THESIS

THE HYDROGEOLOGY OF THE BEAVER CREEK DRAINAGE BASIN
LARIMER COUNTY, COLORADO

Submitted by

Lawrence Arnold Cerrillo

In partial fulfillment of the requirements

for the Degree of Master of Science

Colorado State University

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WE HEREBY RECOMMEND THAT THE THESIS PREPARED UNDER OUR SUPERVISION

BY LAWRENCE ARNOLD CERRILLO

ENTITLED THE HYDROGEOLOGY OF THE BEAVER CREEK DRAINAGE BASIN LARIMER COUNTY, COLORADO

BE ACCEPTED AS FULFILLING THIS PART OF THE REQUIREMENTS FOR THE DEGREE OF MASTER OF SCIENCE.

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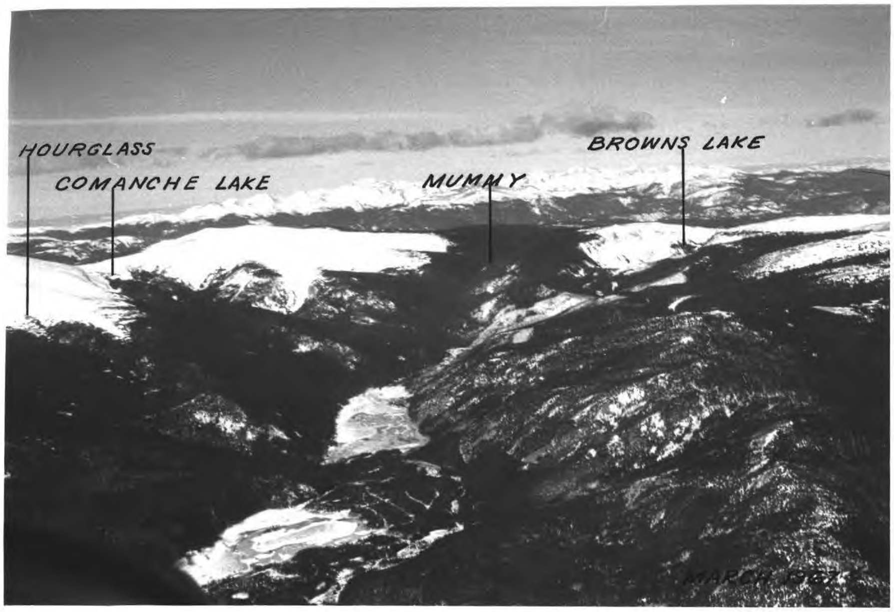

Beaver Creek Basin from Hourglass Reservoir west showing main sub-basins.

PHOTO BY McCALLUM, AUGUST 1964

Comanche Reservoir area looking east. Note Kame terrace remnant at NW edge.

ABSTRACT

Beaver Creek Basin is a glaciated basin of 20.5 square miles located in Larimer County, Colorado. It is comprised of four large sub-basins: Hourglass, Comanche Lake, Mummy, and Browns Lake, and two small sub-basins. Two existing surface reservoirs, Comanche and Hourglass (for which adjudicated water rights are approximately 2,600 and 1,600 acre feet respectively) are located within the basin.

The basement rocks in the basin consist of highly jointed granites, gneisses, and schists, overlain by glacial drift from four advances of Wisconsin glaciation (Bull Lake and Pinedale I, II, and III) and two advances of Recent age (Temple Lake and Gannett Peak). Extensive outwash deposits associated with the drift in the main basin, and especially in the vicinity of the reservoirs, are estimated to be 60 to 110 feet thick. These materials result in high infiltration rates to ground water within the main basin. Surface water losses to ground water in the sub-basins are due primarily to infiltration from small lakes, ponds, and swampy areas retained by moraines of the Pinedale III advance. Infiltration rates in the vicinity of the reservoirs range from 4 inches per hour to more than 23.4 inches per hour. Loss of surface water in this area is a direct result of high infiltration rates as well as indicated high permeability rates. Chemical and bacteriological quality of surface waters in the basin are excellent for domestic and irrigation needs.

The influence of glacial deposits on the hydrology of the basin makes a combined surface-ground water reservoir feasible.

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June 1967

ACKNOWLEDGEMENTS

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INTRODUCTION

Purpose and Scope

The emphasis placed on the most beneficial utilization of water resources has created interest in mountain drainage basins as sources and storage areas for water supply facilities. In view of this interest, the main purpose of this investigation was to determine the general hydrologic character of the Beaver Creek Basin as affected by the geology. As a result of the geologic investigation, a second purpose evolved--namely, to interpret the glacial stratigraphy of the basin.

The study is of additional interest in that two reservoirs, constructed in 1901 by the City of Greeley, Colorado, are located within the basin. The reservoirs were originally retained by terminal moraines. These were subsequently reinforced by earth dams constructed with materials from adjacent glacial and alluvial deposits. Adjudicated water rights for the reservoirs are 2,629 acre feet for Comanche Reservoir and 1,588.6 acre feet for Hourglass Reservoir (fig. 1). Because of high seepage losses through retaining materials, these amounts have never been physically attained.

Although field work extended beyond the basin divides, only the data pertaining specifically to the basin is discussed. The general geology is considered prior to an evaluation of how it affects the hydrology. The amount of time allotted to field work prohibited collection of extensive hydrologic data. However, the measurements acquired, as well as those given by other investigators, aid in the overall hydrogeologic interpretation.

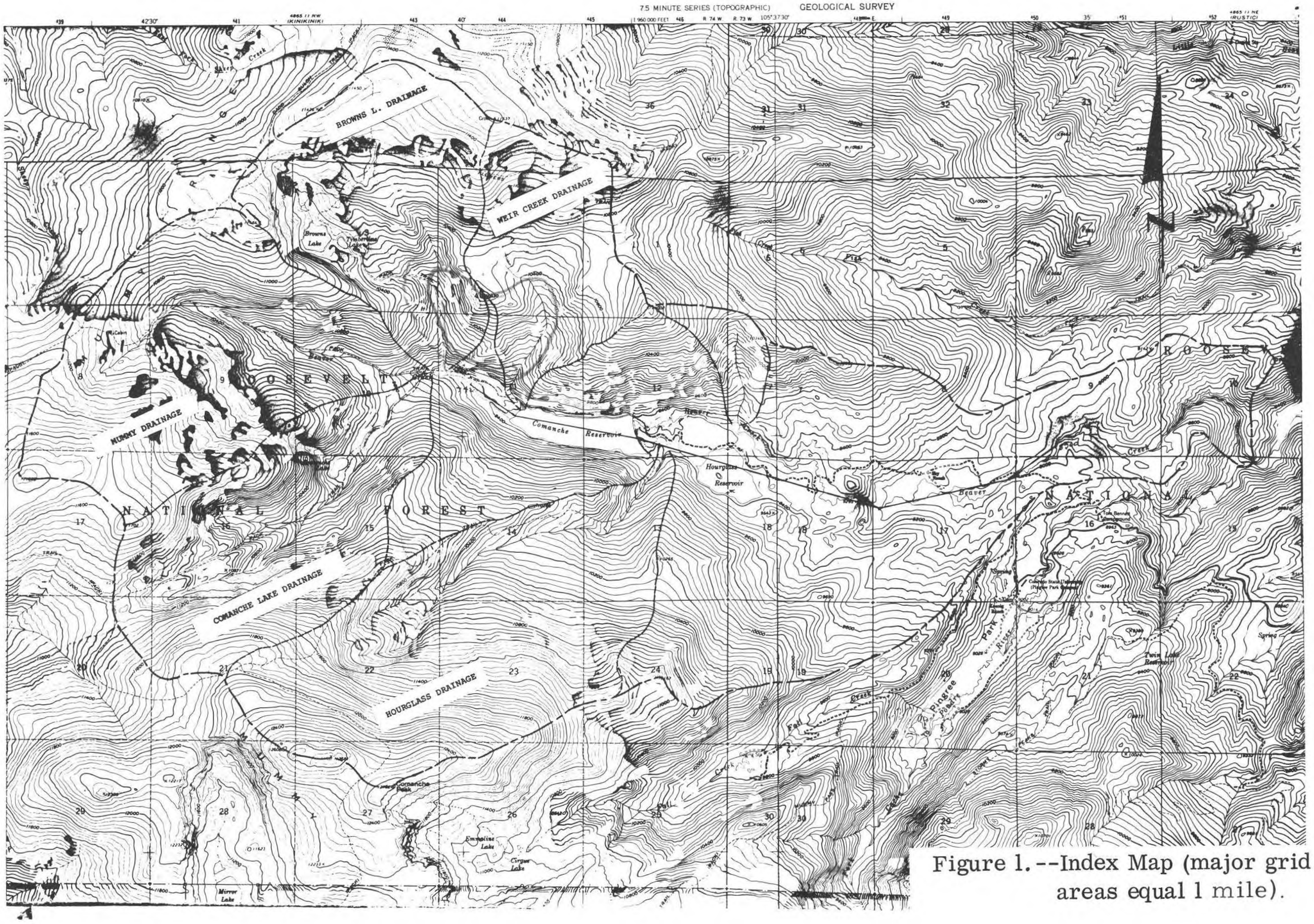


Figure 1.--Index Map (major grid areas equal 1 mile).

Previous Investigations

Within the immediate area, previous investigations include geologic mapping of Precambrian rock and structure (McCallum, 1967, personal communication) and inorganic water quality studies (Mercer, 1966). The Department of Recreation and Watershed Resources (RWR) at Colorado State University has been engaged in studies pertaining to hydrology and forest management supervision. This work has been primarily in adjacent basins, but also includes the Hourglass drainage, a subwatershed of the Beaver Creek Basin. Work by the RWR includes: The effects of glaciation on the hydrologic characteristics (Hansen, 1962), a watershed analysis of the Little South Cache la Poudre River (Johnson, et al, 1963), and a biologic water quality study (Kunkle, 1966).

In other areas of the Front Range of the Rocky Mountains, many investigations have been conducted which deal primarily with glacial stratigraphy. Some of the earlier workers include Blackwelder (1915), Atwood and Atwood (1938), Bryan and Ray (1940), Ray (1940), and Holmes and Moss (1955). Recently, Richmond (1957, 1960, 1965) has conducted extensive investigations of the glacial stratigraphy in the Rocky Mountain Region.

Investigations in progress at the present time include a study relating soil movement to site and environmental factors with the objective of identifying needed ground cover for site stabilization (Johnson, 1967, personal communication), and a study to determine the effects of a forest fire on water quality (Meyer, 1967, personal communication).

Where applicable, data derived from these various investigations are incorporated in this report.

Location and Description of the Area

The Beaver Creek Basin is a sub-basin of the Little South Fork Cache la Poudre River which is a tributary of the Cache la Poudre River. The basin is located in north-central Colorado, Larimer County, approximately 30 miles west of Fort Collins, and 14 miles north of Estes Park (fig. 2). The area is situated in townships 7 and 8 north, and ranges 73 and 74 west (approximate latitude and longitude: 40° 33' to 40° 38' N and 105° 33' to 105° 45' W). The basin is located entirely within Roosevelt National Forest.

