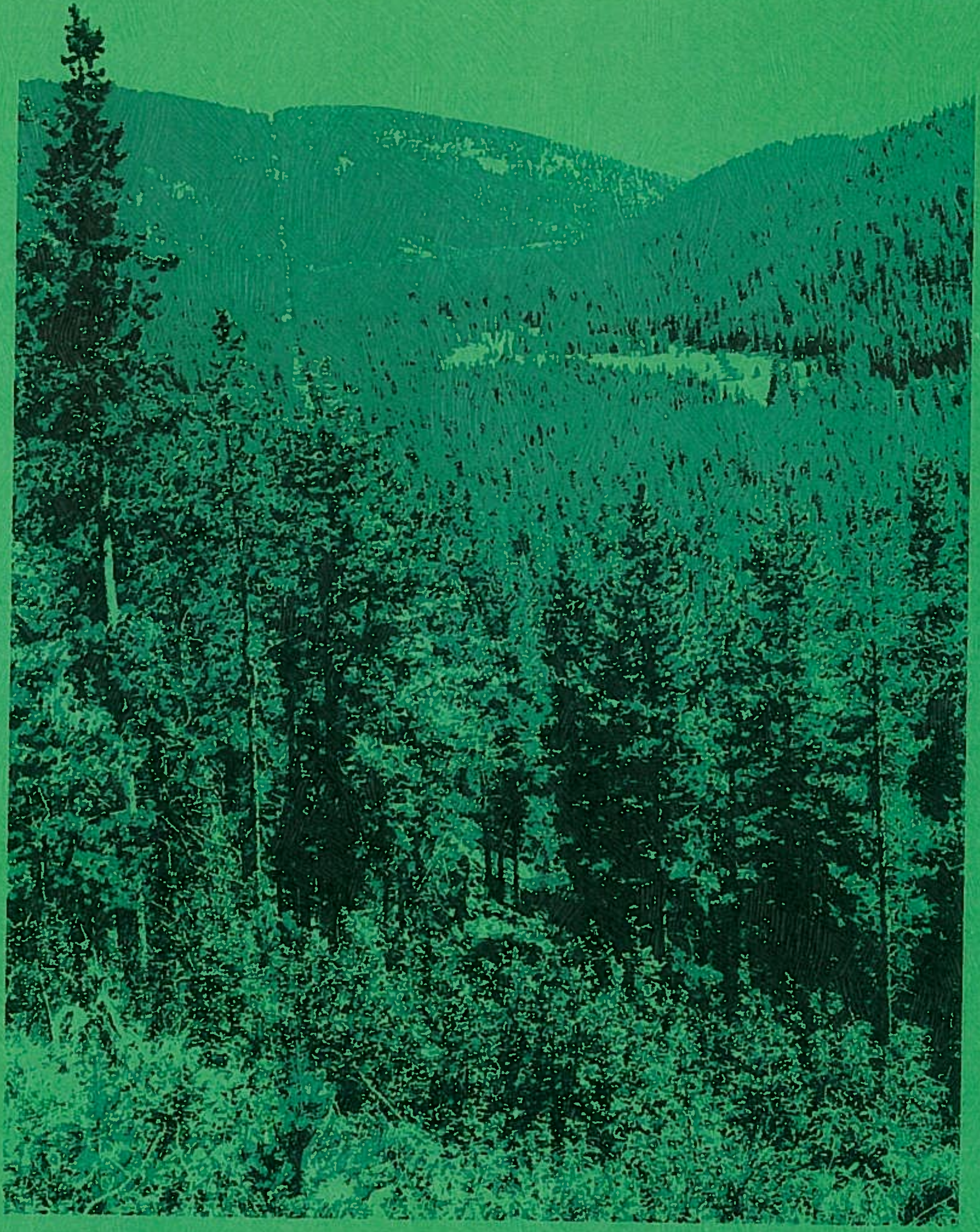
HYDROGEOLOGY OF THE TRI-CREEK BASIN, ALBERTA

D. V. Currie



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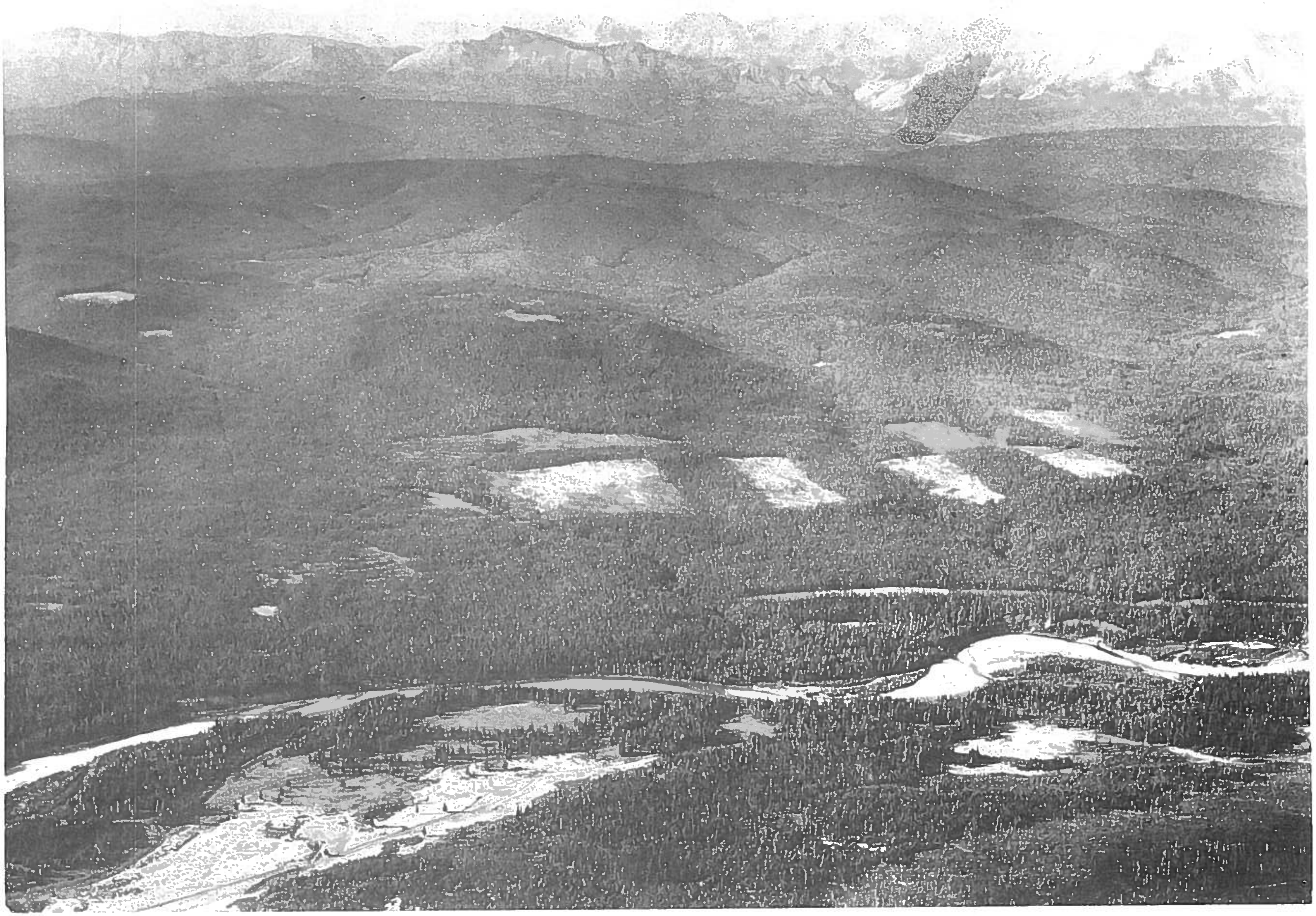

Oblique air view of the study area looking to the south across the McLeod River.

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ABSTRACT

Groundwater flow in Tri-creek basin, a 23-square mile (60 km^2) area of the Rocky Mountain Foothills in western Alberta, is controlled by the surficial and bedrock geology. Flow in the bedrock follows bedding planes and joints; flow in surficial deposits is governed by relative permeability. Flow systems are short, shallow and rapid; the depth of active groundwater flow is probably less than 300 feet (< 91 m) and metamorphosis of groundwater is limited by the short residence time below the surface. Response to changes in precipitation is generally rapid, although slower responses were noted at some points in the region.

Groundwater discharge features observed include springs of several kinds, seepages, hummocky ground, swamps and amphitheater-shaped depressions.

Quantitative drainage pattern data include a bifurcation ratio of 5.6 (indicative of strong geologic control) in one of the three subbasins, and values of less than 5 (little geologic control) in the other two. Average drainage density is 4.1. Relief ratios of 0.04 to 0.06 indicate glacial derangement of drainage.

Depth to water table, estimated from studies of the various phreatophytic plant assemblages, ranges from 1 to 8 feet (0.3 to 2.4 m). A plant association of lodgepole pine, bearberry and brome grass indicates water table depths of from 4 to 8 feet (1.2 to 2.4 m); an association of black spruce, fir, haircap and sphagnum moss indicates a range of from 1½ to 2½ feet (0.5 to 0.8 m). Lodgepole pine-brome grass-bearberry, and white spruce-pine-bilberry-green moss associations indicate natural groundwater recharge conditions; natural groundwater discharge areas are marked by an association of black spruce, haircap and sphagnum moss.

Allowable rates of well pumping vary from 0.5 to approximately 100 imperial gallons per minute (igpm) or 2 to 450 litres per minute (l/min); but values greater than 25 igpm (115 l/min) are associated with scattered deposits of ice-contact drift and are not typical of the area. Wells yield 5-10 ipgm (25 to 45 l/min) on the average.

Erosion hazard in the area ranges from low to high. Glaciolacustrine deposits, which cover a third of the basin, are easily eroded when vegetation cover is artificially disturbed. Logging and strip mining are not recommended in these areas.

The hydrogeological information given in this report may be applicable to those areas of the Rocky Mountain Foothills where similar geologic and climatic conditions exist.

Explanations of hydrogeological concepts and methods used are found throughout the text and in the appendixes.

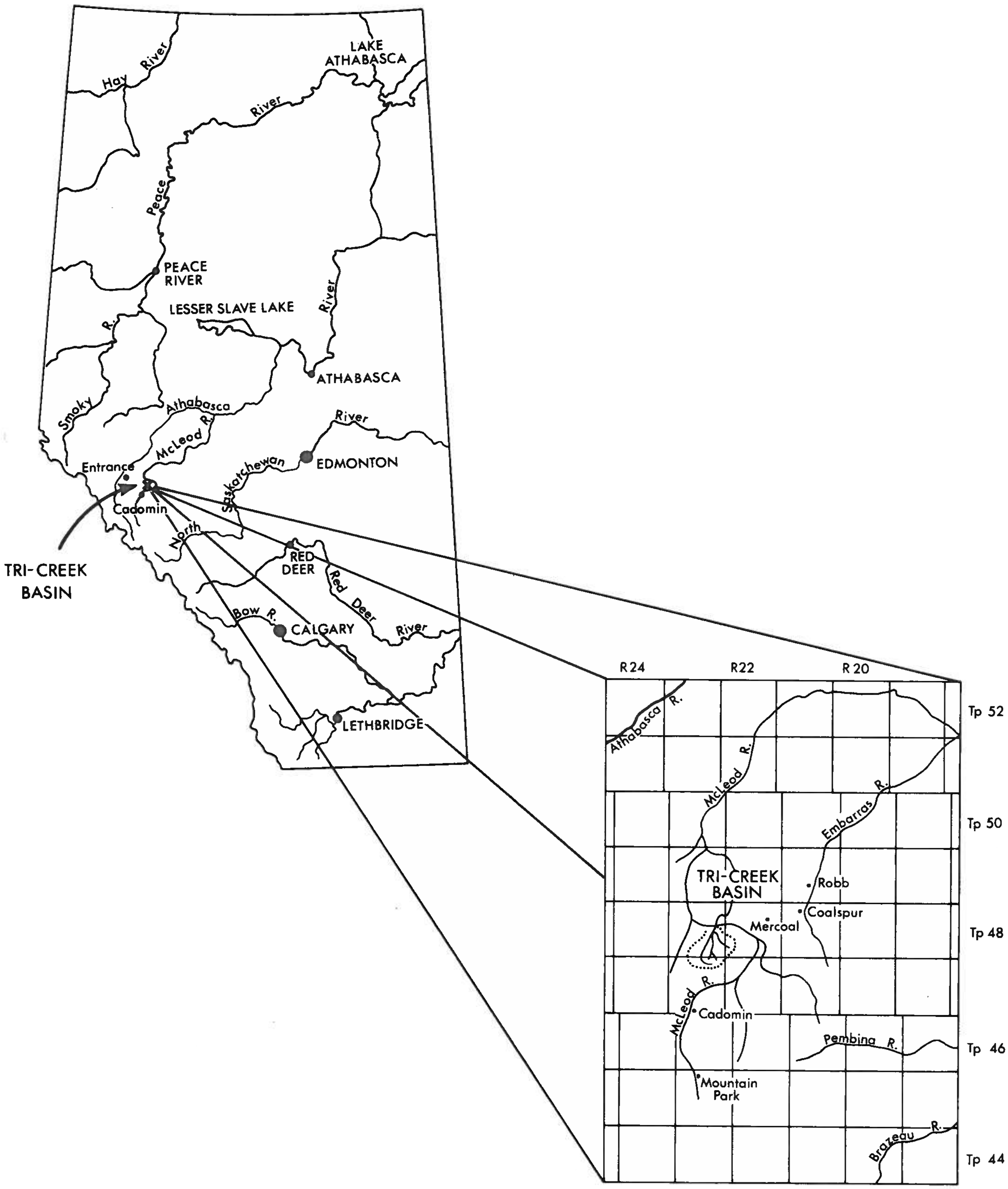


FIGURE 1. Location of study area.

INTRODUCTION

This study establishes relationships between the hydrogeologic environment and the groundwater regime in a small region of the Rocky Mountain Foothills. The investigation also outlines the methodology employed.

LOCATION AND ACCESS

The name "Tri-creek basin" designates the area drained by Wampus, Deerlick and Eunice creeks, three northward-flowing tributaries of the McLeod River in the Foothills physiographic region of western Alberta (Fig. 1). The study area is also designated "International Hydrologic Decade Experimental Research Basin Number 1 W.B.-E.B.-13." Located at 53°09′ north latitude and 117°15′ west longitude, Tri-creek basin covers approximately 23 square miles (59 km^2) and includes parts of townships 47 and 48, and ranges 22 and 23 west of the fifth meridian. The study site is approximately 190 miles (306 km) west-southwest of the city of Edmonton; access is by road from the towns of Cadomin (8 miles or 14 km), Edson (80 miles or 140 km) or Hinton (40 miles or 64 km).

PREVIOUS GEOLOGICAL WORK

Exploitation of coal resources in the Cadomin area, which includes part of Tri-creek basin, began in 1912 and continued until the early 1950's, so early geological work in the Tri-creek area was related to coal exploration. R. L. Rutherford (1924) mapped the general geology between the McLeod and Athabasca rivers, giving special attention to coal reserves. A detailed geological map of the Cadomin area was prepared by R. B. McKay in 1929.

The discovery of petroleum resources in the Foothills brought seismic exploration to the Cadomin area in the 1950's, followed by the drilling of two wells along Eunice Creek:

(1) B.A. *et al.* Kaydee 14-12-48-23W5, drilled in 1959 and abandoned at a depth of 10,031 feet (3057 km);

(2) B.A. *et al.* Kaydee 5-7-48-22W5, drilled in 1960 and abandoned at a depth of 14,058 feet (4288 km).

Both wells penetrated a complexly faulted and folded succession of Mesozoic strata.

METHOD OF STUDY

The two elements fundamental to understanding, describing and predicting groundwater occurrence and movement are hydrology and geology. These elements are combined in the term *hydrogeology*, which has been defined as the study of subsurface waters in their geologic context (Pfannkuch, 1969).

Fundamental to the study of hydrogeology are concepts of *hydrogeological environment* (Rakhmanov, 1962) and *groundwater regime* (Altovsky, 1959). Important components of the hydrogeologic environment are geology, climate and physiography; those of the groundwater regime are the amount of water, media (paths) of water movement, volume and velocity of flow, chemical composition, temperature and regime variance (Tóth, 1970).

In studying the hydrogeology of a stream basin, pertinent aspects of the local geology, topography and climate are integrated to provide an interpretation of the groundwater regime. Field observations, investigations into hydrogeologic parameters of bedrock and surficial deposits within the basin, and a compilation of groundwater chemistry provide the data.

ACKNOWLEDGMENTS

The author wishes to thank the Alberta Forest Service for obtaining water level measurements necessary to the study. Artesia Drilling, Hi-Rate Drilling, and Lousana Water Wells supplied technology and drilling equipment. Mapping of surficial deposits was aided by seismic shothole logs of the British American Oil Company (now Gulf Canada Ltd.). The calcium content of soil samples was determined by the Soils Division of the Alberta Research Council; soil engineering data was generated by the Highway Research Division.

During the summer of 1969, the author was aided by Mr. Calvin King.

Special acknowledgment is due to Mr. D. R. Stevenson, Alberta Research Council, who initiated the author's interest in this project.

The manuscript was critically read by B. Gadd of the Wordworks Ltd., Calgary, and edited by Mrs. A. Campbell, Alberta Research Council.

The author gratefully acknowledges the assistance of all these individuals and organizations.

Table 1. Stratigraphic summary, Tri-creek basin

Series	Group	Formation	Member	Description
		BRAZEAU		green grey, noncalcareous sandstones and shales
UPPER CRETACEOUS	ALBERTA 2000-4100'	WAPIABI 1900'	NOMAD 100'	rusty weathering, rubbly shales grading upwards into greenish grey shales and fine-grained, thinly bedded sandstones
			CHUNGO 260'	light brown weathering, fine-grained, thickly bedded sandstones, and dark grey siltstone
			HANSON 200'	dark grey, rusty weathering, blocky to rubbly shales, with reddish brown weathering concretions
			THISTLE 700'	dark grey to black, grey to light grey weathering, calcareous, platy to fissile shales
			DOWLING 300'	dark grey, rusty weathering, rubbly to platy shales, with reddish brown concretions
			MARSHYBANK 90'	dark grey, massive, argillaceous siltstone, with large reddish brown concretions
			MUSKIKI 250'	dark grey, rusty weathering, rubbly to platy shales, some concretions, slightly banded appearance
		CARDIUM 235'	STURROCK 25'	rusty brown weathering, fine-grained, thickly bedded sandstone
			LEYLAND 80'	dark grey to black, rubbly to blocky shales with large reddish brown concretions
			CARDINAL	dark grey, massive argillaceous siltstone, with large reddish brown concretions (may not be present in the area)
			KISKA	dark grey to black, rubbly to blocky shales with reddish brown sideritic concretions (may not be present)
			MOOSEHOUND 100'	greyish green to brown, carbonaceous, rubbly shales, friable carbonaceous sandstones, thin coal beds, minor conglomerate
			RAM 30'	rusty weathering, fine-grained, thickly bedded sandstone
		BLACKSTONE 1900'	OPABIN 180'	dark grey, rusty weathering, blocky to rubbly shales, with reddish brown weathering concretions
			HAVEN 270'	dark grey to black, rusty weathering, rubbly to platy shales with yellow sulfur staining and fetid odor
			VIMY 550'	dark grey to black, slight grey to white weathering, calcareous, platy to fissile shales (not present in area)
			SUNKAY 550'	dark grey, rusty weathering, rubbly to platy shales, with some argillaceous siltstone large concretions (not present in the area)

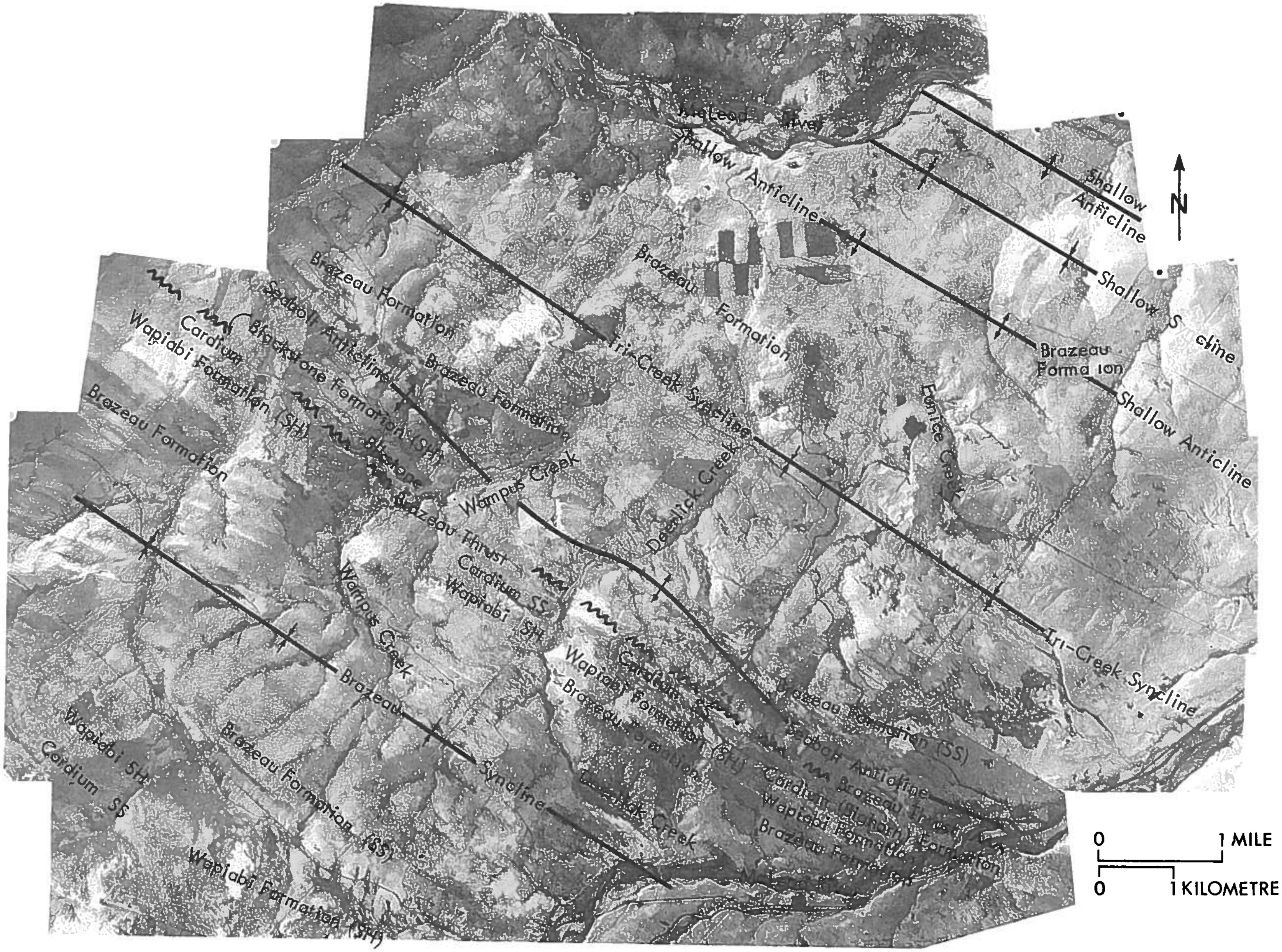


PLATE 1. Air photo mosaic of Tri-creek basin.

HYDROGEOLOGIC ENVIRONMENT

Essential geologic elements in the hydrogeologic environment are attributes of the local bedrock (permeability, structure, stratigraphic relations), and the distribution and composition of surficial deposits. Important climatic elements are precipitation and temperature data, with attention to seasonal variation. Physiographic elements such as topography and drainage network reflect the interaction of geology and climate.

BEDROCK GEOLOGY

Drift and vegetation cover most of the study area and outcrops are rare; however, continuous bedrock exposures are found along strike at the McLeod River nearby. Some of the rock units described in the river valley by Stott (1963) can be recognized in Tri-creek basin; others can be inferred from aerial photography and stratigraphic relationships. Figure 2 outlines the bedrock geology.

Stratigraphy

As shown in Table 1, rocks of Tri-creek basin are Late Cretaceous in age, although some Tertiary strata may be present in the northern part of the study area.

The Alberta Group, a marine sequence of shales and sandstones, and the overlying Brazeau Formation, a mixed marine and nonmarine sequence, are the two stratigraphic units present. The Alberta Group includes the Blackstone, Cardium, and Wapiabi formations. Younger strata corresponding in age to the Belly River, Bearpaw, Horseshoe Canyon and Paskapoo formations of the Interior Plains are found in the Foothills; however, correlations among these units are obscure and the Foothills strata are collectively named the Brazeau Formation (Malloch, 1911).

Structure

Tri-creek basin is located in the Rocky Mountain Foothills belt, a fold and thrust zone characterized by imbricate, southwest-dipping thrust sheets in which the strata have been folded. The intensity of deformation increases from east to west, as does the age of the units involved. On the east margin, open folds occur in Upper Cretaceous and Tertiary strata; to the west Jurassic, Triassic, and Lower Cretaceous strata are closely folded and thrust-faulted. Throughout the Foothills, jointing is generally perpendicular to bedding planes.

This westward increase in deformation is observed in Tri-creek basin (Fig. 3). The northeastern part of the area is underlain by gently folded Upper Cretaceous-Tertiary Brazeau beds (Seabolt anticline and Tri-creek syncline), while the Brazeau thrust brings intensely folded units of the Upper Cretaceous Alberta Group to the surface in the southwestern corner. The west limb of the Brazeau syncline forms the western basin divide; the upper reaches of Wampus Creek flow northwest along its axis. Plate 1 is an airphoto mosaic showing bedrock geology and the structure in Tri-creek basin.

SURFICIAL GEOLOGY

Approximately 40 percent of Tri-creek basin is covered with unconsolidated deposits 10 feet or more (>3 m) in thickness; figure 4, an isopach map constructed from seismic shothole information, shows their thickness and distribution. Largely of glacial origin, these deposits are predominantly tills and glaciolacustrine silts. Alluvial materials associated with present-day drainage channels are also found but are less extensive.

Tills

Till is material deposited directly from melting glaciers without washing or sorting (Pawluk and Bayrock, 1969); often the material reflects the characteristics of the underlying bedrock.

In the basin two glacial tills are recognized. One of these is considered equivalent to the Marlboro till of Roed (1968); the other is designated 'the local till' for the purposes of this report. A third till, found outside the basin boundary in the McLeod River valley, is termed unofficially the 'McLeod Valley limy till'. The tills are distinguishable on the basis of carbonate content and the presence or absence of quartzite pebbles.

The distribution of tills is shown in figure 5. The local till covers most of the basin; the Marlboro till is limited to the northern lower part, where it is overlain by glaciolacustrine deposits; the McLeod Valley limy till is confined to the McLeod River valley.

