawdown H = 72 feet (well loss experienced during the test subtracted) and equivalent transmissibility T_e = 1300 gpd/ft, the equation

$$Q_{20} = \frac{T \cdot H}{2110}$$

gives $Q_{20} \sim 45$ gpm for well yield for 20 years, and $Q_{20S} \sim 30$ gpm, for safe yield, if a safety factor of 0.7 is applied.

Pump test 2, Three Hills Well No. 151a

Time of start and finish of pumping: March 22, 10:00 a.m., March 24, 10:00 a.m. Duration of pumping: 48 hrs. Depth of well: 130 feet. Diameter of well: from 0 to 79 feet — 12 in.; from 79 to 130 feet — 8 in. Casing: from 0 to 79 feet — 10⅝ in. O.D.; open hole from 79 feet to bottom. Pump set at 80 feet. Non-pumping water level: 34.37 feet. Maximum depth to water during pumping test: 50.68 feet. Maximum drawdown reached during test: 16.31 ft. Average pumping rate: 188 gpm. Depth to the top of the first important water occurrence (in the bedrock): 50 feet. Water levels observed in pumping well and one observation well equipped with automatic water-level recorder.

The detailed water-level measurements of this test are included with Appendix E*.

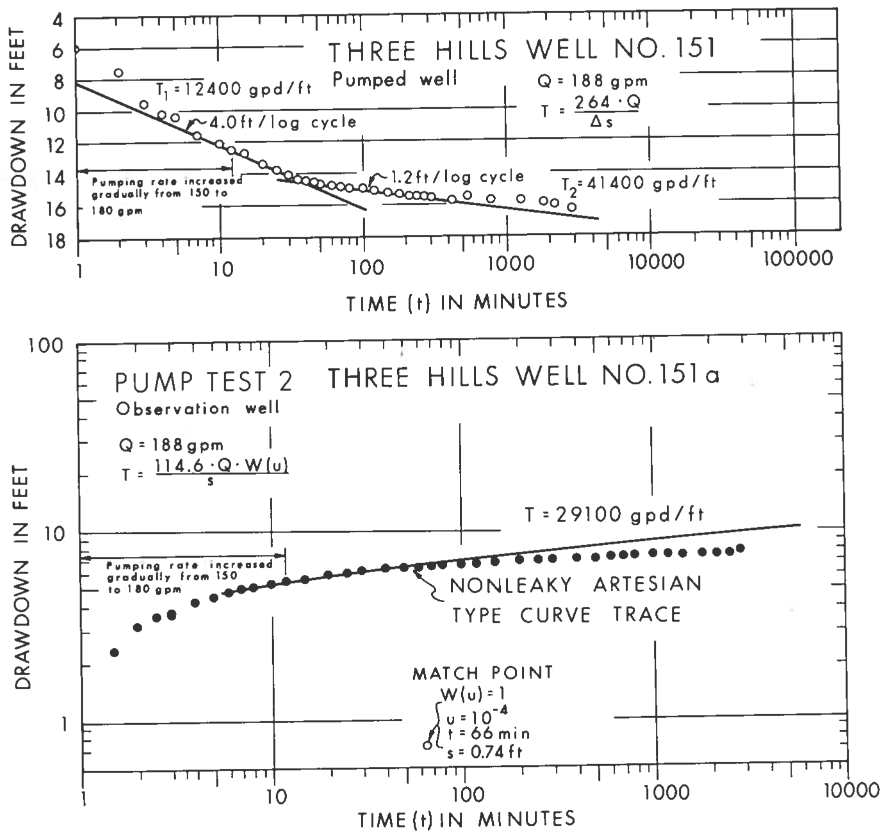

FIGURE 30. Time-drawdown curves for Three Hills Well Nos. 151 and 151a during Pump Test 2.

*Appendix E not included with published report. Copies are available on request.

Figure 30 shows the time-drawdown curves obtained in the pumped well and observation well. The pumping rate gradually increases from 150 gpm to 180 gpm during the first 12 minutes of pumping, the curve becoming straight (Fig. 31, Well No. 151a) after approximately 40 minutes of pumping. Water levels deviate upward from this straight line when the water level is drawn down to approximately 50 feet (a drawdown of 16 feet). Since the top of the aquifer is at a depth of 50 feet, the upward deviation of observed water levels may indicate the confined aquifer becoming a water table one, and may reflect the effect of gravity drainage. If the aquifer is treated as a confined one — the water level is not permitted to drop below its upper boundary (50 feet) — and if the water level is read at the beginning of the second straight limb; i.e. at 40 minutes and at approximately 48.5 feet, H becomes 1.5 feet. The yield of the aquifer for 20 years at this site will then be that rate which causes the water level to drop from 48.5 feet to 50 feet over 6.5 log cycles. With 41,400 gpd/ft for transmissibility (Fig. 30a):

$$Q_{20} = \frac{T \cdot H}{6.5 \cdot 264} = 36 \text{ gpm},$$

or, with a safety factor of approximately 0.7:

$$Q_{20S} = 25 \text{ gpm}.$$

Unfortunately, water level measurements obtained in the observation well could not quantitatively aid in the interpretation because known theoretical curves could not be matched adequately to the field data curve (Fig. 30b). However, the observed curve does indicate a lower rate of drawdown than that expected in a confined aquifer without any source of recharge.

From the available information, the type, location, and extent of this extra source of recharge could not be determined, and the purpose of this test would not have warranted further investigations. At present, the conclusion regarding test site 151 is as follows: the safe yield for 20 years of a single production well, under confined aquifer conditions, is estimated at 25 gpm. If the water levels are allowed to drop below the top of the aquifer, larger yields may be obtained. The most important aspect of this test site is the fact that the possible existence of high permeability formations in high bentonitic, nonmarine Upper Cretaceous strata has been demonstrated.

With respect to development of this aquifer, a well field consisting of several low yield production wells appears to be the best solution at this time. However, further testing is necessary before full-scale development may be considered.

It must be pointed out that, as the water quality in the aquifer is poor (approximately 2700 ppm total dissolved solids), the water is unsuitable for public supply.

Pump test 3, Three Hills Well No. 144a

Time of start and finish of pumping: April 14, 8:00 a.m., April 21, 8:00 a.m. Duration of pumping: 168 hrs. Depth of well: 202 feet. Diameter of well 6¼ in.; size of casing 7 in. O.D. from 0 to 95 feet; open hole from 95 feet to bottom. Pump set at 100 feet. Non-pumping water level: 54.29 feet. Maximum depth to water during pumping test: 93.09 feet. Maximum drawdown reached during test: 38.8 feet. Average pumping rate: 51.2 gpm. Depth to the top of the first important water occurrence: 93 feet. Water levels observed in pumping well and one observation well equipped with automatic water-level recorder.

The detailed water-level measurements of this test are included with Appendix D.

Figure 31 shows the time-drawdown curves obtained in the pumped well and observation well. Once again it is noted that the field data curves match the artesian type curve or follow a straight line for the observation well and pumped well, respectively, during the early and the late portions of the test, and the matching portions are linked by gradually changing transitional sections. The technique of interpretation is basically the same as that described in connection with test 1. Differences in details are caused by locally different geologic conditions, which have to be taken into account in each individual case and cannot be schematized.

The same approach used in the interpretation of test 1 yields the following results for site 144: formation transmissibility: $T = 4650$ gpd/ft; equivalent transmissibility: $T_e = 920$ gpd/ft; safe yield for 20 years: $Q_{20s} = 15$ gpm.

Pump test 4, Three Hills Well No. 7

The time-drawdown and recovery curves obtained during the four-day pumping test (at 7.5 gpm) of Three Hills Well No. 7, a former town supply well, are given in figure 32. From both the drawdown and recovery curves, the straight line method yields $Q_{20s} = 1.5$ gpm for safe yield of this well.

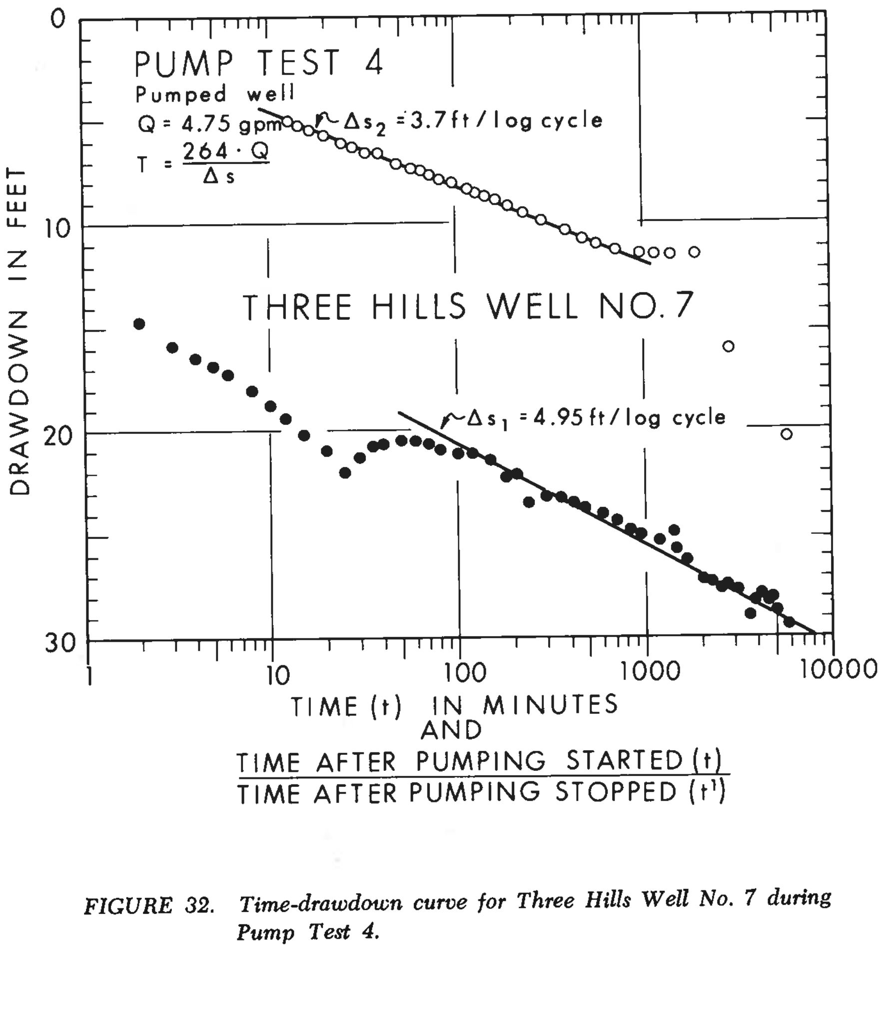

FIGURE 32. Time-drawdown curve for Three Hills Well No. 7 during Pump Test 4.

Thus, the well may be pumped up to 5 gpm for 6 or 8 hours a day if it is not pumped during the remaining time. Due to a low available drawdown (24 feet) combined with low transmissibility (475 gpd/ft), it cannot produce even occasionally at rates over 10 gpm. This implies that the well is of little use for emergency purposes.

TABLE 4. SUMMARY OF PRODUCTION TESTS CONDUCTED DURING THE THREE HILLS TEST PROGRAM

Three Hills Well No.	Date and type of test	Depth of hole at time of test (feet)	Duration of production period	Rate of water withdrawal (gpm)	Depth to nonpumping level at time of test	Available drawdown (feet)	Maximum drawdown during test (feet)	Transmissibility (gpd/ft)		Yield for 20 years (gpm)	Remarks
								of the formation	equivalent		
144	December 7 1965; *bail*	414	120 min	20	54	40	7.01	4061		77	
144	March 29 1966; *bail*	200	120 min	20	52.50	43	22.48	3855		79	Large well loss probably due to partial cementing off of the aquifer
144a	March 30 1966; *bail*	202	120 min	20	52.82	42	7.58	5080		100	
144a	April 14 - April 21 1966; *pump*	202	(7x24) hrs	51.2	54	38	38.80	~4650	~920	15 to 20	T shown is the average for the pumped and observed wells
145	December 15 1965; *bail*	495	150 min	20	17	174	107.63	76		6	No additional drawdown could be observed after 80 min of bailing. Interpretation uncertain
146	December 21 1965; *bail*	200	120 min	10	62	63	48.03	287		8	
147	January 18 1966; *bail*	435	120 min	10	161	210	17.05	800		80	
148	January 13 1966; *bail*	300	60 min	10	51	29	129.34	120		2	
149	February 7 1966; *bail*	330	120 min	20	124	66	4.19	3760		118	
150	February 8 1966; *bail*	305	120 min	20	23	40	3.90	4390		83	
151	February 17 1966; *bail*	325	120 min	20	32	46	1.17	40610		885	
151a	March 22 - March 24 1966; *pump*	130	(2x24) hrs	~188	34.37	18	16.31	41400		36	If partial dewatering of aquifer is allowed yield becomes higher
152	February 21 1966; *bail*	360	120 min	10	17	71	48.84	310		10	
153	February 25 1966; *bail*	150	130 min	20	15	a, 64 b, 90	12.11	2624		a, 80 b, 112	90 ft for available drawdown seems more correct
153a	March 3 1966; *pump*	135	180 min	67	15	85	26.05	3000		121	This was a preliminary pump test
153a	March 7 - March 13 1966; *pump*	135	(6x24 + 12) hrs +50 min	67	15	85	47.50	~3030	~1300	~(42) 45	T shown is the average for the pumped and observed wells
154	March 1 1966; *bail*	152	120 min	20	89	23	4.01	4800		52	
154	March 4 1966; *bail*	310	120 min	20	89 97	23 172	3.00	4800 700		52 57 (109 gpm)	Independent development of the two aquifers is advisable
155	March 17 1966; *bail*	365	120 min	20	30	65 196	13.17	1613 ~800 + 800		I + II together 50 I + II separately 99	Independent development of the two aquifers is advisable
7 (Town Well No. 3)	April 26 - April 30 1966; *pump*		(4x24) hrs	7.5	57.90	24	29.44	475	475	2	

Recommendations for Town's Water Supply

On the basis of geological considerations, flow-system evaluations and the results of bailing and pumping tests, the following recommendations are given with respect to additional development of water supplies for the Town of Three Hills.

The following test sites merit consideration as locations for the development of permanent supply wells for the town: Nos. 144, 149, 150, and 153 (Fig. 3). Test holes Nos. 144a and 153a have been pump-tested and bail-tested. From the production tests and from a comparison of geologic conditions at the test sites, the 20-year safe yields, at continuous pumping, of properly completed and developed supply wells are estimated as follows:

Test site No.	Safe yield (gpm)	Basis of estimate
144	15	pump test
149	35	inference
150	30	inference
153	30	pump test

The major chemical constituents of groundwater at these test sites are listed below (in ppm).

Test site No.	$Na^+ + K^+$	Hardness	$CO_3^{--} + HCO_3^-$	SO_4^{--}	Total solids
144	652	32	995	576	1832
149	422	21	663	336	1156
150	302	162	664	234	1080
153	516	36	868	351	1624

Since a single well will not contribute a major part of the town's water supply and also have acceptable water quality, combined use of several wells is recommended. If the location of the nearest point of the town's existing pipe line is considered, the development and joint use of Wells Nos. 144, 153, and 150 seems most preferable. According to the above estimated safe yields, the combined production of these wells should be 75 gpm, sufficient to supply approximately 2000 new water users at the present (1967) rate of consumption.

If need should arise, a well at site No. 149 may be added to the supply system. Development of a well there, however, should be preceded by further drilling and careful pump testing between sites Nos. 5 and 149 in order to test the inferred presence and high productivity of a channel sandstone aquifer[1].

[1]While this report was being edited during the fall of 1967, the town had two test holes drilled at sites determined by the writer, between former sites 5 and 149. The predicted sandstone channel was found to exist, and preliminary production tests indicated favorable prospects for the development of permanent production wells.

The spread of the cone of influence around prospective Wells Nos. 144a and 153a may affect nearby farm wells. Insufficient field data were collected to determine the shape and magnitude of the pumping cone. Experience in other areas suggests that some drawdown (a few feet) is expected to develop within a radius of approximately ¾ of a mile around Well 144a. Regarding test site 153, observations of water levels during pumping indicate that the main direction of the expansion of the cone of influence is south and southwest. Wells within a wedge shaped sector with the apex at test site 153 and sides oriented southeast and southwest (Fig. 9) will definitely be seriously (several tens of feet) affected by continuous pumping of site 153.

The average rate of present consumption of water by the town is approximately 90 gpm. With a maximum additional development of 75 gpm at sites Nos. 144, 150, and 153, the total may be increased to 165 gpm. Considering that the areal rate of safe production is estimated to be at least 19 gpm per square mile, a maximum area of $165 \div 19 \sim 9$ sq mi should be reserved for the town's water supply purposes. It is recommended, therefore, that withdrawal of groundwater for purposes of the town's supply and normal farm use be permitted only within the area outlined in figure 9.

Areal Availability of Groundwater in the Three Hills Area

From observed fluctuations of water levels and flow-system analysis, it has been estimated that groundwater is renewed annually at an average rate of approximately 20 gpm/sq mi in the Three Hills area. Theoretically, this is the amount of water that may be withdrawn at the expense of natural discharge without drawing on the non-renewing portion of the groundwater reserves. In the absence of detailed knowledge of the distribution and magnitude of the specific yield in the rocks, an estimate of the non-renewable reserves would be purely speculative. Until more detailed information becomes available, all that can be said is that on the average a minimum yield of water of 20 gpm/sq mi may be withdrawn from the upper 300 feet of strata in the Three Hills area without depletion of water stored in the rocks. The upper limit cannot be calculated at this time. However, if it is considered that owing to the high rate of evaporation, 90 per cent of the precipitation cannot even enter the groundwater regime, and that permeabilities are relatively low even in the most permeable regions of the local rocks, it may be inferred that the upper limit of water yield will not exceed the minimum rate by an order of magnitude:

it will be less than 200 gpm. Thus, it is suggested that a safe estimate of the average, permanent groundwater yield that can be developed in the Three Hills area is between 20 and 60 gpm/sq mi.

The amounts and possible rates of withdrawal of mineable, potable water in the Three Hills area are low due to the fine-grained and bentonitic nature, low permeability, and shallow depth of the rocks containing them. It seems, therefore, that the development of major perennial sources of potable groundwater is limited by the renewing portion of the local groundwater reserves.

Although the possible withdrawal of 20 to 60 gpm/sq mi of groundwater has been postulated, the locations which are potentially capable of producing that quantity at economic pumping rates are unevenly distributed within the area. In general, the valley of Ghostpine Creek, primarily its east flank, seems to be the best area for consistent, major developments of groundwater. Also, the quality of water is best here. In Threehills Creek valley prospects are best in the area recommended for the town's supply. The bowl-shaped depression west of Three Hills ridge, although not tested, may present good prospects with its active flow systems and good quality water.

The general area at test site No. 151 seems to be underlain by high permeability, shallow formations, permitting the development of large amounts of groundwater at rates probably in excess of 100 gpm/sq mi. The necessity for a field of several shallow wells to produce large quantities of water at this location and the poor quality of water, however, may be a deterrent to development there. High permeability strata containing inferior quality water were also located at site No. 154.

For further groundwater exploration in this general area the following steps are recommended: (1) detailed investigations in the bowl-shaped area west of Three Hills ridge; (2) detailed investigations in the area surrounding site No. 151; (3) detailed reconnaissance along the east flank of Ghostpine Creek valley; (4) detailed investigations surrounding site No. 154 (Fig. 11).

SUMMARY

Town Supply

In accordance with the first purpose of the present study (see Introduction), supplies of groundwater suitable for use by the Town of Three Hills have been either located or indicated at several sites. The estimated and recommended safe yields for a period of 20 years of continuous pumping at sites Nos. 144 and 153 are 15 gpm and 30 gpm, respectively. Permanent production wells have been partially completed at these sites as part of the test program. Although testing is still required for the final evaluation of the groundwater potential at sites Nos. 149 and 150, it is estimated that a well at each site, capable of producing 35 gpm and 30 gpm, respectively, may be developed. Thus, four sites with a total potential of 110 gpm of groundwater have been located with 45 gpm being immediately available for the town and 65 gpm still requiring some final testing. If the present rate of water consumption is considered, the newly discovered sources of water should satisfy the requirements of an additional population of over 2000.

The total dissolved solids content of the water at these sites ranges between 1000 ppm and 1800 ppm. The hydrochemical facies at each of the mentioned sites is sodium bicarbonate-sulfate, being characterized by a sodium + potassium content of 80 to 100 per cent of the total cations and a bicarbonate + carbonate content of 40 to 74 per cent of the total anions. The balance of the anions is made up almost entirely of sulfate.

Interference between the proposed wells and existing wells in that area is expected. The areal extent and magnitude of the interference cannot be estimated precisely from the available information. It may, however, be several tens of feet to the south of site No. 153 and up to a few feet within ¾ mile around site No. 144.

In case full development of all the above-mentioned sites is planned, an area of over 9 square miles should be reserved for withdrawal of water by the town and normal farm use. The area is outlined in figure 9.

Areal Reserves

The average long-term safe yield of groundwater in the Three Hills area is estimated to be between 20 and 60 gpm/sq mi. Owing to the limited rate of natural recharge and the generally low permeability of the water-bearing formations, the upper limit is not expected to increase significantly, even where the permeabilities of local aquifers are high. Even if hydrogeologic conditions leading to the above restriction are not taken into account, the very favorable local permeabilities found in certain regions (e.g. site No. 151) may result in over-optimistic estimates regarding sustained safe yield of wells in the continental geologic environment of the Three Hills and similar areas.

The quality of water in the area of study varies from good (less than 1000 ppm total dissolved solids) to unsuitable (over 2500 ppm). The most common type of water is sodium bicarbonate-sulfate, although sodium bicarbonate-type water also occurs over relatively large areas.