The basin has an area of 20.5 square miles and a perimeter of 24 miles. Total length of streams within the basin is 22.5 miles, as measured on U. S. Geological Survey 7-1/2 minute Comanche Peak, and Pingree Park topographic maps, 1962. Other descriptive morphometric parameters for the basin and subwatersheds are tabulated in table 1.

Four major subwatersheds, the Hourglass, Comanche Lake, Mummy, and Browns Lake, contribute runoff to Beaver Creek. A small, unnamed stream located at the northwest edge of Comanche Reservoir has been designated as Weir Creek for purposes of this investigation (fig. 1).

Although most of the land within the basin is federally owned, small tracts in the vicinity of, and including, the reservoirs and Browns Lake, are privately owned. A summer camp consisting of 106 acres in the northwest quarter of section 17, T 7N, R. 73 W, is maintained by members of the Fort Collins Trinity Lutheran Church. Approximately 160 acres of private land between Hourglass and Comanche Reservoirs are subdivided into campsites for future development.

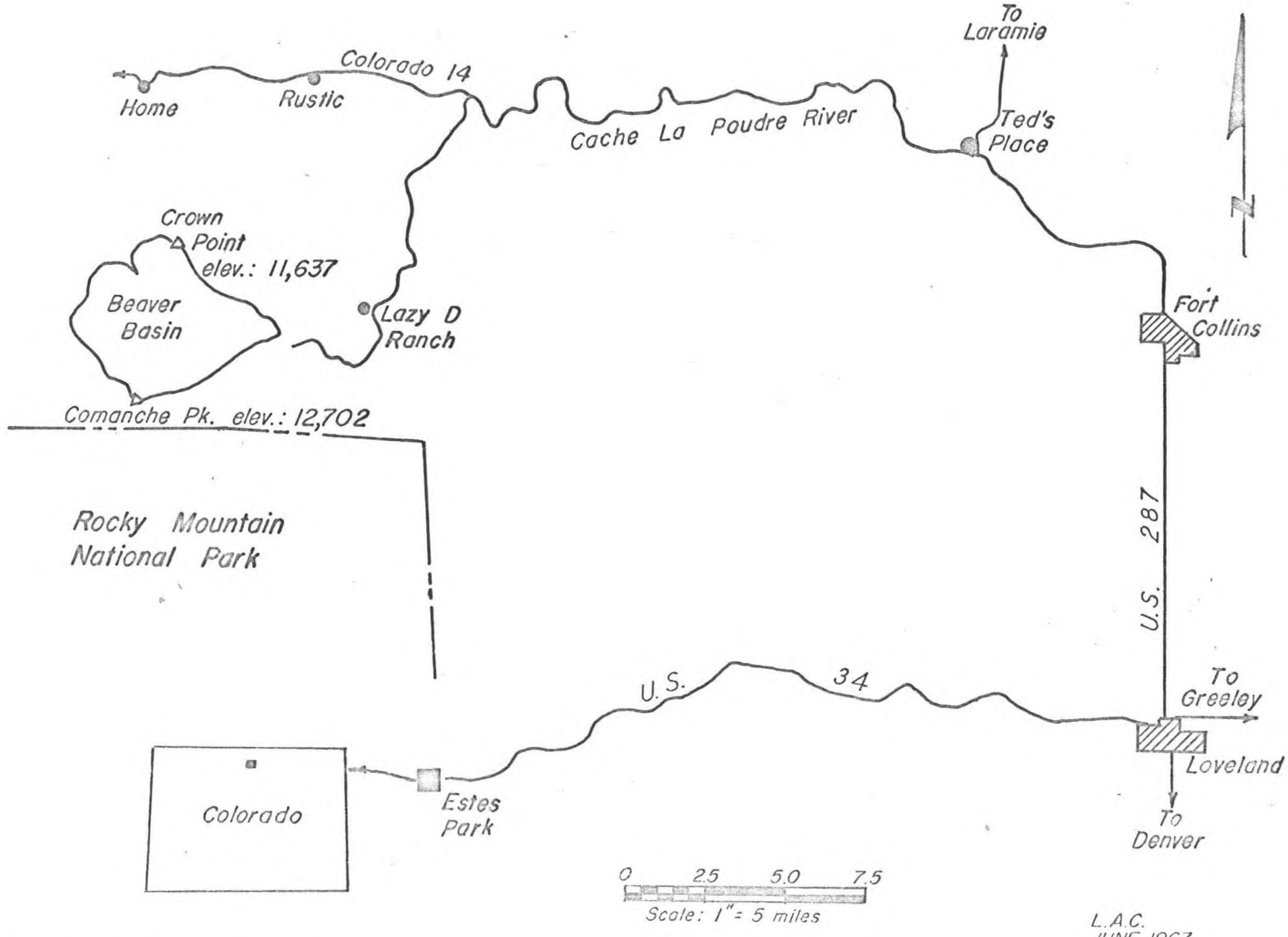


FIGURE 2: LOCATION MAP

Table 1.--Morphometric parameters

Beaver Basin and Subwatersheds	Area sq. mi.	Perimeter mi.	Circularity[1] ratio	Drainage[2] density	Compactness[2] coefficient	Relief ft.	Relief[1] ratio	Total stream length mi.	Main axis length ft.
Beaver Basin	20.5	24.0	0.444	1.10	1.48	3539	0.079	22.5	45,000
Hourglass	3.8	8.6	0.646	0.95	1.24	3302	0.18	3.6	18,000
Comanche L.	2.7	7.7	0.574	1.63	1.31	2102	0.15	4.4	14,500
Mummy	3.4	7.8	0.705	0.82	1.19	2259	0.17	2.8	13,000
Browns L.	2.4	6.4	0.735	1.46	1.15	2037	0.18	3.5	11,500
Weir Creek	1.5	5.3	0.681	0.87	1.21	2237	1.21	1.3	10,500

[1] After Morisawa, 1962.

[2] After Johnson, et al, 1963.

In addition to the uses mentioned above, the basin is a popular outdoor recreational area for hunting, fishing, camping, and hiking. Grazing of sheep in the high alpine meadows during the middle and late summer months is the only known agriculture within the drainage basin.

Climate, Vegetation, and Soil

Most of the precipitation in the Beaver Creek Basin falls as snow between October and April (Johnson, et al, 1963, p. 38). Precipitation at other times of the year is sporadic and occurs as small thunder showers. Climatic data collected by the RWR at the Pingree Park Station to the south of Beaver Creek Basin, and amounts of precipitation recorded by the writer within the Beaver Creek Basin during July and August 1966 are presented in table 2. Although the Pingree station is only about 3 miles from the center of the Beaver Creek Basin and only 1/2 mile from the nearest divide, precipitation amounts must be interpreted with caution because of the orographic influences.

Evaporation values for the basin, as derived from Evaporation Maps for the U. S. for 1946-1955, show an average annual class A pan evaporation of 45-50 inches. Although "...the maps provide the most accurate generalized estimates yet available," the reliability is poorer in these areas of high relief (Kohler, Nordenson, and Baker, 1959, p. 9).

Vegetation in the basin consists mainly of the flora of alpine meadows, spruce fir, lodgepole pine, and scattered growths of aspen.

Soils may be divided into three elevational zones: alpine, above 11,200 feet; sub-alpine, from 11,200 to 9,500; and montane, below 9,500 feet. The first two zones are the most extensive in the Beaver Creek Basin. Soils in the Alpine zone are intrazonal and range in depth from

Table 2.--Climatic data relative to Beaver Creek Basin

Year	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
					Monthly precipitation in inches, Pingree Park Station							
1964	1.04	1.27	1.51	3.86	1.47	1.16	2.47	2.57	1.38	0.11	0.92	2.30
1965	2.75	0.81	2.51	3.95	2.97	3.62	2.08	1.82	2.45	0.65	--	--
1966	0.49	1.15	0.71	2.06	1.37	1.93	2.53	2.82	2.06	0.98	0.25	0.82
					Monthly precipitation, west of Comanche Reservoir							
1966	--	--	--	--	--	--	2.14	2.25	--	--	--	--
					Mean monthly temperature, Pingree Park Station							
1966	12.8	9.7	27.0	28.9	41.4	49.3	56.9	51.3	46.5	36.2	31.0	20.0

14-32 inches (Johnson, et al, 1963, P. 20-26). The sub-alpine soils, almost entirely forested, are characterized by podzols. The podzols are identified by a "dark colored organic mat on the surface two to four inches thick and a leached gray A_2 horizon of about three to five inches" (Johnson, et al, 1963, p. 26). The A_1 horizon is generally absent, except in weakly developed podzols. The montane zone accounts for less than a third of the basin area. Soils in this zone constitute a wide variety and are therefore not discussed further.

Methods of Investigation

Field investigation of the area was conducted from June through August 1966. This work may be divided into two catagories, geologic and hydrologic. The geologic investigation consisted of detailed mapping of glacial deposits, by using aerial photographs and U. S. Geological Survey 7-1/2 minute topographic quadrangles of Comanche Peak and Pingree Park as base maps. The topographic maps were also used as base maps for morphometric calculations. The "blue-line" criterion was used for measuring stream lengths. A Beckman Field pH meter was used for obtaining pH values of soil samples taken from hand-dug holes. Mechanical analyses of selected samples taken from glacial moraines were made in an attempt to differentiate between deposits of the various glacial stades. Heavy minerals were separated and mounted in balsam for petrographic identification, also for the purpose of differentiating glacial deposits. Results of these analyses are inconclusive and, therefore, not included in this report. Seismic work was done with a 12-trace·Model ER 12-75 portable seismograph made by the Electrotech Division of Mandril Industries.

Hydrologic investigations consisted of measurements of streamflow and infiltration rates. A Price current meter was used to measure streamflow at three sections of Beaver Creek. Infiltration values within the reservoir area were obtained by using a double-ring method. This method consisted of two plastic rings, 8 inches and 10 inches in diameter set on undisturbed ground and separated by bentonite clay. A mariotte bottle was used as a water source (plate 1).

Plate 1.--Double-ring infiltration apparatus with mariotte feed bottle.

GENERAL GEOLOGY

Precambrian

Bedrock in the Beaver Creek Basin consists of Precambrian igneous and metamorphic rocks that were uplifted and exposed during the Laramide Orogeny near the end of Cretaceous time. Outcrops are concentrated in the cirque areas, stream bottoms, and valley sides; but occasionally occur protruding through glacial till (plate 2). Igneous rocks consist of fine to coarse-grained, highly jointed granites, quartz monzonites, and pegmatites. In the cirque areas of the Hourglass and Comanche subwatersheds, pegmatitic granites occur as roche moutonnèe.