The local till is dusky, yellow-brown (standard colour 10YR 2/2, Oyama and Takehara, 1967), noncalcareous, sandy loam with subangular cobbles and pebbles of Brazeau Formation lithology probably derived from local

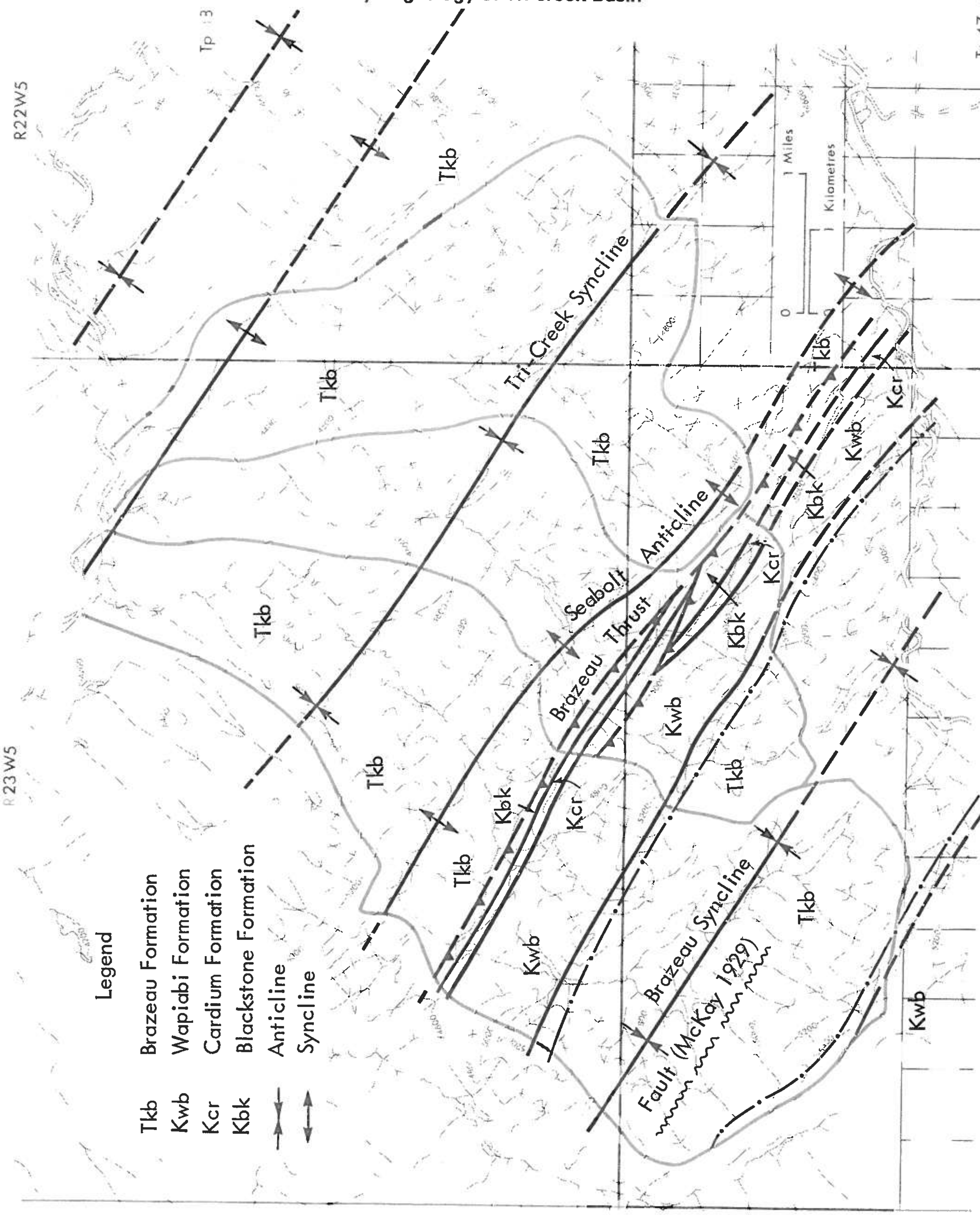


FIGURE 2. Geology of Tri-creek basin.

bedrock. This till is widespread over the basin, and the presence of many soft sandstone fragments in the till indicates a short distance of transport. The carbonate content of the local till is 0.3 percent; however, large Paleozoic carbonate erratics up to an estimated 50 cubic feet (1.4 m^3) in size, medium grey in color (N3), and fresh in appearance are found sporadically throughout the basin, resting on the local till. The presence of these erratics may give a false impression of the carbonate content.

In the Tri-creek basin the Marlboro till is an olive (5Y 5/4), moderately strong, weakly plastic loam to clay-loam. Quartzite is the dominant lithology of boulders, cobbles and pebbles in the coarse fraction. Two quartzite types are present:

1) light-coloured quartzites: well rounded, hard, consisting entirely of fine-grained to very fine-grained quartz, white to buff in colour;
2) dark-coloured quartzites: subrounded to subangular, coarse-grained to conglomeratic quartz pebbles, commonly reddish purple in colour.

The presence of the purple quartzite erratics suggests that this till was deposited by a Cordilleran glacier flowing along the Athabasca Valley (Mountjoy, 1958).

The McLeod Valley limy till, found in the east-west section of the McLeod River valley to the south of Tri-creek basin, is bluish grey (5PB 5/1), stony and calcareous, and contains many angular to subangular limestone erratics. No rounded quartzite pebbles were observed. The fine fraction is sandy in texture.

Glaciolacustrine Deposits

A rather extensive late-Wisconsin proglacial lake deposited glaciolacustrine silt and clay in the valleys of Wampus, Deerlick, and Eunice creeks. The distribution of these materials is shown on the surficial geology map (Fig. 5). The silts are grey (5Y 6/1) when dry and light bluish grey (10B 6/7) when water saturated. Thicknesses range up to 27 feet (8.2 m), and the deposits frequently overlie Marlboro till or ice-contact drift (Plate 2).

Other Glacial Deposits

Ice-contact stratified drift, outwash and deltaic deposits are found in Tri-creek basin but such deposits are not extensive.

Two areas of ice-contact deposits have been mapped at approximately the same elevation (4600 ft or 1400 m above sea level); they consist of interbedded sand, silt

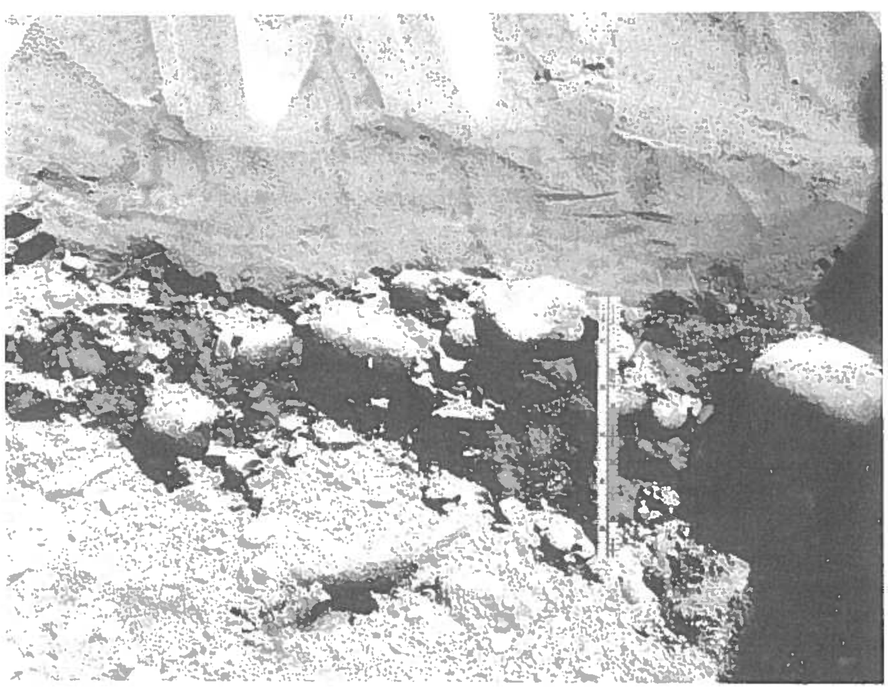


PLATE 2. Glaciolacustrine silts overlying ice-contact stratified drift in Wampus Creek subbasin.

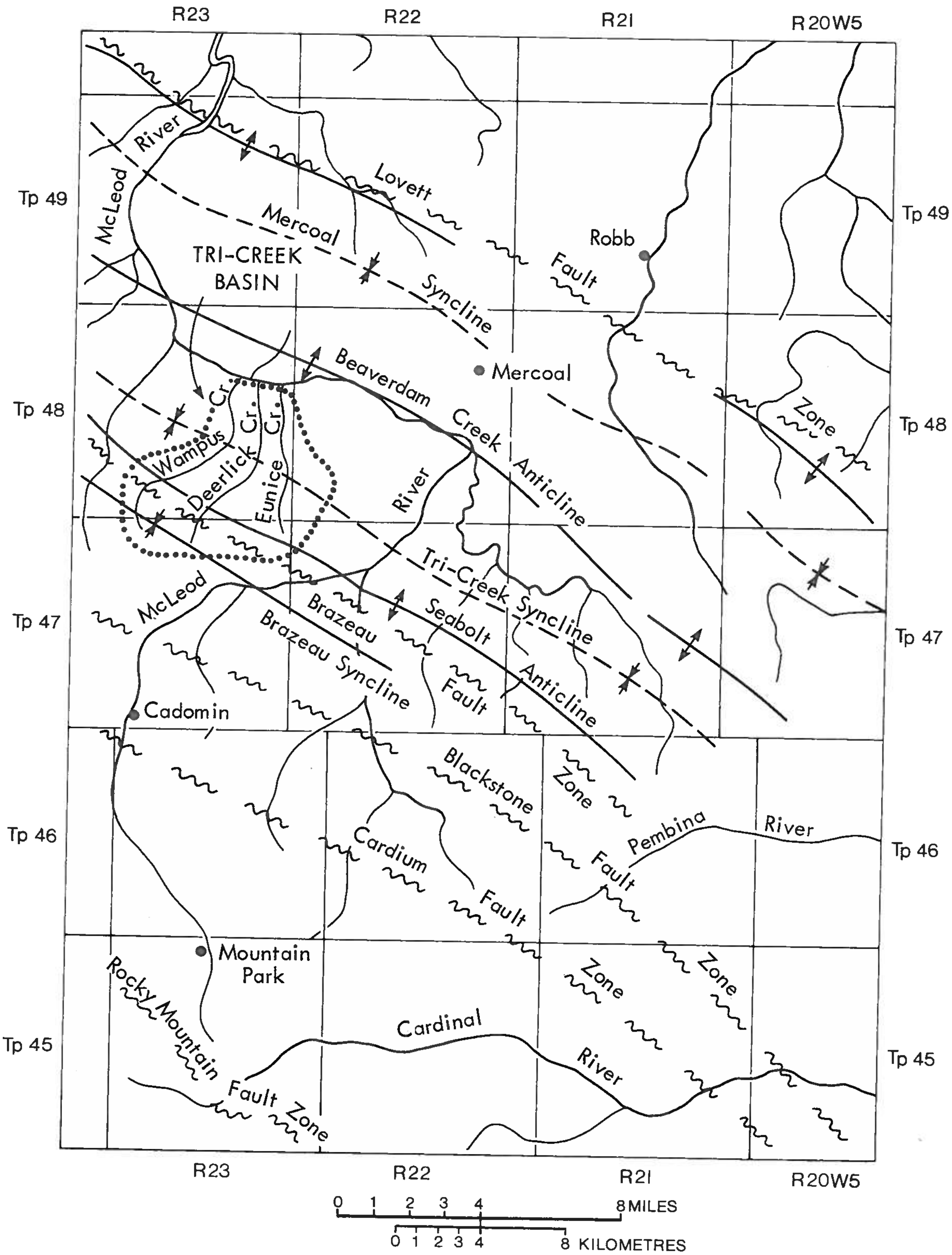


FIGURE 3. Location of Tri-creek basin with respect to major structural features in the McLeod River region.

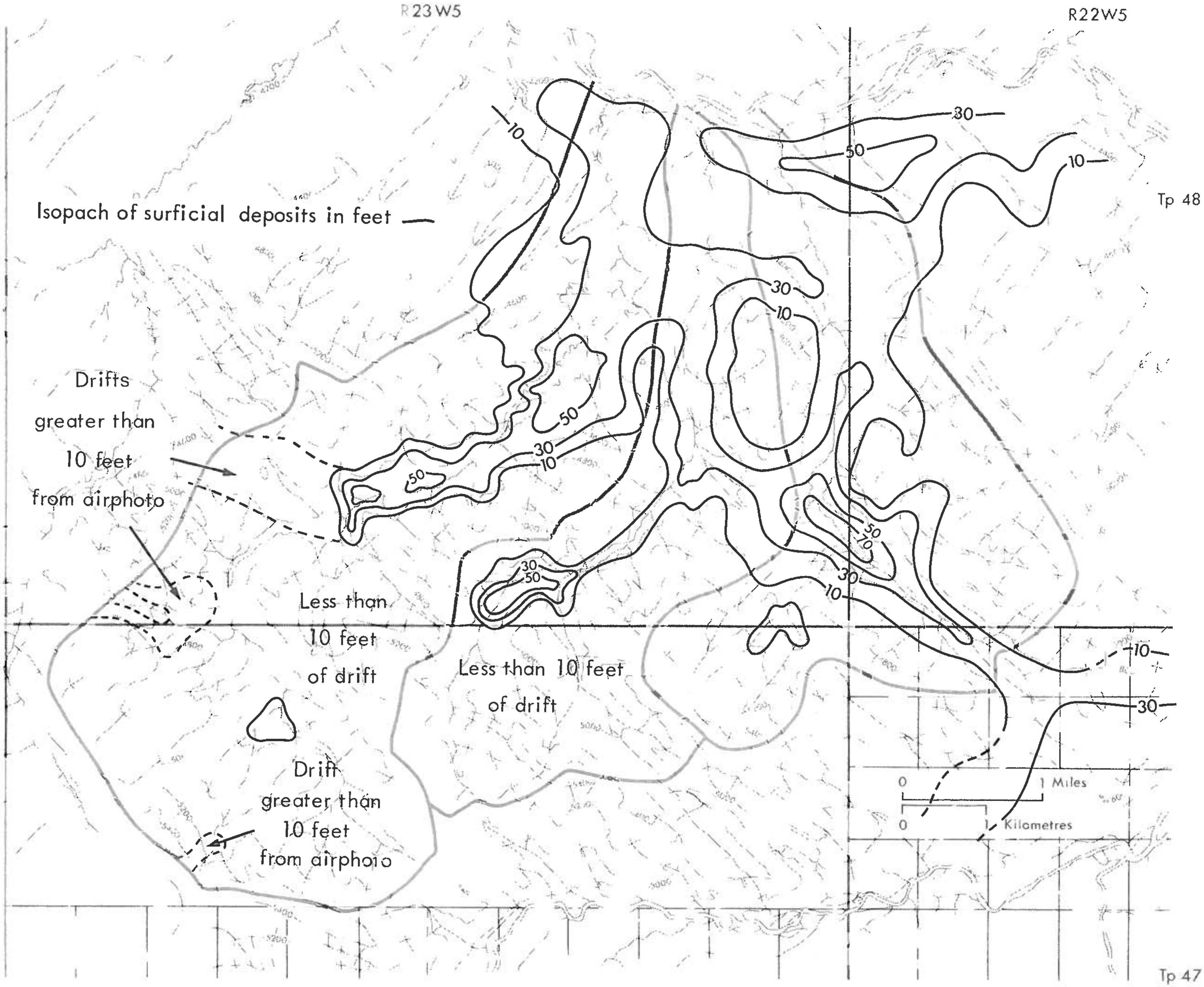


FIGURE 4. Thickness and distribution of surficial deposits in the study area.

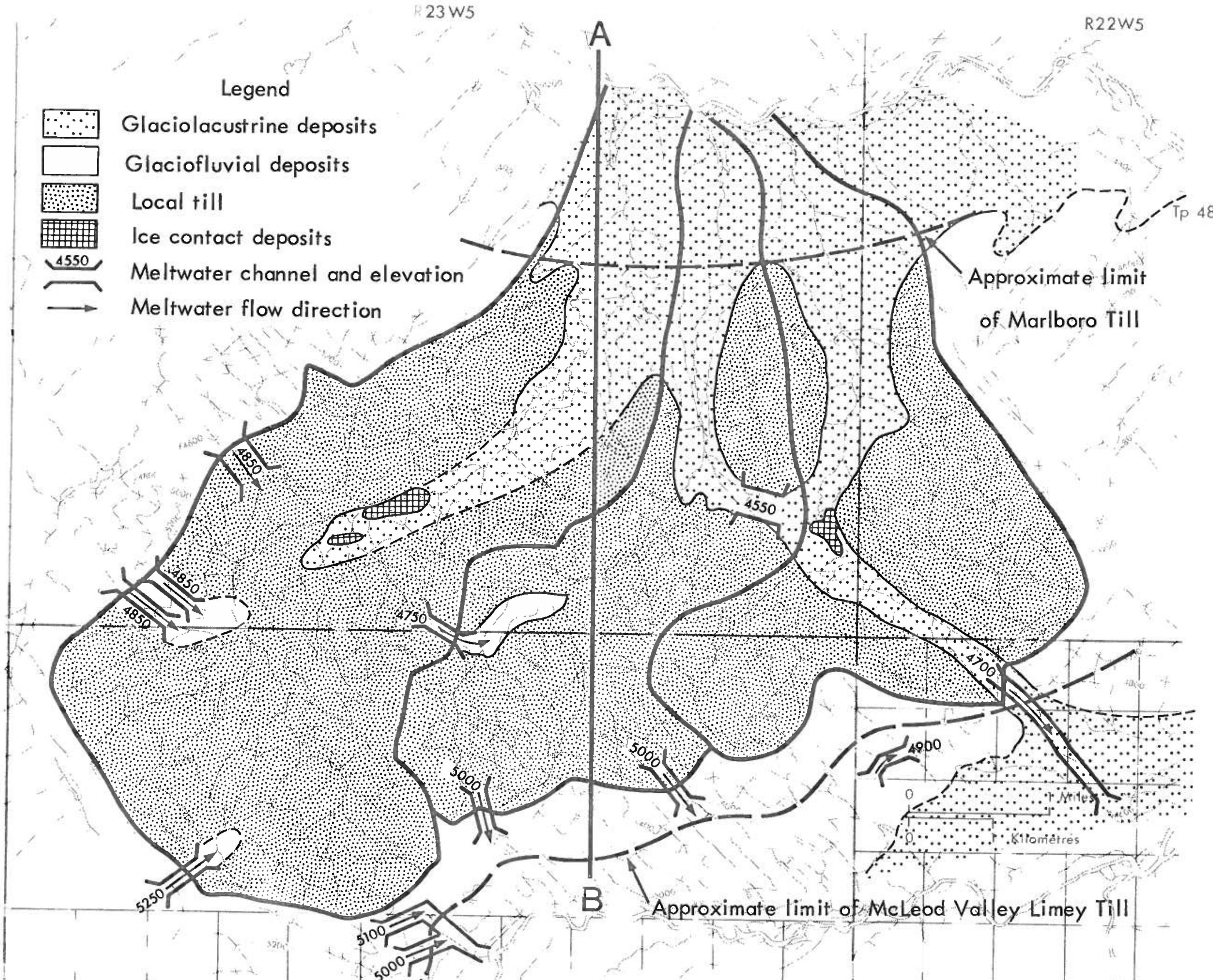


FIGURE 5. Glacial deposits in the study area.

and gravel. Seismic shothole data indicate that these deposits are at least 90 feet (27 m) thick in the Eunice Creek subbasin and 56 feet (17 m) thick in the Wampus Creek subbasin. Outwash is found in the northeast (lowermost) part of the basin, in association with more recent McLeod River alluvium. The areal extent of the outwash is not great, and it is overlain by Marlboro till and glaciolacustrine deposits. Deltaic deposits are located at the mouths of several meltwater channels (Fig. 5). The composition of these deposits is that of bedrock eroded from the channels; the maximum thickness noted was 75 feet (23 m). Meltwater channels in Tri-creek basin are two-sided, indicating that they result from the direct overflow of ponded meltwater when a basin divide is breached (Kendall, 1902). Sediments derived from the resulting trench in the divide are deposited in a delta at the mouth of the channel. (Channels bordered on one side by till or ice-contact deposits are termed 'marginal' by Embleton and King, 1970).

Glacial History

Figure 6, a chronological sequence of block diagrams along line A-B in figure 5, provides a brief outline of the Wisconsin glacial history of Tri-creek basin. Paleozoic limestone erratics found at the highest elevations in the basin indicate that the area was completely covered by glacial ice (6a). As the ice downwasted below topographically high areas, ice-contact gravel, sand and silt were deposited in an ice-marginal lake (6b). Outwash deposits in the northern part of the basin indicate that the glacier retreated from the local area. A later ice advance deposited Marlboro till of Athabasca Valley origin to elevations of about 4300 feet (1310 m), covering portions of the older glaciolacustrine and ice-contact materials (6c). Following deglaciation a proglacial lake formed in the McLeod River valley, and glaciolacustrine silt was deposited over the Marlboro till.

Soils

No detailed soil survey was undertaken in Tri-creek basin; however, the common soil types were discerned by inspecting roads and seismic cut-lines.

Bisequa grey wooded soils are found in association with orthic grey wooded soils in areas where glacial till is the parent material. Glaciolacustrine silts support an orthic grey wooded profile where slopes are greater than 30 percent. Brown wooded soils may also be found associated with orthic grey wooded soils. Organic soils and gleyed profiles occur in areas of groundwater discharge.

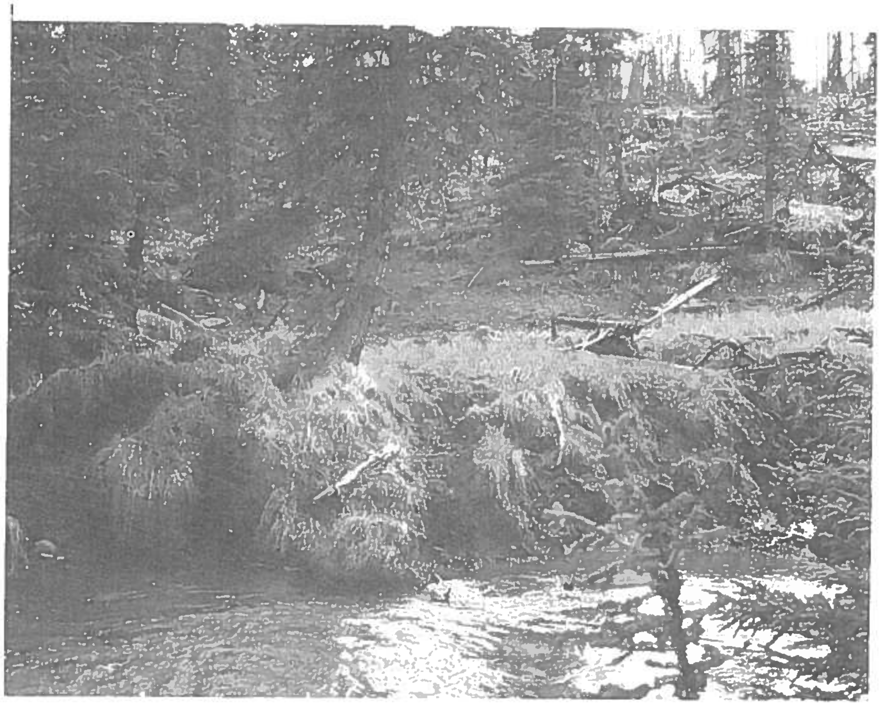
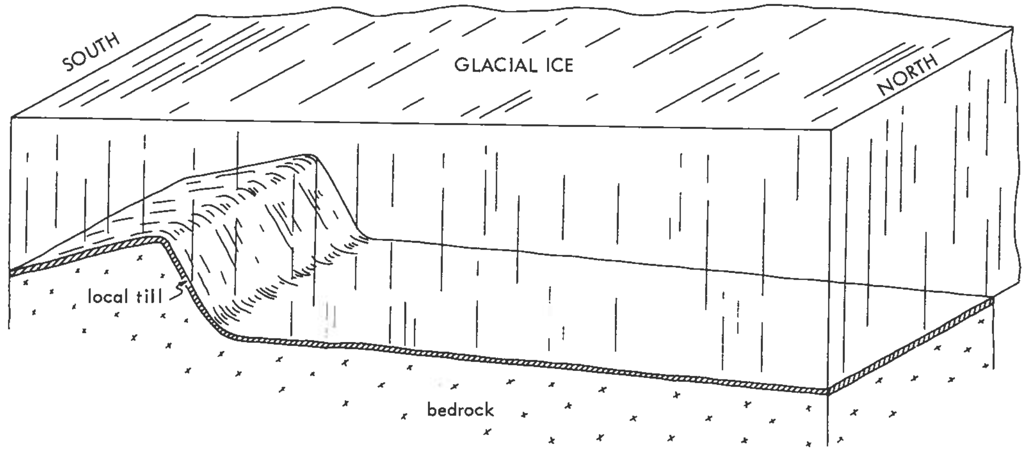
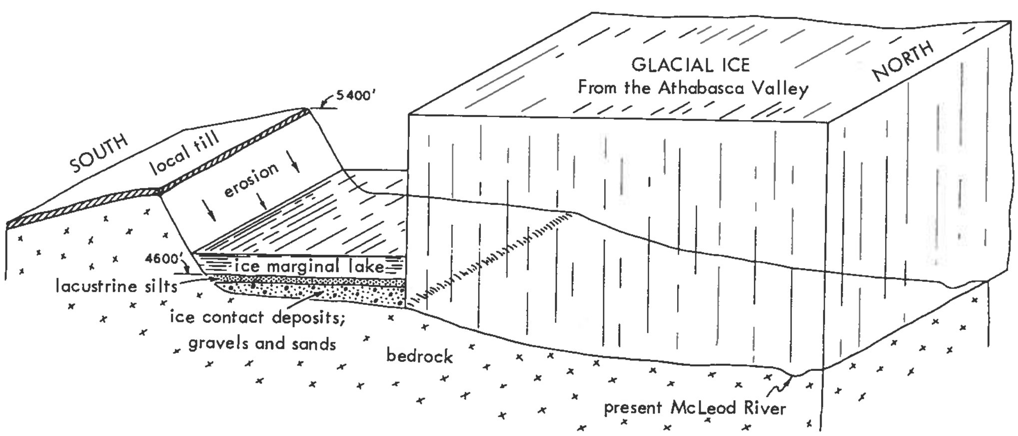


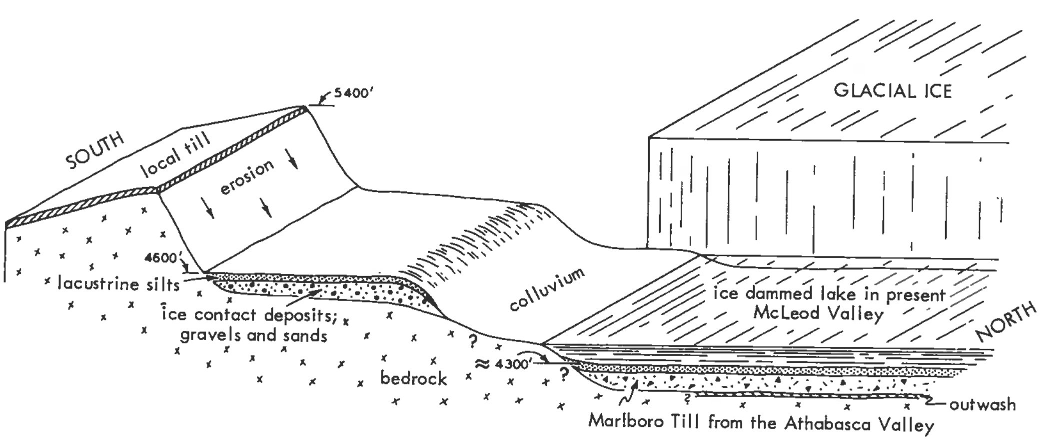
PLATE 3. Slumps associated with past logging operations on Lower Eunice Creek.



6a. Schematic block diagram to show entire area buried by glacial ice.



6b. Schematic block diagram showing deposition of ice contact and glaciolacustrine deposits at 4600 ft. elevation.



6c. Schematic block diagram illustrating deposition of glaciolacustrine silts and Marlboro Till.

FIGURE 6. Schematic block diagrams showing the glacial history of the study area.