Small supplies of groundwater (0 to 5 gpm) can be developed in practically any part of the study area. Medium supplies (5 to 50 gpm) occur in irregularly distributed pockets, and their location and testing may require considerable search and expenditure. Large, permanent supplies (over 50 gpm) are not known to occur in the area, and the prospects for such amounts of water are believed to be very poor.

Research Aspects

Safe Yield Estimates

The peculiar behavior of the time-drawdown curves observed in pump tests of wells in Upper Cretaceous continental strata in other parts of central Alberta was reconfirmed in the course of the present study. The phenomenon consists of the time-drawdown curve being composed of two or more segments, each of which matches certain portions of theoretical curves derived for non leaky confined aquifers of infinite areal extent. The successive limbs are linked by sections of gradual transition, and they cannot be attributed to the effects of well-defined barrier boundaries. The present interpretation of this phenomenon is that the time rate of drawdown along the first limb is determined by the actual transmissibility of the aquifer into which the well is drilled, whilst subsequent time rates of drawdown are governed by the average, diminishing permeabilities of the continuously increasing rock volumes reached by the expanding cone of influence.

Values calculated with transmissibility formulas from later segments of field-data curves are called here "equivalent transmissibility" (T_e) values, and are used in safe yield calculations, since they represent time rates of drawdown which would occur in a truly confined aquifer of infinite areal extent having a transmissibility of T_e. Calculated T_e values are expected to decrease as the duration of pumping increases, approaching a value which is determined by the permeability and thickness of the whole rock complex contributing water to the well; i.e. to the value determining the basin safe yield (see later paragraphs). The final value of T_e may be obtained by means of long pumping tests (7 days $\sim$ 4 log cycles, or more) only, and safe yield estimates based on short pumping tests (few hours or even a day) may be, therefore, quite misleading. Details of safe yield calculations, based on the above observations are found on page 00 (pump test 1).

Electric Model

An electric analog model has been designed, constructed, and applied to modeling fluid-potential distribution along vertical cross sections in three drainage basins of the Three Hills area (Appendix A).

An analysis of the electrical models of the basins shows that the lines of force converge toward areas where, by analogy, the water table has a steep slope, whether these areas are near water divides (recharge areas) or valley bottoms (discharge areas). A steep and high water divide with gently sloping, broad valley flanks (Fig. 13, Basin 1) constricts the recharge end of the flow systems, resulting in the area of downward flow being smaller than the area of upward flow. An inverse situation, namely broad, flat uplands with a narrow, deeply incised valley makes the discharge end of the flow pattern converge, restricting the areas of upward flow to the immediate vicinity of the stream channel. On the average, approximately 50 per cent of the area of study is underlain by areas of downward flow, and 50 per cent by areas of upward flow. However, this distribution may change considerably from basin to basin depending on the topographic configuration of the water table; thus, the relative extent of the area of downward flow varies between 40 per cent (Basin 1) and 70 per cent (Basin 3) in the Three Hills area.

With the aid of the electrical cross sections, abrupt changes in groundwater quality west of Three Hills ridge have been plausibly explained. In this region the boundary between areas of slightly mineralized sodium bicarbonate-type waters and areas of highly concentrated sodium sulfate-type waters coincides with the boundary between the shallow, short, intensive flow systems, and the long, retarded system as obtained from the model.

Depth of Intensive Flow

Test drilling and well surveys indicate that the depth of near-surface economic water occurrences in the Three Hills area is a function of the topography rather than geology. Since the only known active physical process which penetrates from the surface to depths of several hundred feet, and which is closely related to topography, is groundwater flow, it is suggested that an increase in permeability is associated with the zone of relatively intense movement of groundwater in the area of study. This zone is approximately 300 feet deep, except near the Red Deer River, where, probably due to more deeply penetrating flow, it may be 400 feet. The presumed increase in permeability is tentatively attributed to an internal mechanical rearrangement of fine and colloid-size grains in the rock framework, and to a chemical transformation (cation exchange) of the swelling sodium montmorillonite content of the rocks into calcium bentonite which has lower swelling properties.

Natural Basin Yield, Areal Production, Flow Velocity, and Rock Permeability

If observations of water-level changes during periods of ground frost are valid and the 1:1 ratio of recharge areas to discharge areas obtained from the electrical model is accepted, a natural basin yield of 9 per cent of the precipitation can be calculated. This value corresponds to a depth of water of 1.35 in./year or approximately 38 gpm/sq mi. Groundwater is hydraulically discharged at the above rate in the areas of upward flow. The safe, areal production rate of water available for human purposes, the withdrawal of which will not effect stored reserves, is taken to be half of the natural basin yield, i.e. approximately 19 gpm.

With 300 feet for the average depth of the zone of intensive flow and with a porosity of 10 per cent, an average velocity of groundwater flow of 0.1 ft/day or 3 cm/ day is obtained for the mid-line areas of the flow systems. If this value is combined with the natural hydraulic gradients estimated from the water-level map (Fig. 10), the average permeability of the rocks in the Three Hills area is calculated to be $4.5 \cdot 10^{-2}$ gpd/ft^2 or $3 \cdot 10^{-3}$ darcys, a value characteristic of poor aquifers.

Although these results are tentative, being based on incomplete data together with theoretical considerations, they do accord reasonably well with what little similar data has been published. Development and refinement of the theories and techniques upon which these results are based would contribute to the efficiency of locating water supplies in Alberta, to the precision associated with estimating the balance and the reserves of groundwater over extended areas, and to the elucidation of various questions of scientific interest in the realm of hydrogeology.

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APPENDIX A.

ELECTRIC ANALOG MODEL OF REGIONAL GROUNDWATER FLOW

The dual purpose of the design of an electric analog is: (1) to investigate the feasibility of constructing two-dimensional electric models of natural fluid-potential distributions in drainage basins with arbitrary geometry, without the imposed constraint of any *a priori* determined point of the basin surface being a point of input or output (recharge or discharge, respectively); and (2) to obtain an idea of the types, distribution, and intensity of groundwater flow systems in the Three Hills area. This information would be used in estimating natural yield and related basin parameters.

For information regarding the physical nature and mathematically derived, theoretical distribution of fluid potential in natural drainage basins, the reader is referred to previous studies by Hubbert (1940, 1957), Tóth (1963), and Freeze and Witherspoon (1966).

Modeling fluid-potential distribution by electrical analogy is possible because of the physical and mathematical similarities between the laws governing electric currents and the movement of fluids in permeable, regionally extensive media.

The behavior of electric currents is described by Ohm's Law, which in vector form is (Hubbert, 1957, p. 32):

$$\vec{i} = -\delta_e \, \overrightarrow{\text{grad}} \, V \qquad (1)$$

where $\vec{i}$ = current density; δ_e = electric conductivity; and V = electric potential.

On the other hand, Darcy's Law states:

$$\vec{q} = -\delta \, \overrightarrow{\text{grad}} \, \phi \qquad (2)$$

where $\vec{q}$ = specific volume discharge of the moving fluid;

$\delta = \frac{Nd^2\rho g}{\mu}$ = hydraulic conductivity;

N = a shape factor; d = characteristic particle size; ρ = fluid density; μ = viscosity; g = acceleration due to gravity; $Nd^2 = k$ = intrinsic permeability; and ϕ = fluid potential. In an isotropic medium δ is a scalar quantity, and the flow lines $\vec{q}$ and the lines of force $\vec{E} = -\vec{grad}\,\phi$ are parallel. If the solid is anisotropic, δ is a tensor, and the directions of $\vec{q}$ and $\vec{E}$ will generally be different. From the comparison of Ohm's and Darcy's Laws, it is clear that V and ϕ are physically equivalent qualities of the electric and hydraulic force fields, and that in regions of corresponding boundary conditions their distributions will be similar. This recognition forms the basis of modeling fluid flow through permeable media by electric analogy.

For a homogeneous, incompressible fluid, the fluid potential is calculated by:

$$\phi = gz + \frac{p - p_o}{\rho} \qquad (3)$$

where z = elevation above a standard datum; p = fluid pressure; and p_o = atmospheric pressure. At the water table, where $p = p_o$, the fluid potential is: $\phi_t = gz_t$, z_t being the elevation of the water table above the standard datum. The hydraulic head, h, is the elevation above datum to which the fluid rises from a given point of the flow region. Since h and the fluid potential are related by $\phi = hg$, it follows that the fluid-potential distribution in a flow region is equally well characterized by the distribution of h, which is a physically measureable quantity. It is equal to the elevation above datum of the non-pumping water level in a well open to the rocks at one point. Furthermore, the hydraulic head at points of the water table is equal to z_t. This means that knowing the topograhic elevation of the water table at each point is mathematically equivalent to knowing the fluid-potential distribution along the upper boundary of the region of saturated flow.

The electrical analog of a hydraulic flow field, therefore, must consist of an electrically conducting medium with the following properties: a geometry which is similar to that of the hydraulic flow field; an electric potential distribution on the upper surface, which is proportional to the elevation of the water table; and boundary conditions with respect to the electric potential which are similar to those of the hydraulic flow field with respect to the fluid potential.

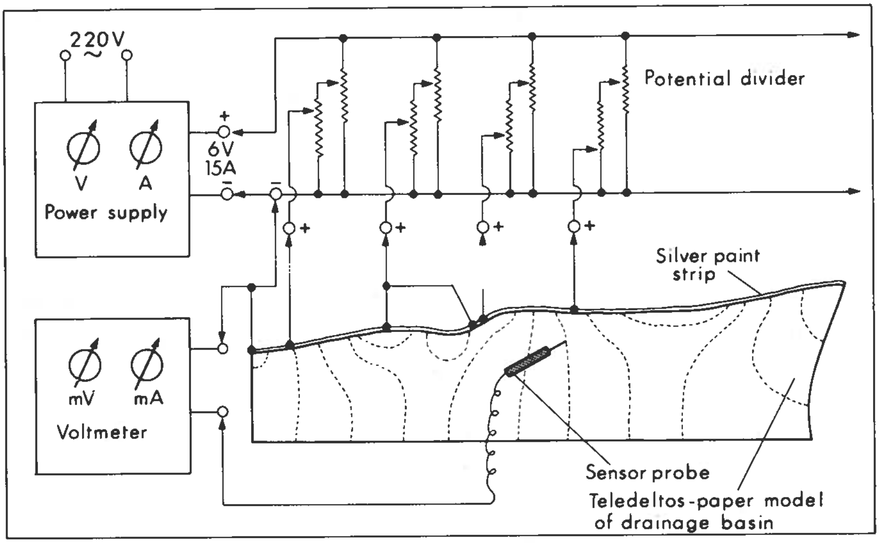
In addition to these criteria, if conditions of a natural drainage basin are to be imitated, then any point of the water table should be allowed to function both as a point of recharge and discharge. The actual aspect should depend only on the integrated effect which all other points have on the potential value at the point in question, i.e. it should be the result of the configuration of the potential at the water table.

There are various ways by which two- and three-dimensional analogs may be constructed (Karplus, 1958). None of the analog types known to the author, however, allow the experimenter to produce arbitrarily variable potential values at a large number of points (e.g. 100) without the direction of the current being predetermined at each point.

A short summary of the design of an electric analog capable of reproducing two-dimensional fields of force and of satisfying each of the above mentioned criterion is given below.

The main components of the electric analog are (Fig. 33b): (1) direct current power supply; (2) potential divider; (3) voltmeter; and (4) electrical conducting paper, or "field map". A schematic circuit diagram is given in figure 33a. The electrical conducting paper is cut to the shape of the cross section of the drainage basin to be modeled. The top of the model cross section represents the configuration of the water table along the cross section of the actual drainage basin. At characteristic points along this upper boundary, pins are inserted into the conducting paper. In order to establish an even distribution of potential along the top, and to provide good contacts between the electrode pins and the paper, a silver-paint strip of approximately 2 mm in width is applied along the upper edge of the conducting paper. The electric potential at each electrode is set by means of a coupled pair of potentiometers of the potential divider, and is adjusted to a value proportional to the topographic elevation of the water table at that point. Differences in electric potentials between any two points of the potential field are measured with a voltmeter, and lines of equal potential are mapped by moving the probe on the paper between points where the value of the measured potential does not change. The customary (but not mandatory) procedure is to measure potential differences with respect to the lowest value in the field and to trace equipotential lines with the aid of a zero-centre galvanometer.

The obtained lines of equal electric potential represent the *lines of force* in the field of fluid potential. The *lines of flow* are parallel to these lines only if the permeable solid is isotropic. If, however, the areal distribution of δ, as a tensor, is known, the flow vector may be calculated in



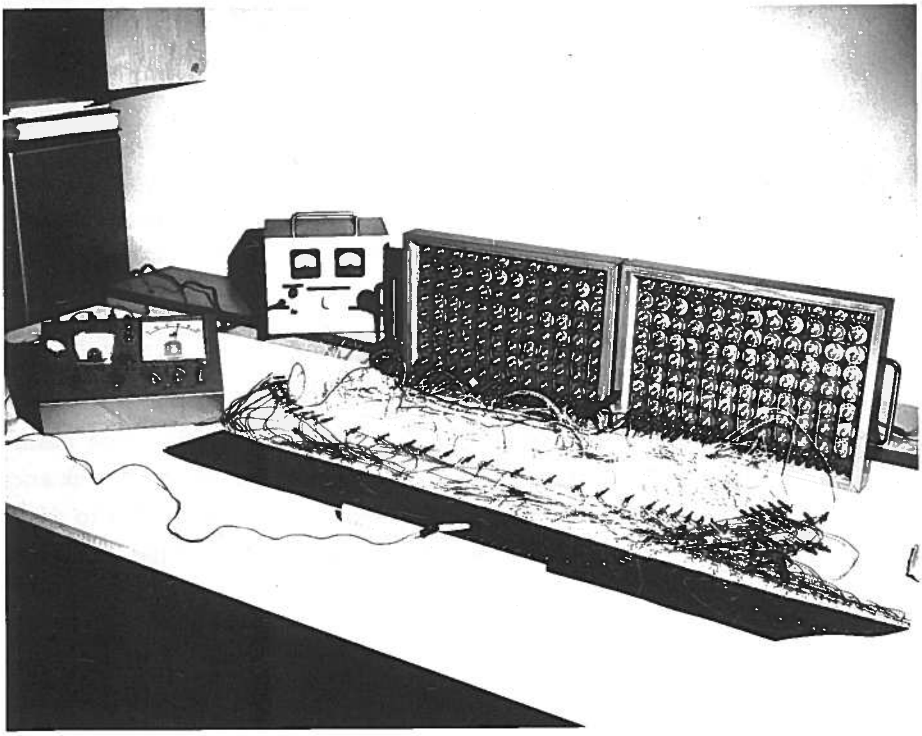


FIGURE 33. Schematic circuit diagram and photograph of electric analog model.

each point of the region from the measured field of force by Darcy's equation. The real problem in actual cases is that the field distribution of δ is unknown and *not* that it cannot be taken into account.

In applying the above outlined electric analog to the Three Hills area, the following assumptions were made (for details see discussion on the hydrogeologic environment): (1) the flow region is hydraulically continuous with a subhorizontal and impermeable lower boundary, whereas its upper boundary is a close replica of the land surface; (2) no groundwater flow crosses the vertical planes under Kneehills ridge and the Red Deer River within 6000 feet of the surface; (3) the hydraulic conductivity is a scalar and is constant.

The first step in modeling the fluid-potential distribution along an east-west vertical cross section across the Three Hills area by means of the outlined electric analog was to determine the nature and position of the boundaries of major groundwater drainage basins, provided these do exist. To this end, a model of a 25-mile long and approximately 6000-foot deep vertical cross section was prepared, reaching well beyond the boundaries of the actual area of study (Figs. 2 and 3), namely from Kneehills ridge (mile 0) to the Red Deer River (mile 25). The obtained distribution of fluid potential is shown in figure 13a. The main conclusion from this result is that the effect of the potential differences associated with the area's major surface-water basins is sufficient to generate vertical potential gradients reaching to the bottom of the 6000-foot deep flow region, thereby dividing the cross sectional area into closed groundwater basins, across the lateral boundaries of which the potential gradient is zero. These groundwater basins may be regarded as the vertical downward extensions of the corresponding surface-water basins. The basins are designated by numbers as follows: No. 1: Threehills basin, extending between the Kneehills and Three Hills ridges, from mile 0 to 11.6; No. 2: Ghostpine basin, extending from Three Hills ridge to the ridge between Ghostpine Creek and the Red Deer River (for short: Red Deer ridge), from mile 11.6 to 21.1; and No. 3: the Red Deer basin, between miles 21.1 and 25 at the Red Deer River.

Probable anisotropy of the geologic formations will result in the flow vectors intersecting the equipotential lines at angles different from 90 degrees in regions where the lines of force are not parallel with the principal directions of the rock-permeability vector. This would result in an increase in the density of flow vectors at shallow depths relative to that of the force vectors, but would leave the distribution, size, and shape of the areas of downward flow and upward flow unchanged. For these reasons, unless the presence of an areally continuous and high-permeability formation, reaching and outcropping beyond the lateral boundaries of the investigated cross section, invalidates the picture obtained from the electric analog, each major surface-water basin in the Three Hills area has an associated groundwater basin with an individual balance of groundwater, which reaches to the depth of the first areally extensive formation of significantly low permeability above a depth of 6000 feet.

Such a regionally extensive formation of significantly low permeability is comprised of the Lea Park-Colorado shale units at an approximate depth of 3000 feet below land surface. Due to the apparent lack of regionally extensive layers of relatively high permeability, and to the demonstrated ability of the groundwater basins to penetrate to at least 6000 feet under the prevailing topographic conditions in a homogeneous environment, the certainty of no interbasin flow occurring above the top of the Lea Park Shale, i.e. within a depth of 3000 feet from the land surface, is even increased. Therefore, it seems justified to consider each groundwater basin under natural conditions in the Three Hills area as an individual entity.

In order to investigate the fluid-potential distribution in greater detail, the individual basins have been reconstructed on a larger scale, as a second step in the analog analysis. As a theoretical impermeable bottom for these basins, the top of the relatively low permeability Lea Park-Colorado unit has been accepted. The lateral boundaries have been determined from the general cross section along lines where $\frac{\partial \phi}{\partial n} = 0$ or $\phi = \text{const.}$, if n is the direction perpendicular to the lateral boundary. The models for Basins 1 and 2 have been constructed this way. (Fig. 13b, c).

Throughout the experiment an exaggeration of the vertical scale of 1:2 was employed. The electrical scale varied between 1 mV to 1 foot and 1 mV to 5 feet of topographic elevation. The type of conducting paper used was Teledeltos L48, with a rated resistance between 1500 and 4000 ohms "per square" of random samples.

For unknown reasons the numerical values of the potentials along the east end of Basin 1 cross section and the west end of Basin 2 cross section, i.e. under Three Hills ridge do not match. Since, however, the discrepancy is small (approximately 40 feet) compared to the total depth of the cross section (3000 feet), and because the rate of vertical potential change is nearly equal in both cases, no attempt was made to eliminate this discrepancy.

APPENDIX B.