Strongly foliated quartzofeldspathic and hornblende-biotite gneisses and schists comprise the bulk of the metamorphic rocks. Foliation planes of these rocks are essentially vertical and strike predominately N45°E. Narrow shear zones that trend NE-SW occur in the Hourglass and Comanche subwatersheds. A similar shear zone, trending nearly E-W, occurs in the Browns Lake subwatershed (McCallum, 1967, personal communication).

Pleistocene-Recent

The present height of the Front Range was attained by further uplift and structural adjustment subsequent to the Laramide orogeny. This new uplift initiated a canyon cutting cycle, still in progress, that created topography conducive to glaciation (Fenneman, 1931, p. 105). Three glacial periods: pre-Wisconsin, Wisconsin, and Recent, are recognized in the Rocky Mountain Region. These are represented by three pre-Wisconsin, five Wisconsin, and two Recent glacial stades (table 3). No pre-Wisconsin

Table 3.--Correlation of nomenclature of moraines and glacial events in Beaver Creek Basin with those used in Rocky Mountain National Park, Colorado, and in Wind River Mountains, Wyoming.

<table>
<tr><th></th><th></th><th>Blackwelder (1915)
(Wind R. Mts.)</th><th>Richmond (1960)
(Rocky Mts.)</th><th>Cerrillo (this paper)
(Beaver Crk. Basin)</th></tr>
<tr><td rowspan="2">Recent</td><td rowspan="2">Neoglaciation</td><td>Historic stade
Spanish Valley</td><td>Gannett Peak stade</td><td>Gannett Peak stade</td></tr>
<tr><td>Temple Lake stade
Castle Valley</td><td>Temple Lake stade</td><td>Temple Lake stade</td></tr>
<tr><td rowspan="5">Late Pleistocene</td><td rowspan="3">Pinedale glaciation</td><td>Late Pinedale stade
Pack Creek</td><td>Late stade</td><td>Late stade
(Pinedale III)</td></tr>
<tr><td></td><td>Middle stade</td><td>Middle stade
(Pinedale II)</td></tr>
<tr><td>Early Pinedale stade
Lackey Creek</td><td>Early stade</td><td>Early stade
(Pinedale I)</td></tr>
<tr><td rowspan="2">Bull Lake glaciation</td><td>Late Bull Lake stade
Porcupine Ranch</td><td>Late stade</td><td rowspan="2">Bull Lake stade
(undifferentiated)</td></tr>
<tr><td>Early Bull Lake stade</td><td>Early stade</td></tr>
</table>

deposits are identified per se in the Beaver Creek Basin. However, the weakly developed "cirque" area of the Mummy sub-basin, as opposed to the well developed cirques in the other sub-basins, suggests evidence for a former local icecap. This icecap most likely existed in pre-Wisconsin time. Deposits in this area are not differentiated. A smaller, more restricted ice lobe apparently occupied the basin periodically during Pinedale time. The Wisconsin period is represented by the undifferentiated stades of Bull Lake and stades of Pinedale I, II, and III. Deposits of Recent glaciation include the Temple Lake and Gannett Peak. Criteria used for distinguishing deposits of the various glacial stades are essentially those used for correlation by Richmond (1960, 1965) in his study of similar deposits in other parts of the Rocky Mountain Region.

Bull Lake Glaciation (Undifferentiated)

Bull Lake deposits are identified on the basis of the following criteria: topographic position, i.e., the terminal moraines are farther advanced, and the lateral moraines are at a higher elevation than younger glacial deposits; relatively smooth surface topography; deeply weathered soil zones; scattered, strongly weathered boulders; and the absence of water filled kettle holes. In addition, materials of Bull Lake age tend to be more compact and contain more silt and clay than the deposits of younger glaciations. Terminal and lateral moraines of Bull Lake age occur in the Beaver Basin at the northern portion of section 16 (plate 2). These moraines resulted from an advance of Bull Lake ice in the Little South Fork Cache la Poudre Basin that cut across the Beaver Creek Basin. Bull Lake deposits elsewhere in the study area are not as clearly defined. However, deposits believed to be of Bull Lake age are located high on the valley sides of the main and sub-basin drainages. These deposits are a result of glaciation within the Beaver Creek Basin.

Pinedale Glaciation

Deposits of Pinedale age are the most extensive in the basin. Three stades and one recessional are recognized. The early and middle stades, Pinedale I and II, are located close together; deposits of the late stade are located farther upstream in each of the sub-basins. The main criteria for recognizing deposits of Pinedale age are: topographic position, i.e., they occur upstream from Bull Lake deposits; hummocky, irregular topography; abundance of slightly weathered boulders; water filled kettle holes; and thinner, less well developed soil horizons. Additional criteria, perhaps peculiar to the Beaver Creek Basin, are the occurrence of composite moraines of Pinedale III stade.

A Pinedale I terminal moraine is located in the main Beaver drainage at an elevation between 9,200 and 9,400 feet. At this point, it both overlies and partially penetrates earlier Bull Lake deposits. This same condition appears to occur at the mouth of the Browns Lake sub-basin. Lateral moraines of the Pinedale I advance are recognized on valley sides up to 10,200 feet. These deposits are characterized by huge boulders surrounded by and intermingled with loose sand and gravel.

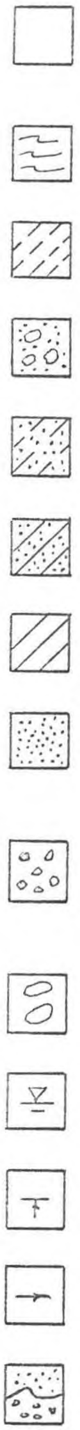
A Pinedale I recessional terminus occurs approximately 1/2 mile upstream from the Pinedale I terminal moraine. The topographic characteristics and the nature of materials are similar to those of Pinedale I.

Although poorly preserved, deposits of a Pinedale II advance are located in the vicinity of Comanche Reservoir Dam. A terminal moraine of this advance is also found in the Browns Lake sub-basin. Ground and lateral moraines of this stade occur in the Comanche Lake and Hourglass sub-basins. The composition of the Pinedale II deposits is coarser, but otherwise similar to deposits of Pinedale I.

Composite Pinedale III terminal moraines are located in all the sub-basins at an elevation of approximately 10,000 feet, with the exception of the Browns Lake Drainage. In this sub-basin Pinedale III occurs above the 10,400 foot elevation as a single terminus. Small lakes, ponds, or swampy areas are retained behind these deposits in all the subwatersheds. Materials of the Pinedale III advance are considerably coarser and the front slopes considerably steeper than earlier Pinedale deposits.

Thick deposits of outwash are associated with glacial deposits of the Wisconsin period. Morainal deposits of Bull Lake age in the north-east corner of section 17, T. 7 N., R. 73 W. appear to have initially dammed Beaver Creek (plate 2). Materials from upstream glacial deposits thus accumulated to thicknesses estimated to be 60 to 110 feet. Outwash retained by each of the successively younger Pinedale moraines is also quite extensive. The nature of these materials in the vicinity of the reservoirs can be seen in figures 3 and 4. Outwash from Pinedale II deposits occur interfingered with finely laminated silts and sands in the vicinity of Hourglass Reservoir (plate 3 and fig. 5). Seismic refraction records indicate these deposits are about 110 feet thick (fig. 6). The silts and sands of lacustrine origin were deposited in the kettle hole now occupied by Hourglass Reservoir.

Deposits of a similar nature may occur in Comanche Reservoir, however, none were exposed. A peat-clay layer, which was encountered during repair of the dam, suggests that a lake was present in this area sometime during Pinedale stades (fig. 6). In the northwest portion of



Fill (embankment materials), sand, loose to medium dense gravelly, slightly silty, moist, red brown or gravel, loose, sandy, silty, moist, red brown (SP or GP).

Sand, loose, clayey organic, wood chunks, moist brown, (topsoil) (SC).

Clay, still, sandy, silty, no gravel to gravelly, red, tan, gray, red brown (CC).

Sand, loose to dense, slightly gravelly to gravelly, clean to slightly clayey, tan, red brown, brown (SP, SP-GP).

Sand, loose, clayey, gravelly, moist, red brown, brown (SC).

Sand, loose, silty, slightly clayey, brown (SM).

Silt, medium dense, sandy to slightly sandy, slightly clayey, moist, brown, dark brown (ML).

Sand, loose to medium dense, slightly silty to silty or interlayered with sandy silt lenses, moist, brown to gray (SP, SP-SM).

Gravel, very dense, sandy, silty to clean, cobbly to scattered cobble with occasional boulders, moist red-brown, yellow-brown, brown (CP).

Boulders, in a sand and gravel matrix.

Free water level.

Indicates practical rig refusal.

Indicates depth at which hole caved.

Gradual change in materials. Exact strata changes not located.

Figure 3.--Legend for figure 4.