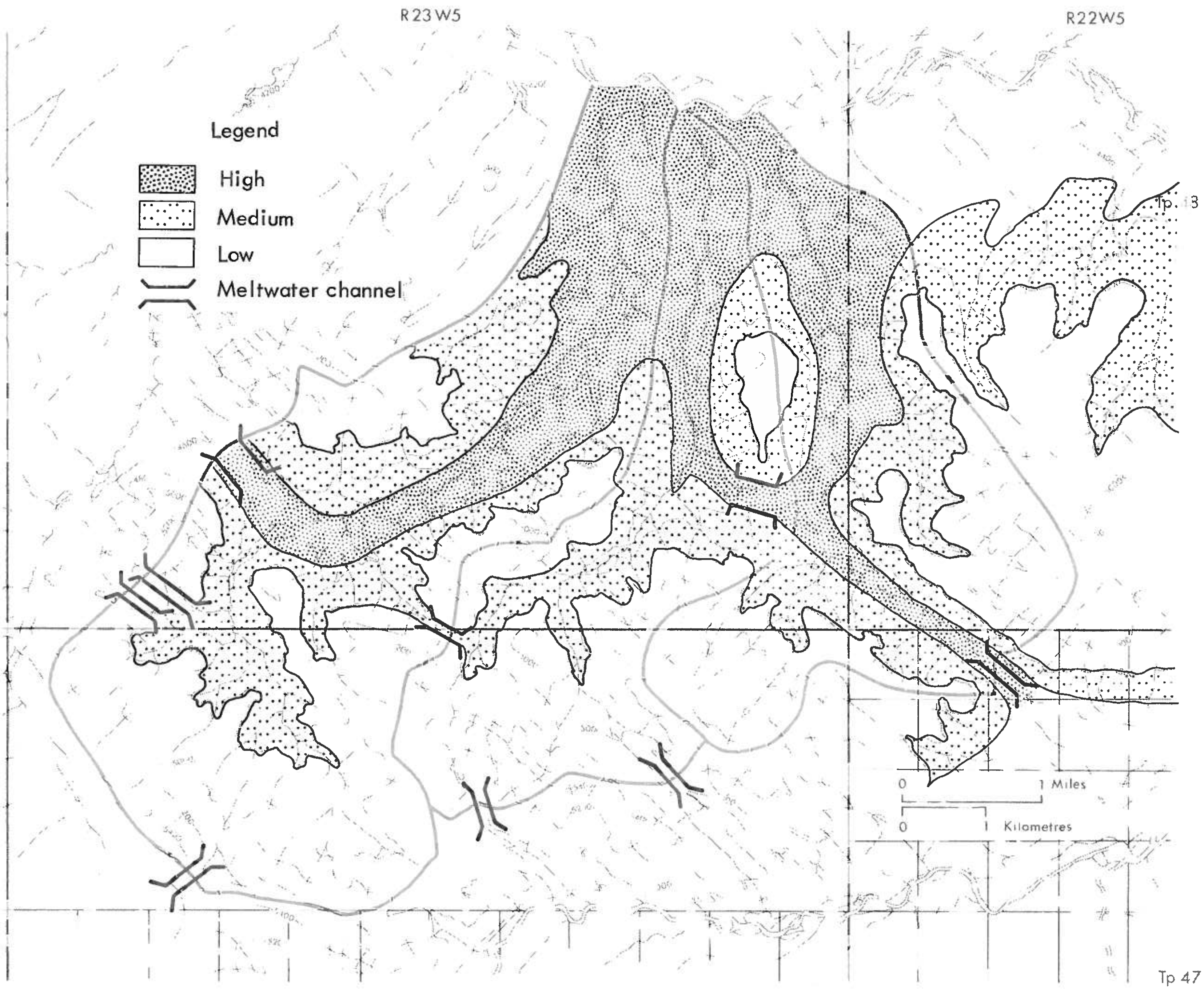


FIGURE 7. Erosion hazard in Tri-creek basin.

However, a study by Beke (1969) of three experimental watersheds in Alberta points out that in Foothills stream basins, numerous soil types are present which do not meet fully the requirements for classfication into the Canadian System of Soil Classification. Beke recommends that the system be revised or amended to accommodate soils from mountainous areas.

Erodibility of Surficial Deposits

The relative erodibility of surficial deposits in Tri-creek basin was determined using a method devised by Rutter (1968), which combines air photograph interpretation, field investigation and laboratory tests. A brief description of the method and a detailed presentation of results are found in Appendix A. The results indicate that the erosion hazard in Tri-creek basin ranges from low to high. Areas of low, moderate and high erosion hazard are shown in figure 7. The low hazard zones are found above the 4800-foot (1460 m) elevation, where bedrock is either exposed or less than 5 feet (1.5 m) below the surface. Moderate hazard zones lie between elevations of 4600 and 4800 feet (1400 to 1460 m), and are predominantly areas where local till overlies bedrock. Zones of high erosion hazard are those areas below 4600 feet (1460 m) in elevation which are covered with glaciolacustrine deposits overlying unconsolidated sediments of various types.

Road construction, logging and seismic exploration in Tri-creek basin provide observational evidence of rapid erosion after disturbance of ground cover in high hazard areas. Logging operations have resulted in gullying and earth slumps (Plates 3, 4); gullying may also be observed along seismic lines (Plate 5). Road construction associated with oilwell drilling activities has resulted in considerable erosion damage (Plates 6, 7). Deep gullies leading to Eunice Creek and deposition of silt into the stream were noted on the upstream side of a culvert.

PLATE 4. Gully eroded into glaciolacustrine deposits at the site of previous logging operations along creek.

PLATE 5. Gullying of glaciolacustrine deposits in lower Wampus Creek subbasin on cut line.

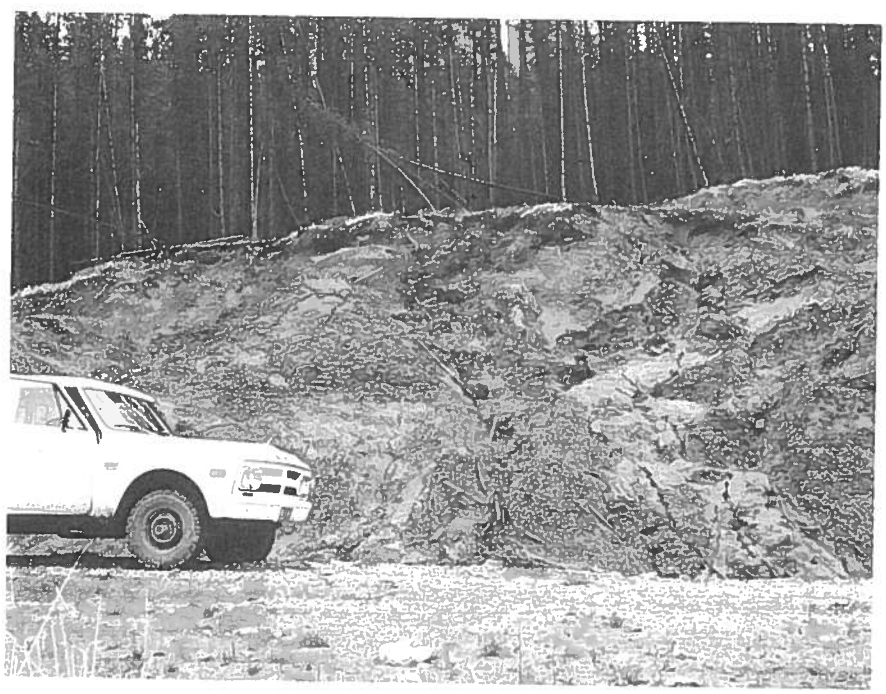


PLATE 6. Road cut in upper Eunice Creek subbasin showing rapid erosion.

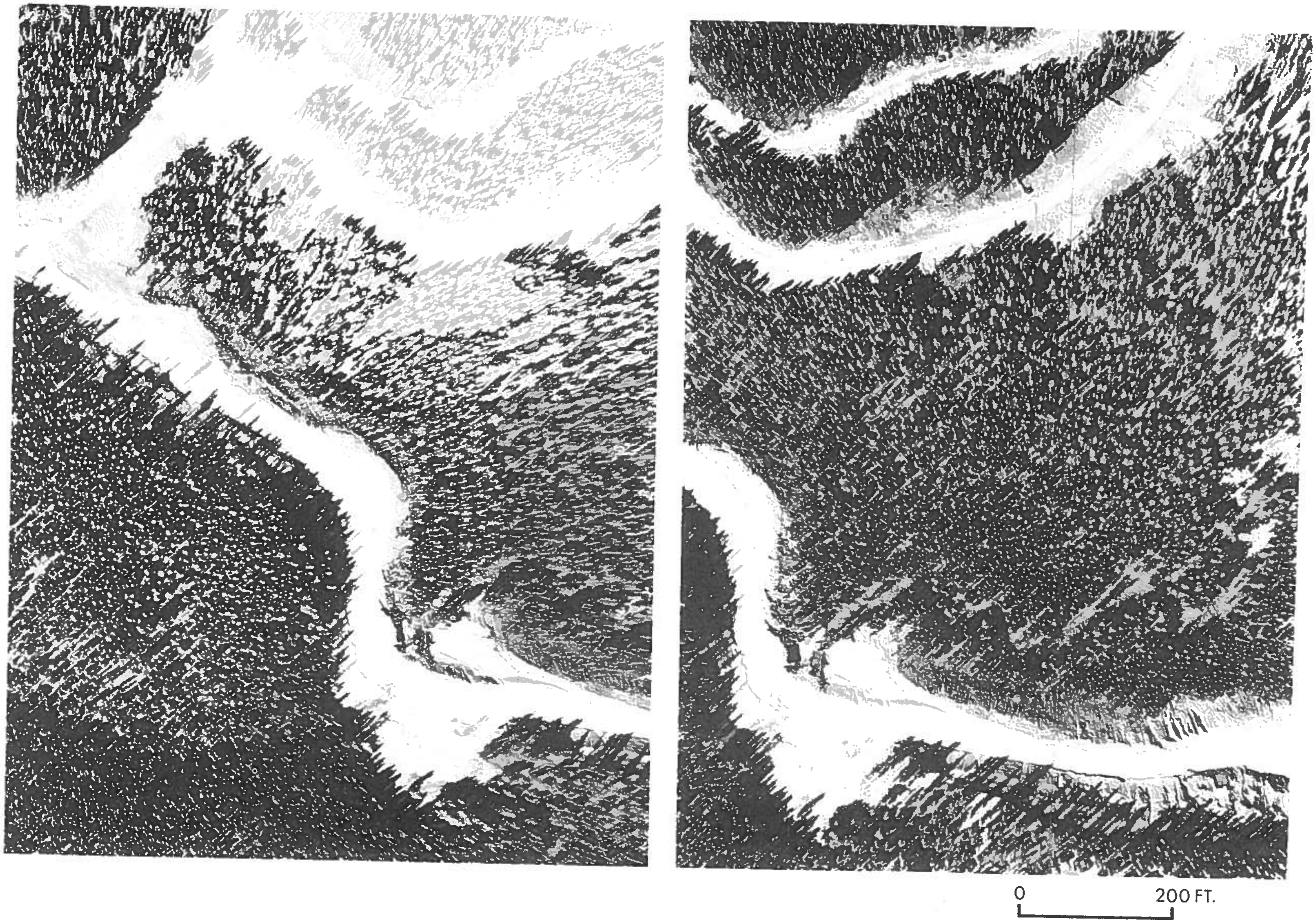


PLATE 7. Stereogram of gully erosion and stream siltation related to road construction in Eunice Creek subbasin.

Table 2. Temperature and precipitation data, Entrance, Alberta

	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Year
Mean daily temperature	12.6	16.6	25.0	37.7	47.7	53.5	58.7	56.0	49.3	40.4	26.8	16.6	36.7
Mean daily maximum temperature	24.0	29.6	37.1	51.2	62.5	67.3	74.0	71.1	63.8	53.2	37.5	27.6	49.9
Mean daily minimum temperature	1.1	3.6	12.9	24.2	32.8	39.6	43.3	41.0	34.8	27.5	16.0	5.6	23.5
Maximum temperature	61	66	71	82	93	94	100	92	91	85	70	64	100
Minimum temperature	-60	-52	-45	-32	10	20	27	27	-3	-13	-38	-53	-60
Mean rainfall (inches)	0.04	Trace	0.05	0.46	1.99	3.59	2.72	3.10	1.68	0.59	0.12	0.07	14.41
Mean snowfall	7.7	7.3	9.2	7.6	1.1	0.0	0.0	0.0	1.3	5.2	8.3	8.0	55.7
Mean total precipitation	0.81	0.73	0.97	1.22	2.10	3.59	2.72	3.10	1.81	1.11	0.95	0.87	19.98
Number of days with measurable rain	*	*	*	2	7	12	10	12	7	3	1	*	54
Number of days with measurable snow	7	6	6	5	1	*	*	*	1	3	5	5	39
Number of days with measurable precipitation	7	6	6	7	8	12	10	12	8	6	5	5	92
Maximum precipitation in 24 hours	1.25	1.00	0.90	1.16	2.12	3.07	2.00	2.68	2.09	1.60	1.25	0.90	3.07

[1]All temperature data in degrees Fahrenheit
Note: Data is 30-year average for the years 1931-1960.

CLIMATE

The climate of the central Foothills belt is classified as humid, microthermal and subarctic (Atlas of Canada, 1957). The climatological letter code for this type is *Dfc*: a rain-snow climate with cold winters (D), precipitation throughout the year (f), and a cool, short summer, with only one to three months of daily mean temperatures about 50° F (c).

Local climatological data are not available for Tri-creek basin; however, reliable precipitation and temperature information collected at Entrance, Alberta, may be considered indicative of conditions in the basin (Table 2). The Entrance weather station is located 30 miles (48 km) to the northwest (Fig. 1) in a similar climatological and geologic setting, although an approximate 1000-foot (305 m) elevation difference between Entrance and Tri-creek basin makes it necessary to subtract 2 to 3° F (1 to 2° C) from the Entrance figures (A. V. Mann, Environment Canada, pers. comm., 1969).

Because it is located to the east of a major Rocky Mountain pass, the Entrance area is subject to chinook (foehn) winds during the winter. A similar situation exists at Tri-creek basin: chinook winds issuing from Cadomin Gap to the west cause anomalously high temperatures in the winter months.

The total precipitation recorded by a standard rain gauge at Wampus Creek was 20.22 inches (51.4 cm) for the period May to December 1969. Of this total, 37 percent or 7.55 inches (19.1 cm) fell during two summer storms. A rainfall intensity recorder in the Wampus Creek subbasin measured a total precipitation of 23.6 inches (59.9 cm) during an 11-month period during 1969. Seven Sacramento storage gauges maintained at various sites in the basin by Atmospheric Environment Services, Environment Canada, gave an arithmetic average of 27.4 and 29.2 inches (69.6 and 74.1 cm) of precipitation for the years 1968 and 1969. At Entrance, the mean total precipitation for the 30-year period 1931-

PLATE 8. Deerlick Creek valley and meadow associated with groundwater discharge. View northeast.

1960 was 19.98 inches (50.7 cm), with the greatest proportion falling as rain during May through September.

The government data have been analyzed by the Thiessen method (Bruce and Clark, 1966) to give a yearly figure of between 24 and 27 inches (61 and 69 cm). However, the duration of precipitation measurement in Tri-creek basin has not been of sufficient length to provide an accurate mean annual value. A reasonable estimate based on the various short-term sources of data and the 30-year average value at Entrance is 23 inches (58 cm). An outline of the Thiessen method and its application to Tri-creek basin, is given in Appendix B.

PHYSIOGRAPHY AND HYDROLOGY

Tri-creek basin is located within the northwest-trending, elongate ridges and valleys of the Foothills physiographic region. The highest elevation is 5524 feet (1684 m) above mean sea level in Deerlick subbasin, and the lowest is approximately 4130 feet (1259 m) at the junction of the three creeks and the McLeod River; total relief is about 1400 feet (425 m).

The general topographic appearance of the study area is shown in an oblique air photograph (frontispiece) taken toward the south from north of the McLeod River. In a closer view (Plate 8), Deerlick Creek is shown in a transverse valley cut through resistant strike ridges of the Brazeau Formation.

Stream courses in the basin trend north and northeast; coupled with a subparallel drainage pattern, this feature contributes to the maintenance of snow cover in the spring of the year. In May 1968, waist-deep snow throughout the basin contrasted sharply with bare ground on south-facing slopes along the McLeod River.

Drainage Network

The drainage network in the basin is subparallel (Zernitz, 1932) and part of the overall trellis drainage pattern in this section of the Foothills.

The terms subparallel and trellis are qualitative terms describing the organization of the drainage network. A quantitative description of drainage organization in Tri-creek basin has been made based on the work of Horton (1945), Strahler (1957, 1964), and Leopold *et al.* (1964). This description is presented in Table 3. Definitions used in the text are taken from the material cited above.

Stream Order

All three subbasins are *fourth-order* basins; that is, water originating in the smallest tributaries will join water from no more than three streams with similar tributary development before passing out of the basin into the McLeod River. The order number is directly proportional to relative basin dimensions, channel size and stream discharge (Strahler, 1957). Despite differences in bedrock and structural disturbance, the stream order and stream frequency values are similar in all subbasins. Commonly, streams of lower order are present in greater numbers than streams of higher order and this rule-of-thumb applies to Tri-creek basin. The ratio of the number of streams of a given order to the number of streams of the next higher order is termed the *bifurcation ratio*; it is a measure of geologic control of drainage. Bifurcation ratios in the study area range from 3.3 to 4.9 for first-order to second-order streams, and from 3.7 to 5.6 for second- to third-order streams. The highest bifurcation ratio — 5.6 in Wampus Creek subbasin — falls within the range of values that indicates geologic control of drainage; this high value is explained by the fact that Wampus Creek flows in a strike valley near its headwaters.

Drainage Density

Drainage density is defined as the ratio of the sum of the stream lengths to the area of the basin. The uniformly low values calculated for the basin indicate that the region has resistant bedrock, permeable subsoil materials and a dense vegetation cover. The low drainage density value of 3.3 for Deerlick subbasin correlates with its elongate shape.

Stream Frequency and Relief Ratio

Stream frequency is the ratio of the total number of streams to basin area and reflects the amount of dissection; in the study area dissection is moderate. Relief ratio, determined by dividing drainage density by stream frequency, is a measure of the consistency of all these quantitative judgments; in most watersheds, the relief ratio is about 0.7 (Melton, 1958). The relief ratio values for Tri-creek basin range from 0.44 to 0.61, somewhat lower than that noted for consistent drainage. These low values may be attributed to derangement of drainage by glaciation.

Streamflow

In Tri-creek basin, variation in streamflow generally corresponds to variation in water table levels. During the study (1968-1969), a sharp rise in the water table occurred during the month of February, coinciding with a period of thaw. The spring rise in water table corresponded with the first high peaks of streamflow; the water table then receded gradually until the following spring. Streamflow records for Wampus Creek and a discussion of methods are found in Appendix C.

GROUNDWATER REGIME

Having considered the geology, hydrology, physiography and climate of the area — in sum, the hydrogeologic environment, it is possible to integrate these factors with a discussion of the groundwater regime.

VEGETATION AND THE WATER TABLE

Meinzer (1923) showed that certain kinds of vegetation are diagnostic of water table levels in certain hydrogeologic environments. Building on this early work, the Russian authors Vereiskii and Vostokova (1963) have discovered general relationships between those components of the landscape which can be easily observed, such as plant associations and topography, and those which are less obvious, such as parent material and depth to the near surface water table. The required data are obtained from field observations, topographic maps and air photograph interpretation. Although a detailed explanation of the Vereiskii and Vostokova method is beyond the scope of this report, results obtained in Tri-creek basin are provided here.

The presence of phreatophytes (plants that habitually obtain their water supply from the zone of saturation) is essential to the method. In Tri-creek basin, most of the local trees and shrubs are phreatophytic, and interpretations of the depth to water table may be made from associations of these plants. Meyboom (1967) established quantitative values of consumptive use for

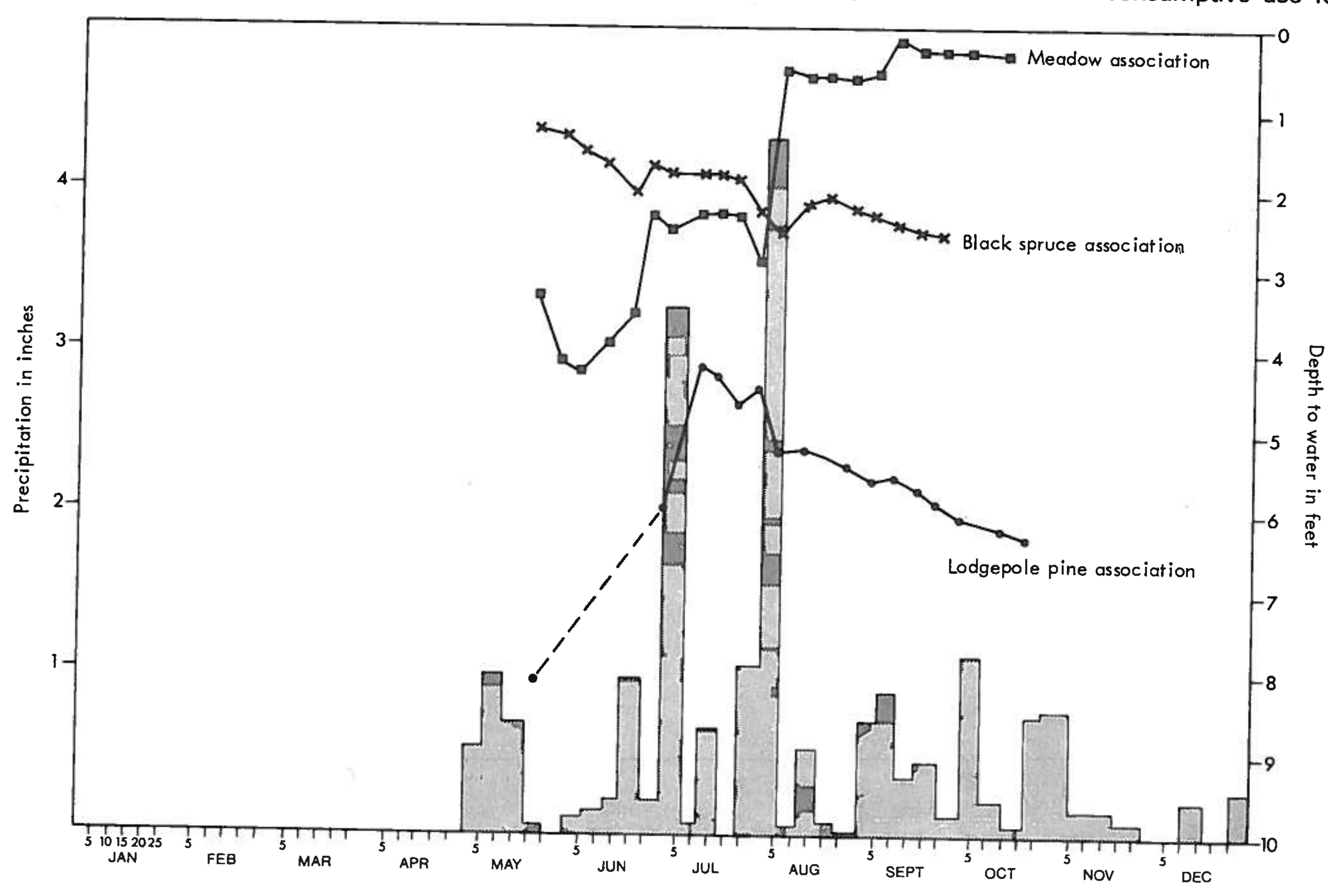


FIGURE 9. ***Comparison of water level fluctuations with precipitation in auger holes under different vegetative covers.***

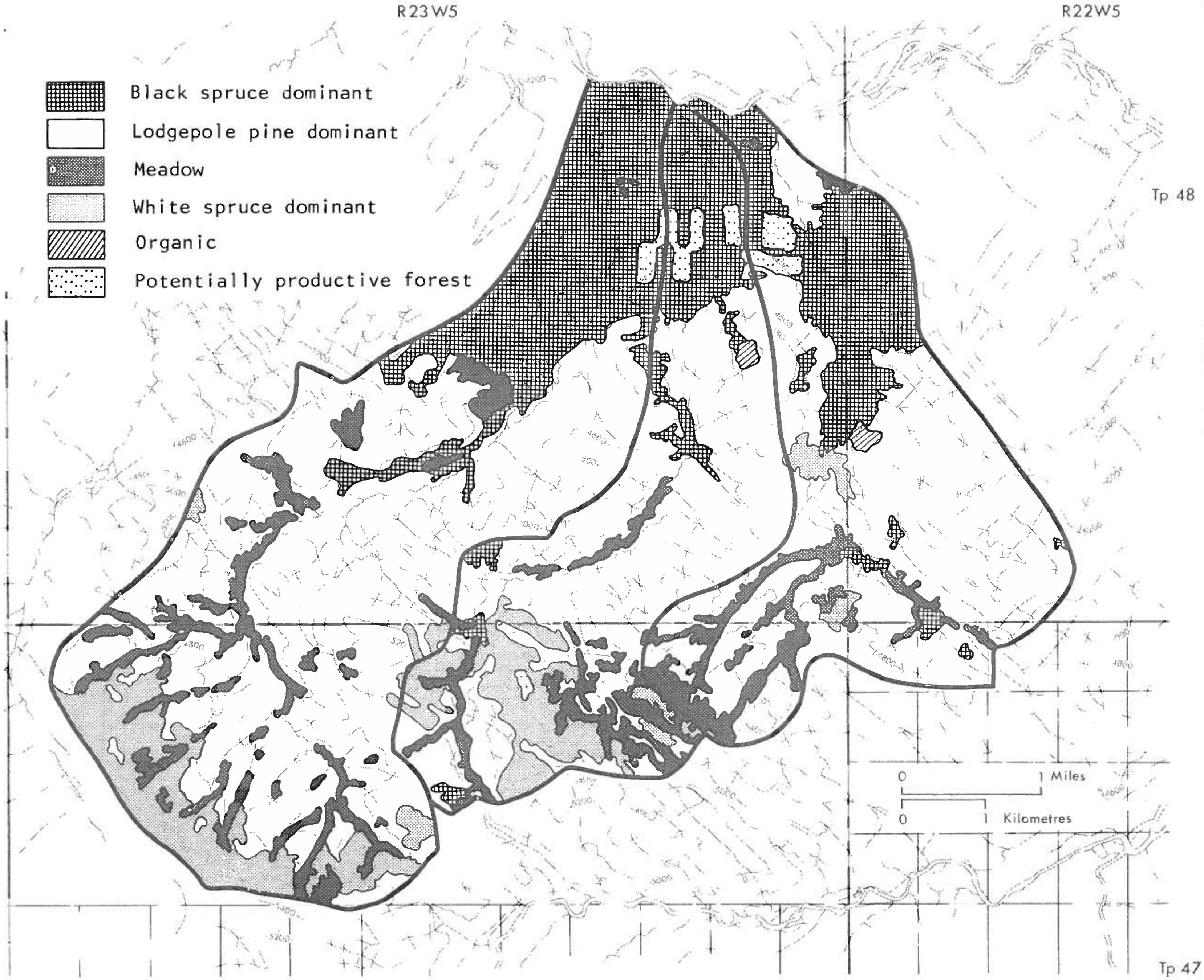


FIGURE 8. Forest cover map of the study area.

