

9. HYDROLOGY

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Three Parshall flumes were installed within East and West Glacier Lakes watersheds during the summer of 1987. Each Parshall flume was prefabricated fiberglass construction fitted with a hypolon liner to bring as much groundwater flow as possible to the surface so that it could be measured by passing the water through the flume. The liner was buried as deep as was practical in front of the flume and to the sides of the flume for as reasonable a distance as was possible to intercept groundwater moving through the area. Some difficulty was encountered in burying the liner at all locations because of large boulders that could not be removed without substantial disturbance.

East Glacier Lake outlet was fitted with a 12-inch Parshall flume and associated stilling well, monitoring equipment, and shelter. Meadow Creek and Cascade Creek inlets to West Glacier Lake were both fitted with 9-inch Parshall flumes and associated stilling wells, recorders, and shelters. An 18-inch Parshall flume had been installed on the West Glacier Lake outlet in 1986. Plexiglass 90° V-notch weirs were fabricated to fit into the Parshall flumes for low flow measurements during the flow season. It was felt that the accuracy gained in measuring flow using the V-notches provided questionable additional accuracy because of substantial fluctuations in flow during the day and ice conditions occurring at night during the fall. V-notches were not used after 1988.

Preliminary Water Balance

Based on meteorological, precipitation, and flow measurement data collected on the GLEES site, an approximate water balance for East Glacier and West Glacier Lakes watersheds was developed. The water balance, and an estimation of the measurement errors associated with the development of the water balance for each watershed, is discussed here. This water balance is based upon limited data available in 1988. Additional data on inputs and flows will improve the calculations of water balance.

These two watersheds posed a unique problem in the development of a water balance because more water flows out of each watershed than is indicated as input from the precipitation gage measurements. For the West Glacier Lake watershed, this is believed to be a result of the large permanent (semi-glacial) snowfield that exists near the upper end (highest elevation areas near the watershed divide) of the watershed. These high-elevation and steep-relief areas collect blowing and drift-

ing snow from adjacent watersheds because they are on the leeward side of the adjacent watersheds, in glacial cirques of the Medicine Bow ridge. Both lakes are close together, with East Glacier Lake at a higher elevation. The amount of water seepage from East to West Glacier Lake is unknown, but may also account for the lack of balance. In addition, the Wyoming-shielded precipitation gages are known to be inefficient collectors of snow in cold, windy areas.

Estimates of surface area hydrologic boundaries for East and West Glacier Lake watersheds used in the water balance studies were determined from a 1:12000 Snowy Range Observatory-Nash Fork Creek topographic map. The Nash Fork Creek map is a photo enlargement of the 1:24000 USGS map and was used because of the greater detail it offers. The East Glacier Lake watershed was selected to determine the extent of any enlargement distortion that may have occurred. Areas were determined with a K & E Vernier planimeter. Five measurements were taken from each map, and the high and low values were discarded. The mean of the remaining three values was calculated and compared. The results of this comparison indicate that the Nash Fork Creek map is suitable for use and that the enlargement process resulted in an overestimation of only approximately 1%. The measurements indicate an area of 24.7 ha (60.95 ac) for East Glacier Lake watershed and 59.3 ha (146.5 ac) for West Glacier Lake watershed. (Note: Actual watershed areas in Chapter 1 as determined from aerial photos are different from those calculated from maps and used for the analysis in this chapter.)

The isohyetal method was used to determine the average precipitation over the East and West Glacier Lake watersheds for the 1988 and 1989 water years. Four precipitation stations were used as control points. These four stations are Brooklyn Lake (0115A-35), Brooklyn Lake (0115-2), Lost Lake (0126), and Glacier Lake (0125). The monthly precipitation data for these stations were compiled from the WWRC Water Resources Data System database. This database extended through June of 1988, and supplemental data were compiled from the weekly strip charts of each station. Although lapses occur in the strip chart data, these omissions are unlikely to have a significant impact on the precipitation totals. The results of the isohyetal analysis indicate 84.10 cm (33.11 in) of precipitation (ppct) for West Glacier Lake watershed, and 95.35 cm (37.54 in) for East Glacier Lake watershed. The amount calculated for West Glacier Lake appears to be low, a result of an apparent under-collection for the Lost Lake precipitation gage and the lack of measurement of snow blown into the area of the permanent snowfield.

Three major streams exist in the Glacier Lakes area: Cascade, Meadow, and West Glacier Lake outlet. All three streams occur within the boundaries of the West Glacier Lake watershed area and all three are gaged with Parshall flumes. Cascade and Meadow Creeks discharge into West Glacier Lake and, as suggested by its name, West Glacier Lake outlet flows out of the lake. The East Glacier Lake watershed does not contain any perennial streams, but intermittent streams and overland flow drain into the lake until all snow cover is gone, and the outlet flows until late summer. Small ephemeral streams exist in the area within the watershed surrounding the lake.