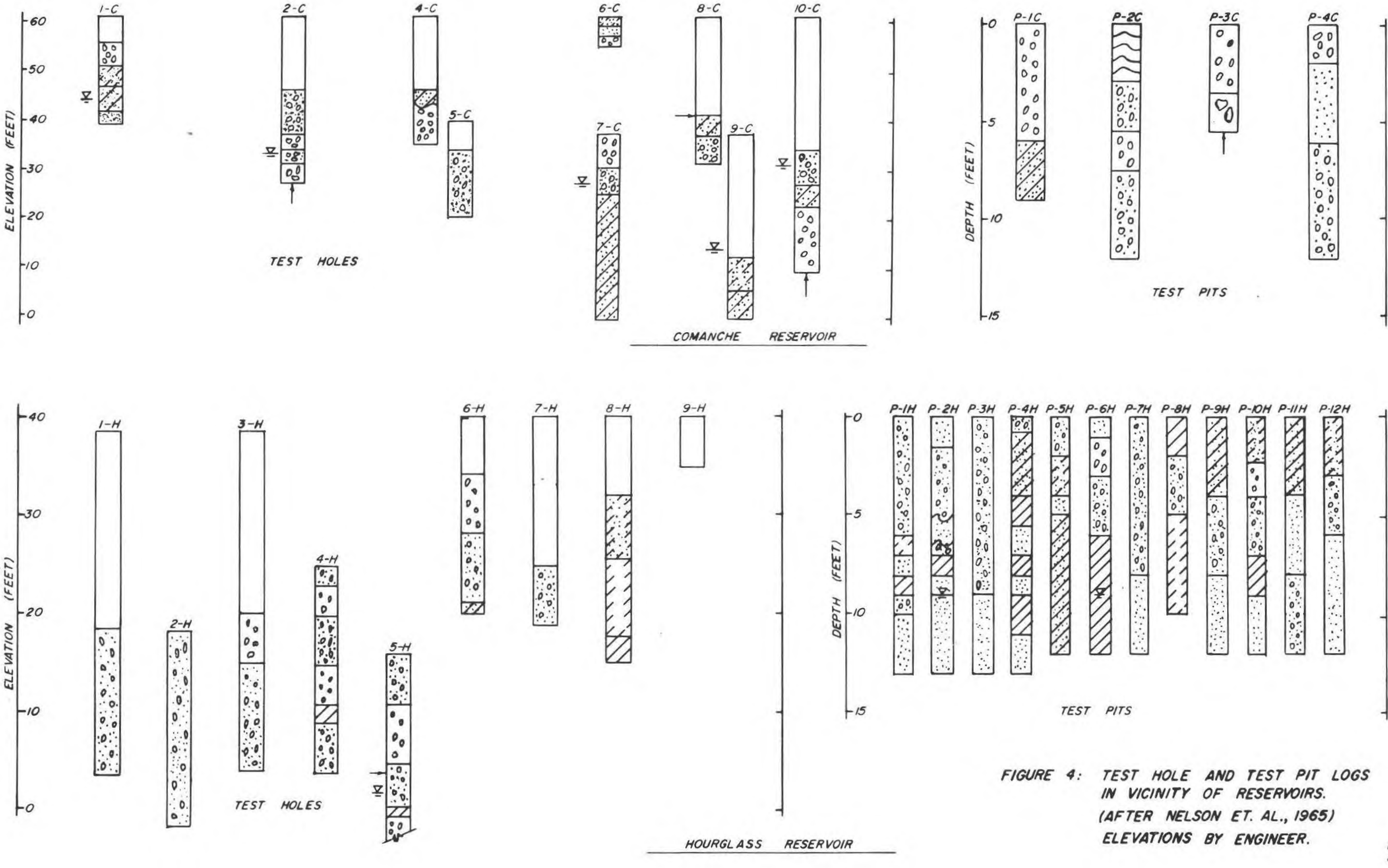


FIGURE 4: TEST HOLE AND TEST PIT LOGS IN VICINITY OF RESERVOIRS. (AFTER NELSON ET. AL., 1965) ELEVATIONS BY ENGINEER.

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JUNE, 1967

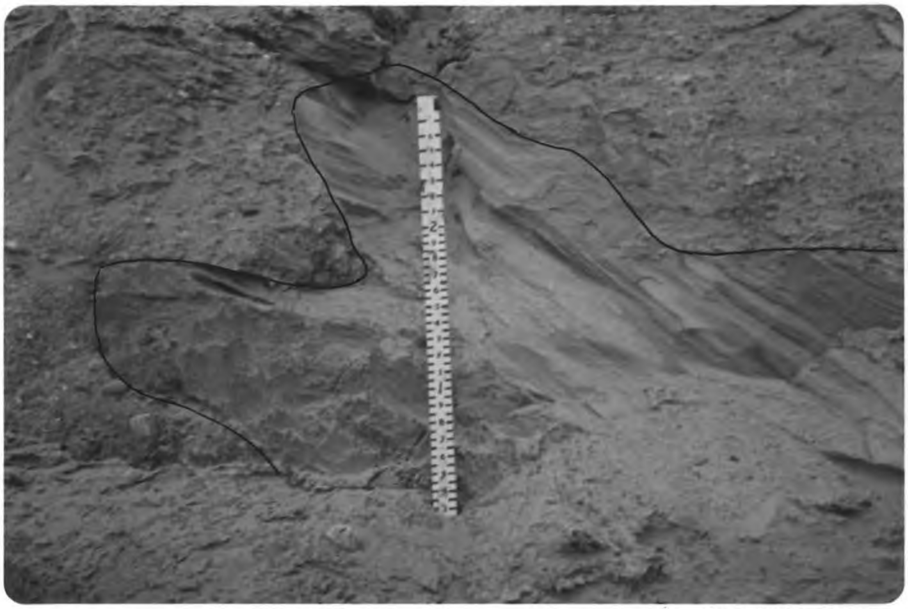

Plate 3.--Lacustrine and glacio-fluvial materials located at south side of Hourglass Reservoir Outlet. Photo taken during repair of outlet facilities.

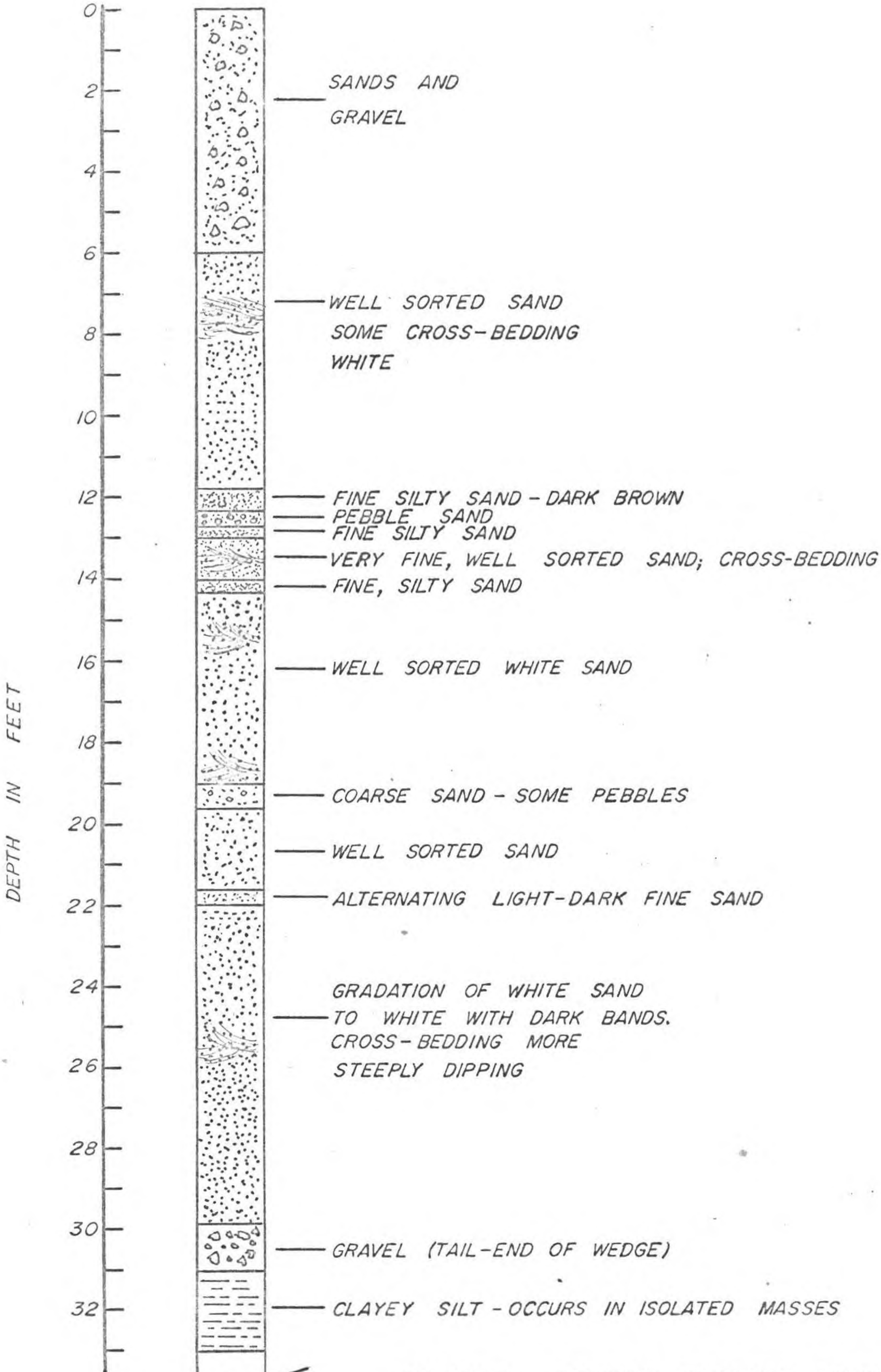

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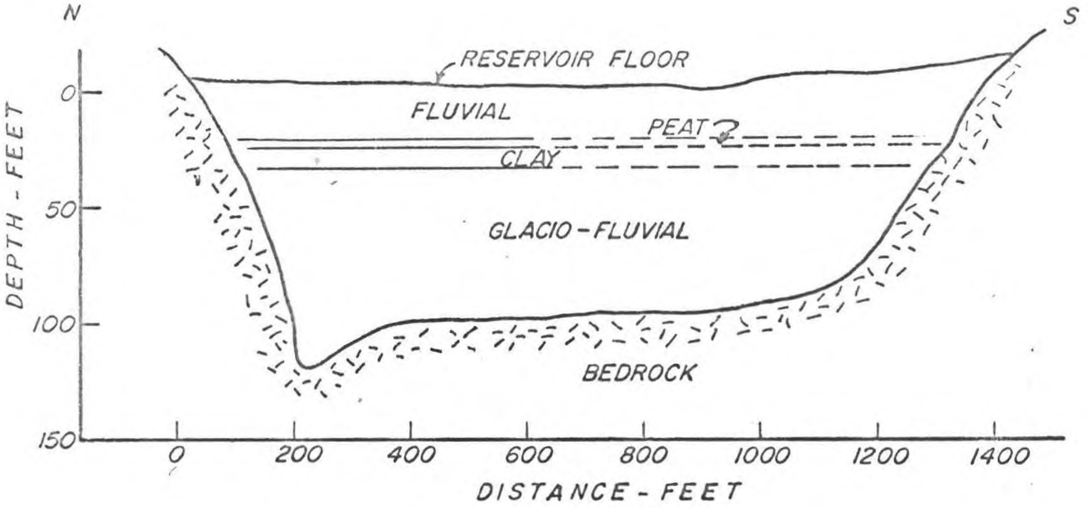
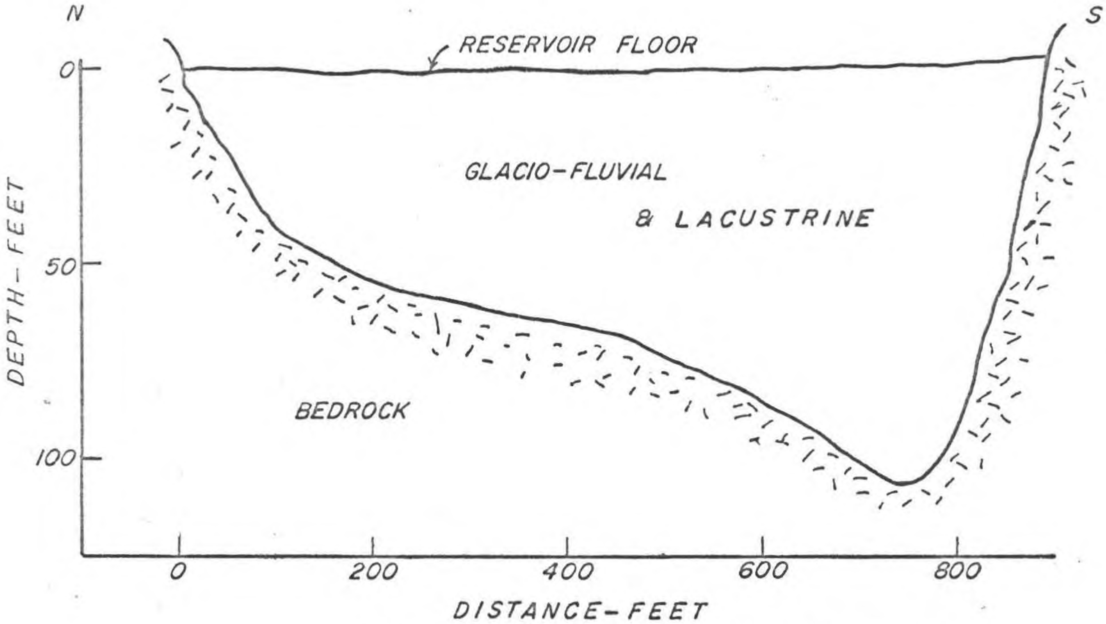
FIGURE 5: SECTION THROUGH SOUTH SIDE OF HOURGLASS OUTLET.