Table 3. Quantitative stream course data, Tri-creek basin

Basin or Subbasin	Area (sq mi)	Stream Order	No. of Streams	Bifurcation Ratio[1]	Total Length (miles)	Stream Frequency[2]	Drainage Density[3]	Relief Ratio[4]
EUNICE CREEK	6.63	1	50	4.55	15.5			
		2	11	3.67	8.0			
		3	3	3.00	2.3			
		4	1		4.1			
Total			65		30.9	9.8	4.7	0.06
DEERLICK CREEK	5.80	1	49	4.90	9.4			
		2	10	5.00	2.9			
		3	2	2.00	2.6			
		4	1		4.1			
Total			62		19.0	10.7	3.3	0.05
WAMPUS CREEK	10.33	1	93	3.30	26.0			
		2	28	5.60	13.6			
		3	5	5.00	3.4			
		4	1		3.3			
Total			127		46.3	12.3	4.5	0.04
TRI-CREEK BASIN	22.76	1	192	3.90	50.9			
		2	49	4.90	24.5			
		3	10	3.30	8.3			
		4	3		11.5			
Total			254		95.2	11.0	4.1	0.37

[1]Number of streams of one order divided by number of streams of next higher order.
[2]Total number of streams divided by basin area.
[3]Total length of streams divided by basin area.
[4]Drainage density divided by stream frequency.

various phreatophytes in the plains region of Saskatchewan. As far as the author is aware, however, there is no similar information for the vegetation of the Alberta Foothills.

The vegetation of the Tri-creek area is predominantly coniferous and classified as subalpine forest (Moss, 1955). A forest cover map prepared by the Alberta Department of Energy and Natural Resources (Fig. 8) shows the distribution of tree types. Lodgepole pine (*Pinus contorta*), white spruce (*Picea glauca*), black spruce (*Picea mariana*) and alpine fir (*Abies ladiocarpa*) are common in the area.

To determine whether or not the Russian method was applicable, water table depths were taken under the various tree types, each type representing a distinct plant association. The consistency in results tended to confirm the method.

Depth to water table under an association of lodgepole pine, brome grass (*Bromus* sp.), and bearberry (*Arctostaphylos ava-ursi*) ranges from 4.2 to 8.1 feet (1.3 to 2.5 m) below groundwater level. This association occurs on the summits and upper slopes of ridges and hills; in some areas it is intermixed with a white spruce, pine, bilberry (*Vaccinium* sp.), and green moss association indicative of a depth to water table of 10 to 16 feet (3 to 5 m). Water table measurements under a black spruce, fir, haircap (*Polytrichium* sp.) and sphagnum moss (*Sphagnum* sp.) association indicate that the depth to the water table ranges from 1.4 to 2.6 feet (0.4 to 0.8 m). This association occurs only in the topographically low northern part of the basin. Meadows, often containing springs and seepages, support the growth of sedge (*Carex* sp.), willow (*Salix* sp.) and swamp birch (*Betula pumilia* var. *glandulifera*); water table depths for this meadow association range from 0.10 inches to 4.2 feet (0.2 cm to 1.3 m).

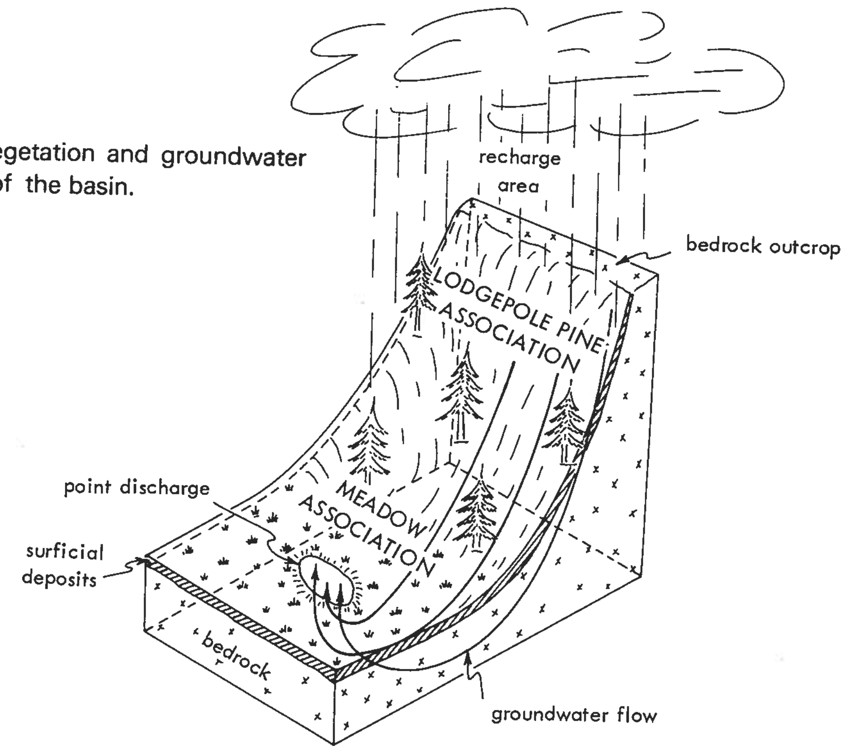
Water table fluctuations measured in auger holes under these plant associations are shown in figure 9, along with standard rain-gauge precipitation measurements. The varying response in water levels to precipitation is evident. The meadow association responded positively and rapidly; one of the two coniferous associations showed a reduced positive response, while the other responded negatively.

VEGETATION AND GROUNDWATER FLOW

Plant associations in Tri-creek basin also can be used to delineate areas of natural groundwater recharge and natural groundwater discharge as defined by Freeze

PLATE 9. Rock debris type spring.

10a. Relationship between vegetation and groundwater flow in the upper part of the basin.



10b. Relationship between vegetation and groundwater flow in the lower part of the basin.

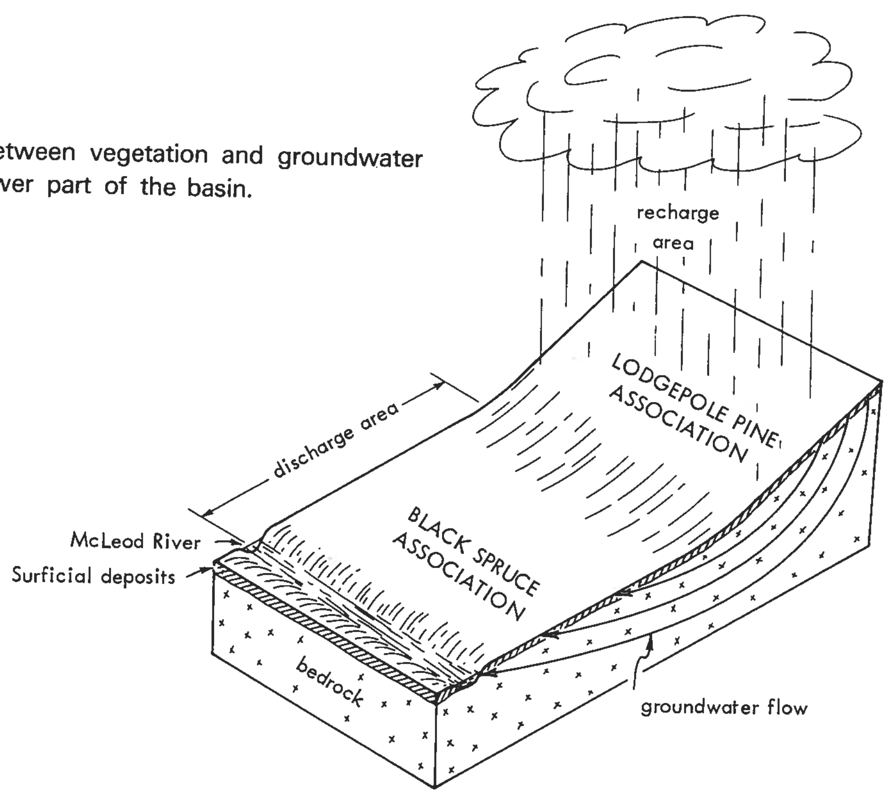


FIGURE 10. Block diagrams showing the relationship between vegetation and groundwater flow in Tri-creek basin.

(1967). The lodgepole pine-brome grass-bearberry, and white spruce-pine-bilberry-green moss associations are indicative of natural groundwater recharge conditions along ridges, where the water table is relatively deep. The black spruce-fir-haircap-sphagnum moss and meadow associations are indicative of natural groundwater discharge in areas of more gentle slopes, where the water table is relatively shallow.

In the topographically lower and less rugged northern part of Tri-creek basin, natural groundwater discharge occurs mainly as transpiration from the black spruce-fir-haircap-sphagnum moss association. Groundwater flow is sluggish, and is dispersed over a wide area. Groundwater flow in the upper, more rugged southern part of the basin is more rapid due to the greater elevation difference between recharge and discharge areas. Natural groundwater discharge is concentrated in the meadow environments at the valley bottoms; discharge is primarily through springs and seepages. These conditions are summarized in figure 10. Figure 11, a schematic cross section of Wampus Creek subbasin illustrates the relationships between topography, vegetation and groundwater flow.

In summary, plant associations are useful as indicators of some aspects of the groundwater regime in Tri-creek basin, and since the flora, physiography, geology, and climate in the study area are similar to those of neighbouring drainage basins, it seems likely that the vegetation-groundwater relationships discussed in this report will be applicable elsewhere in the Foothills.

GROUNDWATER DISCHARGE FEATURES

Groundwater discharge features observed in Tri-creek basin include springs, seepages, hummocky ground, swamps, and amphitheater-shaped depressions.

Springs

A spring is a point of localized natural discharge of water at the surface resulting in a rivulet (Pfannkuch, 1969). Two types of springs have been recognized in Tri-creek basin: the rock debris type and the soap hole type.

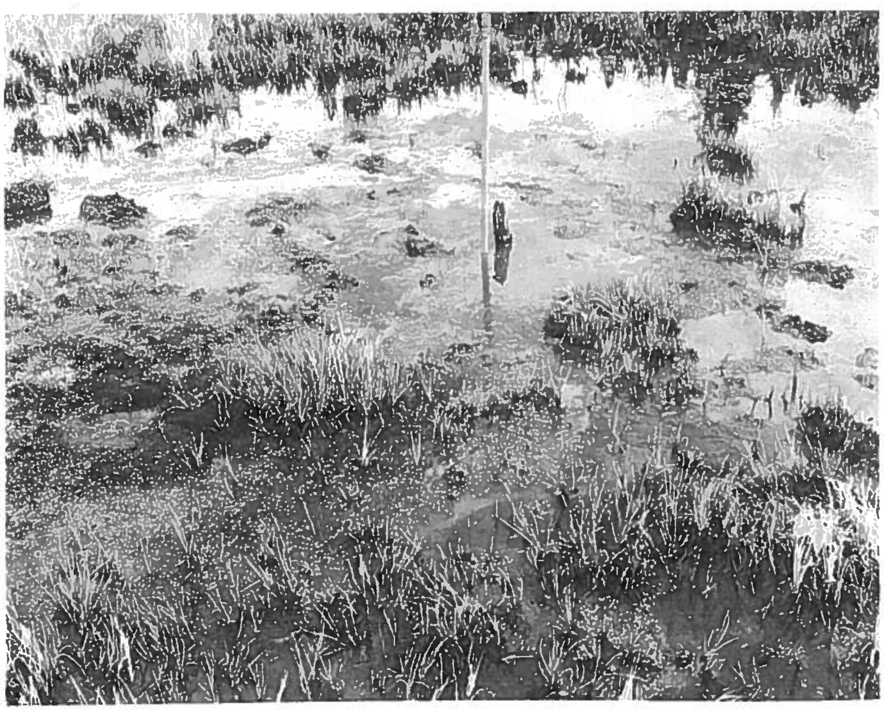


PLATE 10. Soap hole type spring.

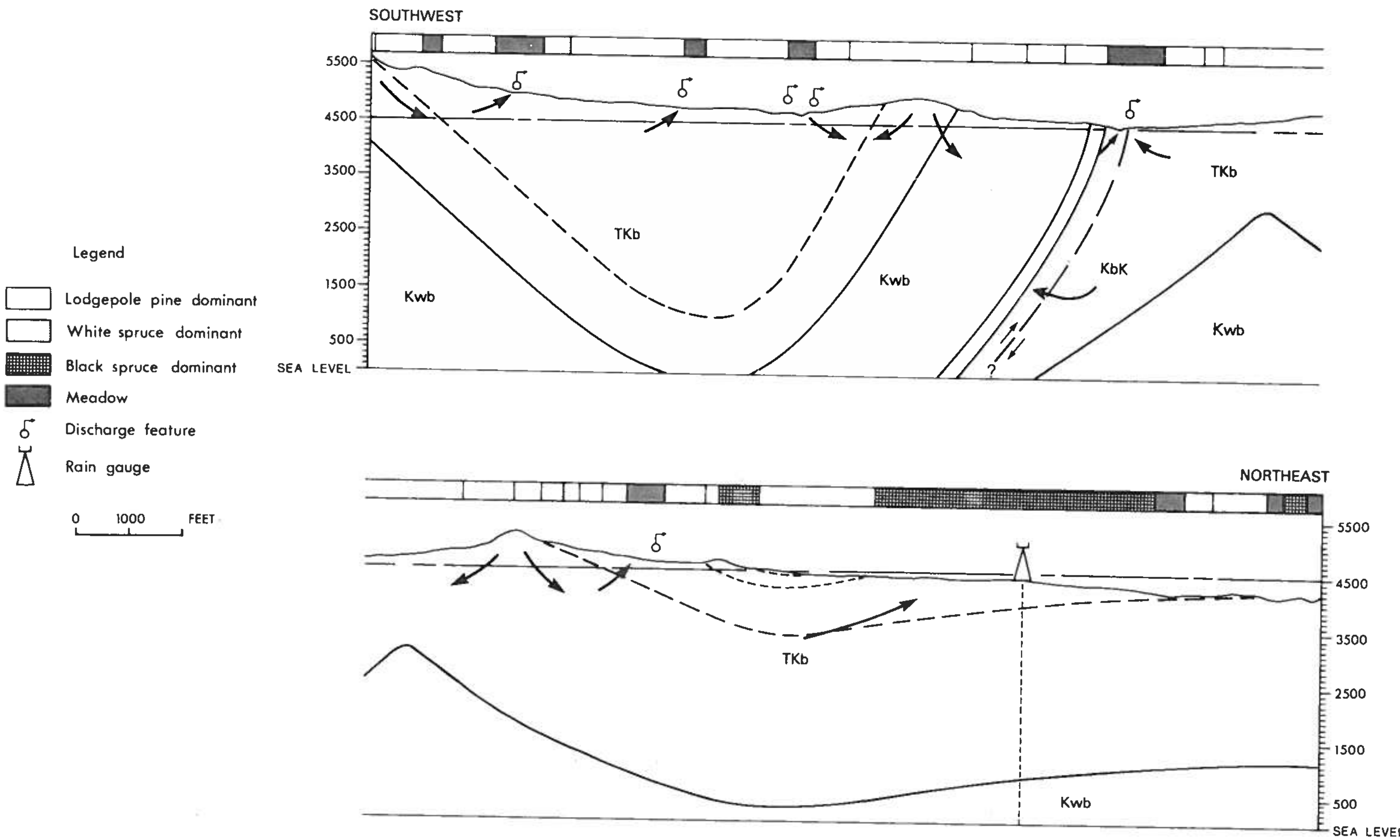


FIGURE 11. Groundwater and vegetation associations in Wampus Creek subbasin.

A spring of the rock debris type issues from the ground where gradient changes from steeper to gentler, and is characterized by a string of angular to subangular boulders of local bedrock in the channel leading away from the spring (Plate 9). The ground around the spring is firm. The measured discharge rate for this type of spring ranges from less than ½ to more than 200 igpm (2 to >900 l/min); the rate varies in response to seasonal changes in the precipitation and temperature.

The soap hole type of spring issues from a vertical cylindrical hole located in an area of locally flat topography (Plate 10). Only organic soil and silt are found marginal to the spring; boulders are not present. The ground around the spring is in a quick condition, caused by upward-flowing groundwater which reduces the effective stress within the earth material to zero (Rutledge, 1940). The rate of discharge ranges from less than ½ to 2 igpm (2 to 9 l/min), and is less variable in response to climatic events than springs of the rock debris type.

Seepages

Groundwater seepage is a diffuse movement of water to the surface at a rate that is not discernible, but which is equal to or exceeds the rate of evapotranspiration. Most seepages located in Tri-creek basin are associated with the meadow environment; marginal to each spring of the soap hole type is an area of groundwater seepage which grades into areas of hummocky ground. In upper Eunice Creek subbasin, a large seepage feature termed herein a seepage pit is associated with soap hole springs and hummocky ground.

Hummocky Ground

This term is used to describe the hummocky surface found in association with groundwater discharge in the meadow environment. The hummocks, hemispherical in shape, range in size from 6 inches to 1 foot (15 cm to 0.3 m) in diameter, are spaced 2 or 3 inches (5 to 8 cm) apart, and are covered with sedge. At many localities the upward-moving groundwater has made the hummocky ground quick; it is wet, and depresses easily

PLATE 11. Hummocky ground.

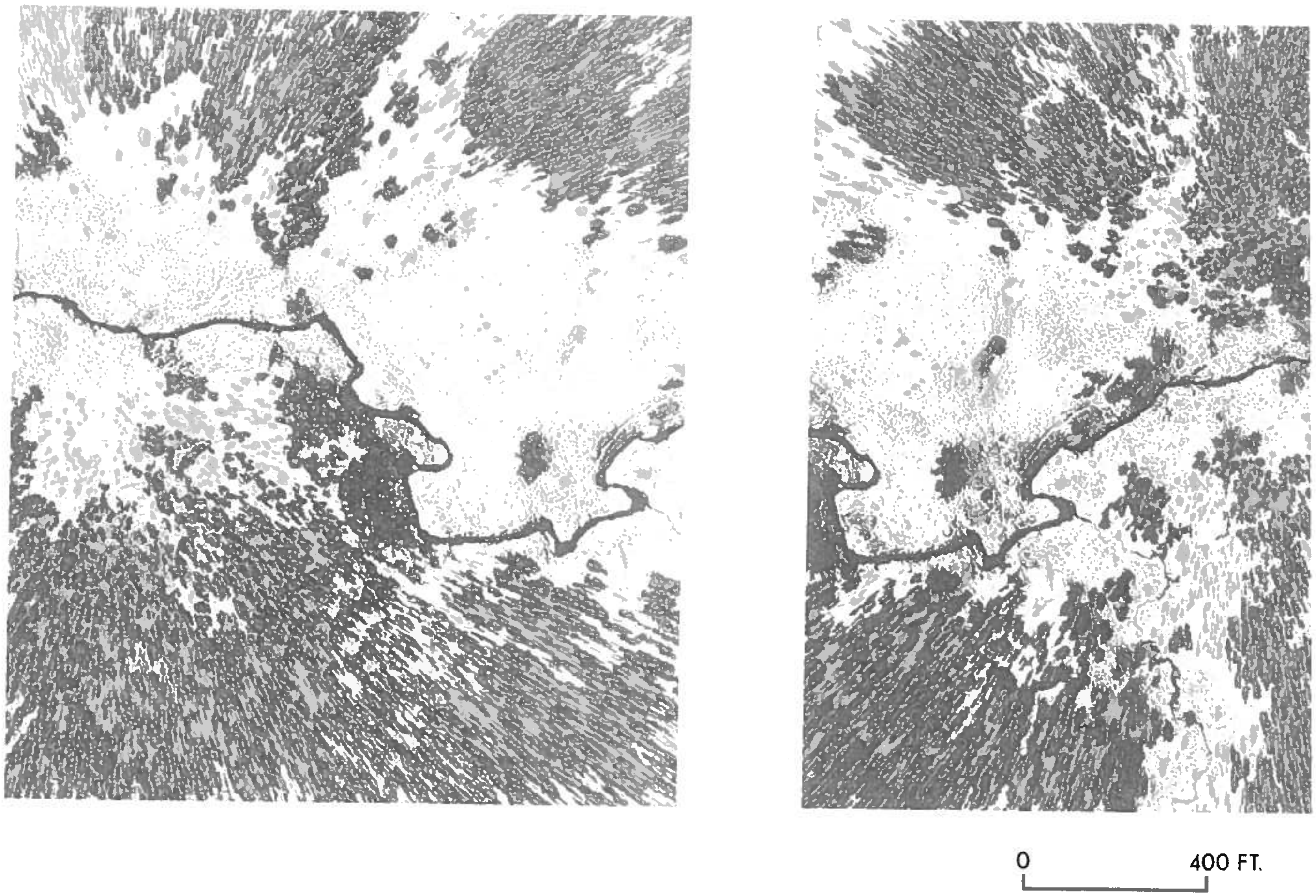


PLATE 12. Stereogram of a groundwater discharge area in Wampus Creek subbasin.

underfoot. Groundwater discharge in these areas is accomplished by either evapotranspiration or seepage, depending upon weather conditions. Plate 11 pictures hummocky ground. The dark area in the top center part of the photograph is a seepage. The vegetation mat in the area pictured is floating, in the sense that it depresses under a man's weight. Waves in such mats can be generated by jumping.

Swamps

There are several swamps in Tri-creek basin which, because of their topographic position, geologic situation, associated quick ground and meadow flora association, are apparently supported by inflowing groundwater; streams neither enter nor leave these localities. The groundwater support is of shallow origin, derived from surface sediments on the immediately adjacent slopes; flow is closely related to climatic events.

Amphitheater-shaped Depressions

Amphitheater-shaped depressions are common geomorphic phenomena associated with groundwater discharge areas on steep slopes. In size, these features grade from small terraces 3 square feet (0.3 m^2) in area to amphitheater-shaped depressions such as an area 120 feet by 140 feet (37 m by 43 m) located in Eunice Creek subbasin. A well developed amphitheater observed on a slope of approximately 40 degrees in Wampus Creek subbasin was investigated. The floor of the amphitheater, which supports short-rooted phreatophytic vegetation, is approximately 30 feet by 40 feet (9 m by 12 m) in area, with a backwall 10 feet (3 m) high. Although the type of vegetation associated with such features indicates groundwater discharge, the morphology of amphitheater-shaped depressions and terraces suggests that mass movement may be involved as well.

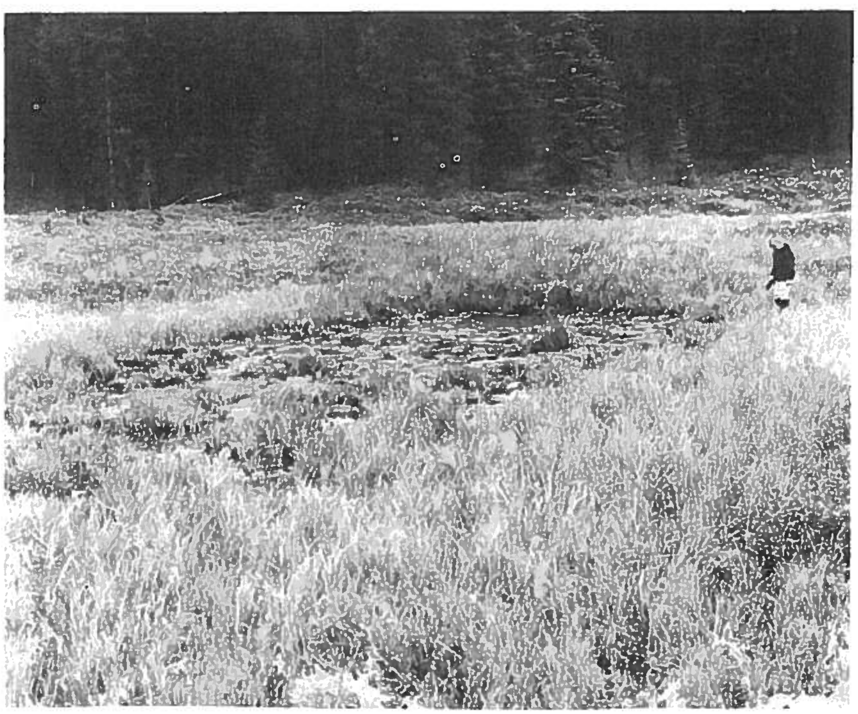


PLATE 13. Soaphole spring and hummocky ground along Wampus Creek.

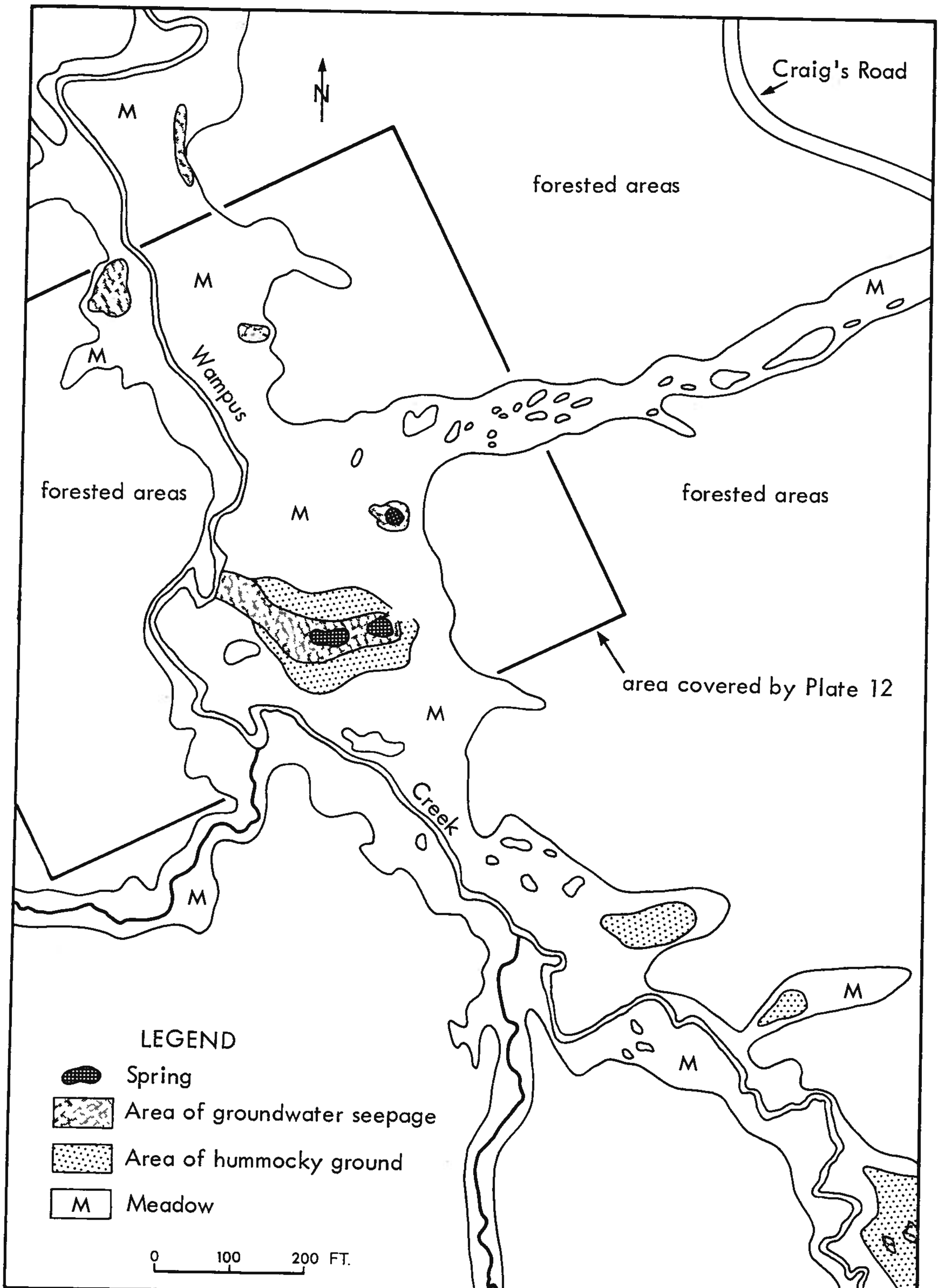


FIGURE 12. Groundwater discharge features, Wampus Creek subbasin.