SCHEDULE OF WATER WELLS IN THE THREE HILLS AREA

Abbreviations Used

s	: surveyed elevation
m	: map elevation
Dr	: drilled well, driller's report
D	: dug well; domestic water supply
S	: stock water supply; lithologic samples or cores
Sh	: seismic shot hole
P	: public water supply; pump test (water levels and flow rate measured)
I	: industrial water supply
Th	: test hole (stratigraphic, water, coal, etc.)
O	: oil and gas well; observation well for water level measurements
e	: estimated (by driller, owner) without controlled test
~	: approximately
P, F, G	: poor, fair, good supply (relative terms, useful for general information only)
Pr	: production records
M	: mechanical logs (electric logs, radioactive logs, etc.)
L	: lithological logs
Ch	: chemical analysis
RCA. f	: Research Council cardex file
RCA. t	: Research Council test program
OG	: Oil and Gas Conservation Board
R	: oil and gas well records
S	: Stalker (1953) report

Three Hills Well No.	Original name of observation point / Type of observation	LOCATION: Distance from ref. point (feet)	LOCATION: Lsd., corner, or 1/4	LOCATION: Sec.	LOCATION: Tp.	LOCATION: R.	LOCATION: West of Mer.	Elevation above mean sea level (feet)	WATER: Rises to: Depth (feet)	WATER: Rises to: Elev. (feet)	WATER: Test rate (gpm)	WATER: Available drawdown (feet)	WATER: Yield for 20 years (gpm)	WATER: Quality: TDS (ppm)	WATER: Quality: Main ions	Temp. F° C°
1	Western Water Wells "Th No. 1"		6	36	31	24	4	2876m	7	2869						
2	Western Water Wells "Th No. 2"		1	35	31	24	4	2874m	30	2844	20	46	36			
3	Western Water Wells "Th No. 3"		1	35	31	24	4	2874m	6	2868	20	37	3			
4	Western Water Wells "Th No. 4"		11	26	31	24	4	2815m	11	2804	20	35	5			
5	Western Water Wells "Well No. 1"	1900W	NE cor.	22	31	24	4	2745.73s	10	2736	28	28	26	782	Na-, HCO_3, SO_4	
6	Western Water Wells "Well No. 2"	2000W 800N	SE cor.	27	31	24	4	2764.35s	22	2742		46		970	Na- HCO_3, SO_4	
7	Western Water Wells "Well No. 3"	980N 145W	SE cor.	27	31	24	4	2778m	40.5 (1947) 57.9 (1966)	2738 2720	test in 1966 7.5	 24	 2.2	 1396	 Na-, HCO_3, SO_4	
8	Western Water Wells "Well No. 4"		1	35	31	24	4	2865.2s	93	2772	50	24	44	1756	Na-, HCO_3, SO_4	
9	Beagrie "Th No. 1"		6	36	31	24	4	2885m			14		e. <14			
10	Beagrie "Th No. 2"		1	35	31	24	4	2865m			10					
11	Beagrie "Th No. 3"		11	26	31	24	4	2820m			60			1994	Na-, HCO_3, SO_4	
12			10	12	31	22	4	2790m	150	2640	3	35				
14									80					e. bad		
15																
16									27				G			
17													G			
18			1	15	32	24	4	2890m	40 117	2850 2773			e. 2-3 e. 2-3			
19		800N 250W	SE	30	32	23	4	2875m	43	2832	15	23		1612	(Mg+Ca), Na- SO_4, HCO_3	50.6°F 10.3°C
20		600E 400N	SW	1	32	22	4	2817m	200	2617		<15	G e. 4	748	Na-, HCO_3, CC_3	43°F 6.1°C
21		150E 150S	NW	36	31	22	4	2814m						786	Na-, HCO_3	42.6°F 5.9°C
22		2300N 50E	SW	2	32	22	4	2933m					G adequate	890	Na-, HCO_3	42.5°F 5.8°C
23		2900N 150E	SW	14	32	22	4	2939m	270	2669		55	G adequate	752	Na-, HCO_3	43.6°F 6.4°C
24		2800E 700N	SW	23	32	22	4	2755m			3			1484	Na-, HCO_3, SO_4	40.5°F 4.7°C
25	spring	2100W 1200N	SE	23	32	22	4	2700m					G e. 2	2482	Na-, SO_4, HCO_3	43.8°F 6.5°C
26		500N 2300E	SW	3	32	22	4	2820m	~120	2700			G adequate	822	Na-, HCO_3	43.8°F 6.5°C
27		2100S 300W	NE	16	32	22	4	2874m	~120	2754			G adequate		Na-, HCO_3	42.4°F 5.7°C
28a	Well No. 1	~1500E 300N	SW	28	32	22	4	2833m						900 8314	Na, HCO_3	
28b	Well No. 2	″						″	66	2767	12			4932	Na, (Ca+Mg)- HCO_3, SO_4	
														3888	Na, (Ca+Mg)- HCO_3, SO_4	
														4952	Na, (Ca+Mg)- HCO_3, SO_4	
									160	2673		91		774	Na-, HCO_3+CO_3	43.0°F 6.1°C
28c	Well No. 3	″						″						5816	Na, (Ca+Mg)- HCO_3, SO_4	
														5674	″	
28d			SE	29	32	22	4	2850m						2898	Na, (Ca+Mg) HCO_3, SO_4	
29		700W 200N	SE	6	32	23	4	3014m	~150	~2864				4532	Na-, SO_4, HCO_3	42.5°F 5.8°C
31		2300N 250E	SW	8	32	23	4	2979m	~80	~2899			P	5220	Na, (Ca+Mg)- SO_4, HCO_3	

Bedrock depth, Elevation (feet)	GEOLOGY OF AQUIFERS: Lithology of aquifers	Depth to top of aquifers (feet)	Elevation of top of aquifers (feet)	Thickness of aquifers (feet)	Transmissibility (gpd/ft²)	WELL: Type	Depth (feet)	Use	Driller, Year	INFORMATION: Source	Available	Remarks
81 2795	fine-med. sd. "	74 94	2802 2782	5 ~7		Dr	94	Th	WWW; 1947	RCA. f	L	
59 2815	cl; coal coal	55 76	2819 2798	4 3	378	Dr	83	Th	WWW; 1947	RCA. f	L, P	
38 2836	med. ss.	43	2831	48	189	Dr	95	Th	WWW; 1947	RCA. f	L, P	With increasing well depth water rises
46 2769	sd, cl, gr. cls. ss.	27 46	2788 2769	19 49	293	Dr	97	Th	WWW; 1947	RCA. f	L, P	
38 2708	fine yel. sd. sft. ss. with hd. layers	28 38	2718 2708	5 58	197	Dr	101	P	WWW; 1947	RCA. f, t	L, P, Ch, Pr	
68 2696	sft. ss.	68	2696	47		Dr	122	P	WWW; 1947	RCA. f	L, Ch, Pr	
82 2696	sft. ss. sft. ss; coal	82 136	2696 2642	22 16+	475	Dr	152	P	WWW, 1947	RCA. f, t	L, P, Ch	4-days pump test: use of this well for town supply discontinued in 1962 (?)
	sft. ss.	117	2748	27	3880	Dr	180	P	WWW; 1955	RCA. f	L, P, Ch, Pr	
70 2815	coal sft. ss.	124 215	2761 2670	4 35		Dr	260	Th	Beagrie 1960	RCA. f	L	Tested production is less than 14 gpm
75 2790	ss. ss.	125 160	2740 2705	19 15		Dr	191	Th	Beagrie 1960	RCA. f	L	
50 2770	ss. (water)	95 149	2725 2671	75 6		Dr	175	P	Beagrie 1960	RCA. f	L	
28 2762		185	2605	5		Dr	200	D	1958	RCA. f, t		
50	ss. ss.	80 190		20 5		Dr	205	D	Beagrie 1955	RCA. f	L	
						Dr	450		Scott 1929	RCA. f		
						Dr	133		1929	RCA. f		
	ss.	80		10		Dr	90		Beagrie 1955	RCA. f	L	
55 2835	ss.	55 119	2835 2771	5 6		Dr	200	D	T. Green 1962	RCA. f	L	
50 2825	ss. (?)	60	2815	20		Dr	80	D	L. Kinsella 1961	RCA. f, t	L, Ch	
						Dr	220	D, S		RCA. t	Ch	
		160(?) 265	2654 2549	20		Dr	265	D	T. Beagrie 1958	RCA. t	Ch	
						Dr	360	D, S	before 1935	RCA. t	Ch	
	"black sand"	325	2614			Dr	330	D, S	1928	RCA. t	Ch	
	ss.	68	2687			Dr	90	D, S	D. Schmidt 1960	RCA. t	Ch	
	ss.									RCA. t		
						Dr	200	D, S	T. Scott	RCA. t	Ch	"Bran" like particles in water when pump set cluse to bottom; H_2S odour
						Dr	312	D, S	T. Scott 1946	RCA. t	Ch	
						Dr	240	D, S	1945?	RCA. f, t	Ch	Water Analysis: March, 1955 Water Analysis: November, 1959
		240	2593			Dr	252?	D, S	Beagrie 1958	RCA. f, t	Ch	Water Analysis: October, 1958
												Water sample taken after 1 1 2 hours of pumping
												Water Analysis: March, 1959
	ss.	251	2582	17			270		T. Green 1962	RCA. f, t	L, Ch	Water Analysis: April, 1965 H_2S odour
							225					Water Analysis: May, 1959
												Water Analysis: November, 1959
						Dr	214	D		RCA. f	Ch	
						Dr	~200	D	1919	RCA. t	Ch	Close to this well water was obtained from 15 to 20 ft deep dug wells by first settlers
						Dr	165	D	1961	RCA. t	Ch	

Three Hills Well No.	Original name of observation point / Type of observation	LOCATION: Distance from ref. point (feet)	Lsd., corner, or 1/4	Sec.	Tp.	R.	West of Mer.	Elevation above mean sea level (feet)	WATER: Rises to Depth (feet)	Rises to Elev. (feet)	Test rate (gpm)	Available drawdown (feet)	Yield for 20 years (gpm)	Quality: TDS (ppm)	Quality: Main ions	Temp. F° C°
32		3000N 400E	SW	17	32	23	4	2936m					P	4214	Na, (Ca+Mg)-, SO_4	43.2°F 6.2°C
33		150S 600E	NW	20	32	23	4	2880m	15	2865		25	15	3520	Na, (Ca+Mg)- SO_4, HCO_3	
34		200S 550E	NW	20	32	23	4	2880m							Na, (Ca+Mg)- SO_4, HCO_3	
35		800N 450W	SE	30	32	23	4	2870m							Na, (Mg+Ca)- SO_4, HCO_3	40.8°F 4.9°C
36		500E 500N	SW	4	32	23	4	2979m	20	2959			G e. 20	1806	(Ca+Mg), Na- SO_4, HCO_3	39°F 3.8°C
37		300E 400N	SW	3	32	23	4	2954m	38	2916	4			2530	Na, (Mg+Ca)- SO_4, HCO_3	
38		400E 400N	SW	3	32	23	4	2954m	10	2944	e. 1		F. 1/2	1620	(Mg+Ca), Na- SO_4, HCO_3	37.4°F 2.9°C
39		2300N 300W	SE	9	32	23	4	2896m	90	2806			G	3618	Na, (Mg+Ca)- SO_4, HCO_3	
40		1500E 300N	SW	16	32	23	4	2955m	~145	~2810			G adequate	in 1964 2766 in 1965 3920	Na-, SO_4, HCO_3 / Na, Mg-, SO_4, HCO_3	42.8°F 6.0°C
41		2100N 300W	SE	20	32	23	4	2881m	~80	~2801			adequate	2504	Na-, SO_4, HCO_3	42.6°F 5.8°C
42		1000E 1500S	NW	33	32	23	4	2850m	43	2807		42		3476	Na, (Ca+Mg)- SO_4, HCO_3	
43		1000E 1700S	NW	33	32	23	4	2848	~32	2816			adequate	3080	Na, (Ca+Mg)- SO_4, HCO_3	
44		3000S 200E	NW	34	32	23	4	2797m	20	2777			adequate	2330	Na-, SO_4, HCO_3	42.0°F 5.5°C
45		1500W 1200N	SE	27	32	23	4	2770m	~50	~2720			adequate	1888	Na-, HCO_3, SO_4	42.4°F 5.7°C
46		1200N 300E	SW	22	32	23	4	2915m					inadequate	5424	Na, (Mg+Ca) SO_4, HCO_3	
47		3000N 300W	SE	3	32	23	4	2801m	~110	~2691			G 10-20	2736	Na, (Mg+Ca) SO_4, HCO_3	
48		500S 200E	NW	36	31	23	4	2799m	97	2702			adequate	1582	Na-, HCO_3, SO_4	42.6°F 5.8°C
49		200W 50N	SE	12	32	23	4	2765m	85	2680		35	adequate	2228	Na-, HCO_3, SO_4	42.8°F 6.0°C
50		800E 200N	SW	6	32	22	4	2729m	60	2669			adequate	1768	Na-, HCO_3, SO_4	42.4°F 5.6°C
51		1200S 250E	NW	5	32	22	4	2681m	1	2680			adequate	1432	Na- (HCO_3+CO_3), SO_4	40°F 4.4°C
52		500E 200N	SW	17	32	22	4	2745m	75	2670			adequate	1442	Na- (HCO_3+CO_3), SO_4	40.6°F 4.8°C
53		700S 200E	NW	17	32	22	4	2725m	65	2660				1432	Na-, HCO_3, SO_4	38.4°F 3.5°C
54		2300W 300N	SE	30	32	22	4	2763m					adequate	1506	Na-, HCO_3, SO_4	42.6°F 5.9°C
55		2200N 400E	SW	31	32	22	4	2758m						1536	Na-, (HCO_3+CO_3), SO_4	37.5°F 3.0°C
56		600S 300E	NW	33	32	22	4	2867m	~35	~2832				2136	Na-, SO_4, HCO_3	
57		300W 150S	NE	34	32	22	4	2841m					I	1730	Na-, SO_4, HCO_3	
58		400S 150E	NW	26	32	22	4	2850m						2420	Na-, HCO_3, SO_4	42.6°F 5.9°C
59		400S 300E	NW	25	32	22	4	2767m	~25	~2742			G	2286	Na-, SO_4, HCO_3	44.4°F 6.8°C
60		300S 1200W	NE	24	32	22	4	2740m	~86	~2654			inadequate at 90' adequate	2026	Na-, SO_4, HCO_3	40.0°F 4.4°C
61		2400E 150S	NW	9	32	22	4	2810m	125	2685		5				
62		75N	SE	5	32	22	4	2731m					>2 1/2	988	(Na+K)- (HCO_3+CO_3), SO_4	41.0°F 5.0°C
63		1900N 400E	SW	25	31	22	4	2797m	150	2647	4	10		2392	Na-, HCO_3, SO_4	43.4°F 6.3°C
64		1000S 200W	NE	22	31	22	4	2810m	~80	~2730			10	930	Na-, HCO_3	43.0°F 6.1°C
65		1400E 200N	SW	27	31	22	4	2744m	~62	~2682			adequate	1178	Na-, (HCO_3+CO_3), SO_4	

Bedrock depth Elevation (feet)	GEOLOGY OF AQUIFERS Lithology of aquifers	Depth to top of aquifers (feet)	Elevation of top of aquifers (feet)	Thickness of aquifers (feet)	Transmissibility (gpd/ft^2)	WELL Type	Depth (feet)	Use	Driller, Year	INFORMATION Source	Available	Remarks
		54 165	2882 2771			Dr	330	D	Schmidt 1959	RCA. t	Ch	
	sd. ss.	40 100	2840 2780			Dr	125	D	T. Green 1962	RCA. t	Ch	
						Dr	180	D		RCA. t	Ch	
						Dr	60-70	S	1935	RCA. t	Ch	
						D	25	D	1910	RCA. t	Ch	
		7 45	2947 2909	23		Dr	72	D	T. Green 1964	RCA. t	Ch	
	ss.					D	14	S		RCA. t	Ch	
						Dr	120	D	F. Peterson 1947	RCA. t	Ch	Reportedly the water rose to within 20 ft from the surface at the time of drilling, and dropped to present 90 ft after seismic work
						Dr	160	D, S	before 1928	RCA. t	Ch	
						Dr	100	D, S	F. Peterson 1949	RCA. t	Ch	
		45 85	2805 2765			Dr	93	D, S	1956	RCA. t	Ch	
						Dr	61	S		RCA. t	Ch	
						Dr	66	S	Davis 1962	RCA. t	Ch	
						Dr	130	D, S	1925	RCA. t	Ch	Occasional H_2S odour
	coal					Dr	173		Scott 1940	RCA. t	Ch	
						Dr	160	D	1915	RCA. t	Ch	Occasional H_2S odour
						Dr	117	D	1908	RCA. t	Ch	Wells on this flat are very good in quality and quantity according to well owner
		120	2645			Dr	125	D	A. Davis 1963	RCA. t	Ch	
	ss.					Dr	97	D	Scott 1935	RCA. t	Ch	
						Dr	60	D	before 1940	RCA. t	Ch	
						Dr	95	D, S		RCA. t	Ch	
						Dr	125	D		RCA. t	Ch	
						Dr	100	D	1920	RCA. t	Ch	Occasional H_2S odour
						Dr				RCA. t	Ch	
						Dr	85	D	1905	RCA. t	Ch	Continuous H_2S odour
		120	2721			Dr	154	D		RCA. t	Ch	Quicksand at 80 to 90 ft
						Dr	160	D	1916	RCA. t	Ch	
						Dr	100	D	1934	RCA. t	Ch	
						Dr	116	D	deepened 1953	RCA. t	Ch	
		130 150	2680 2660			Dr	150	D	1917	RCA. t	Ch	
						Dr	55	D	before 1930	RCA. t	Ch	
		90 160	2707 2637			Dr	165	D	T. Beagrie 1961	RCA. t	Ch	
						Dr	180	D	Peterson 1940	RCA. t	Ch	
						Dr	112	D	T. Beagrie 1949	RCA. t	Ch	

Three Hills Well No.	Original name of observation point Type of observation	LOCATION Distance from ref. point (feet)	Lsd., corner, or 1/4	Sec.	Tp.	R.	West of Mer.	Elevation above mean sea level (feet)	WATER Rises to Depth (feet)	Elev. (feet)	Test rate (gpm)	Available drawdown (feet)	Yield for 20 years (gpm)	Quality TDS (ppm)	Main ions	Temp. F° C°
66		600N 250E	SW	28	31	22	4	2644m	6	2638	12	54		1388	Na-, HCO_3, SO_4	41.0°F 5.0°C
67		1 000S 1 000E	NW	16	31	22	4	2632m	~55	~2577					Na-, HCO_3, SO_4	41.4°F 5.2°C
68		1 000N 2 300E	SW	16	31	22	4	2610m	22	2588					Na-, HCO_3, SO_4	
69		1 650S 150E	NW	11	31	22	4	2711m					G	776	Na-, (HCO_3+CO_3)	44.2°F 6.7°C
70		250N 250W	SE	13	31	22	4	2745m	200	2545		35	1	840	Na- (HCO_3+CO_3), Cl	42.4°F 5.7°C
71		600E 1 100N	SW	6	31	21	4	2726m	~215	~2511			barely adequate	1578	Na-, Cl, HCO_3	
72		200N 600W	SE	3	31	22	4	2630m	134	2496			G	862	Na-, (HCO_3+CO_3)	
73		2 900S 1 700E	NW	4	31	22	4	2685m	~70	~2615			over 3	1654	Na-, HCO_3, SO_4	46.6°F 8.0°C
74		300N 300E	SW	5	31	22	4	2815m	100	2715	6			2116	Na-, SO_4, HCO_3	
75		15N 100E	SW	24	31	22	4	2830m						1748	Na-, HCO_3, SO_4	
76		100W 1 200N	SE	18	31	22	4	2730m					<5	1832	Na-, HCO_3, SO_4	
77		2 400N 250W	SE	19	31	22	4	2733m	~65	~2668			~4	1420	Na, Mg- HCO_3, SO_4	42.0°F 5.5°C
78		50S 200W	NE	30	31	22	4	2721m			3			1586	Na- (HCO_3+CO_3), SO_4	41.6°F 5.3°C
79		3 000W 100N	SE	15	31	22	4	2694m			3		F	996	Na- (HCO_3+CO_3), SO_4	41.4°F 5.2°C
80		1 600N 200E	SW	30	31	22	4	2777m					1 1/2	1828	Na-, HCO_3, SO_4	40.6°F 4.8°C
81		2 400E 250S	NW	24	31	23	4	2855m	~210	~2645			G 1	1802	Na-, HCO_3, SO_4	43.8°F 6.5°C
82		400N 100E	SW	7	31	22	4	2834m	~50	~2784	5	30	G	2756	Na-, SO_4, HCO_3	
83		250N 300E	SW	6	31	22	4	2979m	~165	~2814			inadequate G	2846	Na, SO_4, HCO_3	42.8°F 6.0°C
84		2 000N 100E	SW	1	31	23	4	2980m	70	2910			F	3898	(Ca+Mg), Na- SO_4, HCO_3	43.4°F 6.3°C
85		250E 1 800S	NW	12	31	23	4	2873m	60	2813			5	1704	Na-, (HCO_3+CO_3), SO_4	43.8°F 6.5°C
86		1 600S 800E	NW	14	31	23	4	2986m	50	2936			over 2	684	(Mg+Ca), Na, HCO_3, SO_4	42.6°F 5.8°C
87		1 500S 150W	NE	22	31	23	4	2891m	140	2751			over 3	1918	Na, (Mg+Ca), SO_4, HCO_3	40.6°F 4.8°C
88		300S 150W	NE	9	31	23	4	2960m	130	2830				2090	Na-, SO_4, HCO_3	
89		400N 100E	SW	29	31	23	4	2988m			5			3320	Na-, SO_4, HCO_3	42.2°F 5.6°C
90		2 300S 150E	NW	27	31	23	4	2832m	~82	~2750			F	2988	Na, Mg, SO_4, (HCO_3+CO_3)	43.0°F 6.1°C
91		1 000N 700E	SW	5	31	23	4	2710m	42	2668		63				
92		300S 100W	NE	1	31	24	4	2704m	18	2686			inadequate inadequate adequate	1322	Na-, HCO_3, SO_4	
93a		500S 2 100W	NE	32	30	24	4	2949m								
93b		500S 2 360W	NE	32	30	24	4	2949m	~20	~2929		~40			Na, Mg, (HCO_3+CO_3), SO_4	42.0°F 5.5°C
94		600N 500E	SW	6	31	24	4	3106m	90	3016			G		Na, Mg, (HCO_3+CO_3), SO_4	
95		700S 200W	NE	8	31	24	4	2898m	50	2848			over 2 1/2	1308	Na, Mg, (HCO_3+CO_3), SO_4	42.0°F 5.5°C
96		600E 1 200N	SW	15	31	24	4	2885m	30	2855		30	<2 1/2	1546	Na, Mg, SO_4, (HCO_3+CO_3)	41.4°F 5.2°C
97 or 153c		1 800S 1 500W	NE	14	31	24	4	2730m	11	2719		69	<4	1322	Na-, SO_4, (HCO_3+CO_3)	
98		800E 700N	SW	30	31	23	4	2888m	146	2742	5-6			1094	Na, Mg, HCO_3, SO_4	40.2°F 4.5°C
99		2 400W 200S	NE	24	31	24	4	2822m					over 3	1966	Na, (Mg+Ca)- (HCO_3+CO_3), SO_4	41.6°F 5.3°C