PROFILES 2 AND 3, COMANCHE RESERVOIR



PROFILES 1 AND 2, HOURGLASS RESERVOIR

L.A.C.
JUNE, 1967.

FIGURE 6: CROSS SECTIONS FROM SEISMIC PROFILES

Comanche Reservoir a kame terrace remnant occurs. This is indicative of an active fluvial environment during the stagnation of the Pinedale II glacier. Concurrent or later fluvial activity could thus account for the limited lacustrine deposits found in this area.

Neoglaciation

Glaciation of Recent age has been recognized only in the Hourglass subwatershed (McCallum, 1967, personal communication). Deposits of two stadal advances, Temple Lake and Gannett Peak, were identified. The oldest moraine, Temple Lake, occurs between the 10,600 and 10,800 foot elevations. It is identified by the fresh, angular boulder material, sparse vegetation, highly irregular surface, and very thin azonal soil development.

The Gannett Peak moraine is located near the cirque head at approximately 10,800 feet. Extremely fresh, large, angular boulders, and absence of soil or vegetation characterize the Gannett Peak moraine (plate 4).

Other materials of probable Recent age include scree, boulder deposits, and colluvium. These materials grade imperceptibly into one another with scree mantling the slopes above timberline, boulder deposits extending from the scree into the forest cover, and colluvium on the lower slopes. The boulder deposits are not to be confused with those of probable Pinedale age shown on plate 2.

Plate 4.--Gannett Peak terminal Moraine in the cirque area of Hourglass drainage.

HYDROGEOLOGY

General Statement

Mountain building, structural adjustment, canyon cutting, and glaciation all contributed to the existing physiography and thus to the hydrologic regimen of the basin. Other environmental factors affected by geology, such as precipitation, vegetation, and soil development, also have an affect on hydrology. The purpose of this section, therefore, is to describe the relationship between geology and hydrology, that is, the hydrogeology.

The Front Range mass has an orographic effect that creates increased precipitation at the higher elevations. The cirques provide storage areas for the accumulation of this precipitation, particularly in the form of snow. A direct result of geology and vegetation is the frequency of summer thunderstorms which result from unequal heating in the area. Vegetation also prevents rapid ablation and runoff of snowmelt. Because of the relatively steep slopes and fresh rock materials, the soils tend to be immature and coarse. Infiltration rates are, therefore, believed to be fairly high. In addition to their effect on soil development, the geologic materials have several direct effects on the hydrology. Areas of Precambrian outcrops have distinctly different hydrologic properties than the areas covered with glacial materials.

Metamorphic and Igneous Areas

Metamorphic and igneous rocks generally occur in one of two conditions. They are either dense and cause precipitation to run off; or they contain sufficient fracturing and jointing to allow infiltration and channeling of precipitation. The latter condition tends to be more prevalent in the Beaver Creek Basin. Davis and DeWiest (1966, p. 319) point out that "Solid pieces of fresh metamorphic and plutonic igneous rocks have porosities of less than 3 percent and most commonly less than 1 percent....". In a comparison of laboratory versus field measurements, however, field materials "...were found to be more than one thousand times as permeable..." (Davis and DeWiest, 1966, p. 319). Feth (1964) discusses subsurface percolation of water from basin-margin mountains directly into aquifers of valley basins. He described areas in Utah, California, and Nevada, among others, where basin recharge from consolidated rock aquifers and associated scree and talus, is sufficient to account for discharges in excess of estimated recharge volumes.

In light of the foregoing studies, and the fact that the igneous and metamorphic rocks in the Beaver Creek Basin are highly jointed and fractured, it is possible for similar conditions to exist in this basin. A tenuous estimate of the storage capacity in the bedrock of the main basin, from the Pinedale I terminus to the west end of Comanche Reservoir, was made. Assuming an average fractured depth of 150 feet, and an average porosity of 0.5 percent, approximately 50 acre feet of water could be stored in the area.

Streamflow measurements were taken at gaging sections 1 and 2 (fig. 7 and table 4) in an attempt to detect losses of flow across an area of predominantly metamorphic rock. The stream crosses approximately 4,000 feet of outwash material between sections 1 and 2. Any losses between these sections were not detectable. It may be that no losses do occur, or that ground water inflow from nearby glacial materials

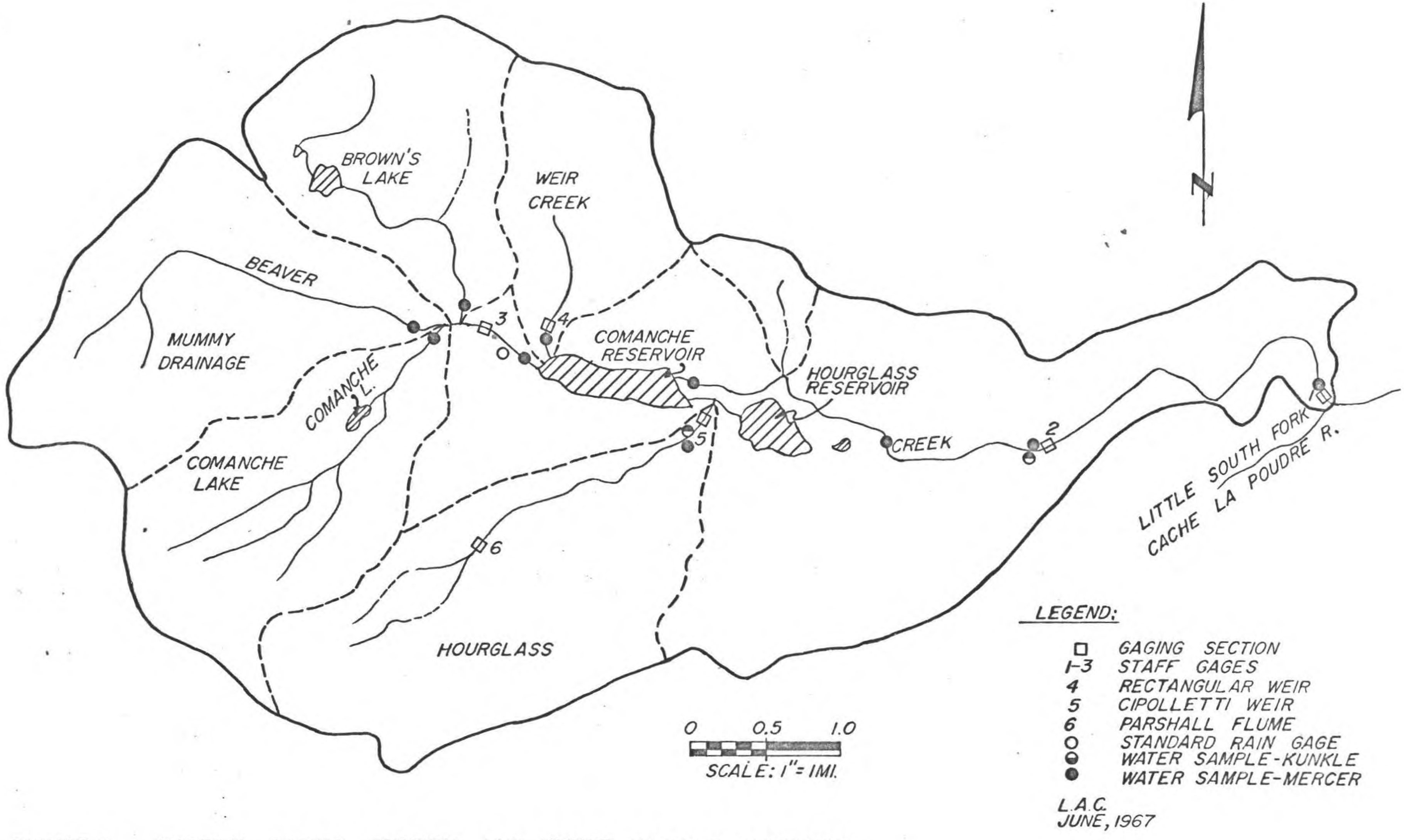


FIGURE 7: STREAM GAGING SECTION AND WATER SAMPLE LOCATIONS

Table 4.--Average monthly runoff in Beaver Creek Basin for July and August 1966 in cubic feet per second indicating losses in downstream direction

	Section 1	Section 2	Totals of Sections 3, 4, & 5	Section 5	Section 6
July	24.22	24.39	41.77	24.19	30.73
August	16.75	9.21	29.49	18.47	21.10

compensate for the losses. Similar conditions are probable in the sub-basins.

Glacial Deposit Areas

The hydrogeologic properties of glacial materials are often found to be highly variable from one locality to another, and often within any one locality. The variabilities are a direct result of the heterogeneity of glacial materials. Differences from one sub-basin to another in the Beaver Creek Basin, however, are negligible, and hydrogeologic comparisons can be made. Geologic similarity of the four main sub-basins is substantiated by the morphometric parameters in table 1.

Comparison of streamflow measurements between sections 5 and 6 in the Hourglass sub-basin indicate net losses of flow volume up to 21 percent (fig. 7 and table 4). On the basis of geologic uniformity, this value might well be characteristic of the Comanche Lake, Mummy, and Browns Lake sub-basins. In that the lakes, ponds, or swampy areas retained by the Pinedlae III moraines intercept part of the runoff, they are believed to be responsible for a portion of these losses. Browns Lake has a maximum depth of 40-45 feet and Timberline Lake has a maximum depth of 12 feet (Game, Fish and Parks Dept., State of Colorado., personal communication). Assuming an average depth of 30 feet for Browns Lake, it is capable of retaining 540 acre feet of water. No values were computed for Timberline Lake because it is controlled by a beaver dam. An assumed average depth of 10 feet for Comanche Lake would allow approximately 75 acre feet of water to be retained. Comanche Lake, as opposed to Browns Lake, has no influent streams. However, since it has an effluent stream, it is believed to be fed in part by ground water.