HYDROGEOLOGY OF TYPICAL GROUNDWATER DISCHARGE AREAS

A detailed discussion of groundwater discharge features in a specific area serves to illustrate the interplay of factors involved in Foothills hydrogeological analysis, as well as to present results that are locally useful. In Tri-creek basin, selected discharge areas in Wampus Creek subbasin and Eunice Creek subbasin were analyzed for this purpose.

Discharge Area in Till

Several springs of the soap hole type occur in the upper part of Wampus Creek subbasin, approximately 1000 feet (300 m) southwest of Craig's road (Fig. 12). The outward gradation from the springs to a seepage area and thence to hummocky ground is illustrated on the map. In a stereogram of the same area (Plate 12), this gradation shows as a tonal change caused by the differing reflective properties of the various types of vegetation. The dark-toned center areas are open water and decayed vegetation. The medium tone of grey indicates the presence of sedge and is mapped as groundwater seepage. Swamp birch and willow are the dominant plant types growing on the rough-textured area mapped as hummocky ground while forests of black spruce enclose the area. The stereogram also shows terraces of the type grouped with amphitheater-shaped depressions. Many game trails can be observed clearly; it is probable that the hummocky surface of the ground is caused in part by the tramping of hoofed animals. A ground photograph (Plate 13) provides a closer view of the discharge area, with special attention given to the vegetation gradation from sedge to swamp birch. Isolated, stunted black spruce are visible both in the stereogram and in the background of the photograph.

An interpretation of the groundwater flow system responsible for discharge features in this locality is illustrated in figures 13 and 14. Figure 13 presents geologic relations in the area, which is located on the east flank of the Brazeau syncline. Conglomeratic beds of the lower Brazeau Formation strike N70°W and dip 50°SW. Bedrock at the discharge area is mantled with less than 10 feet (3 m) of local till. Field observations suggest that the flow of groundwater to this area follows bedding planes and joints within the lower Brazeau Formation. These observations are:

PLATE 14. Basal Brazeau Formation.

1) An outcrop of the lower Brazeau Formation on the crest of the ridge above the discharge area exhibits cracks 2 inches (5 cm) wide along bedding planes, open to an observable depth of 5 feet (1.5 m). Such cracks become infiltration routes for precipitation.

2) The beds dip downslope toward the discharge area.

3) Where exposed by road cuts, rocks of the lower Brazeau Formation are damp or wet along bedding planes (Plate 14). Moisture is also observable along joints and appears to concentrate at the junctions of bedding planes and joints.

Block diagrams (Fig. 14) further elaborate the groundwater flow regime at this locality. Recharge occurs at the crest of the ridge, and on the pine-covered lower slope. Groundwater moving down from the ridge is controlled strongly by bedding planes and joints within the Brazeau Formation; it tends to concentrate at junctions. The overlying blanket of clay-bearing till is less permeable than the underlying jointed bedrock and acts as a deterrent to upward groundwater flow. Thus, water discharges in a pocket of permeable material within the till. The high volume of groundwater flow makes the ground quick in the area of this material and a spring of the soap hole type is formed.

Discharge Area in Glaciolacustrine Silt

This discharge area is located in the upper part of Eunice Creek subbasin, on the west flank of the Tri-creek syncline (Fig. 15). The bedrock is sandstone and shale of the Brazeau Formation, and is mantled with glaciolacustrine silt. A stereogram of the area is included also (Plate 15). Springs of the rock debris and soap hole types are observed, as is a seepage pit. Plate 16 illustrates a typical soap hole spring found in the area. This feature is expressed topographically as a low mound, with the center part or core domed by upward-flowing groundwater. An area of 64 square feet (6 m^2) is in a quick condition due to groundwater flow. The seepage pit is shown in Plate 17. This feature, unique in Tri-creek basin, is a large area of quick ground supported by a groundwater inflow of 10 igpm (45 l/min) or more. Appendix D outlines the method of calculating quick conditions.

The groundwater flow regime in this area of glaciolacustrine silt is given in figure 16, a cross section along line A-B′ of figure 15. The seepage pit is included as is the soap hole spring shown in Plate 13. Groundwater in this area moves from bedding planes and joints of east-dipping Brazeau sediments into semi-permeable silt. In low-lying spots such as the discharge area, quick ground and soap hole springs would be expected from

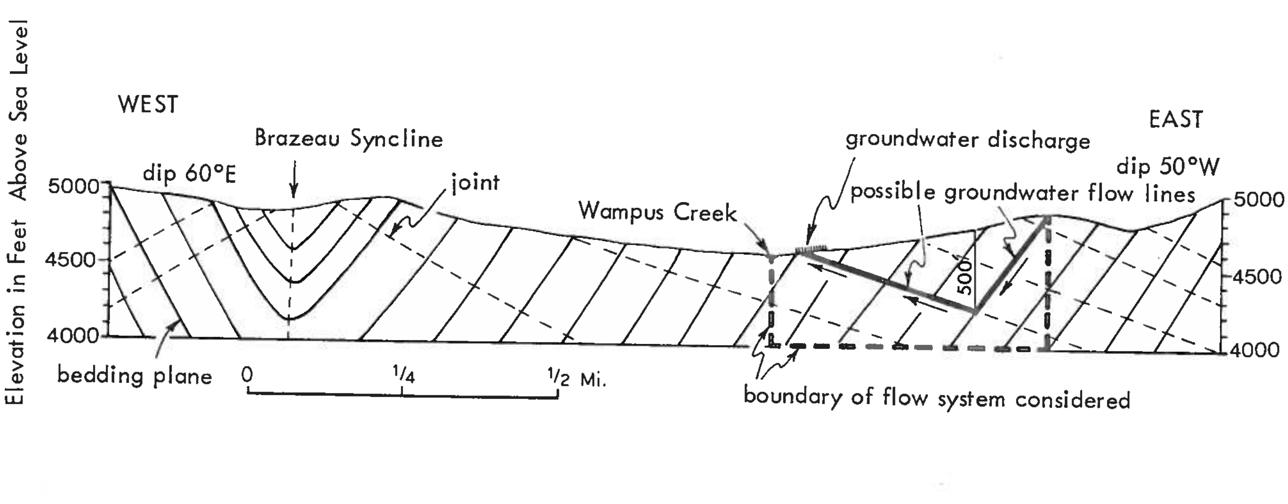
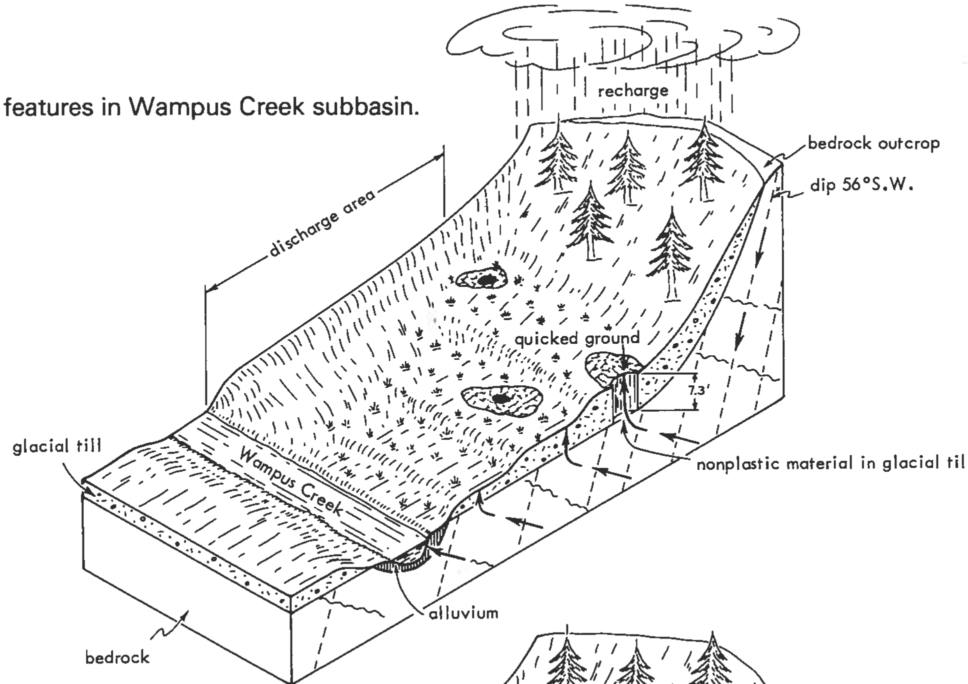


FIGURE 13. Structure cross section, Wampus Creek subbasin.

14a. Block diagram of discharge features in Wampus Creek subbasin.



14b. Block diagram of discharge features — till sheet raised.

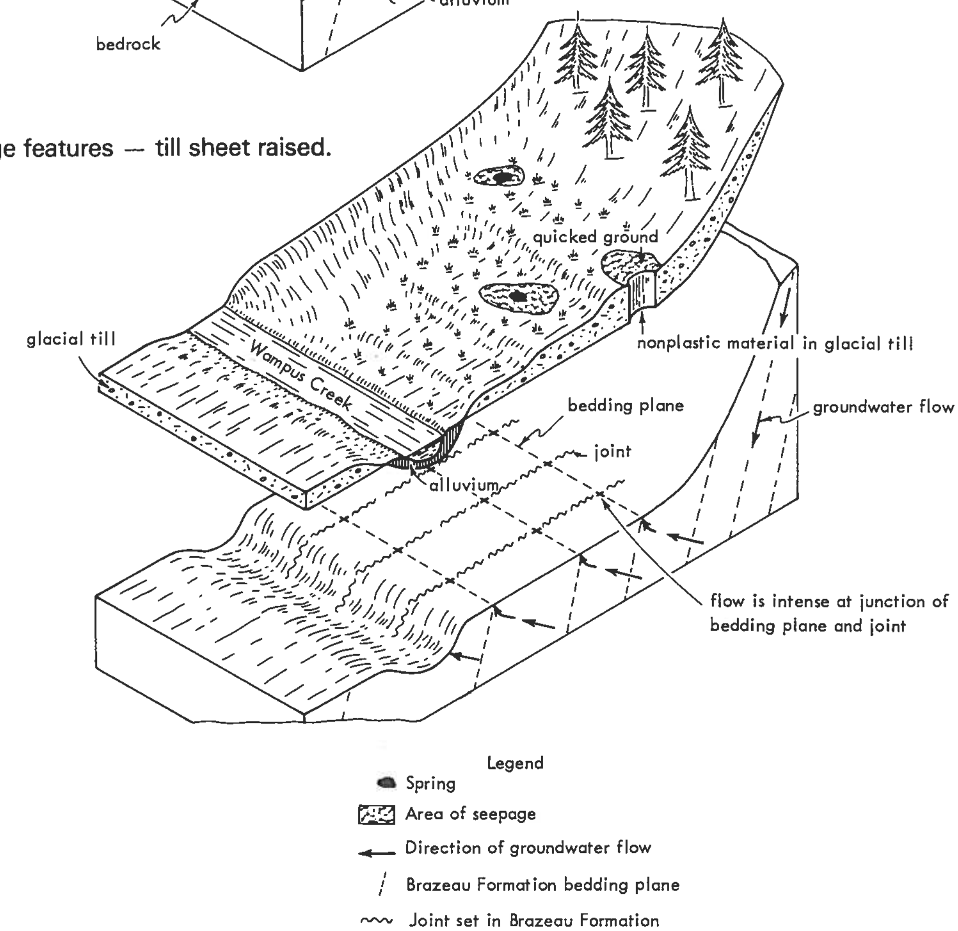


FIGURE 14. Block diagrams of Wampus Creek discharge features.

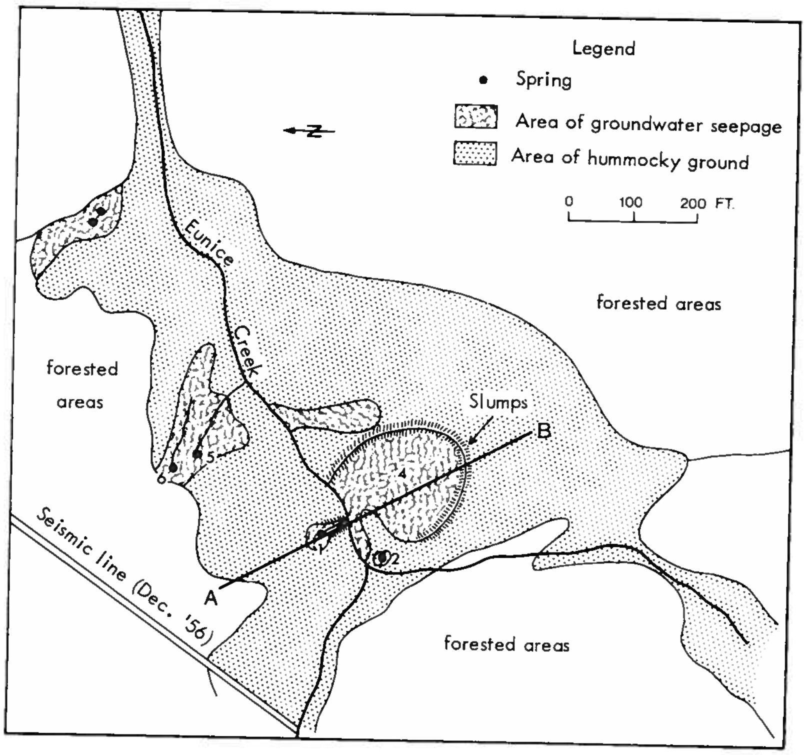


FIGURE 15. Groundwater discharge features, Eunice Creek subbasin.

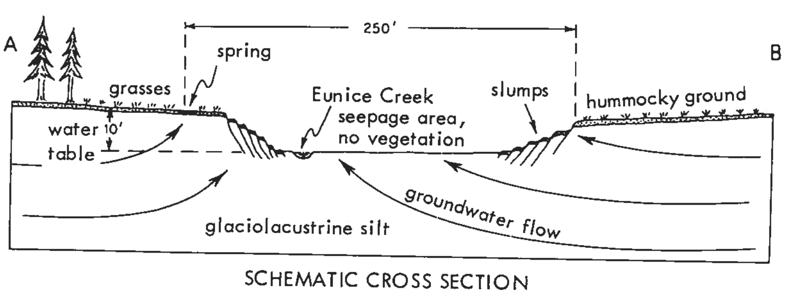


FIGURE 16. Schematic cross section, Eunice Creek subbasin.

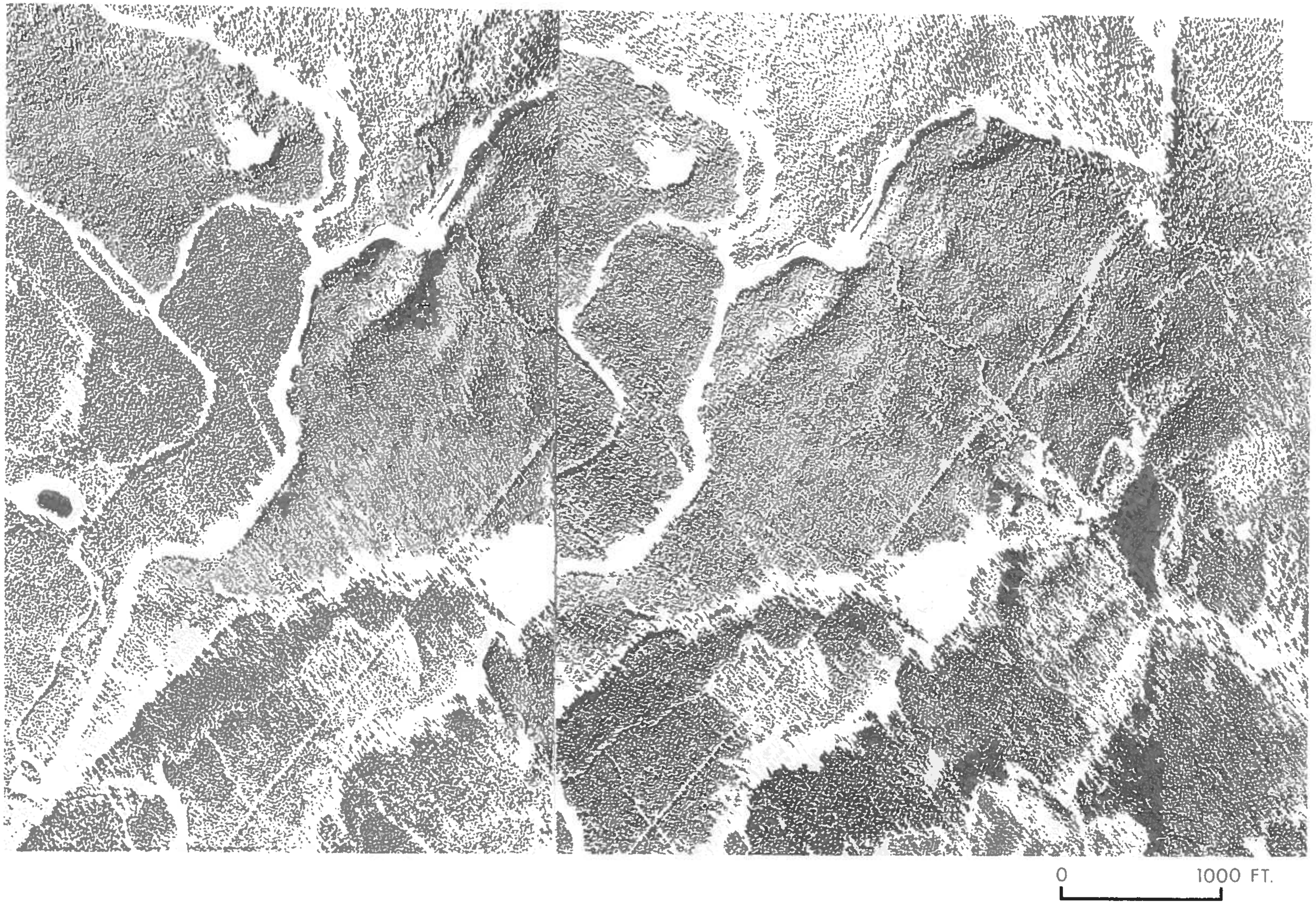


PLATE 15. Stereogram of a groundwater discharge area in Eunice Creek subbasin.

saturation of the flow medium. A very large volume of flow at low velocities could result in a seepage pit type of feature. Groundwater discharging at higher velocities could remove the easily erodible silt in localities of thin surface cover, exposing bedrock and giving rise to a rock debris type of spring (Plate 9).

GROUNDWATER EXPLORATION

To specifically test for quantity and quality of groundwater in Tri-creek basin, 12 exploratory wells were drilled at three sites. Data from pump tests established well and aquifer yields and other hydrogeological parameters; Appendix E outlines the Theis method, the mathematical model used for analyzing the data. This model assumes that the aquifer is homogeneous and isotropic, a condition that is not met by most moderately fractured rocks. Results from the Theis method are sometimes misleading and invalid. However, in this case, it is assumed that the frequency of fracturing is sufficient to make the use of this model appropriate. The results are summarized in figure 17, a well and spring data map of the area. Data from eight selected wells and seven typical springs are given. Summaries of aquifer yield and chemical composition of groundwater obtained are included in this section of the report; drilling logs, pump test data, and related information for the three exploratory sites are given in Appendix F.

Allowable Pumping Rates

The results of pump tests in the various bedrock and surficial geological units penetrated by the exploratory wells can be extended for similar hydrogeologic environments in other parts of the study area. Four hydrogeologic environments are represented, as shown on figure 18 and outlined below. Twenty-year safe pumping rates are given.

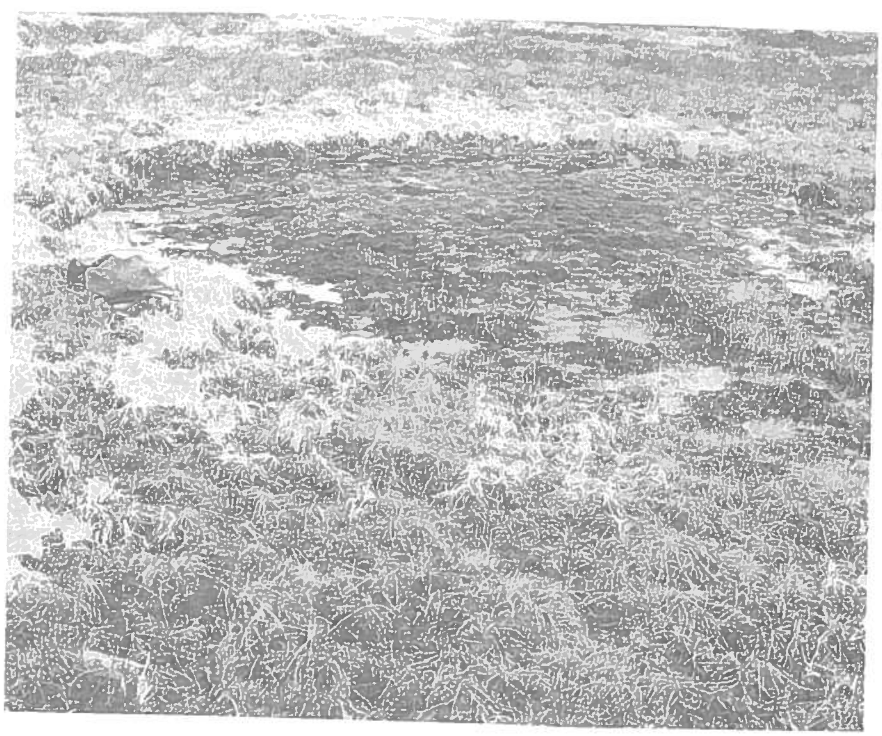


PLATE 16. Soaphole spring in Eunice Creek subbasin.

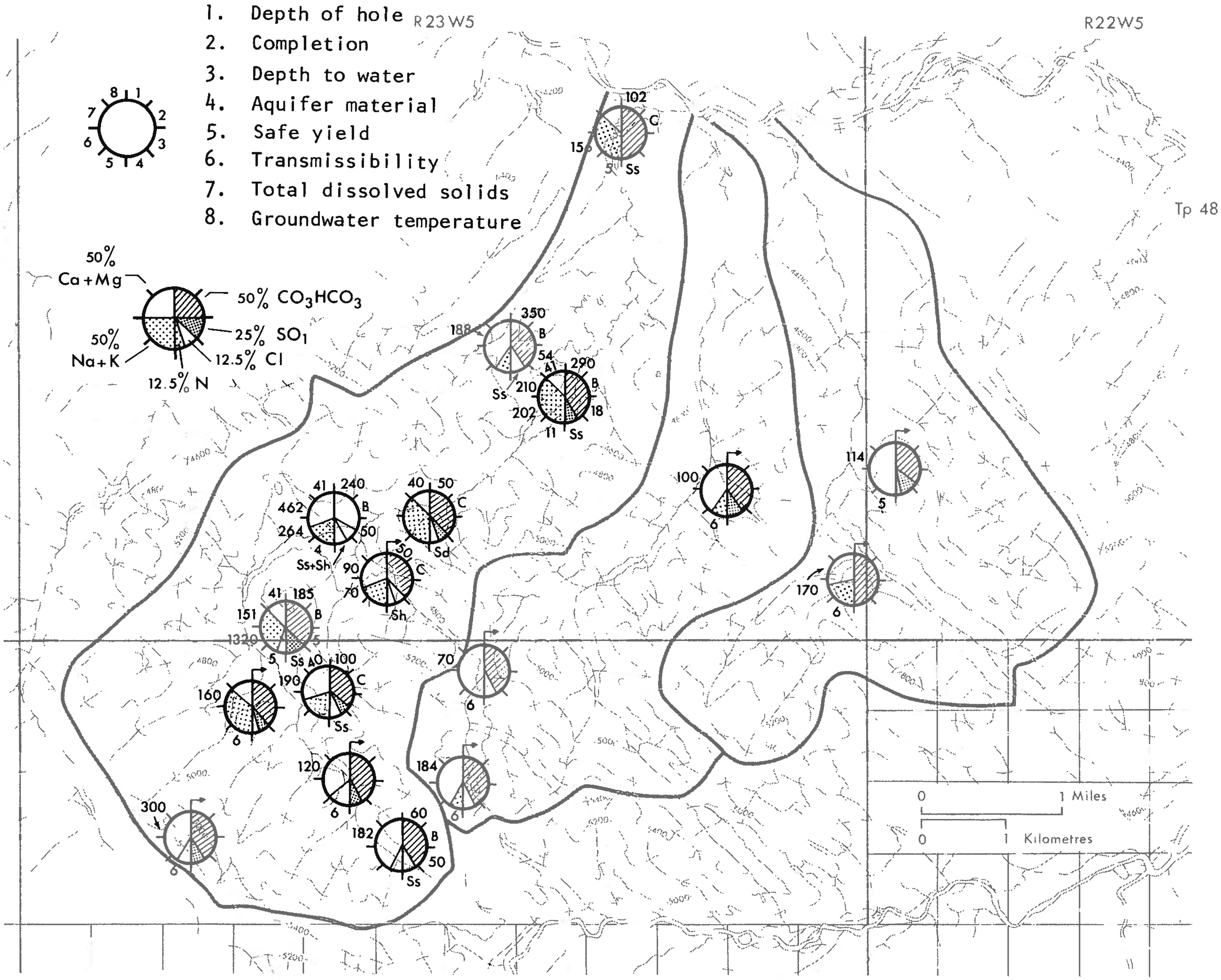


FIGURE 17. Well and spring data in the study area.

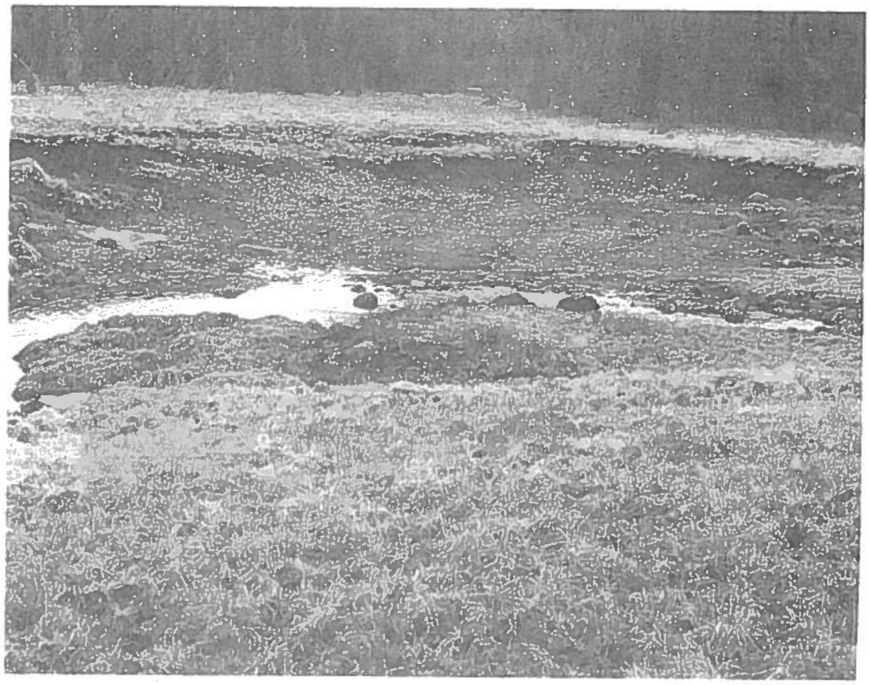


PLATE 17. Seepage pit in Eunice Creek subbasin.

PLATE 18. Pulpwood extraction operations approximately 4 miles northwest of Tri-creek basin.