	GEOLOGY OF AQUIFERS					WELL				INFORMATION		
Bedrock depth, Elevation (feet)	Lithology of aquifers	Depth to top of aquifers (feet)	Elevation of top of aquifers (feet)	Thickness of aquifers (feet)	Transmissibility (gpd/ft^2)	Type	Depth (feet)	Use	Driller, Year	Source	Available	Remarks
	quicksand, coal	30 ~60	2614 ~2584			Dr	94	D	T. Green 1963	RCA. t	Ch	
						Dr	80	D	before 1945	RCA. t	Ch	
						Dr	78	D	Davis 1959	RCA. t	Ch	
						Dr	208	D	before 1936	RCA. t	Ch	Coal at 103 ft
		235	2510	35		Dr	280	D		RCA. t	Ch	
						Dr	250	D	Russel ~1957	RCA. t	Ch	
						Dr	200	D	Gibson 1945	RCA. t	Ch	
	coal ?	~110	~2575			Dr	142	D	Peterson 1941	RCA. t	Ch	
						Dr	110	D	1910	RCA. t	Ch	100 ft south of well reported seismic shothole with water level 6 ft below surface
						Dr				RCA. t	Ch	
		139	2591			Dr	149	D	Davis 1961	RCA. t	Ch	
						Dr	120	D	1916	RCA. t	Ch	
						Dr	114	D	Beagrie 1956	RCA. t	Ch	
						Dr	185	D	before 1930	RCA. t	Ch	
		160	2617			Dr	160	D	1914	RCA. t	Ch	
						Dr	254	D	1924	RCA. t	Ch	
		~80	~2754			Dr	100	D	before 1945	RCA. t	Ch	
						Dr	203	D	1944	RCA. t	Ch	
		~100	~2880			Dr	125	D		RCA. t	Ch	Temporary depletion after pumping of 200 gallons of water
		~50	~2823			Dr	108	D	1945	RCA. t	Ch	Quicksand at approx. 50 ft; water below sand
						Dr	~60	D	1906	RCA. t	Ch	
		180	2711			Dr	220	D	1935	RCA. t	Ch	
						Dr	230	D	1946 deepened in 1963	RCA. t	Ch	H_2S odour first noticed in 1959; disappeared in 1963
		~252	~2736			Dr	252	D	Braconnier 1958	RCA. t	Ch	Lost circulation of drilling mud at 252 ft
		~142	~2690			Dr	142	D	1920	RCA. t	Ch	
		105	2605			Dr	120	D	T. Beagrie 1939	RCA. t	Ch	Owner reports quicksand from surface to 30 ft; hard "rock" from 30 ft to 37 ft; water below rock
		~40 ~90 ~165	~2664 ~2614 ~2539			D Dr Dr	40 90 165	D D D		RCA. t	Ch	
						Dr	60	D		RCA. t	Ch	
		60	2889			Dr	320		T. Beagrie 1963	RCA. t	Ch	
						Dr	140	D	~1920	RCA. t	Ch	
						Dr	80	D		RCA. t	Ch	
	coal ?	60	2825			Dr	100	D	~1945	RCA. t	Ch	
	"soapstone"	80	2650			Dr	165	D		RCA. t	Ch, O	
						Dr	176.5	D		RCA. t	Ch	
	coal	85	2737			Dr	135	D		RCA. t	Ch	

Three Hills Well No.	Original name of observation point / Type of observation	LOCATION: Distance from ref. point (feet)	Lsd., corner, or 1/4	Sec	Tp.	R	West of Mer.	Elevation above mean sea level (feet)	WATER: Rises to: Depth (feet)	Elev. (feet)	Test rate (gpm)	Available drawdown (feet)	Yield for 20 years (gpm)	Quality: TDS (ppm)	Main ions	Temp. F° C°
100		1 300S 300W	NE	21	31	24	4	2832m	55	2777			<3	1638	Na, (Mg+Ca)-SO_4, HCO_3	
101		1 300S 700W	NE	21	31	24	4	2824m	35	2789	10			2006	Na, (Mg+Ca)-SO_4, HCO_3	41.8°F 5.4°C
102		1 800W 1 000N	SE	20	31	24	4	2899m					over 3	2912	Na, (Ca+Mg)-SO_4, HCO_3	41.4°F 5.2°C
103		1 500E 600N	SW	29	31	24	4	2917m	~45	2872		153	over 4	1080	Na-, HCO_3, SO_4	
104		600E 150N	SW	6	32	24	4	2888m	~68	~2820			~1	2690	Na-, SO_4, HCO_3	42.8°F 6.0°C
105		2 400E 300N	SW	3	32	24	4	2834m	30	2804	15		P, G	2848	Na-, SO_4, HCO_3	
106		1 000S 300W	NE	2	32	24	4	2882m	30	2852	8		over 1 adequate	4684	(Mg+Ca), Na, SO_4, (HCO_3+CO_3)	40.6°F 4.7°C
107		2 500E 400N	SW	14	32	24	4	2917m	65 65 97	2852 2852 2820	 5	7 35 134	 adequate	 846	 Na-, HCO_3+CO_3	 40.6°F 4.7°C
108		400S 400W	NE	9	32	24	4	2832m	~19	2813			over 7.5	2181	Na, SO_4, HCO_3	
109		1 000W 500N	SE	15	32	24	4	2885m	80	2805		55	3	558	(Ca+Mg), Na-(HCO_3+CO_3)SO_4	
110		100N 500E	SW	16	32	24	4	2780m	flowing	>2780			flow at ~1/2	1870	Na, (Mg+Ca), SO_4, HCO_3	40.6°F 4.7°C
111		800S 700E	NW	16	32	24	4	2855m	~20	~2835			over 5	2948	Na-, SO_4, HCO_3	41.2°F 5.1°C
112		300N 300W	SE	7	32	24	4	2850m	20	2830		7	under 4	2674	Na(Ca+Mg), SO_4, HCO_3	
113		300W 200N	SE	26	32	24	4	2990m	154	2836		24	G over 10		Na, Mg, SO_4, HCO_3	
114		1 200S 300W	NE	26	32	24	4	2968m	123	2845			over 2.5	3322	Na-, SO_4, HCO_3	42.8°F 5.9°C
115		1 400E 200S	NW	35	32	24	4	3010m	~200	~2810			over 6	1602	Na-, SO_4, HCO_3	
116		1 800N 200E	SW	34	32	24	4	2880m			4		G			40.6°F 4.7°C
117		1 300E 1 000S	NW	31	32	24	4	2820m	6	2814			adequate	1764	Na, (Mg+Ca)-SO_4, HCO_3	
118		1 300E 1 200S	NW	31	32	24	4	2820m	flowing	>2820	9.5		flow at ~3/4	1602	Na, (Mg+Ca) SO_4, HCO_3	41.2°F 5.1°C
119		300S 150W	NE	12	32	24	4	3026m	6	3020			under 5	366	(Ca+Mg), Na-HCO_3, SO_4	36.0°F 2.2°C
120	spring	1 700S 600E	NW	4	32	24	4	2789m					flow at ~4	1394	Na, Mg-SO_4, HCO_3	39.6°F 4.1°C
121		800N 800E	SW	32	31	23	4	2958m	~2	~2956			G	3295	(Ca+Mg), Na SO_4, HCO_3	38.4°F ,3.5°C
122		1 800S 700E	NW	18	31	24	4	2987m	~30	~2957		~10		2092	Na, (Ca+Mg)-SO_4, HCO_3	41.8°F 5.4°C
122a	spring	1 500S 700E	NW	18	31	24	4	2950m		2950						40.8°F 4.8°C
123		1 500E 300S	NW	19	31	24	4	2930m	58	2872	15	45		3648	Na-, SO_4, HCO_3	42.6°F 5.9°C
124		200N 200E	SW	4	31	23	4	2728m					G	1602	Na, (Ca+Mg) SO_4, HCO_3	
125		1 600S 1 800W	NE	36	30	24	4	~2690m	~27	~2663				1588	Na, HCO_3, SO_4	
126		2 000S 200E	NW	4	32	24	4	2821m	~25	~2796			over 3	1624	Na, (Ca+Mg)-SO_4(HCO_3+CO_3)	
127		1 700S 200W	NE	20	32	24	4	2860m						5102	Na, SO_4, HCO_3	
128		2 100S 200E	NW	28	32	24	4	2830m	~12	~2818			over 5			
128a	spring	2 100S 500E	NW	28	32	24	4	2814m	0	~2814			~5			
129		600N 300W	SW	10	31	22	4	2540m	~26	~2514			~1	864	Na, (HCO_3+CO_3)SO_4	
129a		~600N 300W	SW	10	31	22	4	2540m						2374	Na, (HCO_3+CO_3), SO_4, Cl	
130		2 000S 400E	NW	9	31	22	4	2707m	80	2627	5	113		1362	Na, (Ca+Mg)-(HCO_3+CO_3), SO_4	

Bedrock depth, Elevation (feet)	GEOLOGY OF AQUIFERS: Lithology of aquifers	Depth to top of aquifers (feet)	Elevation of top of aquifers (feet)	Thickness of aquifers (feet)	Transmissibility (gpd/ft^2)	WELL: Type	Depth (feet)	Use	Driller, Year	INFORMATION: Source	Available	Remarks
						Dr	65	D	~1920	RCA. t	Ch	H_2S odour first noticed early 1963, approx. 6 months after completion of oil well 3/4 miles SE
						Dr	100	D	Davis 1960	RCA. t	Ch	No H_2S odour in this well; water seam corresponding with Well No. 100 cased off
		35 ~90	2864 ~2819			Dr	92	D		RCA. t	Ch	
		198	2719			Dr	210	D	Davis 1940	RCA. t	Ch	H_2S odour; "water immediately below a very hard rock layer"
						Dr	~200	D		RCA. t	Ch	
						Dr	100	D		RCA. t	Ch	Better supply formerly
		38	2844			Dr	45	D		RCA. t	Ch	
		72 100 231	2845 2817 2686	3 5		Dr	231	D	T. Green 1963	RCA. t	L, Ch	Seven different occurrences of water reported
						Dr	60	D		RCA. t	Ch	H_2S odour is strong but varying
	 coal ?	75 135	2810 2750			Dr	140	D	1926	RCA. t	Ch	
						Dr	25			RCA. t	Ch	
						Dr	40	D		RCA. t	Ch	
	gravel	27	2823			Augered	30	D	1958	RCA. t	Ch	
		178	2812			Dr	184	D		RCA. t	Ch	
						Dr	160	D	1947	RCA. t	Ch	
						Dr	235	D		RCA. t	Ch	
		65 ~80	2815 2800			Dr	126	D	1941	RCA. t	Ch	
						Dr	~60	D	1953	RCA. t	Ch	
						Dr	60	D		RCA. t	Ch	
		3	3023	>7		D	10			RCA. t	Ch	
	gravel									RCA. t	Ch	
						D	25		1910	RCA. t	Ch	Well flowed until 1918
		~40	~2947			Dr	90			RCA. t	Ch	
										RCA. t		
		103	2827			Dr	108		1964	RCA. t	Ch	
						Dr	122	D, S		RCA. t	Ch	
						Dr	92	D	N. Giesbrecht 1928	RCA. t	Ch	
						Dr	58	D		RCA. t	Ch	Strong H_2S odour
						Dr	~110		T. Beagrie 1964	RCA. t	Ch	
							40			RCA. t		
										RCA. t		
						Dr	37			RCA. t	Ch	H_2S odour
							17			RCA. t	Ch	
	ss.	193	2514			Dr	210		T. Beagrie 1955	RCA. t	Ch	

Three Hills Well No.	Original name of observation point / Type of observation	LOCATION: Distance from ref. point (feet)	Lsd., corner, or 1/4	Sec.	Tp.	R.	West of Mer.	Elevation above mean sea level (feet)	WATER: Rises to: Depth (feet)	Rises to: Elev. (feet)	Test rate (gpm)	Available drawdown (feet)	Yield for 20 years (gpm)	Quality: TDS (ppm)	Quality: Main ions	Temp. F° C°
131		2000W 100S	NE	25	32	22	4	2745m	~50	~2695			F ~1	844	Na, (HCO_3+CO_3)	41.4°F 5.2°C
132		2200N 200W	SE	24	32	24	4	2997m	145	2852				1422	Na, $(HCO_3+CO_3)SO_4$	
133		2300N 200W	SE	24	32	24	4	2997m						2840	Na, SO_4, (HCO_3+CO_3)	
134		250W 100S	NE	22	32	24	4	2911m	~120	~2791			~1	872	Na, HCO_3, SO_4	
135		1100S 300E	NW	29	31	24	4	2980m	30	2950		5			Na, (Ca+Mg) SO_4, (HCO_3+CO_3)	
									129	2861	5	61		2336		
136		800W 700N	SE	33	31	24	4	2778m	~15	~2763						
137		1500E 300S	NW	19	31	24	4	2930m	~46	~2884	20	~4		4434	Na, (Ca+Mg) SO_4, (HCO_3+CO_3)	
138		2500W 150N	SE	13	31	24	4	2730m	15	2715	5			1240	Na, (Ca+Mg) HCO_3, SO_4	
139		2200W 150N	SE	5	31	24	4	2967m	51	2916			under 1	1012	Na, HCO_3, SO_4	
140		2200W 150N	SE	5	31	24	4	2967m	6	2961			much better than # 139	1258		
141	spring	1300W 1200N	SE	1	32	24	4	2935m	~1	~2934				3086	Na, (Ca+Mg) SO_4, HCO_3	
142		500N 500E	SW	17	32	24	4	2840m						2738	Na, SO_4, HCO_3	
143		300E 100N	SW	15	32	22	4	2860m					under 1	1240	Na, (HCO_3+CO_3), SO_4	
144		74.8S 74.5W	NE	23	31	24	4	2779.20s	64	2715		10	~1			
									~52	~2727	20	43	~78	1832	Na, HCO_3, SO_4	42.0°F 5.5°C
144a		25 ft. SW of 144		23	31	24	4	~2778	54	2724	51.2	~38	15 to 20	1788	Na, HCO_3, SO_4	
145		117.3N 68.7W	SE	9	32	24	4	2806s	23	2783						
									22	2784						
									II + III 18.5	2787.5	20	~174	~6	984	Na-, (HCO_3+CO_3)	43.0°F 6.1°C
									II + III + IV 16.0	2790						
146		602.6E 28.3N	SW	23	41	24	4	2799.30s								
									56.50	2742.50			under 1			
									~60	2739	10	~65	8.5	2112	Na-, SO_4, HCO_3	42.0°F 5.5°C
147		29.0W 1368.2N	SE	6	32	23	4	2032.30s	134(?)	2898?						
									146	2886				3440	Na, SO_4, HCO_3	
									II + III		10	~210	80	II + III	Na, SO_4, HCO_3	42.5°F 5.8°C
									160	2866				4072		
148		71.5S 1734.0E	NW	36	31	24	4	2901.80s	49.75	2852	10	~29	1.6	I + II	(Mg+Ca), Na- SO_4, (HCO_3+CO_3)	42.5°F .5.8°C
									I + II 51	2851				11960		
149		44.0S 16.2W	Center	29	31	24	4	2926.00s	124	2802	20	66	118	1156	Na-, HCO_3, SO_4	
150		2546.5S 57.5E	NW	7	31	23	4	2711.1s	~28	2683						
									I + II 23.48	2687.52	20	40	83	1080	Na, (Ca+Mg) HCO_3, SO_4	41.5°F 5.3°C
									I + II + III 22.69	2688.41						
151		1903N 9W	SE	28	32	24	4	2866.8s	~32	~2835		18	e. 6-10	2400	Na, (Mg+Ca), SO_4, HCO_3	
									~32	~2835	20	46	885	2696	Na, (Mg+Ca), SO_4, HCO_3	39.9°F 4.4°C
									~32	~2835		141	*(346)			
151a		1878N 9W	SE	28	32	24	4	~2868	~34	2834	188	16		~2900	Na, (Ca+Mg), SO_4, HCO_3	
152		739S 11E	NW	22	32	23	4	2790.2s	16.32	2773.88		34		4160	Na, SO_4, HCO_3	
									14.29	2775.91	10	71	10.4	3208	Na, SO_4, HCO_3	
153		2067S 1134E	NW	13	31	24	4	2731.1s	15	2716	20	90	112	1624	Na-, (HCO_3+CO_3), SO_4	41.0°F 5.0°C

GEOLOGY OF AQUIFERS						WELL				INFORMATION		
Bedrock depth, Elevation (feet)	Lithology of aquifers	Depth to top of aquifers (feet)	Elevation of top of aquifers (feet)	Thickness of aquifers (feet)	Transmissibility (gpd/ft^2)	Type	Depth (feet)	Use	Driller, Year	Source	Available	Remarks
						Dr	280		1928 deepened in 1932	RCA. t	Ch	
	coal strips in shale	290	2707	10		Dr	308		T. Green	RCA. t	L, Ch	H_2S odour
						Dr	160			RCA. t	Ch	
		~170	~2741			Dr	175	D		RCA. t	Ch	
3 2977	blue sh. blue sh. ss.	35 90 190	2945 2890 2790	 10		Dr	201		T. Green	RCA. t	L, Ch	
						Dr	98	D		RCA. t	Ch	H_2S odour developed in fall of 1962; it is intensified before storm; well was flowing before Three Hills drilled present wells in 1947; well completed on a "very hard rock"
2930		~50	~2880			Dr	50	D	Davis 1954	RCA. t	Ch	
	ss.	~40	~2690			Dr	50	D	T. Beagrie 1953	RCA. t	Ch	
						Dr	237	D		RCA. t	Ch	
		~15	~2952				21	D		RCA. t	Ch	
								D		RCA. t	Ch	
	quicksand	34 62	2806 2778			Dr	62	D		RCA. t	Ch	
		120 ?	2740			Dr	280	D	T. Green 1965	RCA. t	Ch	
100 2679	unconsolidated cl; bedrock fragments drift-bedrock contact; soft ss.	74 95	2705 2684	2 35	 ~3900	Dr	735	Th	R. Forrester Dec. 1965	RCA. t	L, B, O, Ch, S, M	Gas at 637–643
	drift-bedrock contact; ss.	93	2685	42	~920	Dr	202	Th	R. Forrester March, 1966	RCA. t	L, B, P, Ch	
55 2751	drift-bedrock contact I coal; sltst. II ss. (main aquifer) III ss, sltst. IV(?)	51 77 191.5 ~275	2755 2729 2614.5 ~2531	5 15 6.5 (?)	~76	Dr	495	Th	R. Forrester Dec. 1965	RCA. t	L, S, B, Ch, M	Gas at 405–407
85 2714	unconsolidated cl, sd, slt, coal I ss. II ss. III	60 100 125	2739 2699 2674	5 5	287	Dr	200	Th	R. Forrester Dec. 1965	RCA. t	L, S, B, Ch, M	
10 3022	slts. I(?) ss. II ss. III	135 170 375	2897 2862 2657	? 20 15	800	Dr	435	Th	R. Forrester Jan. 1966	RCA. t	L, S, B, Ch	
30 2872	ss. I ss. II(?)	80 160	2822 2742	5 15?	120	Dr	300	Th	R. Forrester Jan. 1966	RCA. t	L, S, B, Ch	
35 2891	ss.	190	2736	13	3760	Dr	330	Th	R. Forrester Feb. 1966	RCA. t	L, S, B, Ch	Strong H_2S odour
47 2665	ss. I ss. II ss. III	63 103 192	2648 2608 2519	20 12 11	4390	Dr	305	Th	R. Forrester Feb. 1966	RCA. t	L, S, B, O, Ch	
40 2827	very soft, disintegrated ss. I main aquifer less weathered II coal III	50 78 173	2817 2789 2694	8 19 5	40610	Dr	405	Th	R. Forrester Feb. 1966	RCA. t	L, S, B, O, Ch	Rate of test bailing too low for accurate results
	soft ss.	~50	~2818	46		Dr	130	Th	R. Forrester March 1966	RCA. t	L, P, Ch	
45 2745	coal I soft sltst. II	50 88	2740 2702	9	310	Dr	360	Th	R. Forrester Feb. 1966	RCA. t	L, S, B, Ch	Last water-level measurement after bail test was 17.86 ft below the top of casing, on Feb. 22, 1966; on March 21, 1966 casing was found iced up to the top, and water was observed directly under ice plug, i.e. 3 ft below the top of the casing; when drilling bit was run into hole, water spilled over the top; however, water level was 18 ft. below the top of the casing the next day, March 22, 1966
~55 2676	alternating beds of sltst, ss.	79	2652	31	2624	Dr	150	Th	R. Forrester Feb. 1966	RCA. t	L, S, B, Ch	Main portion of aquifer is from 105 ft to 110 ft

Three Hills Well No.	Original name of observation point / Type of observation	LOCATION: Distance from ref. point (feet)	Lsd., corner, or 1/4	Sec.	Tp.	R.	West of Mer.	Elevation above mean sea level (feet)	WATER: Rises to: Depth (feet)	Elev. (feet)	Test rate (gpm)	Available drawdown (feet)	Yield for 20 years (gpm)	Quality: TDS (ppm)	Main ions	Temp. F° C°
153a		2042S 1134E	NW	13	31	24	4	2731	15	2716	67	85	42	~1700	Na-, HCO_3, SO_4	41.3°F 5.2°C
153b		~2700S 200E	NW	13	31	24	4	2730m	~10 in 1952	2720						
153c	Three Hills Well No. 97															
153d		~2500S 200W	NE	13	31	24	4	2780m	72	2708						
154		2590N 440W	SE	28	31	23	4	2838.5s	~89	2744	20	23	I 52	4492	Na-, SO_4, HCO_3	
									~89	2744	20	I + II + III 15 III	I + II + III 39 III	I + II + III 4720	Na(Ca+Mg)- SO_4, HCO_3	
									97	2736		172	57			
155		880N 31W	SE	20	31	22	4	2643.4s					e. over 5			
									34.5	2609	II + III 20	65	I + II 49.7	II 1908	Na-, SO_4, (HCO_3+CO_3)	
									29	2615		196		II + part of III 1490	Na-, HCO_3, SO_4	
														at full depth 1016	Na, HCO_3, Cl, SO_4	
156	Great Plains Development Co.		10	5	31	23	4	2765m	~79	~2686	20	~101	~3			
									~79	~2686	20	~176	I + II 100			
									~79	~2686	20	~176	I + II + III 180			
157	RCA obs. well No. 17		2	22	31	22	4	2730m	~132	~2598			G			
158	No. 18		5	28	31	23	4	2920m	~28	~2892						
159	No. 19		16	21	32	22	4	2930m	~210	~2720			G			
160	No. 27		13	16	32	23	4	2925m	~91	~2834						
161	No. 28		NW	22	32	24	4	2890m	~54	~2836						
162	No. 41		4	11	31	24	4	2870m	~21	~2849						
163	No. 42		NE	32	31	24	4	2840m	~43	~2797						
164	No. 62		SE	10	31	23	4	2915m	~17	~2898						
165		1340W	NE	7	31	23	4	2785m	flowing	>2785						
166		1840W	NE	9	32	24	4	2809s	flowing	>2809			free flow ~5			
167		55N 50E	NE	8	31	22	4	2709s	flowing	>2709						
168		40S 60E	NE	8	32	24	4	2779s	flowing	>2779						
169		1360S 50E	NE	8	32	24	4	2774s	flowing	>2774						
170		2600S 55E	NE	8	32	24	4	2773s	flowing	>2773						
171		1410N 55E	NE	31	32	24	4	2834s	flowing	>2834						
172		5290W 55N	NE	8	32	24	4	2797s	flowing	>2797						
173		4030E 10N	NE	8	32	24	4	2808s	flowing	>2808						
174		2150E 10N	NE	20	32	23	4	2798s	flowing	>2798						
175		3670E 90N	NE	21	32	23	4	2770s	flowing	>2770						
176		2680W 890N	NE	9	32	24	4	2790m	flowing	~>2790						
177		1720W 50N	NE	9	32	24	4	2809m	flowing	~>2809						
178		55N 50E	NE	35	32	23	4	2709s	flowing	>2709						
180	A.T.C. B-50	1210W 10N	NE	36	32	25	4	2826m	flowing	~>2826						
181	B-51	770W 10N	NE	36	32	25	4	2815m	flowing	~>2815						
182	B-52	340W 10N	NE	36	32	25	4	2820m	flowing	~>2820						
183	B-53	5200W 10N	NE	31	32	25	4	2820m	flowing	~>2820						
184	B-55	4420W 10N	NE	31	32	25	4	2830m	flowing	~>2830						