Comparison of combined streamflow at sections 3, 4, and 5 with section 2 for the two months of record, indicates an approximate loss of flow of 53 percent through the main axis of the basin. These measurements were taken during a period when Comanche Reservoir was essentially drained (plate 5). Even under these conditions, however, the reservoir is still believed to account for a large portion of the measured loss. The topographic character and distribution of outwash materials trending NW-SE across the Pinedale I moraines, provide evidence to suggest the existence of a former meltwater channel. This channel may be entrenched in the bedrock, and perhaps extends across the Beaver Creek Basin into the Little South Cache la Poudre Basin. If such a channel exists, it may intercept a portion of the flow that would normally reach gaging section 2.

Infiltration measurements were taken at ten accessible sites on the floor of Comanche Reservoir (figs. 8 and 9). Measurements taken at locations 1 and 3 had to be discounted because of a high water table. At location 5, infiltration rates exceeded the capacity of the double-ring infiltration apparatus used (>23.4 inches per hour). Recorded values ranged from 6 inches per hour to 18 inches per hour. Infiltration rates recorded in the vicinity of Hourglass Reservoir were also beyond the capacity of the instrument used. These high infiltration rates would seem to indicate that relatively large losses in these areas are possible over a short period of time.

The extensive outwash material associated with each of the terminal moraines, previously described, is ideal for ground water storage. The constriction of the valley at the line between section 17 and 18 partially

Plate 5.--Photograph of Comanche Reservoir when drained. View is to the southeast.

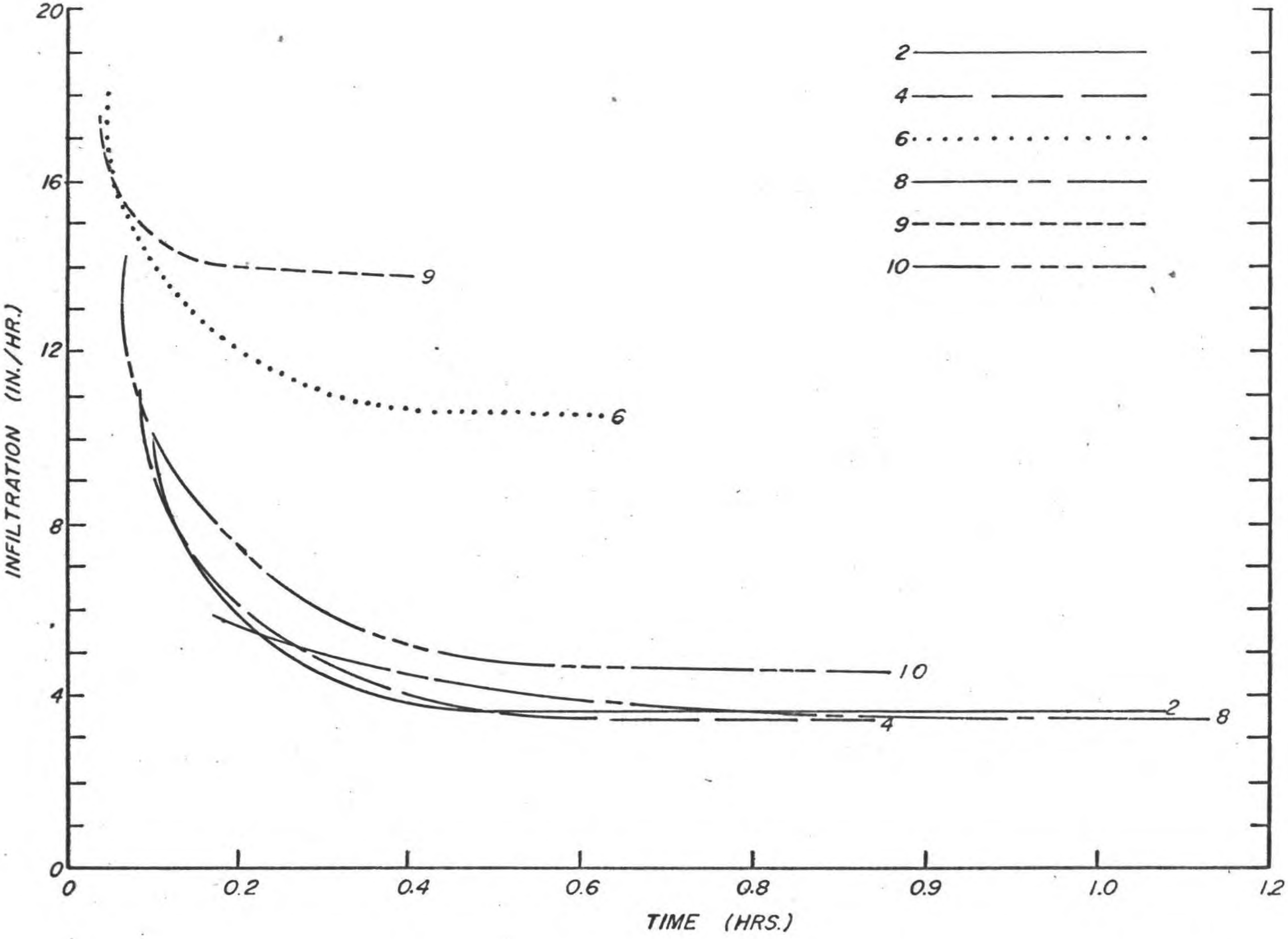


FIGURE 8: INFILTRATION RATES WITHIN COMANCHE RESERVOIR.

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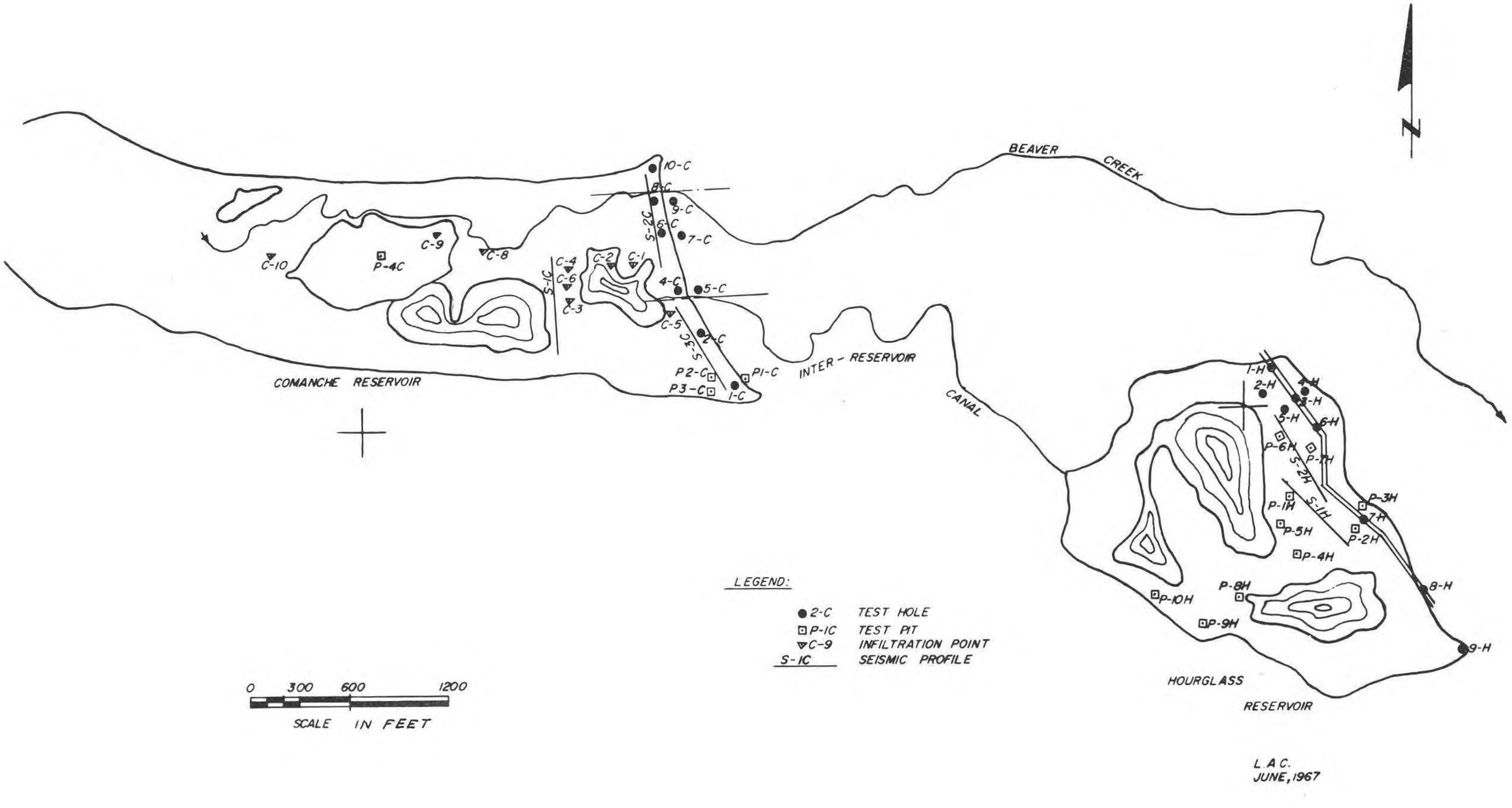

FIGURE 9: TEST HOLE, SEISMIC AND INFILTRATION LOCATION MAP.

dams the ground water and further enhances the storage possibilities (see fig. 1). If the bedrock extends beneath the Pinedale I terminus, perpendicular to this constriction, approximately 8,820 acre feet of water could be stored in this ground water reservoir (fig. 10). This volume does not include Comanche Reservoir, but does include the area of Hourglass Reservoir. An average depth of 80 feet and a porosity of 30 percent were assumed in the storage volume calculations. Porosities of most glacial materials "...should fall in the range of 25 to 45 percent." (Davis and DeWiest, 1966, p. 409).

Water Quality

Inorganic water quality studies of surface streams were conducted by Mercer (1966) for the entire Little South Cache la Poudre Drainage System. Included in this study are values for the Beaver Creek Basin (fig. 7 and table 5). Samples collected by the writer at the same locations showed no significant differences for the constituents tested.