I Lower Brazeau Formation (sandstone, conglomerate, steep dips) 5 to 15 igpm (20 to 70 l/min)

II Alberta Group (predominantly shale; moderate dips) 0 to 5 igpm (0 to 20 l/min)

III Brazeau Formation (sandstone and shale; gentle dips) 5 to 10 igpm (20 to 45 l/min)

IV Ice-contact deposits (unconsolidated sand, gravel, and cobbles), 15 to 100 igpm (70 to 450 l/min)

The area designated environment I in the headwater strike valley of Wampus Creek, which is coincident with the axis of the Brazeau syncline, is assigned a safe rate value of 10 to 15 igpm (45 to 70 l/min) based on pump tests. In addition, this area contains many springs which do not vary in flow rate to the same degree as those observed in other parts of the basin. The assignment of safe rate values to hydrogeologic environments II and III is based upon pump test or short bail test results. The thick sections of ice-contact deposits are probably the areas of highest safe rate, although they were not pump tested due to inaccessibility. The estimated safe rate of 15 to 100 igpm (70 to 450 l/min) is conservative.

Hydrochemistry

All waters sampled during the investigation were of excellent quality. The maximum values of total dissolved solids was 462 ppm, measured in water from Blackstone Formation shale at groundwater exploration site 2. Other constituents were well within the allowable limits set by the Environmental Health Services Division of Alberta Environment.

Water samples taken from the three creeks, many springs and at depth in the drilled wells were analyzed for chemical composition. The results are summarized in a diagram of the type devised by Piper (1944) which classifies water according to chemical composition (Fig. 19). The diagram shows that surface and spring waters in Tri-creek basin are of the calcium/magnesium bicarbonate type, while groundwater encountered during drilling operation is classified as sodium/potassium bicarbonate type.

PLATE 19. Stripmining operations approximately 4 miles west of Tri-creek basin.

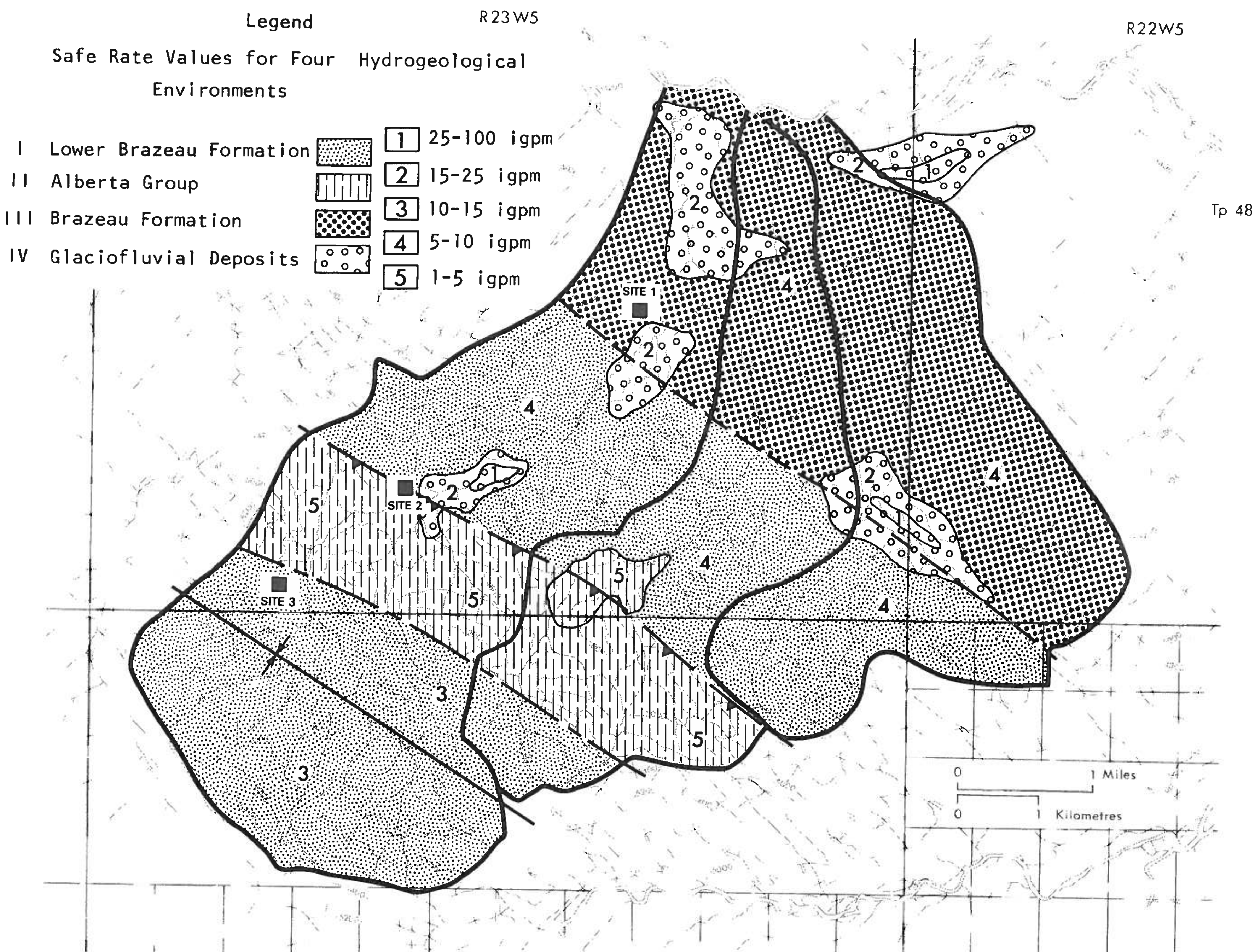


FIGURE 18. Hydrogeological environments, Tri-creek basin.

The hydrochemical analyses suggest that no major chemical alteration of the groundwater occurs within 300 feet (91 m) of the land surface. A conductivity survey of springs and surface waters in the basin did not reveal any significant changes in total dissolved solids content over the extent of the three subbasins. It is usual that conductivity values increase with greater stream length as the mineralized groundwater contribution to stream flow increases; however, this is not the case in Tri-creek basin. The flow systems operative in Tri-creek basin are shallow and rapid, and groundwater is not given sufficient residence time to become significantly mineralized.

RECOMMENDATIONS

Several recommendations should be made in regard to erosion hazard in Tri-creek basin. As outlined previously, glaciolacustrine silts in the study area are readily eroded and present a hazard at elevations below 4600 feet (1400 m). In these high-hazard areas, various kinds of erosion are taking place after disturbance of ground cover during logging operations, seismic exploration and road building activities (Plates 2 to 6). Pulpwood extraction and strip mining in the Luscar area (approximately four miles west of Tri-creek basin) are pictured in Plates 18 and 19; these activities are not recommended for high-hazard zones in Tri-creek basin. Eunice Creek, which flows in glaciolacustrine deposits for most of its length, should remain relatively undisturbed. Logging or mining operations in the other two subbasins must be undertaken with care in order to avoid ground cover disturbance in high-hazard zones.

The determination of the effects of tree removal on the streams of western Alberta is one of the overall interagency objectives of the work in Tri-creek basin. A well-managed cutting program in Tri-creek basin would provide supportive evidence in a reevaluation of forest cutting practices currently in use in a large part of the Foothills belt of Alberta.

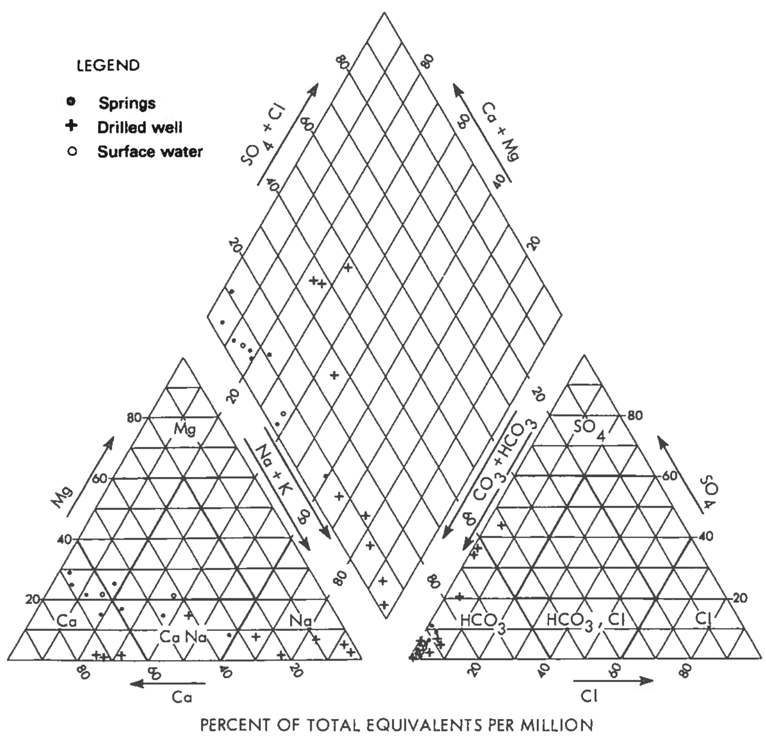


FIGURE 19. Piper diagram showing the chemistry of surface water and groundwater in Tri-creek basin.

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APPENDIX A

DETERMINATION OF EROSION HAZARD IN TRI-CREEK BASIN USING RUTTER'S METHOD

The method used to determine erosion hazard in Tri-creek basin was that devised by Rutter, (1968). Rutter's method was developed specifically for use in the provincial forest reserves of western Alberta and is consequently directly applicable to Tri-creek basin.

The analysis procedure was as follows:

1) Using airphoto interpretation, the types of surficial deposits in Tri-creek basin were determined. These include tills, glaciofluvial and fluvial gravels and glaciolacustrine silt.
2) The general lithology of the surface materials in Tri-creek basin was determined and field checked. The deposits are predominantly similar to the bedrock which is fine-grained clastic (shales, siltstones, sandstones) with lesser proportions of conglomerates and carbonates.
3) Potential erosion hazard was determined using table A-1 (from Rutter, 1968). Table A-2 summarizes these results.
4) A slope angle study of Tri-creek basin was prepared so that actual erosion potential (potential modified by topographic placement) of any deposit could be determined.
5) A graph relating potential erodibility of surficial material type to potential erodibility due to slope was constructed (Fig. A-1) following Rutter's example. Applying the graph to any individual area of interest gives the actual erosion hazard of that area. In Tri-creek basin, where various kinds of surficial deposits are found on slopes of various angles, the graph was applied on a unit-area basis and a map compiled (Fig. 7, in text).

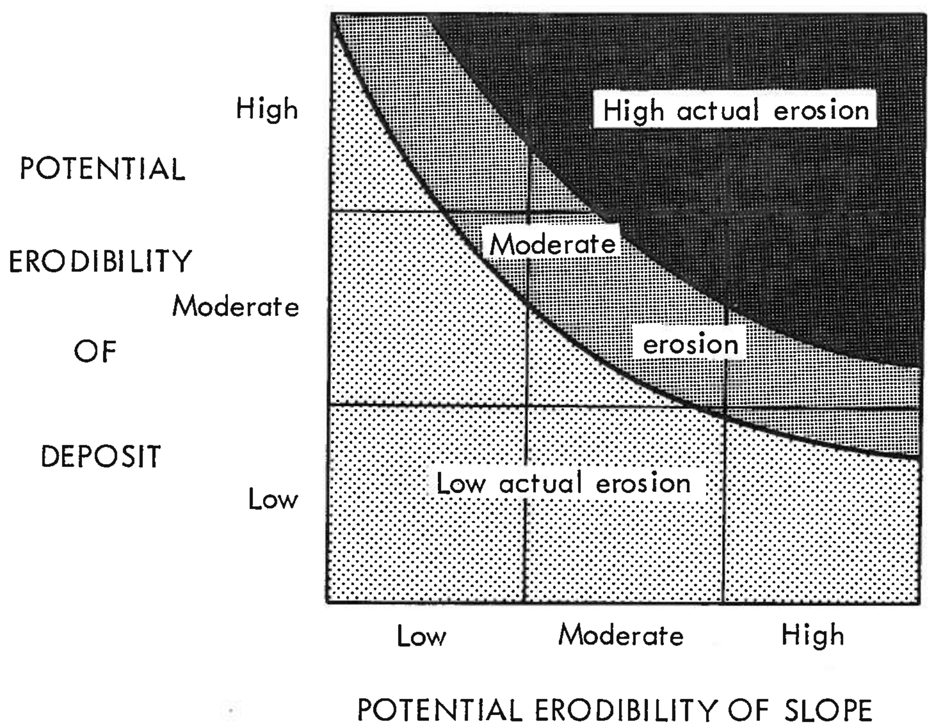

FIGURE A-1. The relationship between potential erodibility of deposits and slopes.

Table A-1. Relative erodibility of soils found in the Rocky Mountain Forest Reserve considering only their inherent properties (from Rutter, 1968).

Soil	Infiltration Rate	Grain Size Characteristics	Carbonate Cement	Binding Strength of Silt and Clay	Erosion Hazard
Low Erosion till	low	> 20% gravel sized	high	high	low
Moderate Erosion Till	low	> 20% gravel sized	low to absent	high	moderate
High Erosion Till	low	< 20% gravel sized	low to absent	high	high
Modified Low Erosion Till	low to moderate	> 20% gravel sized	high	moderate	low to moderate
Modified Moderate Erosion Till	low to moderate	> 20% gravel sized	low to absent	moderate	moderate
Modified High Erosion Till	low	< 20% gravel sized	low to absent	high	high
Glacial Outwash	high	> 20% gravel sized	low	low	low
Alluvial Fan Deposits	high	> 20% gravel sized	low	low	low
Recent Flood Plain Deposits	high	> 20% gravel sized	low	low	low
Talus	high	> 20% gravel sized	low	low	low
Colluvium	moderate	> 20% gravel sized	variable	variable	low to moderate
Lake, Pond, Muskeg Deposits	low	mostly clay and silt	variable	high	high
Soil possibly derived from underlying bedrock	low	mostly clay, silt and sand	low to absent	high	high

Table A-2. Description of surficial deposits in Tri-creek basin for use in evaluating erosion hazard

Material	Infiltration Rate	Carbonate Content (percent)	Gravel Content (percent)	Carbonate Cement Strength	Binding Strength of Clay	Potential Erosion Hazard
Glaciolacustrine silt	low	0.35	<20	none	moderate	high
Local till	low	0.29	<20	none	moderate	high
Marlboro till	low	1.00	<20	none	moderate	moderate
McLeod Valley limey till	low	10.00	<20	weak	moderate	high
Glacial outwash	high	moderate	>20	moderate	low	low

APPENDIX B

ESTIMATING AVERAGE PRECIPITATION IN THE STUDY AREA BY MEANS OF THE THIESSEN POLYGON METHOD

The basis of the Thiessen polygon method is that each precipitation measurement station represents a proportionate part of the total area. That part depends on its proximity to other stations.

A grid of polygons is formed by joining the perpendicular bisectors of lines joining adjacent stations. The areas of the polygons, determined by planimeter measurement, are used as weighting factors in an average of precipitation measured at the various stations. The average is obtained by multiplying the precipitation measured at each station by its polygon area, then dividing the sum of the results by the sum of all the areas.

Figure B-1 depicts an application of the Thiessen method to Tri-creek basin. The various precipitation measurement stations are indicated, as are the boundaries of the polygons. The yearly mean precipitation determined for the entire basin by this method was 27.21 inches (69.11 cm) for the period October 1967 to October 1968 (Table B-1). During the same period the following year average precipitation was 24.19 inches (61.44 cm).

Table B-1. Mean precipitation data for Tri-creek basin using Thiessen polygon method

	A Precipitation (inches)		B		Product A x B	
	1967-68	1968-69	Polygon area (sq mi)	Area (acres)	1968	1969
Deerlick A	26.1	29.5	2.89	1,850	48,285	54,575
Deerlick C	27.6	33.4	1.92	1,230	33,948	41,082
Eunice B	26.1	31.7	3.58	2,290	59,767	72,593
Eunice D	30.0	35.0	2.34	1,500	45,000	52,500
Wampus B	26.6	32.8	2.57	1,650	43,890	54,120
Wampus G	27.1	7.1	7.26	4,640	125,744	32,480
Wampus F	28.6	35.0	1.62	1,020	29,171	35,700
Totals	192.1	204.5	22.08	14,180	385,806	343,050

Yearly average precipitation ($\frac{A \times B}{\text{total } B}$) for October 1967 to October 1968: 27.21 inches.

Yearly average precipitation ($\frac{A \times B}{\text{total } B}$) for October 1968 to October 1969: 24.14 inches.

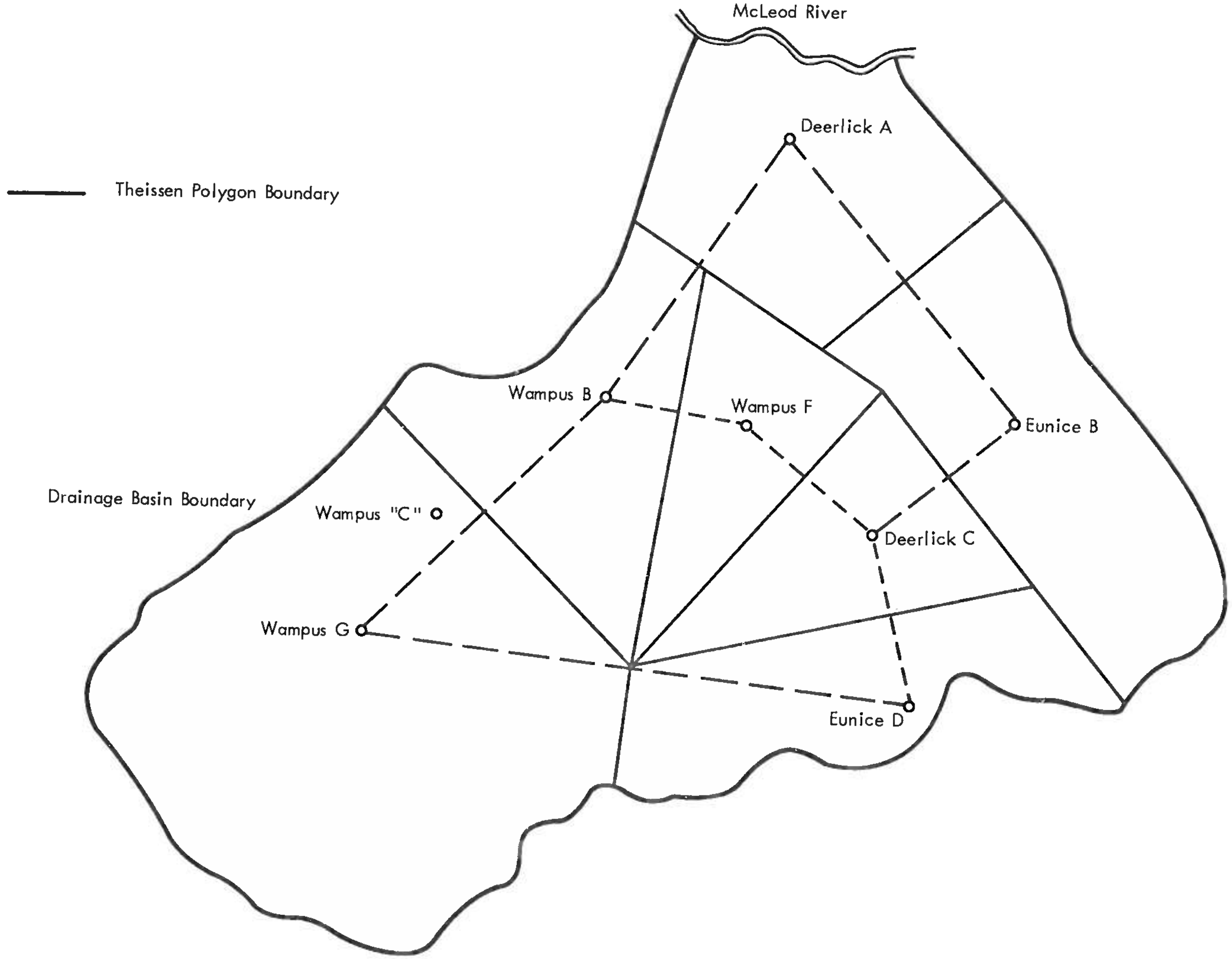

FIGURE B-1. Tri-creek basin divided into Thiessen polygons.

APPENDIX C

STREAMFLOW RECORDS

In order to obtain discharge and water level measurements, a number of wells and weirs were constructed in the study area. A concrete, triangular broad-crested weir and an accompanying 5-foot (15 m) diameter well were constructed at each of the outlets of Wampus and Deerlick Creeks. At Eunice Creek only a 5-foot (15 m) diameter water-level well was constructed. At all sites Stevens A-35 recorders were installed.

The recording of streamflow measurements began in October 1967. Low temperature and icing conditions at the weirs prevented the recording of measurements during January to April each year. However, the streams flow even on the coldest days and springs feeding the creeks stay open all winter. Some melting of snow followed by streamflow may occur during the times when chinook winds issuing from Cadomin Gap raise the winter temperatures to anomalous highs.

The hydrograph of Wampus Creek for the period April to December 1969 shows the response of streamflow to high-intensity summer storms (Fig. C-1). Also plotted are the fluctuations of the water table in the well adjacent to the stream gauging station. A marked correlation between periods of high flow rates and rises in the water table is evident.

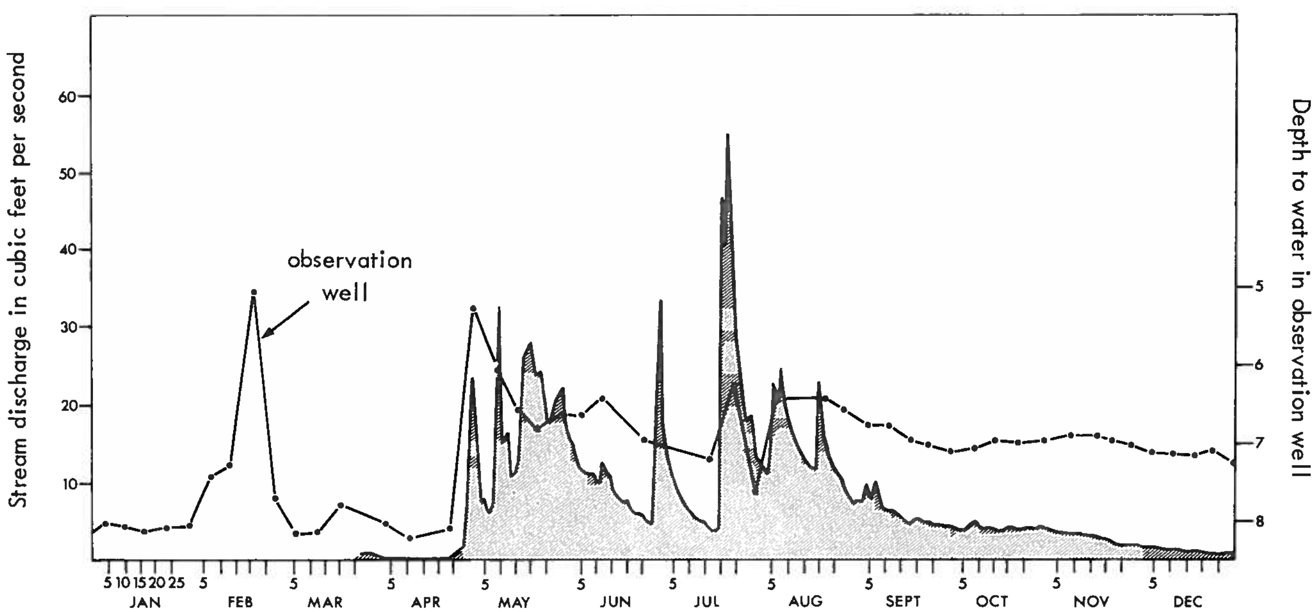

FIGURE C-1. Stream discharge and observation well measurements, Wampus Creek outlet.

APPENDIX D

METHOD FOR CALCULATING GROUNDWATER FLOW REQUIRED TO MAINTAIN QUICK GROUND IN A GIVEN LOCALITY (RUTLEDGE, 1940)

Quick ground results when upward-flowing groundwater relieves the stress between grains of soil material; that is, when the volume and speed of upward flow is sufficient to bear the weight of the soil through which flow occurs. If the composition of the soil is known, the flow required to cause a quick condition can be calculated.

The calculation is done in several steps. First, the critical hydraulic gradient (i.e. hydraulic gradient at which the stress is equal to zero) is determined through the equation:

$$i_c = \frac{G_s - 1}{1 + e} \qquad (1)$$

$$= \frac{2.66-1}{1+0.78} = 0.93$$

where

i_c = critical hydraulic gradient;

G_s = specific gravity of soil solids;

e = void ratio. Void ratio is defined as the volume of the voids divided by the volume of soil solids.

The flow necessary to cause quick conditions can be calculated from Darcy's law:

$$Q = KiAt \qquad (2)$$

where

Q = total quantity of water flowing through area A, in time t, under hydraulic gradient i.

The quantity of water flowing through the soil in a unit of time t is:

$$q = \frac{Q}{t} = KiA \qquad (3)$$

Since q is a volume per unit of time, L^3/T; and A is an area, L^2; then Ki must be a velocity, L/T. This velocity is designated V_d and called the discharge velocity.

The discharge velocity is the velocity at which the same volume of water as flows through the soil would flow through an area equal to the total area of the soil.

Because the water flows only through the void spaces and not through the soil solids the velocity of water parallel to the direction of flow must be somewhat greater than the discharge velocity. The seepage velocity (V_s) is the velocity at which the line of wetting will progress in the direction of flow in a dry soil.

The range of the coefficient of permeability (K) for mixtures of sand, silt, clay and till, etc., given by Means and Parcher (1963) is from 10^{-3} to 10^{-7} cm/sec. The mean value of 10^{-5} cm/sec is used in the following calculations.

The discharge and seepage velocities in a glaciolacustrine silt under a critical hydraulic gradient of 0.93 can be calculated as follows:

$$V_d = Ki_c \qquad (4)$$

$$= 1 \times 10^{-5} \times 0.93$$

$$= 9.3 \times 10^{-6} \text{ cm/sec}$$

and

$$V_s = V_d \frac{1+e}{e} \qquad (5)$$

$$= 9.3 \times 10^{-6} \times \frac{1+0.78}{0.78}$$

$$= 21.4 \times 10^{-6} \text{ cm/sec}$$

where

V_d = velocity discharge;

K = coefficient of permeability;

V_s = seepage velocity.

The flow necessary to cause quick conditions over the 64-square foot area of the soap hole spring shown in Plate 12 can be calculated from the equation:

$$q = KiA \quad (6)$$

$$= (1 \times 10^{-5}\ cm/sec) \cdot (0.93) \cdot (59458\ cm^2)$$

$$= 0.55\ cm^3/sec$$

$$= 0.0075\ igpm.$$

The quantity of flow measured in the channel leading from the soap hole spring on May 26, 1967, was 1.5 igpm (113.5 cm^3/sec). This quantity of flow could quick an area of:

$$A = \frac{q}{Ki_c} \quad (7)$$

$$= \frac{113.5\ cm^3/sec}{9.3 \times 10^{-6}\ cm/sec}$$

$$= 12.2 \times 10^6\ cm^2\ (13,200\ sq.\ ft.).$$

This calculation indicates that a flow of 1.5 igpm is more than sufficient to quick the materials underlying all the groundwater discharge features in Tri-creek basin except the seepage pit, which has an area of 16,800 square feet. A minimum flow of 10 igpm is estimated for the seepage pit. This volume of flow is variable and diffuse, but would be more than sufficient to quick the area concerned.