Bedrock depth, Elevation (feet)	GEOLOGY OF AQUIFERS: Lithology of aquifers	Depth to top of aquifers (feet)	Elevation of top of aquifers (feet)	Thickness of aquifers (feet)	Transmissibility (gpd/ft^2)	WELL: Type	Depth (feet)	Use	Driller, Year	INFORMATION: Source	Available	Remarks
~55 2676	alternating beds of sltst., ss.	70	2661	57	3030 equivalent T 1301	Dr	135	Th	R. Forrester March, 1966	RCA. t	L, P, Ch	Main portion of aquifer is from 100 ft to 127 ft
		87	2643			Dr	97	D	1952	RCA. t	O	
						Dr				RCA. t	O	
53 2780	alternating beds of sltst., ss. I	112	2721	33	4800	Dr	310	Th	R. Forrester March, 1966	RCA. t	L, S, B, Ch	Main portion of aquifers I is from 130 ft to 145 ft
	alternating beds of sltst., ss. II	163	2670	22	I + II + III 5500							
	coarse sltst. with some ss. III	269	2565	14	III 700							
67 2577	unconsolidated sd, drift bedrock contact I	60	2584	7		Dr	365	Th	R. Forrester March, 1966	RCA. t	L, S, B, Ch	Main portion of aquifer II is from 101 ft to 111 ft; with independent development of the aquifers estimated yields would be the following: I:~5 gpm; II:~25 gpm; III:~74 gpm
	ss. coal II	95	2549	16	I + II 1613							
	ss. III	225	2418	4								
58 2707	sltst., ss. I	180	2585		I ~70	Dr	538	Th	R. Forrester June, 1965	Dr	L, B	
	ss. II	255	2510	20	I + II ~1200							
	sltst. III remainder of hole under II to 422 ft.	275	2490	147	I + II + III ~2200							
						Dr	~150	Abandoned farm well		RCA. t	O	Water-level records for June, 1962 to June, 1963
						Dr	~72	"		RCA. t	O	
						Dr	~250	"		RCA. t		
						Dr	~136	"		RCA. t	O	
						Dr	~72	"		RCA. t	O	
						Dr	~24	"		RCA. t	O	
						Dr	~88	"		RCA. t	O	
						Dr	~41	"		RCA. t	O	
						Dr	60	Sh		RCA. f		
						Dr	185	Sh		RCA. f		
						Dr	30	Sh	1958(9?)	RCA. f		
						Dr	20	Sh	1958(9?)	RCA. f		
						Dr	80	Sh	1958(9?)	RCA. f		
						Dr	80	Sh	1958(9?)	RCA. f		
						Dr	45	Sh	1958(9?)	RCA. f		
						Dr	40	Sh	1958(9?)	RCA. f		
						Dr	35	Sh	1958(9?)	RCA. f		
						Dr		Sh	1958(9?)	RCA. f		
						Dr		Sh	1958(9?)	RCA. f		
						Dr		Sh		RCA. f		
						Dr		Sh		RCA. f		
						Dr		Sh		RCA. f		
						Dr		Sh	1965	Mobil Oil, Calg. Expl. District		
						Dr		Sh	1965	"		
						Dr		Sh	1965	"		
						Dr		Sh	1965	"		
						Dr		Sh	1965	"		

Three Hills Well No.	Original name of observation point / Type of observation	LOCATION: Distance from ref. point (feet)	LOCATION: Lsd., corner, or 1/4	LOCATION: Sec.	LOCATION: Tp.	LOCATION: R.	LOCATION: West of Mer.	Elevation above mean sea level (feet)	WATER: Rises to: Depth (feet)	WATER: Rises to: Elev. (feet)	WATER: Test rate (gpm)	WATER: Available drawdown (feet)	WATER: Yield for 20 years (gpm)	WATER: Quality: TDS (ppm)	WATER: Quality: Main ions	WATER: Temp. F° C°
185	A.T.C. B-56	3990W 10N	NE	31	32	25	4	2830m	flowing	~>2830						
186	B-61	1740W 10N	NE	31	32	25	4	2830m	flowing	~>2830						
187	B-67	4440W 10N	NE	32	32	24	4	2835m	flowing	~>2835						
188	B-69	3850W 10N	NE	32	32	24	4	2830m	flowing	~>2830						
189	Three Hills Core Drill Test #1	3150W 800S	14	22	31	24	4	2787s								
190	Test #3		2	14	31	24	4	2862.8s								
191	Test #4		9	36	31	24	4	2966.3s								
192	Test #7	2600W 400S	NE	2	31	24	4	2840m								
193	Test #9		9	19	31	24	4	2859.6s								
194	Test #10		4	4	31	24	4	2989m								
195	Test #11		14	12	31	24	4	2713.3s								
196	Test #12		16	23	31	24	4	2758m?								
197	Test #13		16	4	32	24	4	2797.3s								
198	Test #14A		4	5	31	23	4	2683s								
199	Test #15		NE	9	31	23	4	2971.3s								
200	Test #16		NE	34	31	23	4	2864.4s								
201	Test #17	500N 20E	NE	7	31	23	4	2857.4s								
202	Test #18	450S 55E	NE	1	31	24	4	2694.1s								
203	Test #19	950S 10E	NE	16	31	24	4	2880.5s								
204	Test #20	2640W 75N	NE	11	31	24	4	2879.4s								
205	Test #21		8	10	31	24	4	2910m								
206	Test #22		8	29	31	24	4	2558s								
207	Test #24A		8	1	32	25	4	2845s								
208	Test #25A		8	32	31	24	4	2838s								
209	Test #26	175N 60E	NE	30	31	24	4	2958.2s								
210	Test #27	350E 10S	NE	31	31	24	4	2873.2s								
211	Test #28	1300S	NE	34	31	24	4	2812s								
212	Test #29	380N 60E	NE	20	31	24	4	2850.2s								
213	Test #30	175N 50W	NE	8	31	24	4	2853s	flowing	>2853						
214	Test #31	2630W 2630S	NE	26	31	24	4	2799.4s								
215	Test #33		16	19	31	23	4	2974.3s								
216	Test #34		1	25	31	24	4	2865.2s								
217	Test #35		12	30	31	24	4	3023s								
218	Test #36	1350W 8N	NE	35	30	24	4	2829.3s								
219	Test #37	1700W 9N	NE	33	30	23	4	2970s								
220	BA. CPR. Equity 1-21		1	21	32	23	4	KB: 2921 GL: 2907.6								
221	Arrowex et al. Ghost Pine 10-9		10	9	31	22	4	KB: 2603 GL: 2592								
222	Socony North Three Hills 11-14		14	11	32	24	4	KB: 2891								
223	McAlaster Ghost Pine 11-2		11	2	31	22	4	KB: 2715 GL: 2702								
224	South Brazeau Emjay 1		9	12	31	22	4	KB: 2766.3 GL: 2753.8								
225	Zapata AP		10	12	31	22	4	KB: 2775 GL: 2763								

Bedrock depth, Elevation (feet)	GEOLOGY OF AQUIFERS: Lithology of aquifers	Depth to top of aquifers (feet)	Elevation of top of aquifers (feet)	Thickness of aquifers (feet)	Transmissibility (gpd/ft²)	WELL: Type	Depth (feet)	Use	Driller, Year	INFORMATION: Source	Available	Remarks
						Dr		Sh	1965	Mobil Oil, Calg. Expl. District		
						Dr		Sh	1965	" "		
						Dr		Sh	1965	" "		
						Dr		Sh	1965	" "		
35 2752						Dr	403	Th	1943	OG. Reservation Report #164	L	
25 2838						Dr	405	Th	"	" "	L	
10 2956						Dr	728	Th	"	" "	L	
						Dr	270	Th	"	" "	L	
						Dr	240	Th	"	" "	L	
						Dr	300	Th	"	" "	L	
						Dr	330	Th	"	" "	L	
						Dr	410	Th	"	" "	L	
						Dr	150	Th	"	" "	L	
						Dr	350	Th	"	" "	L	
						Dr	170	Th	"	" "	L	
						Dr	470	Th	"	" "	L	
						Dr	160	Th	"	" "	L	
10 2684						Dr	300	Th	"	" "	L	
						Dr	100	Th	"	" "	L	
						Dr	96	Th	"	" "	L	
						Dr	160	Th	"	" "	L	
						Dr	110	Th	"	" "	L	
						Dr	155	Th	"	" "	L	
						Dr	166	Th	"	" "	L	
						Dr	330	Th	"	" "	L	
~10 ~2863						Dr	191	Th	"	" "	L	
						Dr	131	Th	"	" "	L	
~40 ~2810						Dr	160	Th	"	" "	L	Difficult to maintain circulation from: 100-104 and 107-160; hole takes water
~15 2838	ss, sh	20	2833	20		Dr	460	Th	"	" "	L	Flowing well at hole depth of 42 ft
~84 ~2715						Dr	130	Th	"	" "	L	
						Dr	175	Th	"	" "	L	
~55 ~2810						Dr	100	Th	"	" "	L	
						Dr	400	Th	"	" "	L	
						Dr	100	Th	"	" "	L	
						Dr	140	Th	"	" "	L	
~70 ~2838						Dr	7600	O	1961	OG, R	L, M, S	
~40 ~2552						Dr	4862	O	1962	OG, R	L, M, S	
						Dr	7450	O	1954	OG, R	L, M, S	Lithol. samples from 600 ft
						Dr	4870	O	1960	R	M	
						Dr	5390	O	1952	R	M	
						Dr	4910	O	1962	R	M	

Three Hills Well No.	Original name of observation point / Type of observation	LOCATION: Distance from ref. point (feet)	LOCATION: Lsd., corner, or 1/4	LOCATION: Sec.	LOCATION: Tp.	LOCATION: R.	LOCATION: West of Mer.	Elevation above mean sea level (feet)	WATER: Rises to: Depth (feet)	WATER: Rises to: Elev. (feet)	WATER: Test rate (gpm)	WATER: Available drawdown (feet)	WATER: Yield for 20 years (gpm)	WATER: Quality: TDS (ppm)	WATER: Quality: Main ions	WATER: Temp. F° C°
226	A. Pine 15-14		15	14	31	22	4	KB: 2826								
227	Sun Socony Pine 9-22		9	22	31	22	4	KB: 2787								
228	Feldman Sun Nakaska 4-26		4	26	31	22	4	KB: 2787 GL: 2775.8								
229	Sun Pine 6-35		6	35	31	22	4	KB: 2826 GL: 2814								
230	Mobil Oil Equity South 14-1		14	1	31	23	4	KB: 3027 GL: 3016.8								
231	Mobil Oil Sunnyslope 7-6		7	6	31	24	4	KB: 2975 GL: 2965								
232	Anglo-Socony Twining 1		8	9	31	24	4	KB: 2974								
233	Anglo-Twining 10-12		12	10	31	24	4	KB: 2963								
234	Mobil Twining 8-32		8	32	31	24	4	KB: 2862.5								
235	Mic Mac Mobil Twining 6-34		6	34	31	24	4	KB: 2815.35 GL: 2802.5								
236	L-M Twining 6-35		6	35	31	24	4	KB: 2854 GL: 2842								
237	Feldman Sun Pine 2-2		2	2	32	22	4	KB: 2879								
238	Pan Am B.A. B-1 Equity		11	19	32	23	4	KB: 2944 GL: 2930								
239	Mic Mac Twining 8-4		8	4	32	24	4	KB: 2793 GL: 2780.5								
240	Mic Mac Twining 14-4		14	4	32	24	4	KB: 2788 GL: 2775								
241	Pacific Twining 6-6		6	6	32	24	4	KB: 2843 GL: 2830.7								
242	L-M Twining 14-8		14	8	32	24	4	KB: 2814.35 GL: 2802.35								
243	Mobil CT Twining 14-18		14	18	32	24	4	KB: 2877.9 GL: 2863.2								
244	Mic Mac et al. Twining 16-19		16	19	32	24	4	KB: 2345.9 GL: 2833.4								
245	Mobil CT Twining 6-29		6	29	32	24	4	KB: 2839.8 GL: 2827.1								
246	Mic Mac et al. Twining 6-30		6	30	32	24	4	KB: 2873 GL: 2862								
247	Mic Mac et al. Twining 8-30		8	30	32	24	4	KB: 2844.4 GL: 2831.9								
248	Ashland Twining North 16-30		16	30	32	24	4	KB: 2819 GL: 2807								
249	Mic Mac et al. Twining N. 6-31		6	31	32	24	4	KB: 2822.3 GL: 2809.8								
250	Ashland Twining North 8-31		8	31	32	24	4	KB: 2841 GL: 2828.7								
251	Mic Mac et al. Twining N. 14-31		14	31	32	24	4	KB: 2846.4 GL: 2833.9								
252	Mic Mac et al. Twining N. 16-31		16	31	32	24	4	KB: 2832 GL: 2820								
253		450N 10W	NE	3	31	22	4	2702s								
254		1250S	NE	12	31	22	4	2743s								
255		117N 40E	NE	13	31	22	4	2788.83s								
256		5270N	NE	13	31	22	4	2738s								
257		1770E 10N	NE	15	31	22	4	2818s								
258		13E 61W	NE	24	31	22	4	2764.09s								
259		100S 11E	NE	25	31	22	4	2787s								
260		1665S 55E	NE	27	31	22	4	2799s								
261		930N 10E	NE	35	31	22	4	2818.45s								
262		64N 3W	NE	36	31	22	4	2788.4s								
263		5N 813E	NE	12	32	22	4	2771.09s								
264		235N 10E	NE	13	32	22	4	2763.17s								

Bedrock depth, Elevation (feet)	GEOLOGY OF AQUIFERS					WELL				INFORMATION		Remarks
	Lithology of aquifers	Depth to top of aquifers (feet)	Elevation of top of aquifers (feet)	Thickness of aquifers (feet)	Transmissibility (gpd/ft^2)	Type	Depth (feet)	Use	Driller, Year	Source	Available	
						Dr	5495	O	1955	R	M	
						Dr	6810	O	1955	R	M	
						Dr	4907	O	1956	R	M	
						Dr	4861	O	1955	R	M	
						Dr	5900	O	1957	R	M	
						Dr	620	O	1958	R	M	
						Dr	8200	O	1952	R	M	
						Dr	5610	O	1953	R	M	
						Dr	5563	O	1962	R	M	
						Dr	5395	O	1962	R	M	
						Dr	5444	O	1962	R	M	
						Dr	5036	O	1956	R	M	
						Dr	5381	O	1962	R	M	
						Dr	5405	O	1961	R	M	
						Dr	5401	O	1962	R	M	
						Dr	5568	O	1963	R	M	
						Dr	5486	O	1962	R	M	
						Dr	5564	O	1962	R	M	
						Dr	5565	O	1962	R	M	
						Dr	5532	O	1962	R	M	
						Dr	5550	O	1962	R	M	
						Dr	5477	O	1962	R	M	
						Dr	5488	O	1962	R	M	
						Dr	5467	O	1962	R	M	
						Dr	5486	O	1962	R	M	
						Dr	5467	O	1962	R	M	
						Dr	5450	O	1962	R	M	
						Dr	1020	Th	1954	OG	M	
						Dr	1470	Th	1953	OG	M	
						Dr	400	Th	1953	OG	M	
						Dr	1420	Th	1953	OG	M	
						Dr	920	Th	1954	OG	M	Blind hole
						Dr	380	Th	1953	OG	M	
						Dr	400	Th	1953	OG	M	
						Dr	998	Th	1954	OG	M	
						Dr	420	Th	1953	OG	M	
						Dr	400	Th	1953	OG	M	
						Dr	380	Th	1953	OG	M	
						Dr	360	Th	1953	OG	M	

Three Hills Well No.	Original name of observation point / Type of observation		LOCATION: Distance from ref. point (feet)	LOCATION: Lsd., corner, or 1/4	LOCATION: Sec.	LOCATION: Tp.	LOCATION: R.	LOCATION: West of Mer.	Elevation above mean sea level (feet)	WATER: Rises to Depth (feet)	WATER: Rises to Elev. (feet)	WATER: Test rate (gpm)	WATER: Available drawdown (feet)	WATER: Yield for 20 years (gpm)	WATER: Quality TDS (ppm)	WATER: Quality Main Ions	WATER: Temp. F° C°
265			265W 34N	NE	24	32	22	4	2752.60s								
266			12N 485W	NE	25	32	22	4	2764.69s								
267			1030N 15E	NE	26	32	22	4	2754s								
268			49E 22S	NE	27	32	22	4	2850.83s								
269			75S 12W	NW	32	32	22	4	2786s								
270			143S 50E	NE	31	32	22	4	2789s								
271			17E 82S	NE	34	32	22	4	2834s								
272			17E 82S	NE	34	32	22	4	2834.31s								
273			52N 80E	NE	35	32	22	4	2774.54s								
274			205S 81E	NE	24	32	23	4	2695s								
275			228N 51E	NE	25	32	23	4	2734s								
276			125W 10N	NE	36	32	23	4	2745s								
277			11N 15W	NE	36	32	23	4	2752s								
278	Well No. 3	in Tp. 31-22		NW	6	31	22	4	2855a					G			
279	5	"		SE	7	31	22	4	2736a	90	2646			G			
280	6	"		NE	10	31	22	4	2710m					F			
281	8	"		SW	14	31	22	4	2765a					G			
282	10	"		SW	17	31	22	4	2740a	104	2636			G			
283	11	"		SE	17	31	22	4	2650a	70	2580			G			
284	12	"		SE	20	31	22	4	2635a	20	2615			G			
285	14	"		SW	23	31	22	4	2800m					G			
286	15	"		SE	26	31	22	4	2799a					G			
287	16	"		NE	26	31	22	4	2825a	240	2585			G			
288	17	"		NE	27	31	22	4	2790m	155	2612			G			
289	18	"		SW	28	31	22	4	2621a	10	2611			G			
290	19	"		NE	30	31	22	4	2728a					G			
291	20	"		SW	32	31	22	4	2700a					G			
292	21	"		SW	35	31	22	4	2778a	150	2628			G			
293	22	"		SW	36	31	22	4	2871a					G			
294	23	"		NW	36	31	22	4	2774a					G			
295	2-3	31-23		NW	4	31	23	4	2833a					G			
										169	2664			G			
296	4	"		SW	14	31	23	4	2995a					F			
297	5	"		SW	14	31	23	4	2995a					F			
298	7	"		SW	16	31	23	4	2887a					F			
299	8	"		SW	16	31	23	4	2895a					adequate			
300	9	"		SE	16	31	23	4	2951a					G			
301	10	"		NW	16	31	23	4	2927a	43	2884			G			
302	11	"		NW	16	31	23	4	2927a					G			
303	12	"		NE	16	31	23	4	2979a	12	2967			G			
304	13	"		NW	20	31	23	4	3002a					P			
305	15	"		SW	25	31	23	4	2719a					P			
306	16	"		SW	27	31	23	4	2826a								
														G			
307	18	"		SE	28	31	23	4	2864a					G			
308	20	"		SW	29	31	23	4	2986a					P			
309	22	"		SE	32	31	23	4	2980a					G			
310	23	"		NW	32	31	23	4	3002a					F			

	GEOLOGY OF AQUIFERS					WELL				INFORMATION		
Bedrock depth, Elevation (feet)	Lithology of aquifers	Depth to top of aquifers (feet)	Elevation of top of aquifers (feet)	Thickness of aquifers (feet)	Transmissibility (gpd/ft^2)	Type	Depth (feet)	Use	Driller, Year	Source	Available	Remarks
						Dr	360	Th	1953	OG	M	
						Dr	360	Th	1953	OG	M	
						Dr	1126	Th	1953	OG	M	
						Dr	900	Th	1953	OG	M	
						Dr	935	Th	1953	OG	M	
						Dr	1137	Th	1953	OG	M	
						Dr	1199	Th	1953	OG	M	
						Dr	1200	Th	1953	OG	M	
						Dr	400	Th	1953	OG	M	
						Dr	600	Th	1954	OG	M	
						Dr	1060	Th	1954	OG	M	
						Dr	950	Th	1953	OG	M	
						Dr	600	Th	1954	OG	M	
		~80	~2775			Dr	80	D, S		S		
		~120	~2616			Dr	120	D, S		S		
		~175	~2535			Dr	~175	D, S		S		
		~265	~2500			Dr	~265	D, S		S		
		~150	~2590			Dr	150	D, S		S		
		~110	~2540			Dr	110	D, S		S		
		~80	~2555			Dr	80	D, S		S		
		~157	~2643			Dr	157	D, S		S		
		~250	~2549			Dr	250	D, S		S		
		~270	~2555			Dr	270	D, S		S		Unfit for consumption
		~185	~2605			Dr	185	D, S		S		
		~93	~2528			Dr	93	D, S		S		2 feet of coal at 47 ft
		~125	~2603			Dr	125	D, S		S		
		~30	~2670			D	30	D, S		S		
		~180	~2598			Dr	180	D, S		S		
		~280	~2591			Dr	280	S		S		Unfit for consumption
		~200	~2574			Dr	200	D, S		S		
		~170	~2663			Dr	194	D, S		S		Unfit for consumption
		~194	~2639									
		~265	~2730			Dr	265	D, S		S		
		~242	~2753			Dr	242	D, S		S		
		~60	~2827			Dr	60	D, S		S		
		~104	~2791			Dr	104	D, S		S		
		~120	~2831			Dr	120	D, S		S		
		~210	~2717			Dr	210	D, S		S		Hard water at 90 ft
		~120	~2807			Dr	120	D, S		S		
		~30	~2949			bored	30	D, S		S		
		~>80	~<2922			Dr	>80	D, S		S		
		~110	~2609			Dr	110	D		S		
		~80	~2746			Dr	124	S		S		
		~124	~2702									
		~210	~2654			Dr	210	D, S		S		
		~110	~2876			Dr	~110	S		S		
		~140	~2840			Dr	~140	D, S		S		
		~56	~2946			Dr	56	D, S		S		