Mercer discusses two water quality anomalies of Beaver Creek Basin as compared to other subwatersheds of the Little South Cache la Poudre. One of these anomalies was a high silica content for which two possible explanations were described: (1) increased solubility due to warmer temperatures and (2) increased ground water contribution to streamflow (Mercer, 1966, p. 18). Mercer indicated increased water temperatures were the main factor. Water temperature and pH values were taken by the writer at stream gaging sections during the months of July and August. Water temperatures ranged from 7 to 9° C upstream from Comanche Reservoir, and 12 to 14° C downstream from the reservoir. These values are based on

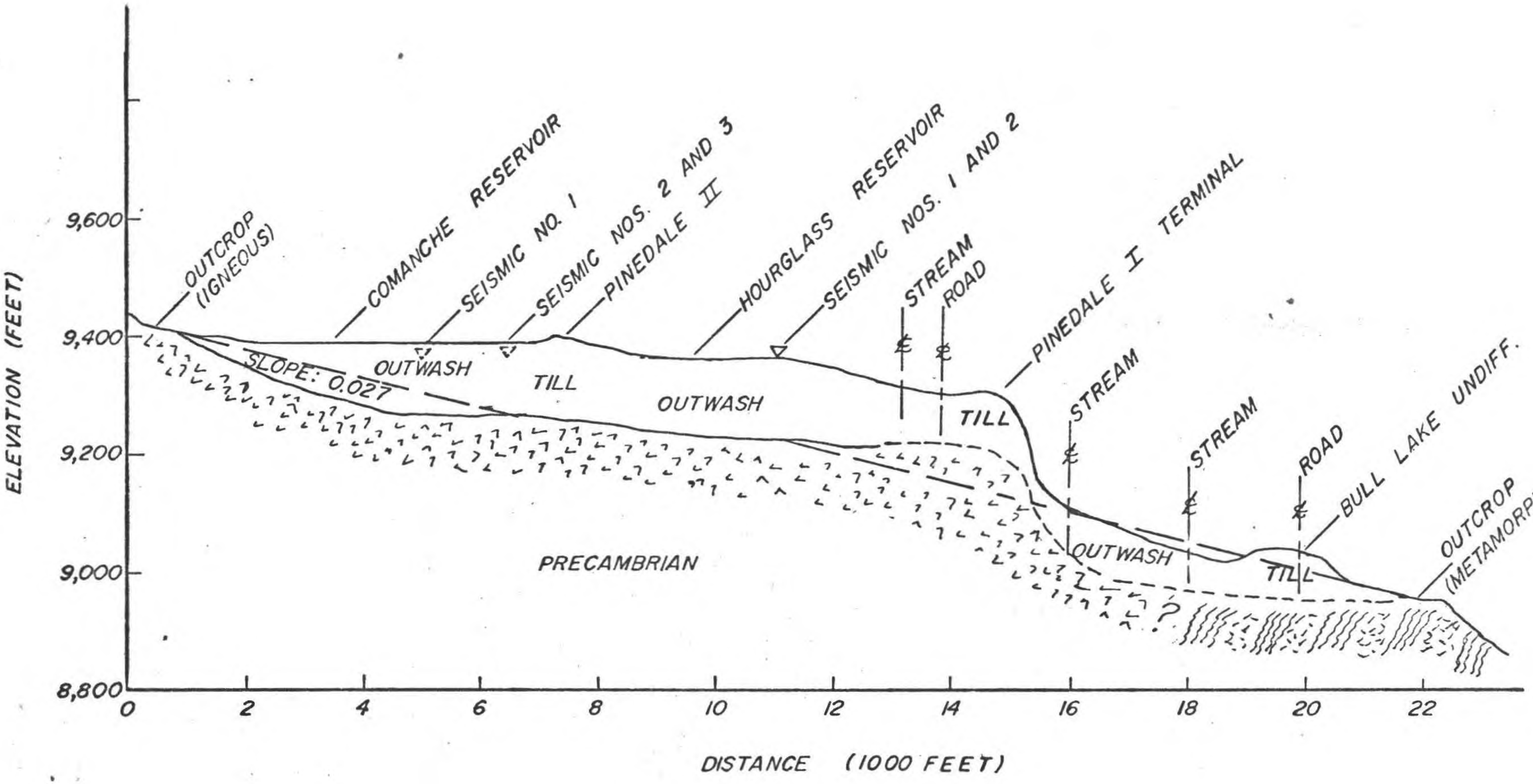

FIGURE 10: SECTION ALONG AXIS OF MAIN BASIN (SEE FIG. 1 FOR LOCATION)

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Table 5.--Concentrations of principal mineral constituents in Beaver Creek Waters.[1]

Constituents	*Concentrations, ppm July-August, 1965 Max.	Mean	Min.	**Concentrations, ppm December, 1965 Max.	Mean	Min.
Silica	27.4	20.8	14.0	18.6	17.6	16.6
Calcium	7.0	4.8	2.0	8.0	6.8	5.0
Magnesium	6.0	3.4	0.0	8.0	4.0	1.0
Sodium	1.9	0.9	0.5	1.2	1.1	1.0
Potassium	1.3	0.6	0.4	0.8	0.7	0.5
Bicarbonate	19.0	14.8	11.0	20.0	16.8	10.0
Sulfate	5.0	2.9	1.0	5.0	3.6	2.0
Chloride	3.0	2.4	1.5	3.5	3.0	2.5
Nitrate	0.2	0.1	Tr	0.1	0.1	0.0
Iron	0.3	0.1	0.1	0.4	0.2	0.1
TDS	56.0	44.0	30.0	51.0	47.0	41.0

[1] From Mercer, 1966, p. 18.
* Based on eight observations.
** Based on four observations.

18 readings taken between 8 a.m. and 5 p.m. This difference in temperature remains constant to the confluence of the Beaver Creek and Little South Fork. Field pH values ranged from 7.7 to 7.9 for all samples except those from Mummy and Hourglass drainages which were 7.4.

The water temperature values would seem to indicate that no ground water inflow to Beaver Creek occurs between Comanche Reservoir and the confluence of the Little South Fork. The relatively constant pH values indicate that acidity has little or no effect on silica solubility rates in this area. Thus, Mercer's conclusion is substantiated.

The second water quality anomaly found in the Beaver Creek Basin was a high concentration of iron immediately downstream from the Comanche Reservoir outlet. Mercer attributed this intensive concentration to iron-fixing bacteria in the Beaver Creek Basin.

Of additional interest in regard to water quality are the bacteriological studies conducted by Kunkle (1966). His work involved two sampling points within the Beaver Creek Basin (fig. 7). Maximum coliform values recorded at the Hourglass station in 1965 were less than 50 colonies per 100 ml. For section 2, maximum values recorded for 1964 and 1965 were less than 400 colonies per ml.

CONCLUSIONS

1) Glacial stade deposits mapped in the Beaver Creek Basin on the basis of topographic position, topographic character, and degree of weathering of surficial material, correlate favorably with deposits described elsewhere in the Rocky Mountain Region.

2) Absence of Neoglaciation in all sub-basins, except Hourglass, may be attributed to changing wind directions or local orographic effects.

3) Topographic evidence suggests the former existence of a local icecap that occupied the "cirque" area of the Mummy sub-basin in pre-Wisconsin time.

4) The igneous and metamorphic rocks are sufficiently jointed and fractured to permit some infiltration of water. These materials and the associated scree and talus slopes, form a large ground water reservoir which is recharged during periods of rainfall and snowmelt.

5) The terminal moraines and associated outwash deposits of Wisconsin age provide natural conditions for ground water recharge and storage respectively.

6) Measured losses of surface runoff are believed to occur primarily in areas of extensive outwash deposits. However, losses occurring through bedrock, and as a result of evaporation and transpiration, may also be significant.

7) Morphometric parameters, particularly circularity ratio and relief ratio, provide a means to determine the geologic homogeneity of an area. These and other parameters provide the hydrologist with a means of extrapolating data from basins in which hydrologic factors are measured to those in which no measurements are available.

8) Lacustrine deposits in the vicinity of Hourglass Reservoir indicate the former existence of a large lake in this area between Pinedale I and Pinedale II time. The former existence of a lake in Comanche Reservoir is suggested by the presence of a peat-clay layer.

9) Organic and inorganic surface water studies indicate excellent quality for general use.

10) The drainage basin is not deemed feasible as a location solely for surface water storage. However, development of a combined surface-ground water storage area appears feasible.

RECOMMENDATIONS FOR FUTURE RESEARCH

1) A drilling program coordinated with electrical resistivity readings should be initiated to determine the thickness and nature of outwash materials and the bedrock topography beneath outwash deposits in the vicinity of the reservoirs. This work would provide a sound basis for continued and/or expanded use of existing water supply storage facilities. The feasibility of developing a combined ground water-surface water supply system could also be determined with data from this program.

2) Gaging equipment should be installed on reservoir outlets and stream gaging sections 1, 2, and 3 should be stabilized to provide an analysis of the surface water budget. Values recorded over a longer period of time would provide needed data for better operation of reservoir facilities.

3) The geologic uniformity of the sub-basins provides an excellent area in which additional quantitative geomorphic studies could be conducted. Results from such an investigation would be valuable for interpretation of similar basins along the eastern Front Range of the Rocky Mountains.

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APPENDIX

Table 6.--Equations used to calculate morphometric parameters.

$$\text{Circularity ratio} = C_r = \frac{A_b}{A_c \text{ with } P_c = P_b}$$

where A_b = area of basin
A_c = area of circle
P_b = perimeter of basin
P_c = perimeter of circle

$$\text{Drainage density} = D = \frac{\Sigma L}{A}$$

where L = total length of streams in miles
A = surface area in square miles

$$\text{Compactness coefficient} = \frac{(0.28)\ (\text{perimeter, miles})}{\sqrt{\text{area}}}$$

$$\text{Relief ratio} = \frac{\text{total relief}}{\text{longest dimension parallel to principal drainage line}}$$