APPENDIX E

THEIS METHOD FOR CALCULATING HYDROGEOLOGIC PARAMETERS FROM PUMPING TESTS

D. Todd (1967), *Ground Water Hydrology,* John Wiley & Sons, pp. 90-93, and

P. A. Domenico (1972), *Concepts and Models in Groundwater Hydrology,*

McGraw-Hill Book Company, p. 321-327 (405 pages)

The Theis (or nonequilibrium) equation is extensively used to determine hydraulic properties of aquifers using data obtained from pump tests of wells. Once these are determined it is possible to calculate:

1) the theoretical drawdown at any distance from a single well at a given rate for any length of time;
2) the theoretical drawdown at any point in the aquifer for any length of time in response to a series of wells pumping at various rates. In using this method the nonequilibrium equation is expressed as

$$h_o\text{-}h = \frac{114.6Q}{T} W(u)$$

where h_o-h is the drawdown in feet, Q is the well discharge in gallons per minute, T is the coefficient of transmissivity in gallons per day per foot and W(u) is the exponential integral called a "well function." Its argument u is given by

$$u = \frac{1.87r^2S}{Tt}$$

where S is the dimensionless storage coefficient, r is the distance in feet from the discharging well to the observation well and t is the time in days since pumping started.

To obtain the aquifer constants, Theis suggested an approximate solution based on a graphical method of superposition.

A plot on logarithmic paper of W(u) versus u, known as a "type curve" is prepared. Values of drawdown h_o-h are plotted against values of r^2/t on the logarithmic paper of the same size as for the type curve. The observed data curve is superimposed on the type curve, keeping the coordinate axes parallel, and adjusted until a position is found wherein most of the observed data points fall on a portion of the type curve. An arbitrary point is chosen on the coincident portion and the coordinates of this matching point are recorded. With the values of W(u), u, h_o-h and r^2/t now determined, S and T can be calculated using the equations given previously.

APPENDIX F

GROUNDWATER EXPLORATION DATA

To evaluate the groundwater regime in the study area in quantitative terms, three sites were selected for investigation by means of drilled wells. All three sites were chosen keeping accessibility to the truck-mounted drilling rigs in mind and consequently are all in the Wampus Creek subbasin. These sites are considered to be representative of three of the four hydrogeologic environments mapped in Tri-creek basin. Environment IV, scattered deposits of glaciofluvial materials, could not be explored because of access difficulties.

Each site consisted of a pumped well and one or more observation well. Static water levels, water level drawdowns and water level recoveries before, during and after the pumping test were recorded and then analyzed using the Theis method (Appendix E) to obtain aquifer coefficients.

The pumped wells were drilled using cable tools, a technique which provides better control of downhole conditions and more accurate information on lithologies than does the faster air rotary method employed in drilling the observation wells.

Groundwater exploration site 1, in SW ¼, Sec. 14, Twp. 48, R. 23, W5, is in an area of groundwater discharge. The bedrock is gently folded Brazeau Formation representative of hydrogeologic environment III (see p. 41). Figure F-1 shows the locations of the four observation wells in relation to the pumped well and gives well data. The lithology encountered in drilling the pumped well is given in figure F-2. Results of pump tests are presented graphically in figures F-3 through F-5; the calculated hydrogeologic parameters are summarized in Table F-1.

Groundwater exploration site 2, located in Lsd. 14-15, Sec. 4, Twp. 48, R. 23, W5 is situated in discharge area adjacent to the downstream end of a meltwater channel and proximal to the Brazeau Thrust (Fig. F-6). The site overlaps environments I and II. This site was especially interesting because here the hypothesis that the Brazeau Thrust is transmitting groundwater to the surface could be tested. The results were inconclusive, however.

Figure F-7 gives the relative locations of the pumped well and the three observation wells, and includes basic hydrogeologic data. Figure F-8 is a lithologic log of the pumped well. Two distinct aquifers were encountered: 12 feet (36 m) of surficial sand and gravel overlying the shaly Blackstone Formation bedrock and 22 feet (66 m) of fractured siltstone in the 148-foot to 170-foot interval, lying between shale beds. Figures F-9, F-10, and F-11 are graphs of the pump tests of these aquifers and Table F-2 summarizes the results of the aquifer tests.

A 12-hour pump test was used to calculate hydrogeologic parameters at this site. The results are shown graphically in figures F-12, F-13, and F-14. Drawdown was not observed in observation well 3; thus, no graph is presented for this well. Table F-3 summarizes the hydrogeologic parameters.

Groundwater exploration site 3, in SW ¼, Sec. 5, Twp. 48, R. 23, W5 is found between a groundwater recharge area occurring in fractured Brazeau conglomerates and a discharge area of soap hole springs in the valley bottom. The site may be assigned to hydrogeological environment I. Location of the site is shown in figure 18. Figure F-15 is a lithologic log of the pumped well. Of the five aquifers noted during drilling, three were isolated in the pumped well and tested. Figures F-16, F-17 and F-18 give drawdown data for each; results are tabulated in Table F-4.

Parameters of hydrogeologic conditions at site 3 were obtained from pump tests, varying in length from 3 to 90 hours. Graphs of the two longer tests are given in figures F-19 and F-20; Table F-5 summarizes the results. The data gathered during these tests do not, however, fit any known groundwater flow model. The explanation may relate to the complexity of the local hydrogeologic environment.

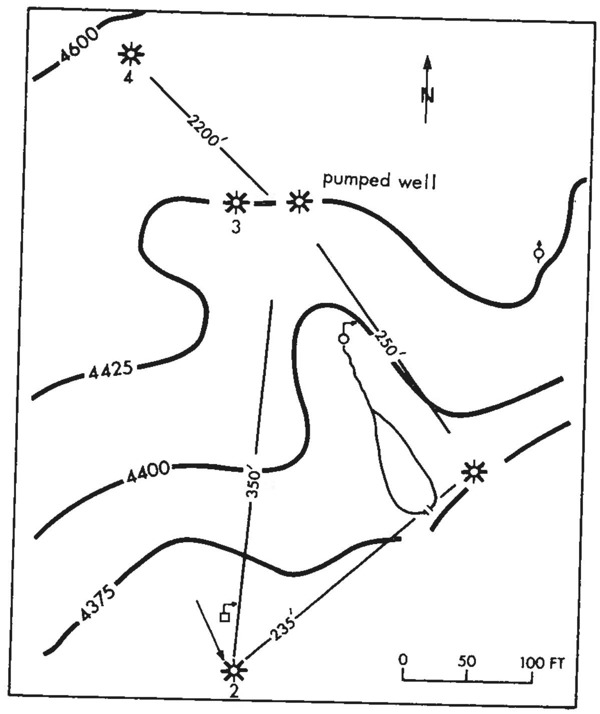

FIGURE F-1. Groundwater exploration site 1.

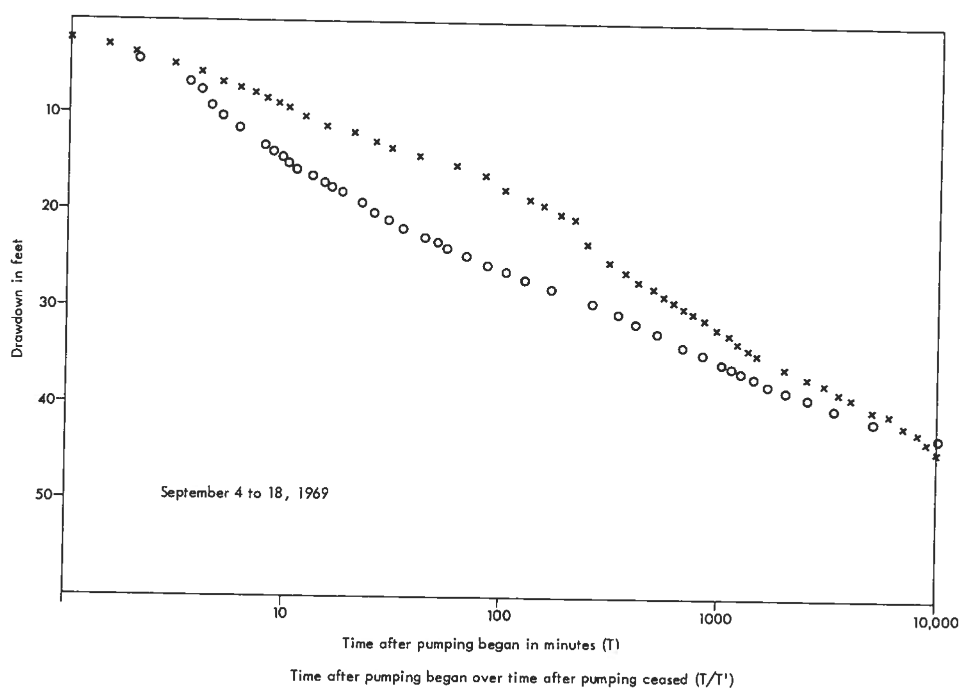

FIGURE F-3. Drawdown and recovery curves for pumped well, exploration site 1.

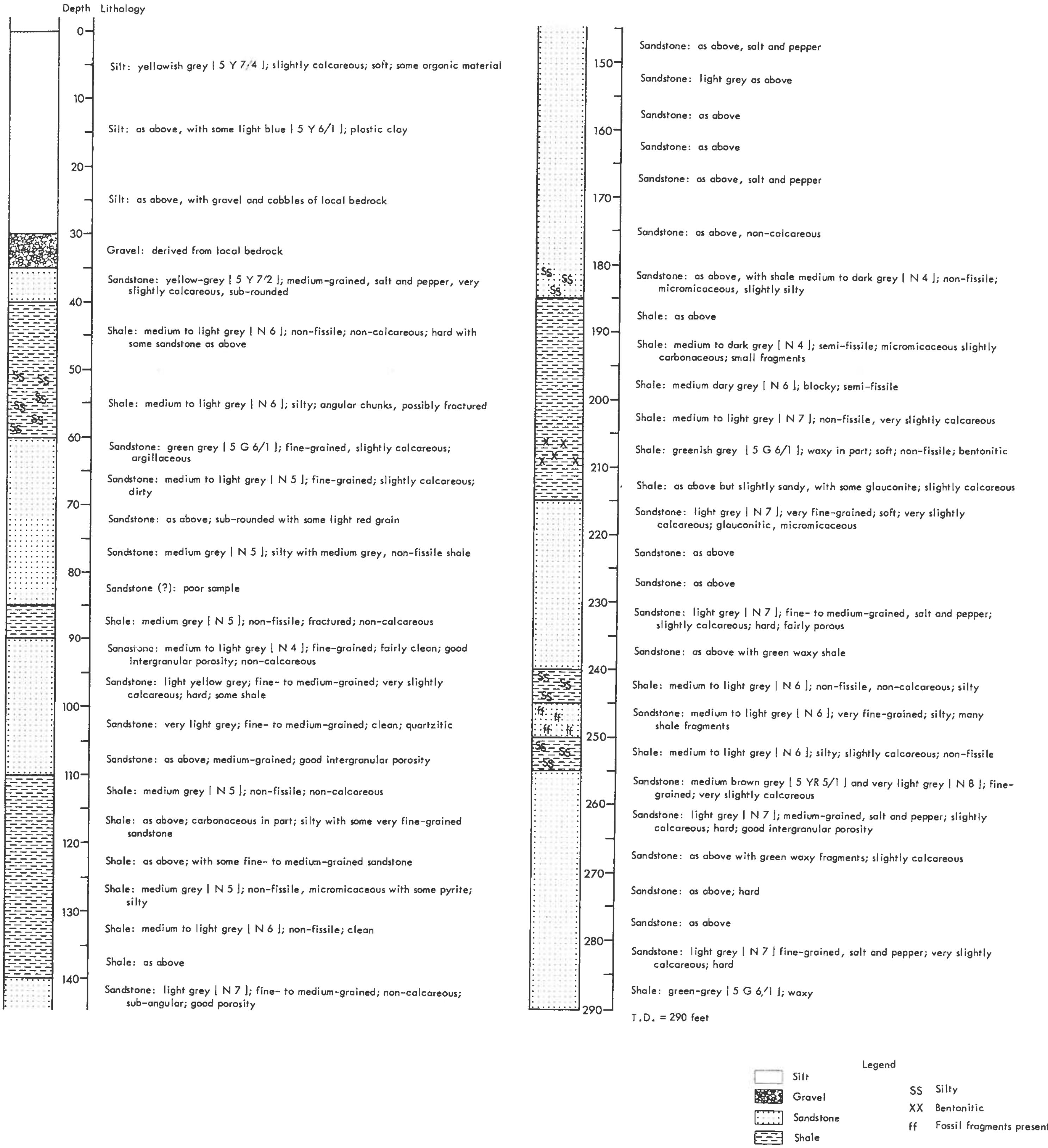

FIGURE F-2. Lithology log of pumped well, groundwater exploration site 1.

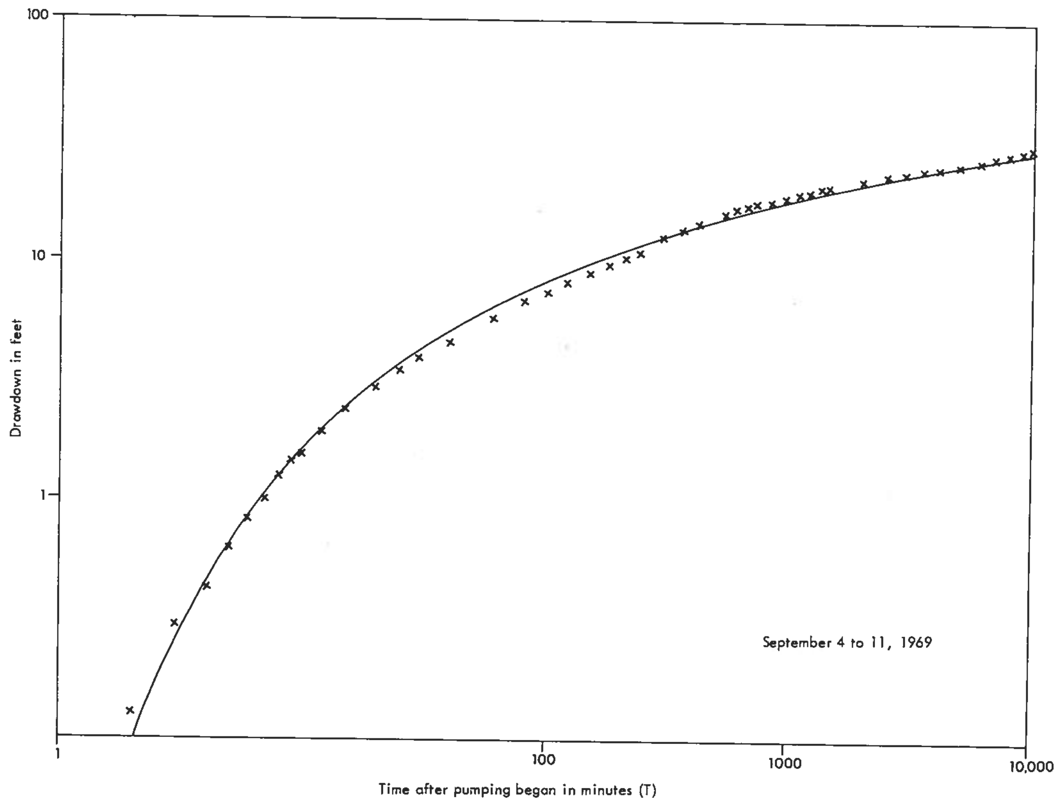

FIGURE F-4. Drawndown curve for observation well 3, exploration site 1.

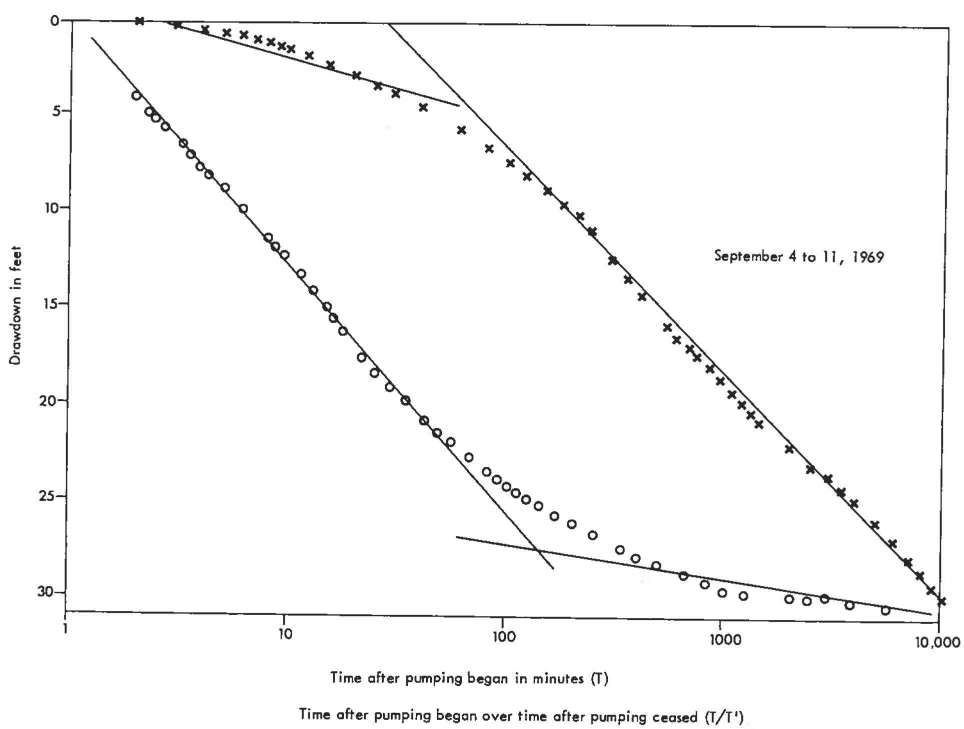

FIGURE F-5. Drawdown and recovery curves for observation well 3, exploration site 1.

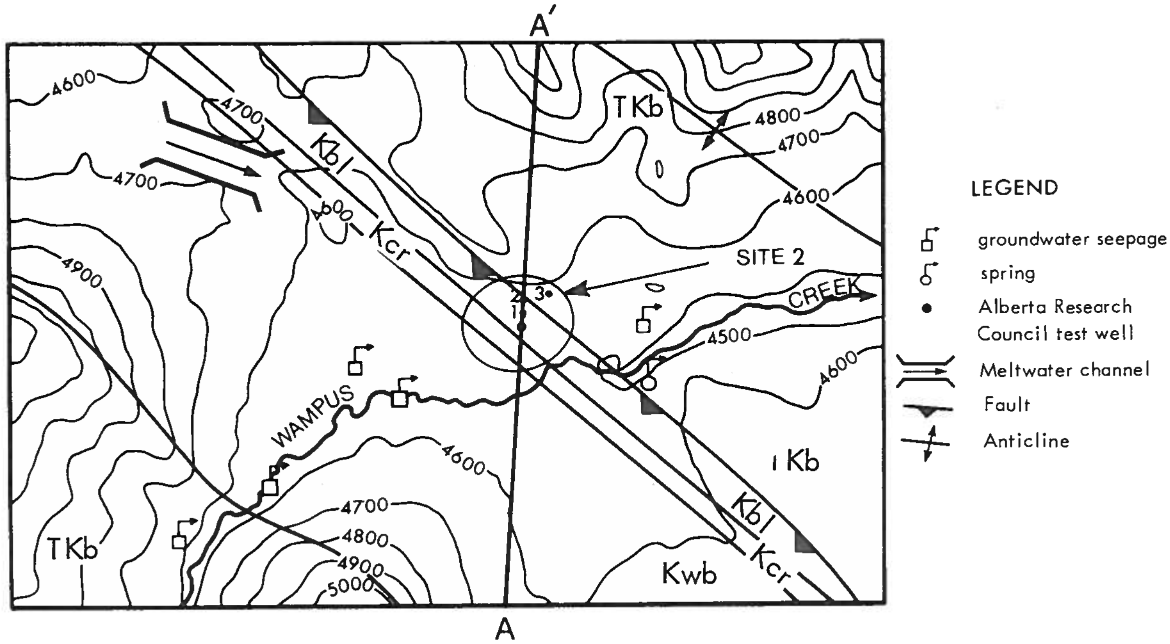

FIGURE F-6. Location of groundwater exploration site 2

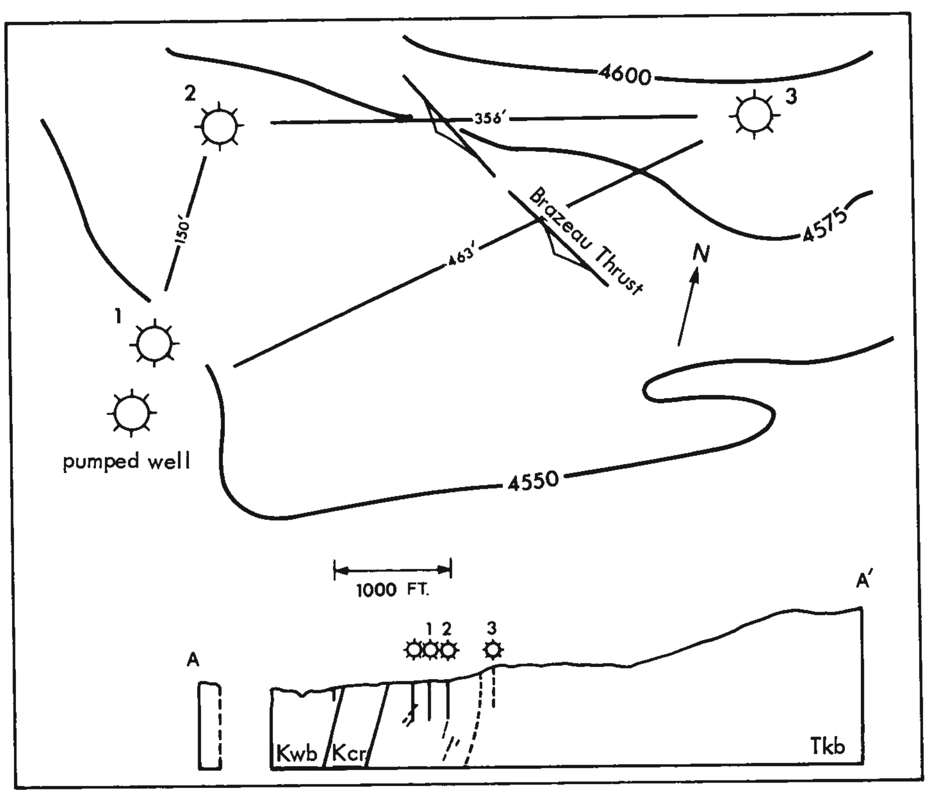

FIGURE F-7. Map and geologic cross section of groundwater exploration site 2.

Table F-1. Summary of data obtained from 168-hour pump test, groundwater exploration site 1

Data	Pumped Well	Observation Wells 1	2*	3	4
Drilling method	cable	rotary	rotary	rotary	rotary
Depth (ft)	190	265	10	190	350
Open hole interval (ft)	145 (55-190)	193 (72-265)	-	150 (40-190)	329 (21-350)
Distance from pumped well (ft)	0	250	350	50	2200
Initial water level (ft)	24.3	flowing 4 igpm	flowing	25.2	54.6
Pumping rate (igpm)	6	-	-	-	-
Total drawdown (ft)	45.0	flow ceased at 55.5 hrs	-	30.0	1.3

Results	Jacob modified nonequilibrium formula, and Theis recovery formula	Nonleaky artesian-type curve (observation well 3)
Transmissibility (igpd/ft)	72	208
Coefficient of permeability (igpd/ft^2)	0.54	2
20-year safe pumping rate (igpm)	5	10

*Observation well 2 sloughed prior to testing.

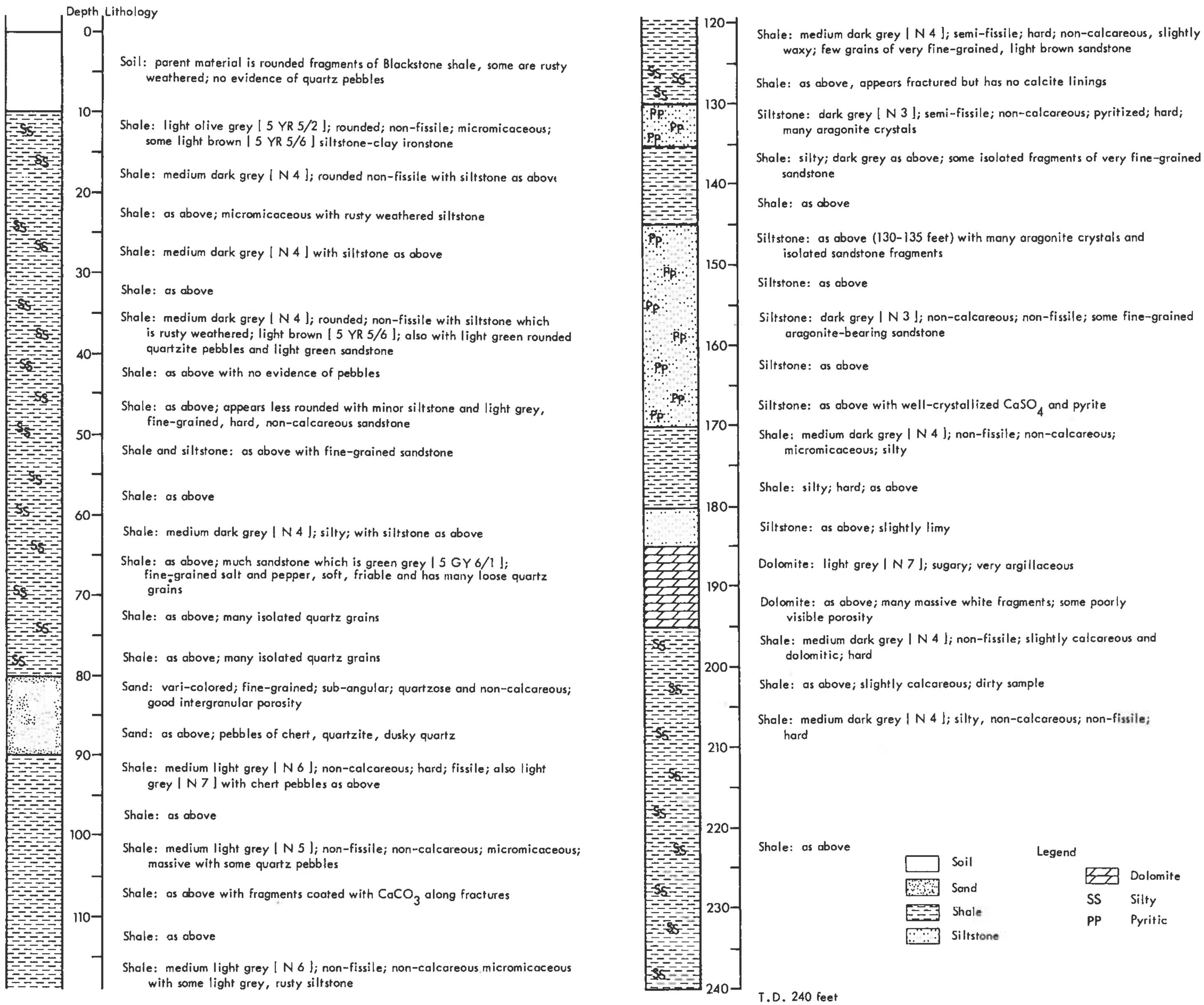

FIGURE F-8. Lithology log of pumped well, groundwater exploration site 2.