Three Hills Well No.	Original name of observation point / Type of observation		LOCATION: Distance from ref. point (feet)	Lsd., corner, or 1/4	Sec.	Tp.	R.	West of Mer.	Elevation above mean sea level (feet)	WATER: Rises to: Depth (feet)	Elev. (feet)	Test rate (gpm)	Available drawdown (feet)	Yield for 20 years (gpm)	Quality: TDS (ppm)	Main ions	Temp. F° C°
311	Well No. 24	in Tp. 31-23		NE	33	31	23	4	2970m					G			
312	25	"		NW	34	31	23	4	2950a					e. 2			
313	26	"		NW	34	31	23	4	2923a					P			
314	27	"		NE	34	31	23	4	2870m					G			
315	28	"		SW	36	31	23	4	2837a					F			
316	29	"		SE	36	31	23	4	2810m					G			
317	1	31-24		NE	4	31	24	4	2931a					e. 1			
318	5	"		NW	6	31	24	4	3030a					G			
319	6	"		SE	10	31	24	4	2872a					G			
320	7	"		SE	10	31	24	4	2872a					inadequate			
321	9	"		NW	18	31	24	4	2972a	37	2935			F			
322	10	"		NW	18	31	24	4	2964a					F			
323	11	"		NE	19	31	24	4	2904a					G			44.0°F 6.6°C
324	12	"		SW	24	31	24	4	2795a					G			
325	13	"		NE	24	31	24	4	2816a	88	2728			G			
326	14	"		NE	26	31	24	4	2845a					G			
327	15	"		SE	27	31	24	4	2745a	14	2731			F-G			
328	16	"		SE	30	31	24	4	2939a					G			
329	17	"		NW	30	31	24	4	3050a					G			
330	18	"		NE	30	31	24	4	2977a	100	2877			G			
331	19	"		NW	32	31	24	4	2899a					G			
332	2	32-22		SE	1	32	22	4	2774a	280	2494			F			
333	5	"		SE	9	32	22	4	2790m					G			
334	6	"		SW	10	32	22	4	2825m					G			
335	7	"		NE	12	32	22	4	2712a					F			
336	8	"		SW	13	32	22	4	2799a					F			
337	9	"		SE	13	32	22	4	2726a					P			
338	1	32-23		SE	2	32	23	4	2776a					G			
339	5	"		SW	5	32	23	4	3010a					F			
340	6	"		SW	8	32	23	4	2991a					P			
341	8	"		NE	10	32	23	4	2898a					F			
342	9	"		SW	14	32	23	4	2890m					G			
343	10	"		SW	15	32	23	4	2865a					G			
344	11	"		NW	15	32	23	4	2893a	100	2793			G			
345	13	"		SW	18	32	23	4	3032a					G			
346	14	"		NE	19	32	23	4	2893a	50	2843			G			
347	15	"		SW	20	32	23	4	2898a	90	2808			G			
348	17	"		NE	20	32	23	4	2796a	30	2766			G			
349	18	"		SW	21	32	23	4	2940m					G			
350	19	"		SE	28	32	23	4	2780a	6	2753			G			
351	20	"		SE	32	32	23	4	2890a	75	2815			G			
352	21	"		SW	34	32	23	4	2789a	80	2709			G			
353	1	32-24		NE	1	32	24	4	2974	18	2956			G			
354	2	"		SE	2	32	24	4	2869	60	2809			G			
355	5	"		NE	5	32	24	4	2824					G			
356	7	"		NE	14	32	24	4	2964					G			
357	8	"		NE	20	32	24	4	2856	40	2816			G			
358	9	"		NW	21	32	24	4	2840	35	2805			G			
359	10	"		NE	22	32	24	4	2896	90	2806			G			
360	11	"		SE	24	32	24	4	2974					F			
361	12	"		SE	24	32	24	4	2974					G			
362	13	"		NW	24	32	24	4	3052	250	2802			F			
363	14	"		NE	25	32	24	4	2922	100	2822			G			
364	16	"		SE	26	32	24	4	2989					1/4			

	GEOLOGY OF AQUIFERS					WELL				INFORMATION		
Bedrock depth, Elevation (feet)	Lithology of aquifers	Depth to top of aquifers (feet)	Elevation of top of aquifers (feet)	Thickness of aquifers (feet)	Transmissibility (gpd/ft^2)	Type	Depth (feet)	Use	Driller, Year	Source	Available	Remarks
		~220	~2750			Dr	220	D,S		S		
		~212	~2738			Dr	212	D,S		S		
		~230	~2693			Dr	230	D,S		S		
		~165	~2705			Dr	165	D,S		S		
		~200	~2637			Dr	200	D,S		S		
		~200	~2610			Dr	200	D,S		S		
		67	2864			Dr	89	D,S		S		
		125	2905			Dr	125	D		S		
		~140	~2732			Dr	140	S		S		Hard water spring at same location
		~250	~2622			Dr	250	abandoned		S		
10 2962		40	2932			Dr	60	D,S		S		
		~30	~2934			Dr	30	D		S		
		~80	~2824			Dr	80	D,S		S		
		~125	~2670			Dr	~125	D,S		S		
		~105	~2711			Dr	105	D,S		S		
		~150	~2695			Dr	150	D,S		S		
		~50	~2695			Dr	50	D,S		S		
		~140	~2799			Dr	~140	S		S		
		~60	~2990			Dr	60	D,S		S		
		~150	~2827			Dr	150	D,S		S		
		~250	2649			Dr	~250	S		S		
		~340	~2434			Dr	340	S		S		
		~165	~2625			Dr	165	D,S		S		
		~160	~2665			Dr	160	D,S		S		
		~340	~2372			Dr	340	D		S		
		~192	~2607			Dr	192	D,S		S		
		~250	~2476			Dr	250	D		S		
		~170	~2606			Dr	170	D,S		S		
		~180	~2830			Dr	180	D,S		S		
		~330	~2661			Dr	330	S		S		
		~300	~2598			Dr	300	D,S		S		
		~110	~2780			Dr	110	D,S		S		
		~177	~2688			Dr	177	D,S		S		
		~130	~2763			Dr	130	D,S		S		
		~210	~2822			Dr	210	D,S		S		
		~90	~2803			Dr	90	D,S		S		4 feet of coal at 70 ft
		~100	~2798			Dr	~100	D,S		S		
		~107	~2689			Dr	107	D,S		S		
		~100	~2840			Dr	100	D,S		S		
		~152	~2628			Dr	152	D,S		S		Hard water at 25 ft
		~85	~2805			Dr	85	D,S		S		
		~102	~2687			Dr	102	D,S		S		
		~22	~2952			D	22	D,S		S		
		~160	~2709			Dr	160	D		S		Poor drinking water
		~150	~2674			Dr	150	D,S		S		
		~150	~2814			Dr	150	D		S		2 aquifers used
		~60	~2796			Dr	60	D,S		S		
		~50	~2790			Dr	50	D		S		
		~110	~2786			Dr	110	D,S		S		Poor drinking water
		~75	~2899			Dr	75	D		S		
		~120	~2854			Dr	120	S		S		
		~280	~2772			Dr	280	D,S		S		Hard water at 110 ft
		~120	~2802			Dr	120	D,S		S		
		~80	~2909			Dr	80	D		S		

Three Hills Well No.	Original name of observation point / Type of observation	LOCATION: Distance from ref. point (feet)	LOCATION: Lsd., corner, or 1/4	LOCATION: Sec.	LOCATION: Tp.	LOCATION: R.	LOCATION: West of Mer.	Elevation above mean sea level (feet)	WATER: Rises to: Depth (feet)	WATER: Rises to: Elev. (feet)	WATER: Test rate (gpm)	WATER: Available drawdown (feet)	WATER: Yield for 20 years (gpm)	WATER: Quality: TDS (ppm)	WATER: Quality: Main ions	WATER: Temp. F° C°
365	Well No. 17 in Tp. "		NW	28	32	24	4	2814	flowing 1	2814			G			
366	18 "		NE	31	32	24	4	2836	7	2829			G			
367	19 "		NE	32	32	24	4	2837	12	2825			G			

Bedrock depth, elevation (feet)	GEOLOGY OF AQUIFERS: Lithology of aquifers	Depth to top of aquifers (feet)	Elevation of top of aquifers (feet)	Thickness of aquifers (feet)	Transmissibility (gpd/ft²)	WELL: Type	Depth (feet)	Use	Driller, Year	INFORMATION: Source	Available	Remarks
		~12	~2802			D	12	S		S		
		~60	~2776			Dr	60	D,S		S		
		~64	~2773			Dr	64	D,S,I		S		Water poor for garden

APPENDIX D.

LIST OF CHEMICAL ANALYSES OF WELL WATERS IN THE THREE HILLS AREA.

Three Hills Well No.	Depth of well at time of sampling (feet)	Date of sampling	Total solids (ppm)	Ignition loss (ppm)	Hardness (ppm) ($CaHCO_3$)	Na^+ (epm)	Na^+ %	K^+ (epm)	K^+ %	Ca^{++} (epm)	Ca^{++} %	Mg^{++} (epm)	Mg^{++} %	$Na^+ + K^+$ (epm)	$Na^+ + K^+$ %
5	101	Feb. 15/60	782	94	100										84
6	122	Sept. 19/64	970	116	110										86
7	152	Sept. 14/64	1396	112	50										95
8	180	1955	1280	90	30										97
"	180	Sept. 14/64	1756	154	25										98
11	175	Sept. 14/64	1994	126	25										98
19	80	Apr. 27/65	1612	160	700	6.7	32	0.08	1⁻	5.89	29	8.1	39	6.78	32
20	220	Apr. 30/65	748	30	0	13.6	99	0.08	1⁻	0	0	0	0	13.68	100
21	265	Apr. 26/65	786	20	0	9.75	99	0.05	1⁻	0	0	0	0	9.8	100
22	360	Apr. 26/65	890	18	0	15.80	99	0.1	1⁻	0	0	0	0	15.9	100
23	330	Apr. 26/65	736	16	0	13.25	99	0.08	1⁻	0	0	0	0	13.33	100
24	90	Apr. 26/65	1484	20	30	24.60	97	0.15	0.6	0.56	2.2	0.04		24.75	98
25	(spring)	Apr. 26/65	2482	30	90	38.2	95	0.13	1⁻	1.37	3.4	0.44	1.1	38.33	95.5
26	200	Apr., 1963	850		85										89
"	"	Apr. 22/66	822	20	0	14.0	98	0.15	1	0	0	0	0	14.15	99
27	312	Apr. 22/66	874	24	30	9.19	93	0.08	1⁻	0.44	4.4	0.15	1.5	9.27	93
28a	240	1955	900	50	20									14.82	97
"	"	Nov., 1959	8314	1050	1000⁺					Ca + Mg =		20⁺	17		
28c	225	May, 1959	5816	160	290					Ca + Mg =		5.8	7	75	94
"	"	Nov., 1959	5674	224	310					Ca + Mg =		6.2		74	92
28b	252	Nov., 1958	4932	300	385					Ca + Mg =		7.7		60	89
"	"	Dec., 1958	3888	160	215					Ca + Mg =		4.3		49.5	92
"	"	Mar., 1959	4952	200	325					Ca + Mg =		6.5			
"	270	Apr. 22/65	774	12	0	9.05	99⁺	0.05	1⁻	0	0	0	0	9.1	100
28d			2892	132	80					Ca + Mg =		1.6		43.9	96
29	200	Apr. 27/65	4532	218	200	67.0	91	2.56	3.5	2.42	3.3	1.58	2.1	69.56	94.5
31	165	Apr. 27/65	5220	214	1040	57.9	71	2.3	3	11.31	14	9.5	12	60.2	74
32	330	Apr. 27/65	4214	436	1810	23.5	39	0.41	1⁻	20.82	35	15.4	26	23.9	39
33	125	Apr. 27/65	3520	190	570	44.1	85	2.3	4.4	3.81	7.3	1.9	3.6	46.4	89
34	180	1941	4730	488	802					Ca + Mg =		16		50	76
35	65	Apr., 1965	2432	230	825	14	45	0.26	1⁻	6.81	22	9.7	32	14.3	45
36	25	Apr. 27/65	1806	216	1000	8.8	30	0.15	1⁻	11.89	41	8.1	28	8.95	31
37	72	Apr. 27/65	2530	304	685	25.5	64	0.31	1	5.76	15	8.0	20	25.81	65
38	14	Apr. 28/65	1620	196	880	9.4	35	0.13	1⁻	6.31	23	11.3	42	9.53	35
39	120	Apr. 28/65	3618	150	345	47.0	83	2.7	5	2.55	4.5	4.35	7.5	49.7	88
40	160	Apr. 16/64	2766		190					Ca + Mg =		3.80		38.43	91
"	"	Apr. 28/65	3920	194	375	50.0	83	2.8	5	0.8	1	6.7	11	52.8	88
41	100	Aug. 8/61	2634	168	305					Ca + Mg =		6.1		50.22	89
"	"	Apr. 28/65	2504	90	125	35.2	92	0.64	2	0.86	2	1.57	4	35.84	94
42	93	Sept., 1956	2414	240	340					Ca + Mg =		6.8		29.64	81
"	"	Mar., 1965	3476	494	1000⁺					Ca + Mg =		20⁺		29.53⁻	60⁻
43	61	May, 1964	2368	254	405					Ca + Mg =		8.1		28.29	78
"	"	Mar., 1965	3080		950					Ca + Mg =		19		27.33	59
44	66	Apr. 28/65	2330	98	120	32.5	92	0.66	2	1.36	4	1.04	2	33.16	94
45	135	Apr. 28/65	1888	76	30	29.6	96	0.53	2	0.24	1	0.36	1	30.13	98
46	173	Apr. 28/65	5424	376	910	58.2	72	3.85	5	5.31	7	12.9	16	62.05	77
47	160	Apr. 28/65	2736	164	260	37.0	86	0.38	1	1.04	2	4.35	11	37.38	87
48	117	Apr. 29/65	1582	64	20	25.4	96	0.64	2	0.4	2	0	0	26.04	98
49	125	Apr. 29/65	2228	94	80	33.5	94	0.51	1	0.32	1	1.28	4	34.01	95
50	97	Apr. 29/65	1768	112	90	26.1	92	0.38	1	1.30	5	0.5	2	26.48	93
51	~60	Apr. 29/65	1432	116	0	22.7	99	0.31	1	0	0	0	0	23.01	100
52	95	Apr. 29/65	1442	94	35	21.6	95	0.38	2	0.40	2	0.30	1	21.98	97
53	125	Apr. 29/65	1432	262	60	18.9	93	0.31	1	0.48	2	0.72	4	19.21	94
54	100	Dec. 12/63	1500		45					Ca + Mg =		0.90		23.37	96
"	"	Apr. 29/65	1506	66	25	23.1	96	0.38	2	0.48	2	0.02	1⁻	23.48	98
55		Apr. 29/65	1536	66	50	21.6	88	1.92	8	0.78	3	0.22	1	23.52	96

Ca^{++}/Mg^{++}	Cl^- (epm)	%	SO_4^{--} (epm)	%	HCO_3^- + CO_3 (epm)	%	NO_3 (epm)	%	Fe	Fl	Hydro-chemical facies of water	Remarks
	0.2	2	4.43	36	7.7	62	0	0	0.2	0.3	II	
	0	0	5.13	33	10	67					II	
	0.14	1^-	8.78	40	13	60			tr	0.6	II	
	0.25	1	7.85	39	12	60			5^+		II	
	0.17	1^-	8.46	30	17.7	70				0.91	II	
	0.84	3	14.63	48	14.6	49	0	0	tr	0.76	II	
0/0	0.14	1^-	16.23	60	10.5	40	0	0	1.0	0	III	Analysis questionable
0/0	0.51	4	0	0	12.82	96	0	0	tr	1.56	I	
0/0	0.56	2	0.63	2	13.03	96	0	0	1.0	1.56	I	Questionable
0/0	0.31	2	1.20	7	14.55	91	0	0	tr	1.67	I	
0/0	1.04	8	0.33	2	12.02	90	0	0	tr	1.67	I	
14	0.2	1	7.10	28	17.98	71	0.01		tr	0.03	II	
3.12	0.2	1^-	19.93	49.5	20.2	50	0	0	tr	0.03	II	
	0.34	2	0.70	5	14.24	93	0	0	2.0	2.4	I	
0/0	0.31	2	0.78	5	13.80	93	0	0	tr	0.14	I	H_2S odour
2.9	0.59	3.2	1.55	9.8	13.65	87	0	0	tr	0.12	I	Questionable
	0.42	2.8	0.8	5.3	14.0	92			0.1		I	
	5.2	4.6	92.5	81	14.0	12.6	2	1.8	0.9		IV	The following history on "Well group No. 22" may be pieced together: "Well No. 28a" was drilled in 1945; had good water until "Well No. 28b" was drilled in Nov. 1958. This well struck bad water and ruined "No. 28a". Successive attempts to clean old wells and to drill "Well No. 28c" in May, 1959 failed to improve quality or to locate good water. "Well No. 28b" was deepened finally in 1962 to 270 ft. Good water was found
	0.79	1^-	47.2	58	32.9	41	0	0	1.5		II	
	0.44	1^-	41.2	51	39.0	48	0	0	1.2		II	
	0.6	1	39.6	59	26.7	39	0.6	1	1		IV	
	0.65	1	30.3	56	23.0	42	0.2	1^-	1.5		II	Sample taken after 1 1/2 hrs of pumping
	1.7	2	40.5	59	26.0	38	0.5	1^-	1.2		IV	
0/0	0.65	4.3	0.5	3.3	14.0	92	0	0	0.01	0.03	I	Questionable. Well was deepened to 270 ft in 1962
	0.16	1^-	21.8	48	23.6	51	0	0	1.6		II	
1.46	1.84	2.8	48.85	73	16	24	0	0	5.2	1.27	IV	Questionable
1.19	0.84	1	64.05	80	15	19	0.4	1^-	3.0	0.48	IV	
1.36	0.28	1^-	50.95	90	5.5	9.7	0.2	1^-	1.4	0.76	III	?
2.0	0.22	1^-	39.35	79	10.2	20	0	0	5^+	1.13	IV	?
	0.28	1^-	56.1	85	9.98	14	0	0			IV	
0.7	0.42	1	25.6	66	13	33	0.1	1^-	0.3	0.42	III	?
1.34	0.34	1	18.8	68	8.5	31	0.1	1^-	0.4	0.11	III	
0.72	0.42	1	26.33	68	12.0	31	0.2	1^-	0.2		III	
0.56	1.0	4	15.68	61	9.0	34	0.3	1	0.2		III	
0.59	0.23	1^-	35.5	63	21.0	36	0.03	1^-	2.9		IV	
	0.2	1^-	26.53	63	15.70	36	0.1	1^-	tr		IV	
0.12	0.37	1^-	39.48	65	18.7	34	0.3	1^-	0.4		IV	
	0.37	1^-	25.18	45	30.8	55	0	0	0.8		II	
0.52	0.08	1^-	24.43	63	14	37	0	0	5	0.62	IV	
	0.11	1^-	22.23	61	14.1	39	0	0	3		IV	
	0.2	1^-	38.83	78	10.5	22	0.2	1^-	tr		III	
	0.11	1^-	21.58	60	14.7	40	0	0			II	
	0	0	35.33	76	11	24	0.2	1^-	0	0.22	III	
1.31	0.08	1^-	22.10	62	13.8	38	0	0	5^+	0.57	IV	
0.67	0.08	1^-	11.08	36	19.5	64	0.3	1^-	5.6	0.54	II	
0.41	0.08	1^-	66.25	84	12.8	16	0.2	1^-	1.2	0.42	IV	Water is from coal
0.24	0.23	1^-	23.85	56	18.5	44	tr	1^-	0.4	0.25	II	
	0.17	1^-	7.38	28	18.8	72	0	0	0.2	0	II	
0.25	0.37	1	16.18	45	19.0	54	tr	1^-	5^+	0	II	
2.6	0.23	1	10.35	36	18.0	63	0	0	3.3	0	II	
0/0	0.76	3	5.23	23	17.0	74	0	0	0.3	0	II	
1.33	0.28	1	8.95	39	13.5	60	0	0	4	0	II	
0.67	0.14	1	6.80	33	13.5	66	0	0	3.8	0	II	
	0.34	1	10.53	43	13.4	56	0	0	0.3	0.42	II	
24	0.36	2	10.1	42	13.5	56	0	0	0.5	0	II	
3.55	0.14	1	10.9	44	13.5	55	0	0	0.3	0	II	