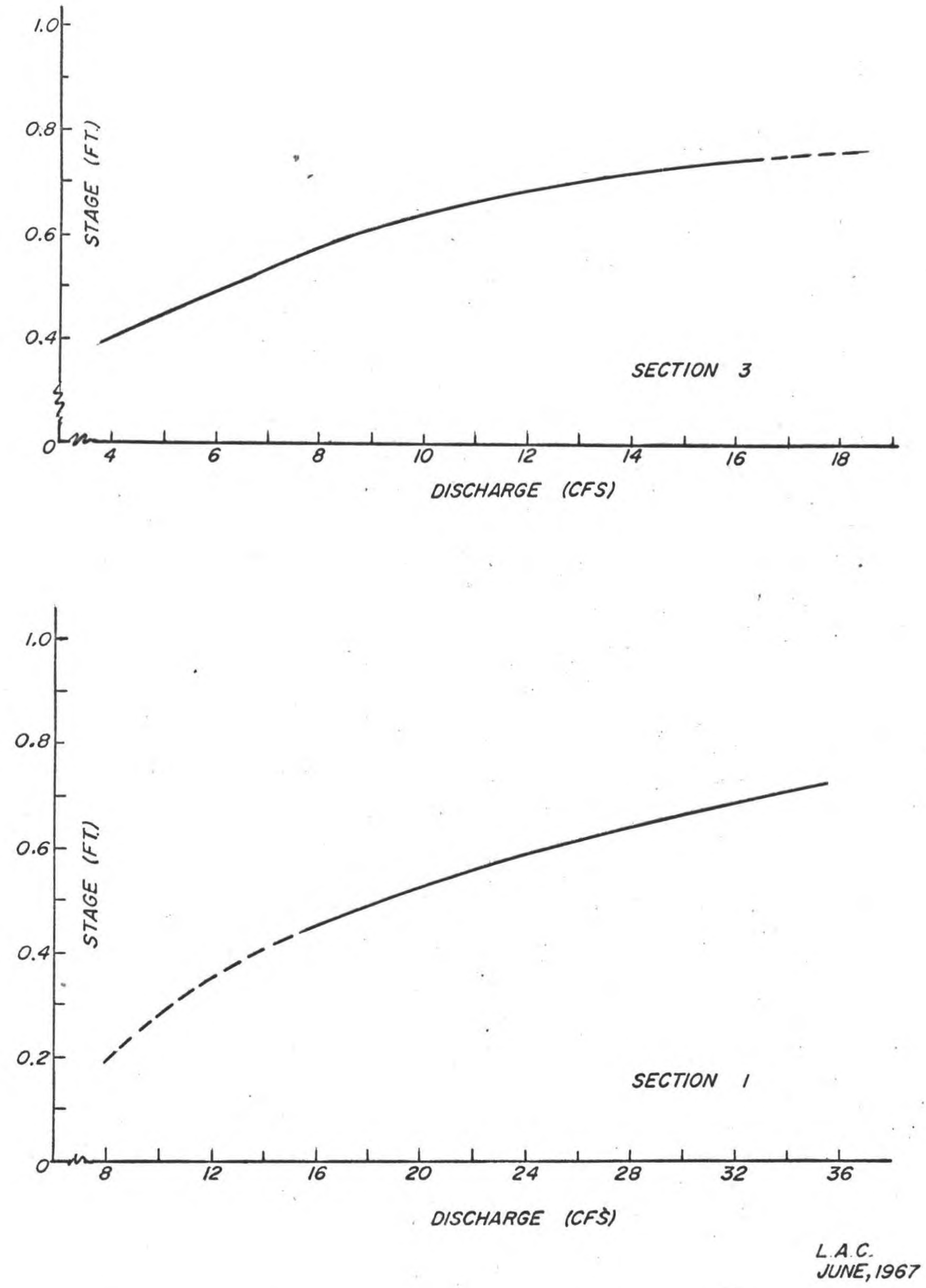

FIGURE 11: STAGE-DISCHARGE CURVES, BEAVER CREEK SECTIONS 1 AND 3

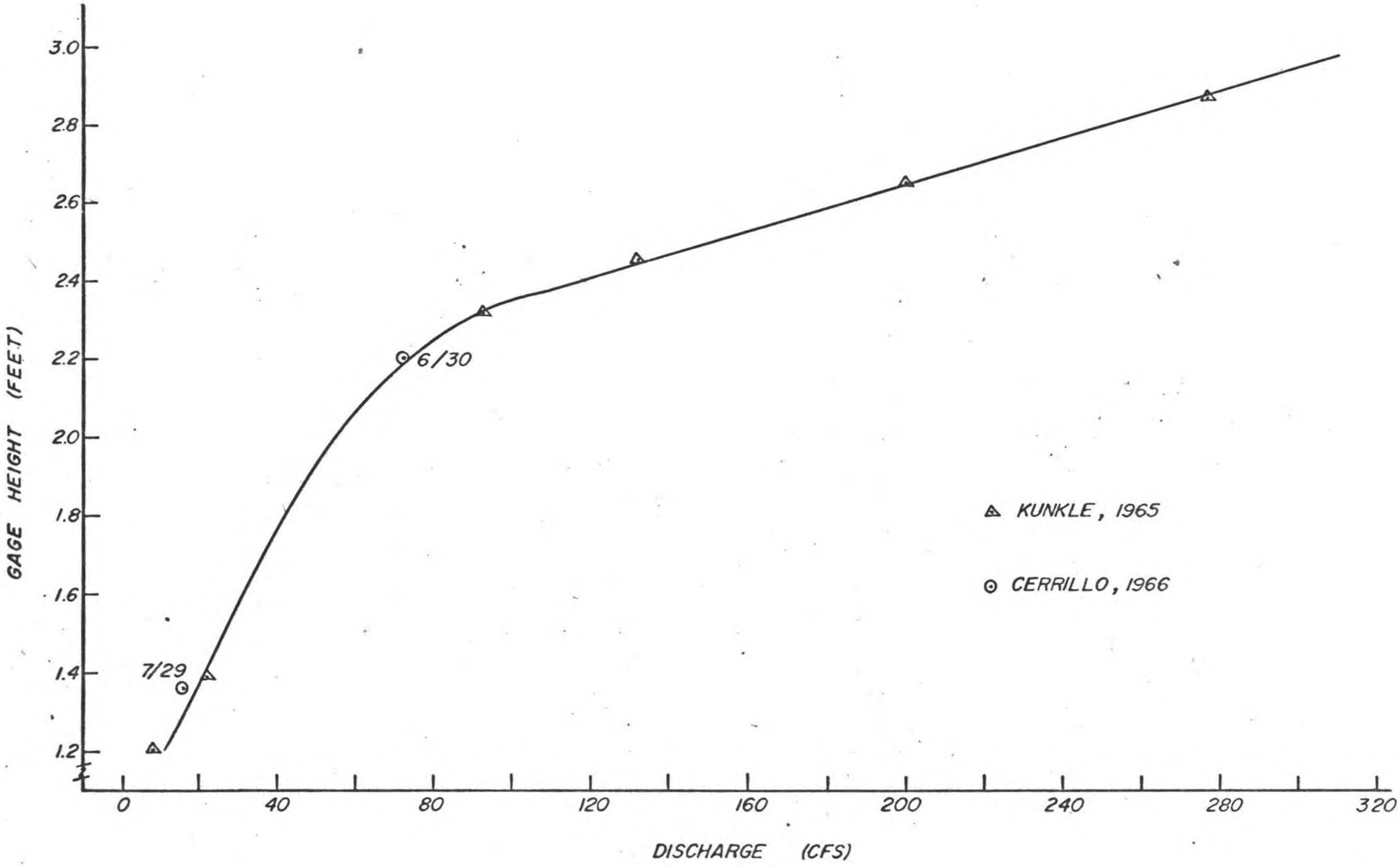

FIGURE 12: STAGE-DISCHARGE CURVE, SECTION 2 (AFTER KUNKLE, 1967)

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Pinedale I terminus along section line 17-18, T 7N, R 73 W. View is toward the south.

Reservoirs and proposed development area. View is west and northwest.

Plate 6.

PLATE 10

GEOLOGIC MAP
of the
UPPER FALL CREEK AREA

MUMMY RANGE
LARIMER COUNTY, COLORADO

J. W. MERCER
1966

LITHOLOGIC UNITS

QUATERNARY

- Qrg — Rock Glacier (?)
- Qgac — Glacial, Colluvial and Alluvial materials (undifferentiated)
- Terminal Moraine

PRECAMBRIAN

- p€g — Granite
- p€a — Amphibolite
- p€gn — Biotite-Quartzo-Feldspathic Gneiss
- p€s — Biotite Schist

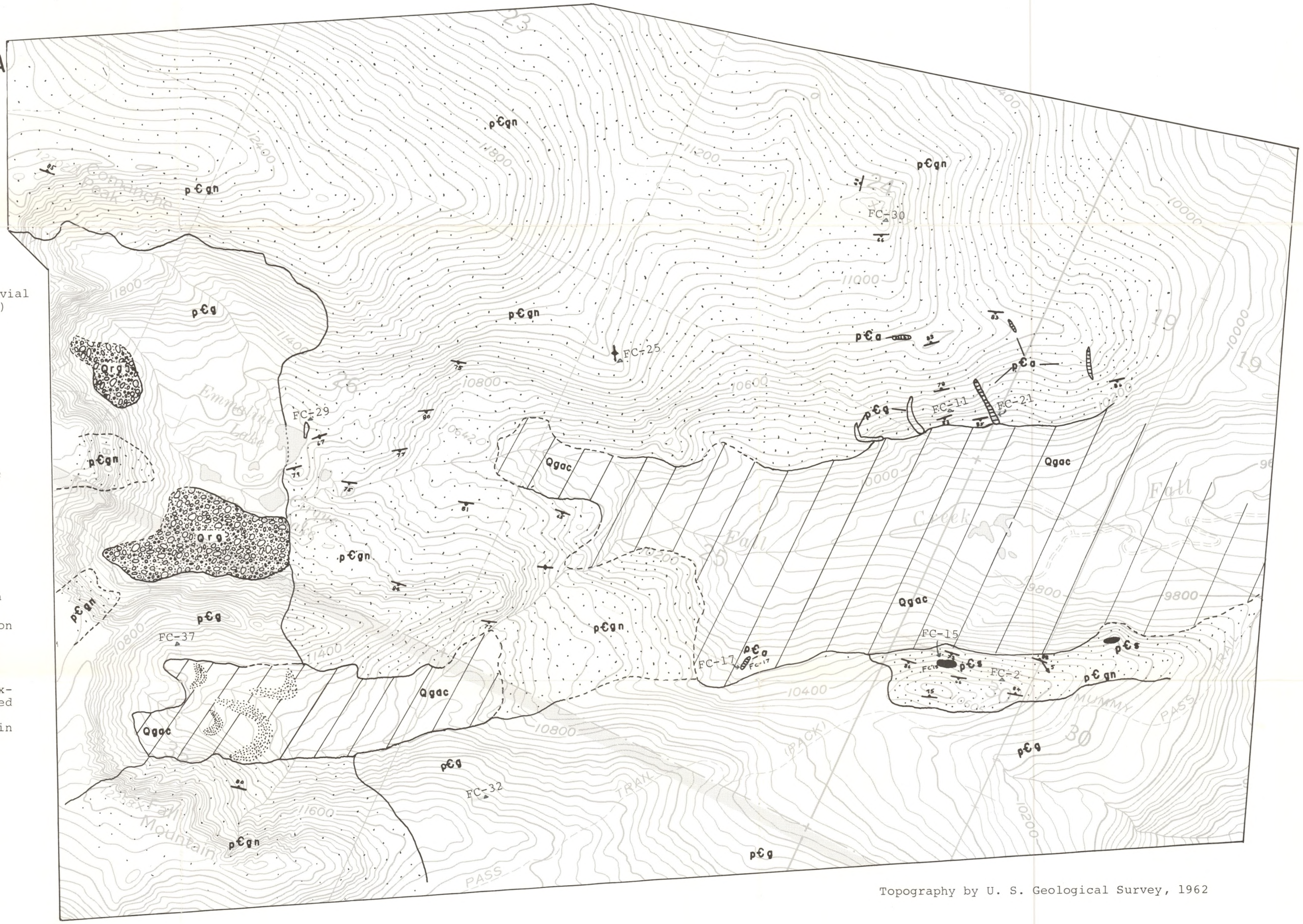
MAP SYMBOLS

- Strike and dip of foliation
- Strike of vertical foliation
- Foliation with azimuth and plunge of lineation
- Contact, solid where approximate, dashed where inferred
- FC-15 — Sample number referred to in text

APPROXIMATE MEAN DECLINATION
1962

CONTOUR INTERVAL 40 FEET
DATUM MEAN SEA LEVEL

miles



Topography by U. S. Geological Survey, 1962