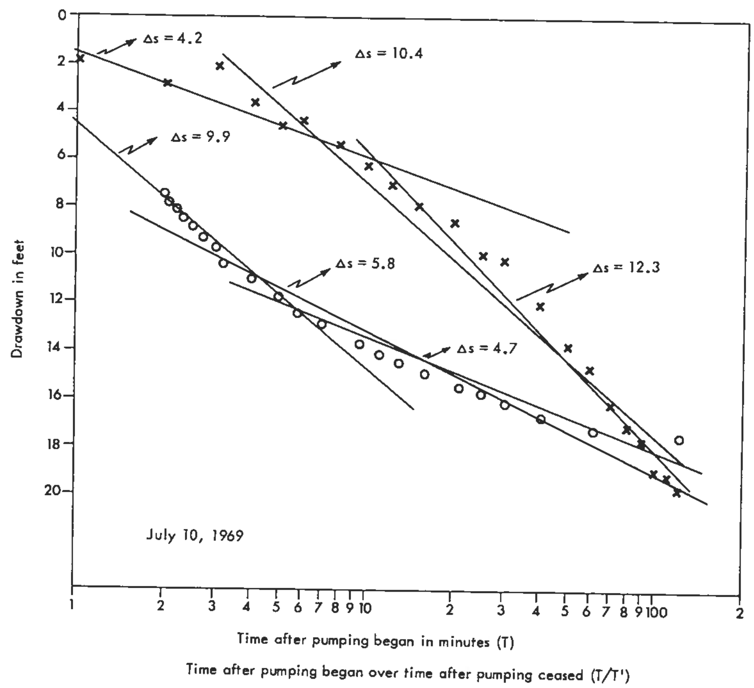

FIGURE F-9. Drawdown and recovery curves for bail tested well, bail test 2, exploration site 2.

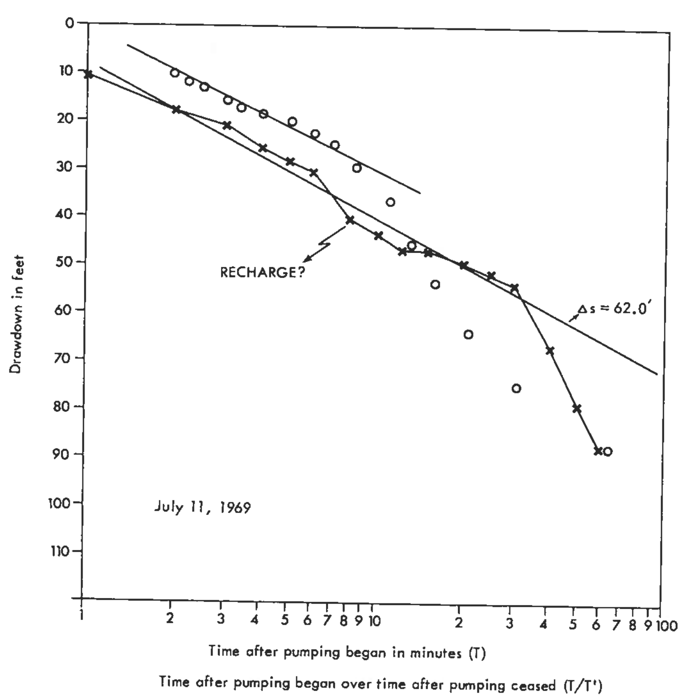

FIGURE F-10. Drawdown and recovery curves for bail tested well, bail test 3, exploration site 2.

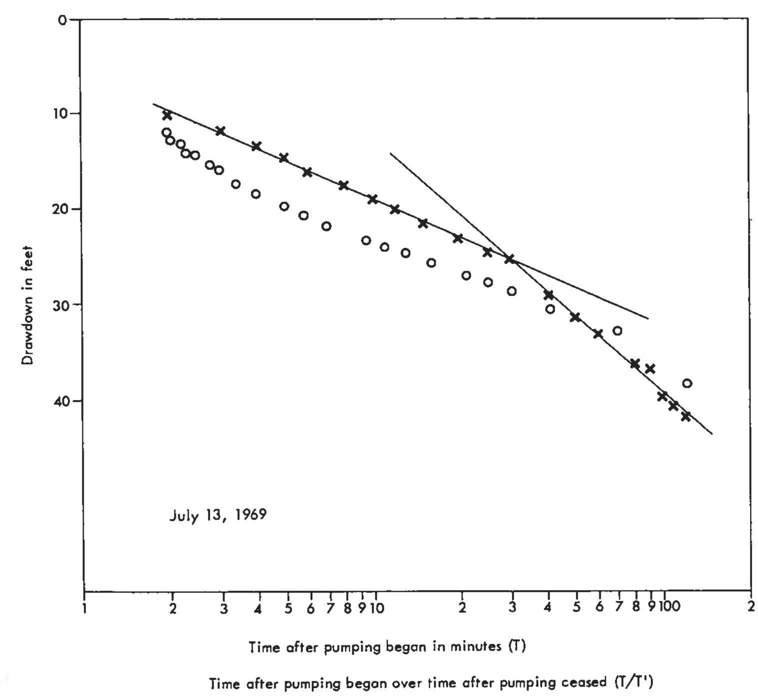

FIGURE F-11. Drawdown and recovery curves for bail tested well, bail test 4, exploration site 2.

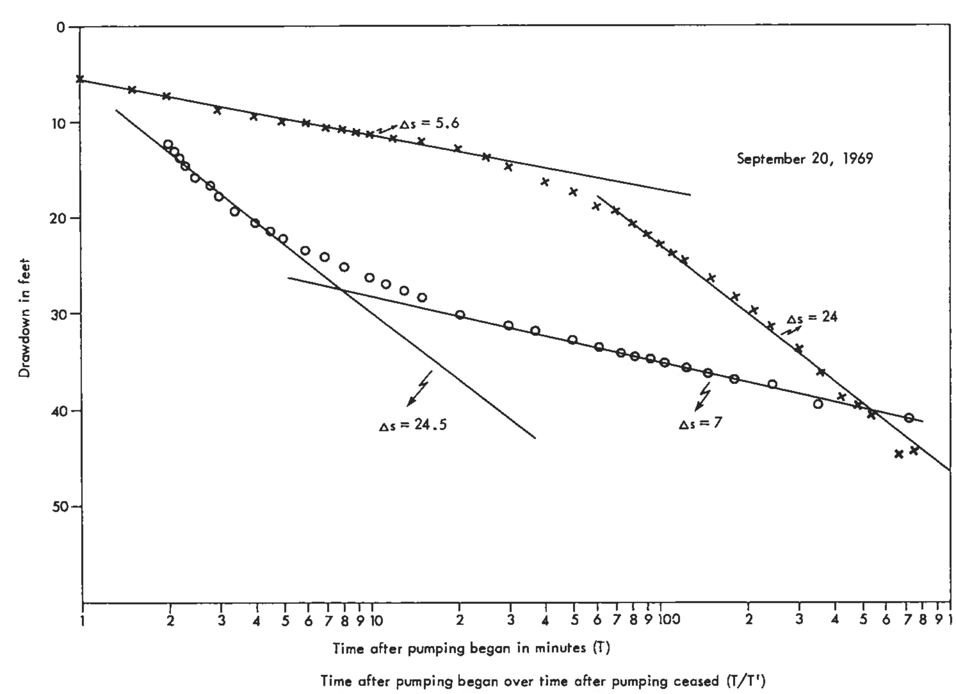

FIGURE F-12. Drawdown and recovery curves for pumped well, exploration site 2.

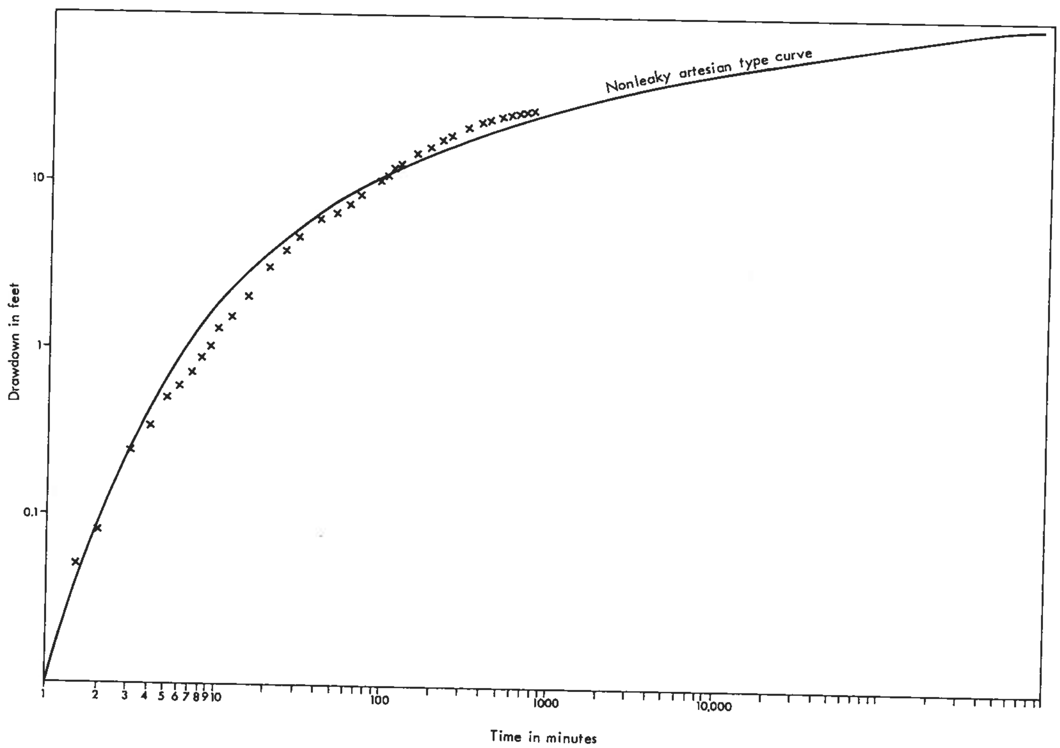

FIGURE F-13. Drawdown curve for observation well 1, exploration site 2.

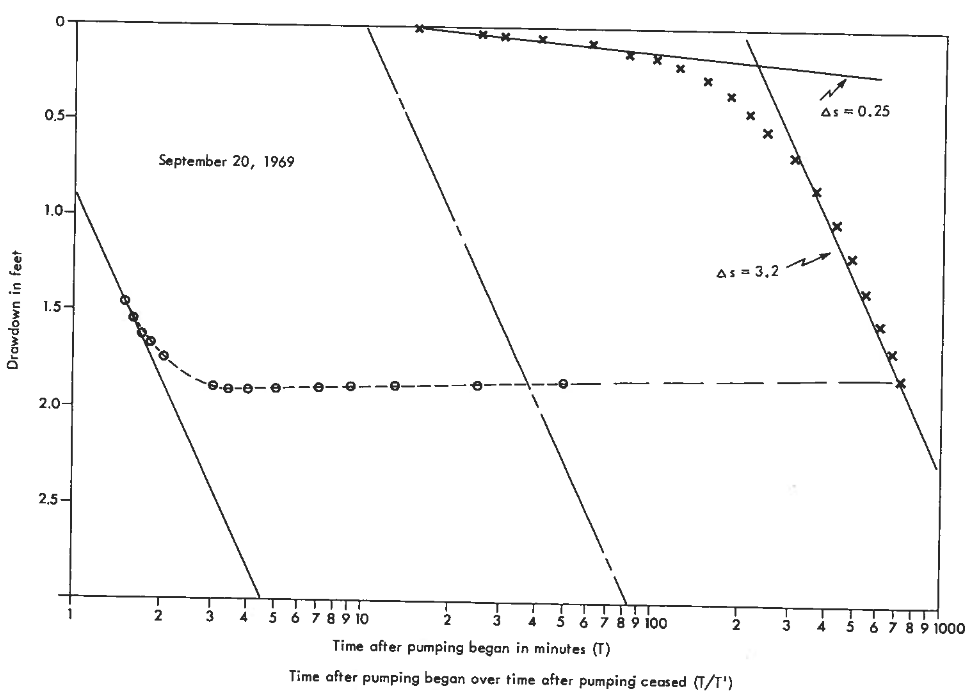

FIGURE F-14. Drawdown and recovery curves for observation well 2, exploration site 2.

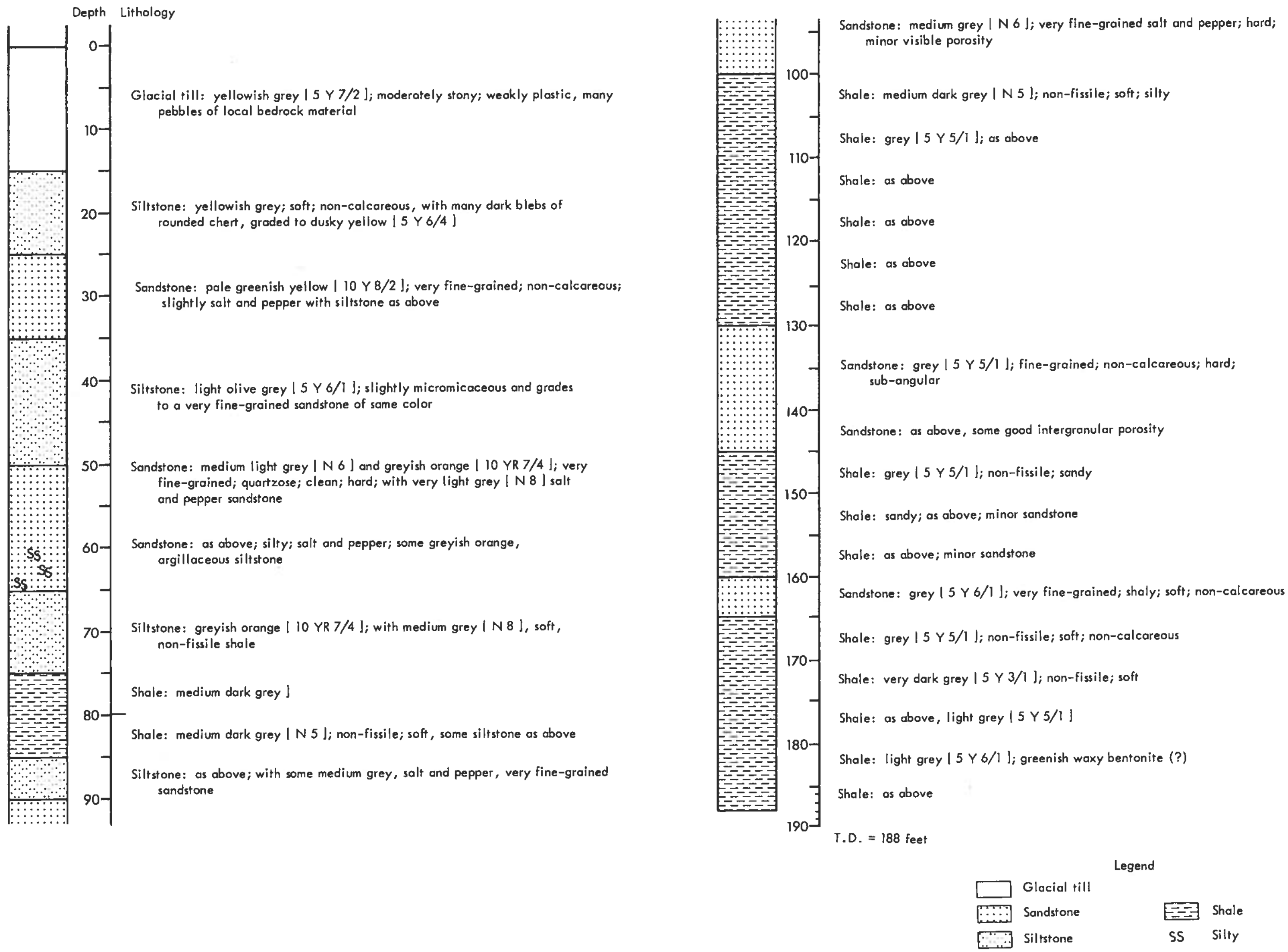

FIGURE F-15. Lithology log of pumped well, exploration site 3.

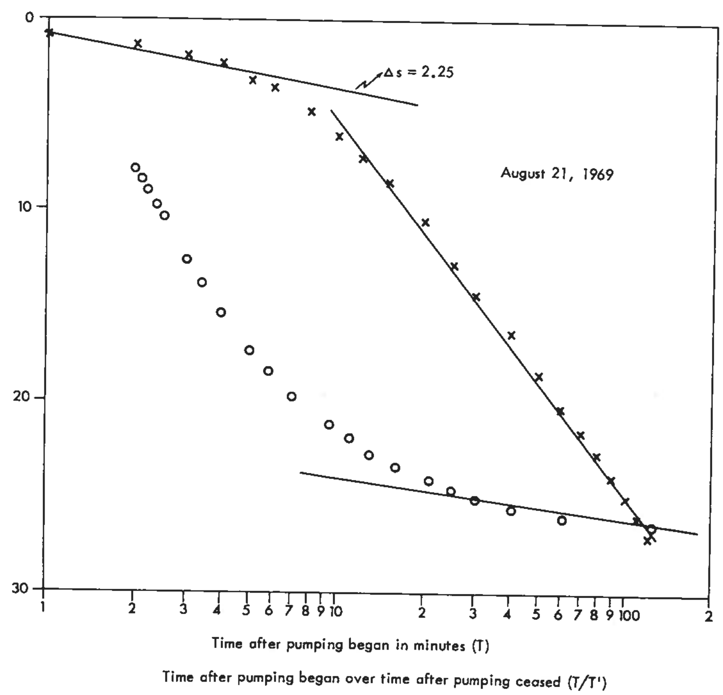

FIGURE F-16. Drawdown and recovery curves for pumped well, pump test 1, exploration site 3.

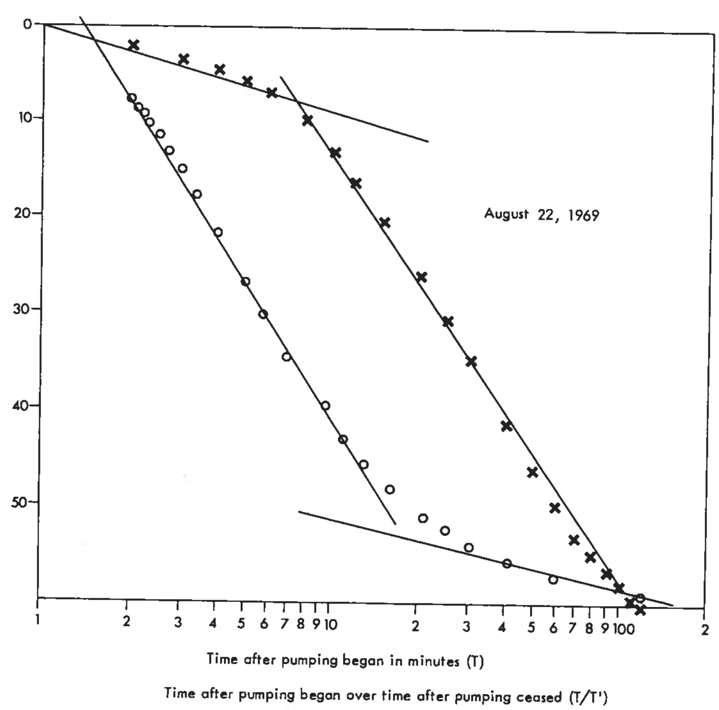

FIGURE F-17. Drawdown and recovery curves for pumped well, pump test 2, exploration site 3.

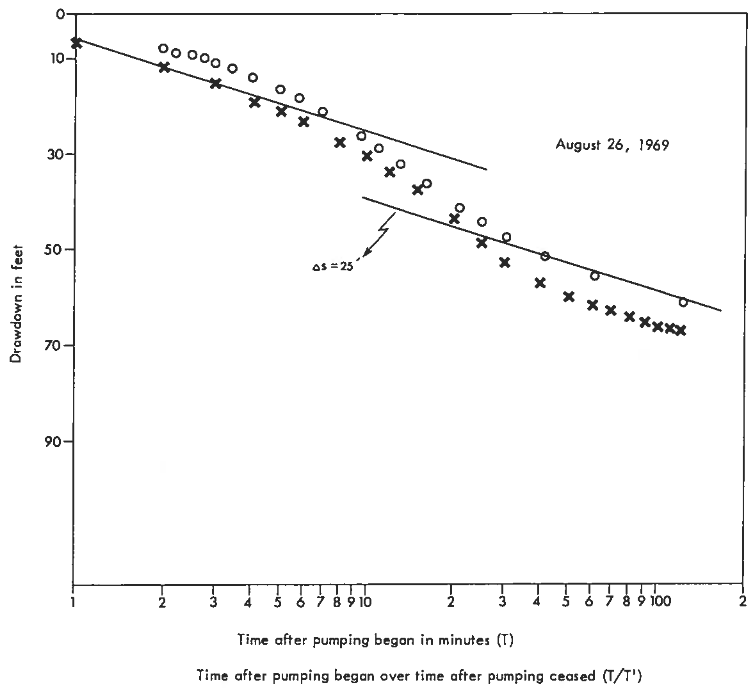

FIGURE F-18. Drawdown and recovery curves for pumped well, pump test 3, exploration site 3.

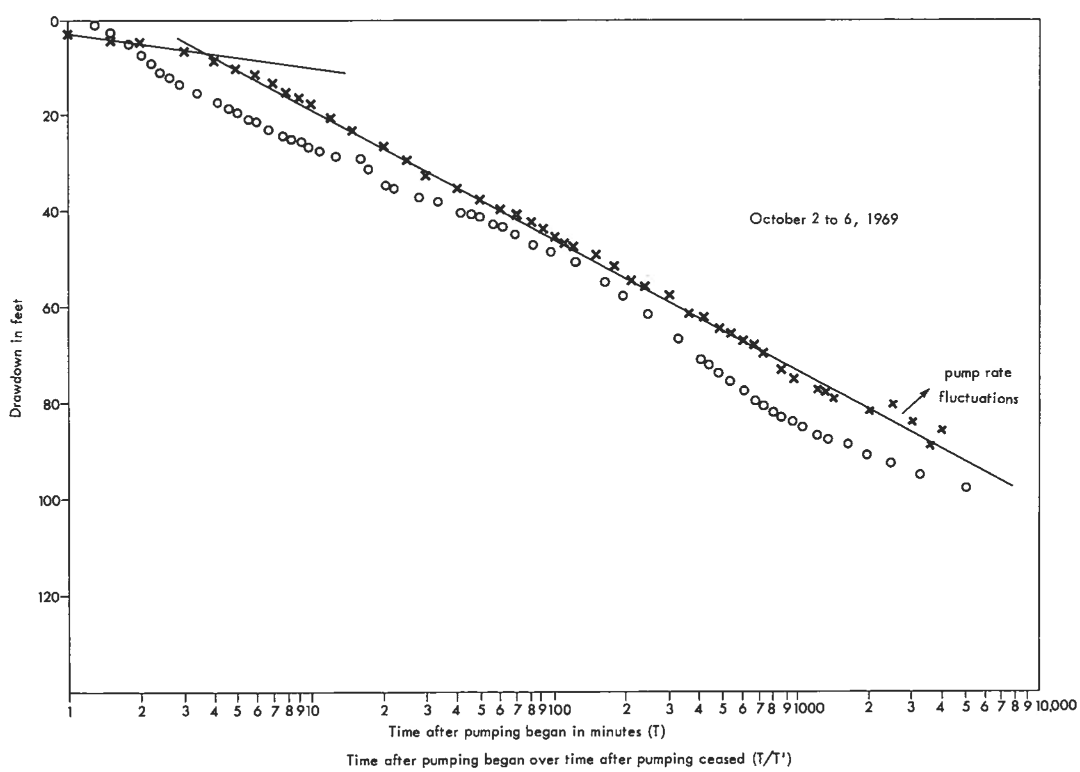

FIGURE F-19. Drawdown and recovery curves for pumped well, pump test 4, exploration site 3.

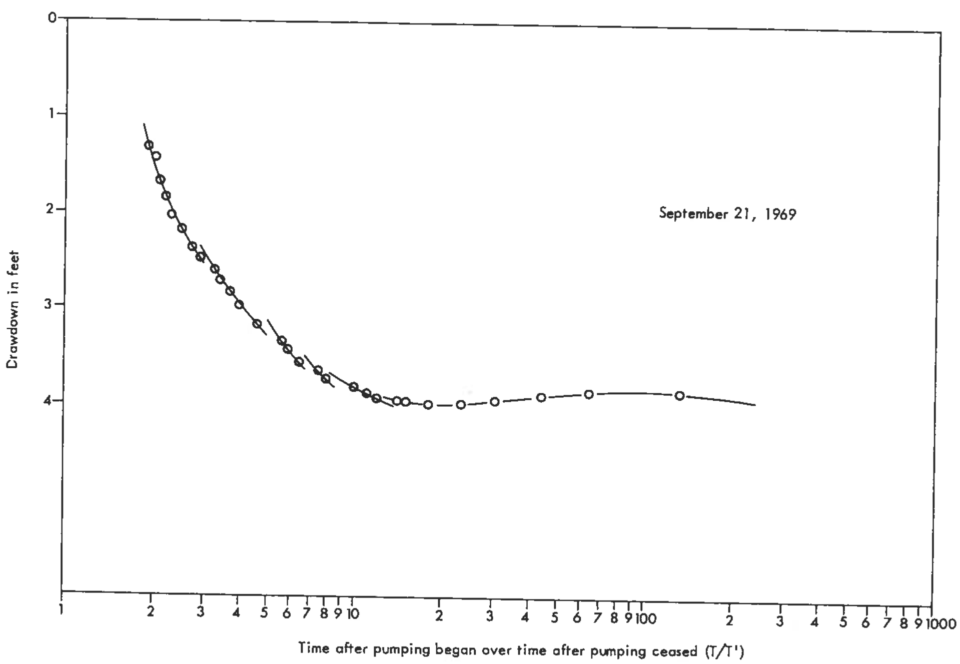

FIGURE F-20. Recovery curve for observation well, exploration site 3.

Table F-2. Results of three 2-hour pump tests, groundwater exploration site 2

	Test 1 Surficial Aquifer	Test 2 Siltstone Aquifer	Test 3 Siltstone Aquifer[1]
Open hole interval (ft)	39 (73-112)	58 (112-170)	82 (113-195)
Transmissibility (igpd/ft)	152-352	85	244
Coefficient of permeability (igpd/ft^2)	4-9	1.5	3
20-year safe pumping rate (igpm)	4-10	4	15

[1]Repeat of test 2, but longer open hole interval.

Table F-3. Summary of data obtained from 12-hour pump test, groundwater exploration site 2

Data	Pumped Well	Observation Wells 1	2	3
Drilling method	cable	rotary	rotary	cable
Depth (ft)	235	240	250	166
Open hole interval (ft)	155	167	190	148
Distance from pumped well (ft)	0	50	200	463
Initial water level (ft)	47.3	49.8	52.4	48.4
Pumping rate (igpm)	6	-	-	-
Total drawdown (ft)	44.3	27.9	1.8	*

Results	Pumped Well + Observation Wells 1 and 2	Observation Well 3
Transmissibility (igpd/ft)	66-264	44-1584
Coefficient of permeability (igpd/ft^2)	0.5-2.0	0.3-12.0
20-year safe pumping rate (igpm)	1-4	1-25

Table F-4. Results of two-hour pump tests on aquifers, groundwater exploration site 3 Jacob method of analysis

	Test 1 (Sandstone and Siltstone Aquifer)	Test 2 (Sandstone Aquifer)	Test 3 (Sandstone Aquifer)
Open hole interval (ft)	72 (18-100)	35 (100-135)	50 (135-185)
Transmissibility (igpd/ft)	26	18	73
Coefficient of permeability (igpd/ft^2)	1.00	0.18	1.50
20-year safe pumping rate (igpm)	1-2	2	9-13

Table F-5. Groundwater exploration summary, site 3 long-duration pump tests

	1		2		3		4	
	Pumped Well	Observation Well	Pumped Well	Observation Well	Pumped Well	Observation Well	Pumped Well	Observation Well
Duration (hrs)	3		21.5		50		80	
Pump rate (igpm)	6		6		6-9		9	
Transmissibility (igpd/ft)	47	2200	74	382	106	365	88	491
Coefficient of permeability (igpd/ft^2)	0.26	3.10	0.41	5.60	0.60	5.20	0.49	7.00
20-year safe pumping rate (igpm)	3	63	5	11	7	11	6	14

*The data were not readily adaptable to any known groundwater flow model. The values on this table, calculated from the Jacob and Theis models, are to be considered as approximations only.