Three Hills Well No.	Depth of well at time of sampling (feet)	Date of sampling	Total solids (ppm)	Ignition loss (ppm)	Hardness (ppm) ($CaHCO_3$)	Na^+ (epm)	Na^+ %	K^+ (epm)	K^+ %	Ca^{++} (epm)	Ca^{++} %	Mg^{++} (epm)	Mg^{++} %	$Na^+ + K^+$ (epm)	$Na^+ + K^+$ %
56	85	Apr. 29/65	2136	210	85	27.5	86	2.56	9	1.44	4	0.26	1	30.06	95
57	154	Apr. 29/65	1730	70	50	24.62	88	2.18	8	0.88	3	0.12	1-	26.80	96
58	160	Apr. 29/65	2420	40	40	35.40	91	3.00	8	0.08	1-	0.20	1-	38.40	99
59	100	Apr. 29/65	2286	54	30	32.84	91	2.56	8	0.36	1	0.24	1-	35.40	99
60	116	Apr. 29/65	2026	72	35	28.8	90	2.56	8	0.36	1	0.34	1	31.36	98
62	55	Apr. 30/65	988	58	25	13.9	86	1.69	10	0.48	3	0.02	1-	15.59	96
63	165	Apr. 30/65	2392	76	20	35.9	92	2.82	7	0.05	1-	0	0	38.72	99
64	180	Apr. 30/65	930	36	0	14.0	95	0.77	5	0	0	0	0	14.77	100
65	112	Apr. 30/65	1178	218	25	15.75	91	1.02	6	0.28	2	0.22	1	16.77	97
66	94	Apr. 30/65	1388	58	0	21.6	93	1.28	7	0	0	0	0	22.88	100
67	80	Apr. 30/65	1716	50	25	26.1	93	1.54	5	0.36	1	0.14	1-	27.64	98
68	78	Apr. 30/65	1700	66	0	25.4	94	1.54	6	0	0	0	0	26.94	100
69	208	Apr. 30/65	776	34	0	9.1	96	0.38	4	0	0	0	0	9.48	100
70	280	Apr. 30/65	840	44	0	14.1	95	0.77	5	0	0	0	0	14.87	100
71	250	Apr. 30/65	1578	72	0	25.0	94	1.54	6	0	0	0	0	26.54	100
72	200	Apr. 30/65	832	24	0	14.8	95	0.77	5	0	0	0	0	15.57	100
73	142	Apr. 30/65	1654	54	0	24.9	94	1.54	6	0	0	0	0	26.44	100
74	110	Apr. 30/65	2116	28	50	31.0	91	2.05	6	0.9	3	0.1	1-	33.05	97
75		May 17/65	1748	96	40	26.9	96	0.35	1	0.4	1	0.4	1	27.25	97
76	149	May 17/65	1832	110	90	27.1	93	0.36	1	1.22	4	0.58	2	27.46	94
77	120	May 17/65	1420	394	175	15.35	81	0.20	1	1.06	5	2.44	13	15.55	82
78	114	May 17/65	1586	72	140	24.0	89	0.30	1	0.34	1	2.45	9	24.3	90
79	185	May 17/65	996	42	35	16.65	95	0.22	1	0.16	1	0.54	3	16.87	96
80	180	May 18/65	1828	84	90	27.1	93	0.35	1	0.54	2	1.26	4	27.45	94
81	254	May 18/65	1802	56	25	28.3	97	0.27	1	0.34	1	0.16	1-	28.57	98
82	100	May 18/65	2756	106	65	41.6	96	0.45	1	0.32	1	0.98	2	42.05	97
83	203	May 18/65	2846	100	55	43.4	96	0.52	1	0.22	1-	0.88	2	43.92	97
84	125	May 18/65	3898	608	1660	19.7	37	0.38	1	17.22	32	16.00	30	20.08	38
85	108	May 18/65	1704	140	100	25.9	92	0.29	1	0.24	1	1.76	6	26.19	93
86	60	May 18/65	684	156	460	2.98	24	0.06	1-	3.53	29	5.67	46	3.04	24
87	220	May 18/65	1918	208	185	23.5	85	0.5	2	1.08	5	2.62	8	24.0	87
88	230	May 18/65	2090	144	65	29.6	95	0.36	1	0.78	2	0.48	2	29.96	96
89	252	May 18/65	3320	82	55	49.3	96	0.65	1	0.20	1-	0.89	2	49.95	97
90	142	May 18/65	2988	206	290	39.8	87	0.34	1	0.50	1	5.30	11	40.14	88
91	120	May 18/65	1298	90	135	17.6	85	0.35	2	0.30	1	2.80	13	17.95	87
92	165	May 19/65	1322	96	65	18.7	92	0.38	2	0.46	2	0.84	4	19.08	94
93a	60	May 19/65	924	58	125	13.05	82	0.44	2	0.20	1	2.30	14	13.49	84
94	140	May 19/65	1018	58	115	14.6	84	0.45	3	0.20	1	2.10	12	15.05	87
95	80	May 19/65	1308	122	130	17.3	85	0.37	2	0.5	2	2.10	10	17.67	87
96	100	May 19/65	1564	130	240	18.8	79	0.32	1	0.48	2	4.32	18	19.12	80
97	165	May 19/65	1322	96	50	18.6	93	0.40	2	0.28	1	0.72	4	19.00	95
98	176.5	May 19/65	1094	124	140	14.9	83	0.30	2	0.36	2	2.43	13	15.2	85
99	135	May 19/65	1966	180	170	26.8	88	0.26	1	0.76	2	2.64	9	27.06	89
100	65	May 20/65	1638	206	165	20.3	86	0.20	1	0.8	3	2.3	10	20.5	87
101	100	May 20/65	2006	180	210	25.1	85	0.26	1	1.36	5	2.84	9	25.36	86
102	92	May 20/65	2916	280	580	33.7	74	0.40	1	6.23	14	5.37	10	34.1	75
103	210	May 20/65	1080	130	75	17.9	92	0.18	1	0.24	1	1.26	6	18.08	93
104	200	May 20/65	2690	150	160	36.3	93	0.42	1	0.11	1-	2.30	6	36.72	94
105	100	May 20/65	2848	84	130	39.8	93	0.32	1	1.68	4	0.91	2	40.12	94
106	45	May 20/65	4684	828	2390	15.4	24	0.13	1-	18.82	30	28.98	44	15.53	25
107	231	May 20/65	846	80	30	13.5	97	0.03	1-	0.16	1	0.24	2	13.53	97
108	60	May 27/65	2184	140	50	32.1	97	0.07	1-	0.54	2	0.45	1	32.17	97
109	140	Aug. 16/63	578	128	350					Ca + Mg	=	7.00		3.31	32
"	"	May 25/65	558	160	290	3.78	38	0.28	3	3.36	34	2.44	25	4.06	41
110	25	May 25/65	1870	132	190	24.8	87	0.05	1-	1.70	6	2.10	7	24.85	87
111	40	May 25/65	2948	102	140	39.9	93	0.12	1-	1.32	3	1.48	3	40.02	94
112	30	May 25/65	2674	272	735	25.9	64	tr	1-	8.01	20	6.69	16	25.9	64
113	184	May 25/65	2502	97	380	33.1	82	0.1	1-	0.52	1	7.08	17	33.2	82
114	160	May 25/65	3322	98	110	48.5	95	0.14	1-	1.60	3	0.6	1	48.64	96
115	235	May 25/65	1602	96	25	23.1	97	0.23	1	0.50	2	0	0	23.33	98
116	126	May 25/65	2094	92	60	30.0	95	0.23	1	0.60	2	0.59	2	30.23	96
117	60	May 25/65	1764	202	330	20.9	75	0.15	1	2.72	10	3.86	14	21.05	76

Ca^{++}/Mg^{++}	Cl^- (epm)	%	SO_4^{--} (epm)	%	$HCO_3^- + CO_3$ (epm)	%	NO_3^- (epm)	%	Fe	Fl	Hydro-chemical facies of water	Remarks
5.54	0.08	1^-	16.05	51	15.70	49	0	0	1.1	0	II	
7.34	0.14	1^-	19.20	54	16.00	46	0.01	1^-	0.9	0	? II	
?	0.11	1^-	16.35	41	23.31	59	0.01	1^-	2.2	0	? II	
1.50	0.31	1	18.75	52	17.00	47	0	0	1.2	0	II	
1.06	0.48	1	16.68	50	16.2	49	tr	0	2.7	0	II	
24.0	0.34	2	4.58	28	11.4	70	0	0	0.9	0	II	
	0.08	1^-	14.30	39	24.7	61	0	0	2.8	0	? II	
0/0	0.31	2	0.35	2	14.2	96	0	0	2.6	0.84	I	
1.28	0.28	2	2.65	15	14.5	83	0.1	1^-	tr	0.84	I	
0/0	0.65	3	6.35	28	15.9	69	0	0	1.2	0	II	
2.58	0.4	1	11.70	42	15.6	57	0	0	3.8	0	II	
0/0	0.37	1	11.55	43	15.0	56	0	0	1.9	0.57	II	
0/0	0.56	4	0.30	2	13.0	94	0	0	1.7	1.83	I	
0/0	1.82	12	0.6	4	12.2	83	0	0	0.6	1.83	I	
0/0	18.0	68	0.23	1	8.16	31	0	0	1.7	0.57	IV	
0/0	0.98	6	0.25	2	14.4	92	0	0	0.5	1.61	I	
0/0	0.14	1	11.25	43	15.0	56	0	0	0.6	0	II	
9	0.08	1^-	17.60	52	16.4	48	tr	1^-	0.3	0	II	
1.0	0.34	1	10.38	38	17.3	61	0	0	0.2	0.28	II	
2.1	0.17	1	12.10	41	17.0	58	tr	1^-	0	0.2	II	
0.44	0.37	2	5.55	29	13.2	69	0	0	tr	0	II	
0.14	0.42	2	8.18	30	18.50	68	0	0	0.2	0	II	
0.3	0.25	1	2.13	12	15.20	87	0	0	0.3	1.35	I	
0.43	0.17	1	12.63	43	16.40	56	0	0	tr	0.56	II	
2.13	0.14	1^-	12.15	42	16.7	58	0	0	tr	0.36	II	
0.33	0.14	1^-	21.30	49	22.0	51	0	0	3.8	0.28	II	
0.25	0.42	1	21.23	47	23.5	52	0.02	1^-	2.4	0.05	II	
1.1	0.93	2	43.3	86	6.0	12	0.3	1^-	5.2	0.7	? III	
0.14	0.14	1^-	19.08	48	20.69	52	tr	1^-	0.2	0.08	? II	
0.62	0.65	6	4.50	43	5.4	51	0.06	1^-	0.6	0	? II	
0.41	0.42	1	18.38	65	8.97	31	0.91	3		0.16	? IV	
1.63	0.42	1	17.89	57	13.0	42	0	0	tr	0.5	II	
0.22	0.23	1^-	30.95	60	20.0	40	0	0	2	0.11	II	
0.09	0.23	1^-	32.13	63	18.5	36	0	0	10^+		? IV	
0.11	0.34	2	9.88	48	10.5	51	0	0		0	II	
0.54	0.20	1	9.68	44	10.5	55	tr	1^-	tr	0.67	II	
0.09	0	0	4.50	28	11.5	72	0	0	1.8	1.90	II	
0.1	0.06	1^-	5.35	31	12.00	69	0	0	0	1.1	II	
0.24	0.14	1	9.78	48	10.40	51	0.07	1^-	tr	0	II	
0.11	0.11	1^-	14.70	61	9.20	39	0	0	10^+	0	IV	
0.39	0.14	1	10.83	55	9.00	44	0	0	3	1.8	II	
0.15	0.22	1	4.63	26	13.20	73	0.1	1^-	0.6	1.5	II	
0.20	0.22	1	14.35	47	16.00	52	tr	1^-	10^+	0.14	II	
0.35	0.17	1	13.83	58	9.90	41	0	0	3.2	0.14	II	H_2S odour
0.48	0.28	1	21.05	70	9.00	29	0	0	5^+	0.2	IV	
1.17	0.42	1	32.85	72	12.6	27	tr	1^-	5^+	0.31	IV	
0.19	0.23	1	8.20	42	11.2	57	0	0	0.4	1.07	II	
0.05	0.14	1^-	27.98	69	12.7	31	tr	1^-	5.6	0.5	IV	
1.84	0.23	1	31.15	73	11.50	26	0	0	3.6	0.45	IV	
0.65	0.56	1	56.33	89	6.50	10	0.2	1^-		0.45		
0.67	0.36	2	0.03	1^-	14.50	97	tr	1^-	tr	1.75	I	
1.22	0.08	1^-	17.55	53	15.50	47	0	0	4.9	0.28	II	H_2S odour fluctuating in intensity
	0.51	5	3.52	34	6.1	59	0.18	2	0		II	
1.38	0.54	6	2.65	27	6.5	66	0.1	1	tr	0		
0.86	0.14	1^-	17.55	61	11.0	39	0	0	5^+	0.19	IV	Flowing
0.89	0.14	1^-	30.30	71	12.5	29	tr	1^-	1.0	0.31	IV	
1.20	0.25	1	30.73	75	10.00	24	0.02	1^-	1.0	0.11	III	
0.07	0.14	1^-	27.23	67	13.50	33	tr	1^-	2.0	0.22	IV	
2.67	0.23	1^-	35.65	72	14.00	28	0.06	1^-	tr	0.39	IV	
0.5/0	0.2	1	13.8	58	10.00	41	tr	1^-	tr	0.73	II	
1.00	0.17	1	20.48	65	10.80	34	tr	1^-	4.2	0.28	IV	
0.7	0.17	1	16.90	61	10.50	38	0	0		0	IV	

Three Hills Well No.	Depth of well at time of sampling (feet)	Date of sampling	Total solids (ppm)	Ignition loss (ppm)	Hardness (ppm) ($CaHCO_3$)	Na^+ (epm)	Na^+ %	K^+ (epm)	K^+ %	Ca^{++} (emp)	Ca^{++} %	Mg^{++} (epm)	Mg^{++} %	$Na^+ + K^+$ (epm)	$Na^+ + K^+$ %
118	60	May 25/65	1602	126	310	19.2	75	0.29	1	3.01	13	3.20	12	19.49	76
119	10	May 25/65	366	188	210	1.13	15	tr	1⁻	3.31	45	2.90	40	1.13	15
120	0	May 26/65	1394	150	250	16.7	76	0.16	1	1.8	8	3.2	15	16.86	77
121	25	May 26/65	3294	142	1480	21.2	42	0.1	1⁻	17.82	35	11.78	23	21.3	42
122	90	May 27/65	2092	196	350	28.6	80	0.34	1	3.61	10	3.39	9	28.24	81
123	108	May 27/65	3648	132	230	55.05	92	0.31	1	2.67	4	1.93	3	55.86	93
124	122	June 1/65	1602	190	290	19.7	76	0.28	1	2.91	11	2.9	11	19.95	77
125	92	June 1/65	1588	164	50	22.1	94	0.44	2	0.40	2	0.59	2	22.54	96
126	58	Sept. 28/65	1624		330					Ca + Mg =		6.60		18.40	74
127	110	Nov. 10/65	5120		100					Ca + Mg =		2.00		73.29	97
128a	0														
129	37	Mar. 3/64	864		20					Ca + Mg =		0.40		10.65	96
129a	17	Apr. 21/64	2374		65					Ca + Mg =		1.30		38.50	97
130	210	Aug. 8/62	1362		115					Ca + Mg =		2.30		18.81	89
131	280	Apr. 22/63	844		40					Ca + Mg =		0.80		13.99	95
132	308	July, 1962	1422		95					Ca + Mg =		1.90		21.58	92
133	160	July, 1962	2840	124	220					Ca + Mg =		4.40		39.48	90
134	175	Aug. 3/64	872		25					Ca + Mg =		0.50		14.53	97
135	201	May 11/64	2336	236	355					Ca + Mg =		7.10		28.90	80
136	98	Sept. 9/64	1354		85					Ca + Mg =		1.70		20.01	92
137	50	Sept., 1964	4434		395					Ca + Mg =		7.90		58.75	88
138	50	Sept. 6/61	1240		110					Ca + Mg =		2.20		18.09	89
139	237	July, 1962	1012		60					Ca + Mg =		1.20		15.85	93
140	21	Sept. 4/62	1258		540					Ca + Mg =		10.80			
141	0	Apr. 23/64	3086		1000⁺					Ca + Mg =		20⁺		22.56⁻	53⁻
142	62	Sept. 15/62	2738		50					Ca + Mg =		1.0		40.16	98
143	280	July, 1965	1240	240	40					0.28	1	0.52	3	17.55	96
144	1., 100	Nov. 25/65	2076	488	93					1.45	5	0.41	1	27.40	94
144	2., 414	Dec. 7/65	1832	424	32					0.55	2	0.16	1	28.38	97
144a	202	Apr. 14/65	1788	220	40					0.55	2	0.25	1	28.46	97
145	1., 295	Dec. 3/65	984	296	45					0.65	4	0.25	1	15.85	95
145	2., 495	Dec. 15/65	760	224	17					0.25	2	0.08	1	13.20	97
146	200	Dec. 21/65	2112	532	37					0.50	2	0.25	1	31.10	97
147	1., 231	Dec. 23/65	3440	432	92					1.10	2	0.74	1	50.40	97
147	2., 435	Jan. 18/66	4072	412	132					1.75	3	0.99	2	55.05	95
148	225	Jan. 11/66	11960	1280	4144					20.81	13	61.98	37	82.52	50
149	330	Feb. 7/66	1156	132	21					0.25	1	0.16	1	18.35	98
150	305	Feb. 8/66	1080	176	162					1.85	11	1.40	9	13.13	80
151	1., 78	Feb. 11/66	2400	228	301					2.89	8	3.12	9	28.56	83
151	2., 325	Feb. 17/66	2696	304	277					2.74	7	2.79	7	35.19	86
151a	1., 130	Mar. 22/66	2960	376	324					3.34	8	3.12	8	33.83	84
151a	2., 130	Mar.23/66	2800	360	277					2.75	7	2.80	7	33.49	86
151a	3., 130	Mar.24/66	2896	464	275					2.75	7	2.79	7	33.43	86
152	1., 60	Feb. 11/66	4160	460	122					1.20	2	1.23	2	55.41	96
152	2., 360	Feb. 21/66	3280	380	61					0.9	2	0.33	1	43.75	97
153	1., 150	Feb. 25/66	1624	296	36					0.55	2	0.16	1	22.44	97
153a	1., 135	Mar. 7/66	1828	376	44					0.55	2	0.33	1	23.80	97
153a	2., 135	Mar. 8/66	1720	320	45					0.65	3	0.25	1	23.33	96
153a	3., 135	Mar. 15/66	1656	336	52					0.80	4	0.25	1	21.50	95
154	1., 152	Mar. 1/66	4492	232	237					3.99	6	0.71	1	60.82	93
154	2., 310	Mar. 4/66	4720	444	358					5.09	7	2.06	3	63.41	90
155	1., 143	Mar. 9/66	1908	308	17					0.25	1	0.08	1⁻	25.80	99

Ca^{++}/Mg^{++}	Cl^- (epm)	%	SO_4^{--} (epm)	%	$HCO_3^- + CO_3$ (epm)	%	NO_3^- (epm)	%	Fe	Fl	Hydro-chemical facies of water	Remarks
0.94	0.17	1	16.08	62	9.6	37	0	0		0	IV	Flowing
1.13	0	0	1.13	22	3.5	70	0.4	8		0	II	?
0.56	0.14	1	13.20	61	8.50	38	0	0	0.4	0.14	IV	Spring; at approximately 4 gpm
1.52	0.37	1	43.88	86	6.80	13	tr	1-	5.6	0.19	III	
1.06	0.2	1	21.60	66	10.60	33	0.05	1-	0.3	0.08	IV	?
1.38	0.28	1	41.25	75	13.40	24	0	0	0.4	0.79	IV	?
1.0	0.37	1	10.63	40	15.20	58	0.02	1-	5	0	II	?
0.68	0	0	11.10	47	12.50	53	0	0		0.84	II	
	0	0	13.70	55	11.30	45	0	0	tr	0	II	
	0.56	1	61.93	82	12.80	17	tr	1-	2		IV	
										2.1		Spring
	0.85	2	1.60	14	8.60	84	0	0	0	2.2	I	H_2S odour - changing by year
	4.65	12	10.25	26	24.90	62	0.13	1-	tr		II	
	0.23	1	9.88	47	13.00	52	0	0	tr		II	
	0.61	4	0.58	4	13.60	92	0.04	1-	tr	1.9	I	
	0.25	1	10.63	45	12.60	54	0	0		0.79	II	H_2S odour, first noticed in 1964
	0.28	1	28.00	64	15.60	35	0	0	1	0	IV	
	0.08	1	2.35	16	12.60	83	0	0	0.5	1.8	I	
	0	0	22.50	62	13.50	38	0	0	2		IV	Water is mixture from aquifers at 90 ft and 190-200 ft
	0.51	2	8.80	44	12.30	54	0	0	0	1.3	II	Flowing originally; H_2S since 1962
	0.20	1-	48.85	73	17.60	27	0	0	3.8		IV	
	0.71	4	7.98	39	11.60	57	0	0	0.8		II	
	0.37	2	5.28	31	11.50	67	0	0	tr		II	
	0.17				7.10		0	0	3.3			
	0.76	2	32.90	77	8.90	21	0.04	1-	tr		III	Spring
	0.48	1	30.38	74	10.30	25	0.02	1-	0.2	0.85	IV	
0.54	0.25	1	2.60	16	15.50	83	0	0	6.0		I	Water from 120 ft
3.54	0.23	1	11.88	40	17.15	59			0.6	0.6	II	Sample taken in the course of drilling
3.44	0.23	1	11.98	43	15.78	57			2.0	0.8	II	Sample taken after 2 hr bail test at 23 gpm
2.2	0.23	1	12.15	44	15.12	55			0.5	0.8	II	Sample taken after 50 min of pumping at approximately 51 gpm
2.6	1.47	9	0.69	4	14.59	87				2.8	I	Sample taken in the course of drilling
3.13	0.90	7	0.60	4	12.03	89			1.4	3.3	I	Sample taken after 2.5 hr bail test at 23 gpm
2.0	0.34	1	16.64	52	14.87	47			0.7	0.6	II	Sample taken after 2 hr bail test at 11.5 gpm
1.49	0.34	1	35.34	67	16.56	32			0.3	0.8	IV	Sample taken during drilling
1.77	0.45	1	38.85	67	18.49	32			0.3	0.7	IV	Sample taken after 2 hr bail test at 11.5 gpm
0.34	0.90	1	147.22	89	17.19	10			2.5	0.5	III	Sample taken during drilling
1.56	0.34	2	6.99	37	11.43	61			tr	1.8	II	Water from 190-203 ft; sample taken after 2 hr bailing at 23 gpm
1.32	0.28	2	4.87	29	11.23	69			2.9	1.0	II	Mixed water of aquifers at 63 ft, 103 ft, and 192 ft. Sample taken after 2 hr bail test at 23 gpm
0.93	0.28	1	23.96	69	10.33	30			0.15	0.7	IV	Sample taken during drilling
0.98	0.17	1-	27.66	68	12.89	32			0.1	0.9	IV	Sample taken after 2 hr bail test at 23 gpm
1.07	0.34	1	27.29	68	12.66	31			0.9	0.6	IV	Sample taken after 3 hr pumping at approx. 185 gpm
0.98	0.23	1	26.08	67	12.73	33			0.4	0.6	IV	Sample taken after 30 hrs pumping at approx. 185 gpm
0.99	0.23	1	26.08	67	12.66	32			0.3	0.6	IV	Sample taken after 48 hrs pumping at approx. 185 gpm
0.99	0.17	1-	38.83	67	18.84	32			0.3	1.1	IV	Water from coal; sample taken during drilling
2.73	0.23	1	28.89	64	15.86	35			0.4	1.4	IV	Main contribution from 88 ft; sample taken after 2 hrs bailing at 11 gpm
3.44	0.23	1	7.30	31	15.62	68			0.2	2.0	II	Sample taken after 2 hrs bailing at 23 gpm
1.67	0.23	1	8.05	32	16.40	67			0.5	1.5	II	Sample taken after 30 min pumping at 68 gpm
2.60	0.28	1	7.88	33	16.07	66			0.4	1.5	II	Sample taken after 23 hrs pumping at 68 gpm
3.20	0.23	1	7.26	32	15.06	67			6.5	2.0	II	Sample taken after 6 1/2 days of pumping at 67 gpm + approx. 1 day of recovery
5.62	0.45	1	45.09	69	20.01	30			0.4	0.5	IV	Sample taken after 2 hrs of bailing at 23 gpm
2.47	0.39	1	43.93	62	26.24	37			2.4	0.4	IV	Sample taken after 2 hrs of bailing at 23 gpm
3.13	0.90	3	12.77	49	12.46	48			tr	1.0	II	Sample taken during drilling

APPENDIX C. LITHOLOGIC STRIP LOGS OF THREE HILLS WELLS.

FIGURE 3. MAP SHOWING LOCATIONS AND NATURE OF OBSERVATION POINTS AND BOREHOLES AND LOCATIONS OF GEOLOGIC AND ANALOG HYDRAULIC CROSS SECTIONS.

To accompany Research Council of Alberta Bulletin 24, by J. Tóth.

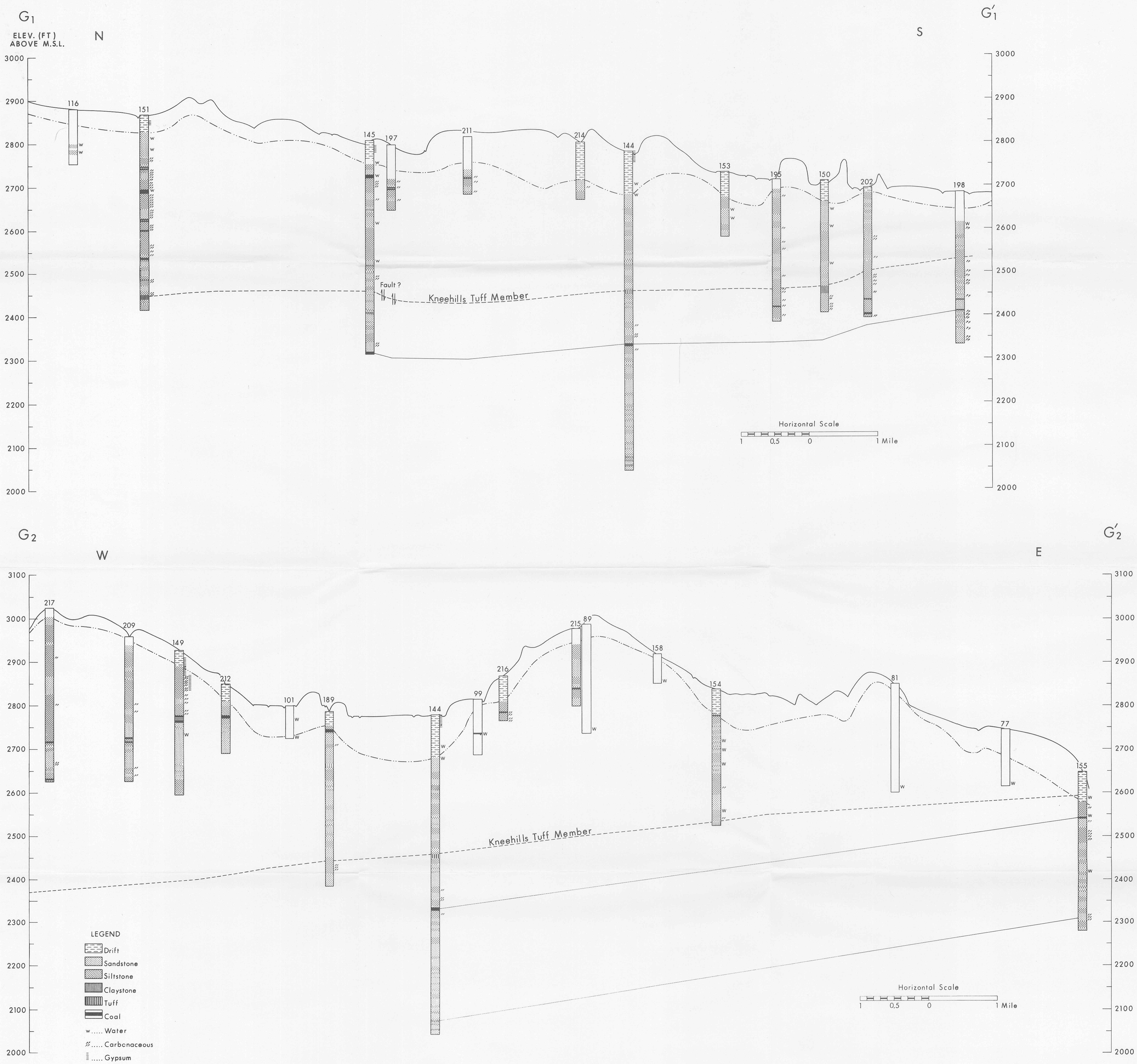


FIGURE 7. LITHOLOGIC LOGS FOR WELLS ALONG CROSS SECTIONS G_1 - G_1' AND G_2 - G_2' (FIG. 3.).

To accompany Research Council of Alberta Bulletin 24, by J. Tóth.

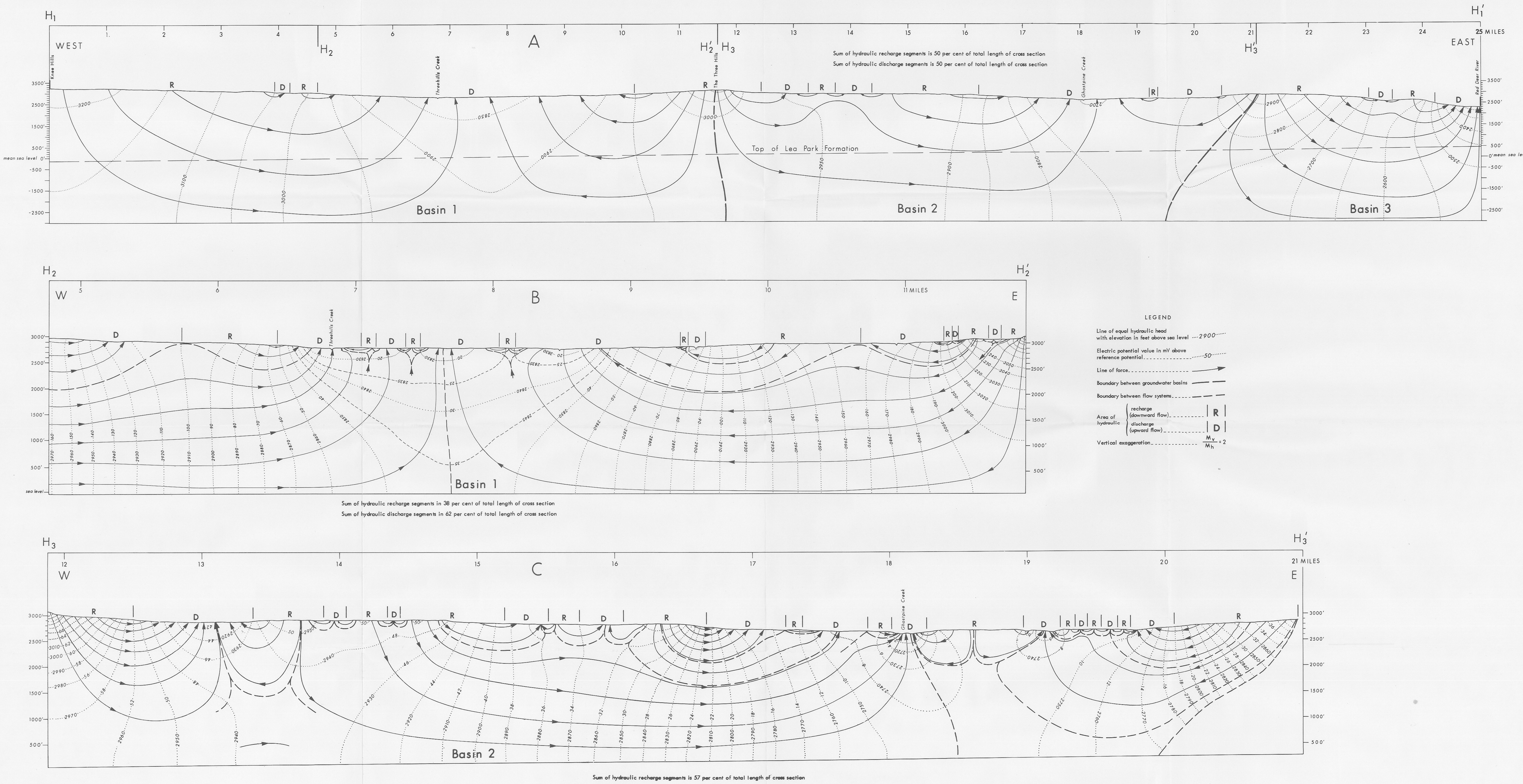
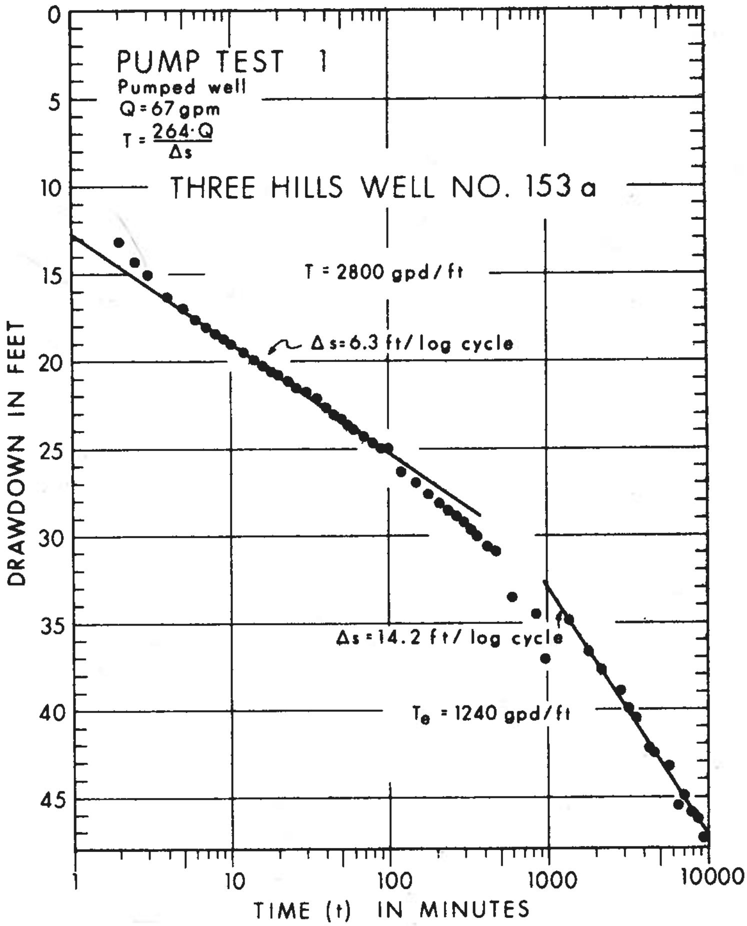


FIGURE 13. ELECTRIC ANALOG MODELS OF THE DISTRIBUTION OF FLUID POTENTIAL AND FORCE FIELD ALONG WEST-EAST CROSS SECTIONS.

To accompany Research Council of Alberta
Bulletin 24, by J. Tóth.



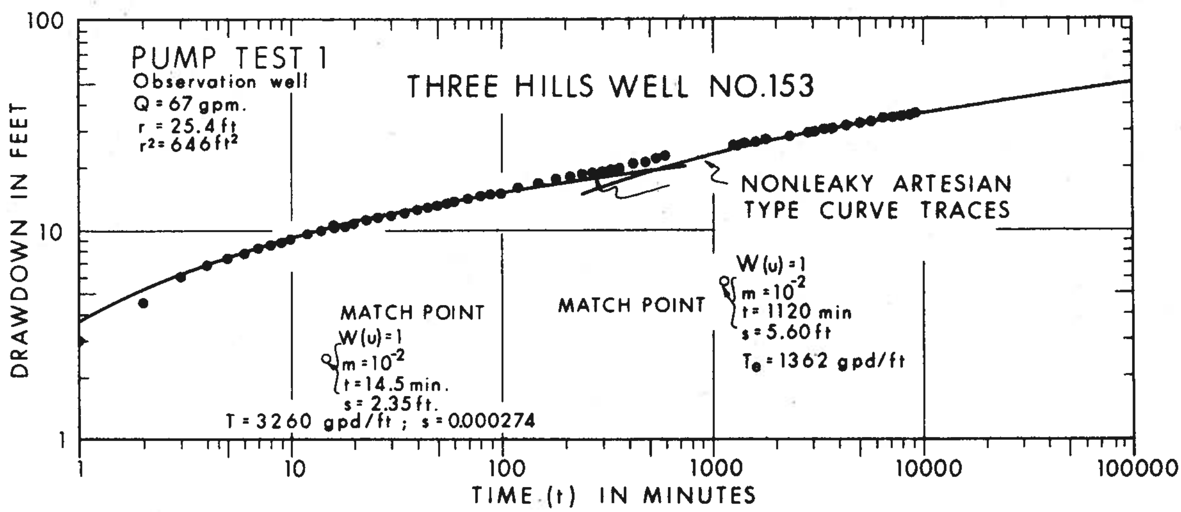
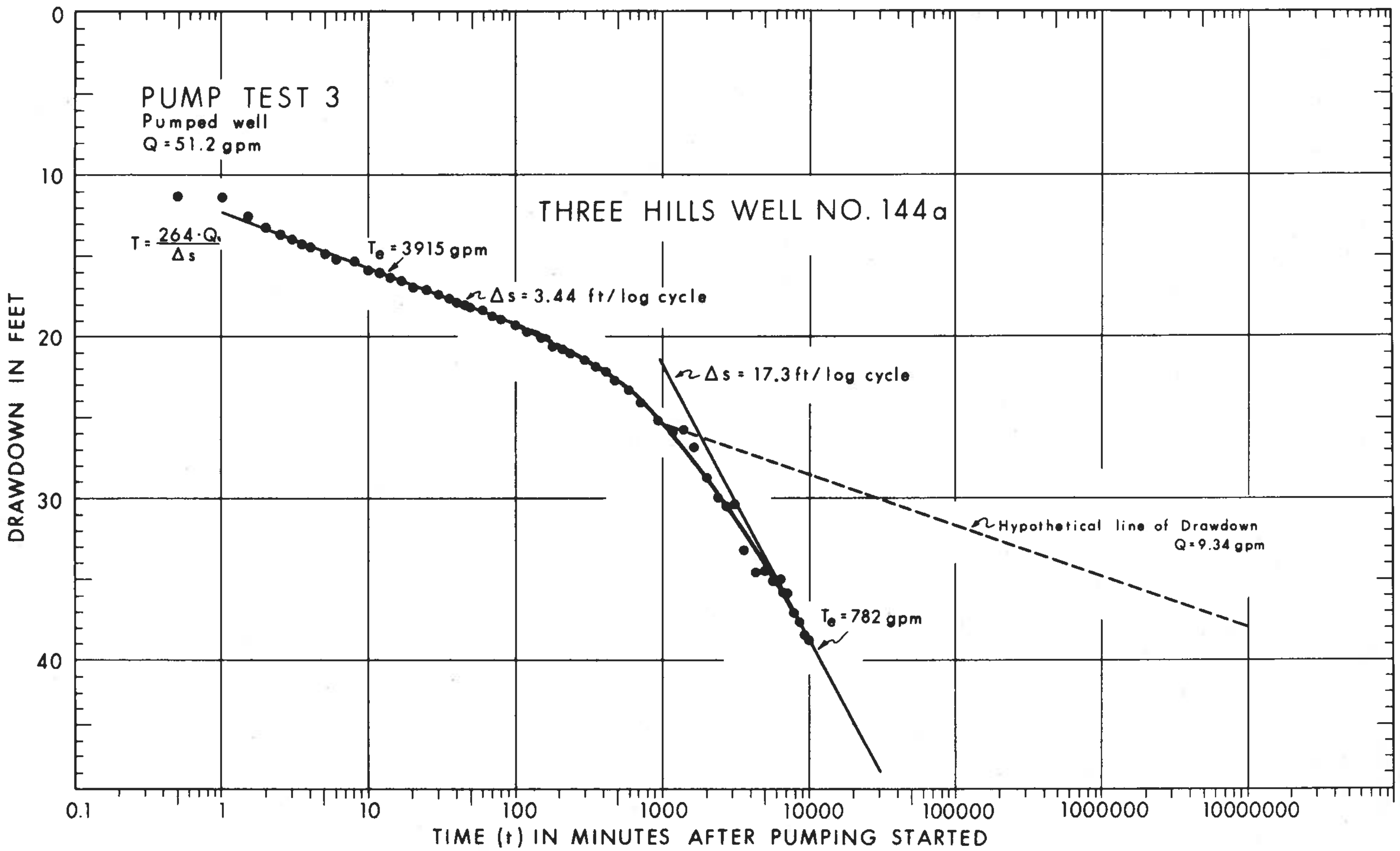


FIGURE 29. Time-drawdown curves for Three Hills Well Nos. 151 and 151a during Pump Test 3.

To accompany Research Council of Alberta Bulletin 24, by J. Toth.



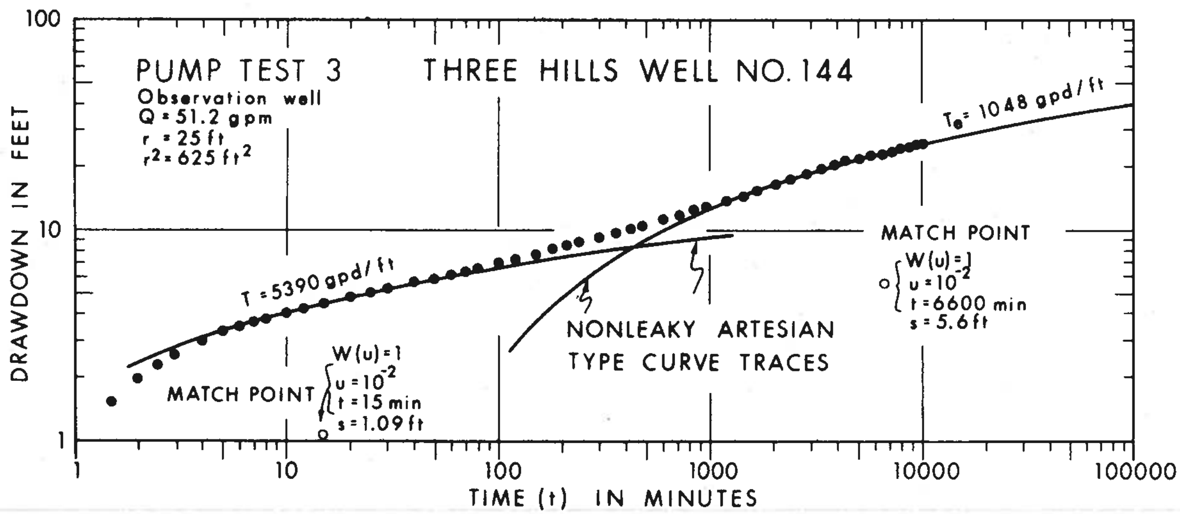


FIGURE 31. Time-drawdown curves for Three Hills Well Nos. 144 and 144a during Pump Test 3.

To accompany Research Council of Alberta Bulletin 24, by J. Tóth.