The total annual flows for the Cascade, Meadow, and West Glacier Lake outlet were calculated for the 1988 water year. The record for this year extends from May 24 to September 30, with several daily records missing, as noted in WWRC Water Resources Data System database. It is assumed that although some flow may occur intermittently from October through April, these volumes are insignificant. Furthermore, records are not available for this time period.

A regression analysis was performed on Meadow and Cascade Creeks for the 1988 water year to derive missing streamflow data for Cascade Creek during that year. The Minitab statistical software package was used to perform the analysis. A review of the database and regression analysis found a water yield of 138.84 ac ft annual flow from Cascade Creek, 110.10 ac ft annual flow from Meadow Creek, for a total of 248.94 surface flow into West Glacier Lake from Cascade and Meadow Creeks. West Glacier outlet flow was 623.72 ac ft for May 24 through Sept 30, 1988. Monthly flow data is presented in table 9.1. The data suggest that the high flows in Cascade Creek, as reflected by the mean monthly flows, are lagged relative to the high flows in Meadow Creek. The direct correlation between the two streams for the period of record available is generally poor, with the exception of the month of July. The flow lag and correlation differences are difficult to explain.

Lag of High Flows

Although both Cascade and Meadow Creeks are in steep, rugged terrain with similar geological features,

Table 9.1.—Monthly flows for Cascade Creek, Meadow Creek, and West Glacier Lake outlet, 1988.

	May	June	July	Aug	Sep	Total
Meadow Creek						
Total (cfs)	3.79	22.50	16.61	8.96	3.67	
Mean (cfs)	.47	.75	.54	.29	.12	
Ac ft	7.46	44.63	32.95	17.77	7.28	110.09
Cascade Creek						
Total (cfs)	2.72	24.40	21.96	14.50	6.36	
Mean (cfs)	.34	.81	.71	.47	.21	
Ac ft	5.40	48.38	43.66	28.90	12.50	138.84
West Glacier Lake outlet						
Ac ft	46.73	262.81	199.54	81.12	33.52	623.72

differences exist between the two watersheds. Cascade Creek is fed primarily by the permanent snowfield and is strictly channelized flow. Meadow Creek is also fed by the permanent snowfield, but is less steep terrain, has large areas of the catchment that melt out, and runs through a large meadow area uphill from the outlet. Although the 1988 isohyetal map suggests that precipitation over the two catchments is essentially the same, more snow is likely deposited in the area of the permanent snowfield, affecting Cascade Creek more than the Meadow Creek catchment. These differences may influence the lag of high flows in the two catchments.

Variations in net solar radiation input between the two areas may be partially responsible for the lag. The topographic map indicates that this area scribes a 1/4 circle from north to NW, with Meadow Creek flowing generally north to south, and Cascade Creek flowing NW to SE. The differences in slope aspect may be sufficient to cause the observed lag in flows because the Meadow Creek watershed would receive more direct solar radiation input for a longer duration of time during the late spring and summer months. The result would be that the snowpack in the Meadow Creek watershed would begin to melt earlier and at a faster rate than the snowpack in the Cascade Creek watershed and would be expressed as larger early season flow, as observed.

The above hypothesis is based on limited information. To determine the validity of this hypothesis, the necessary equipment to determine the solar radiation influx has been installed. The data provided by the instrumentation will allow for the calculation of potential rates of melting. In addition, the potentially significant effects of a large permanent snowfield in this area can not be ignored. It has been assumed, for purposes of the above argument, that this snowfield covers both watersheds uniformly and can therefore be considered a constant (i.e., affecting the watersheds in a manner similar to uniform precipitation). In reality, most of the Meadow Creek watershed melts out, with only a small portion of this watershed fed by the snowfield after July. Much of the upper portion of the Cascade Creek watershed is snow-covered year round. Cascade Creek also has much steeper relief than Meadow Creek, which may be related to the differences.

Correlation of Streamflows

As indicated, the data show poor correlation, with the exception of the month of July. Although this poor correlation may be due to random events, it is proposed that what may actually be occurring is a transition between two states of equilibrium. These two states of equilibrium are categorized, for purposes here, as "winter equilibrium" and "summer equilibrium" with the transition between the two states occurring at different rates in the two catchments. The winter equilibrium state for both catchments would be characterized by the following conditions:

- 1) Soil and zone of interflow are frozen to the frost line.

- 2) Deactivation of the groundwater system directly results from this interflow.
- 3) Losses in the catchment are only a result of surface flow, evaporation (sublimation), and transpiration (affecting only waters directly adjacent to roots of coniferous vegetation).

The period of equilibrium under these conditions would exist from late October or early November to late April or early May.

The summer equilibrium state would be characterized by different conditions. These would include:

- 1) An entirely thawed zone of interflow.
- 2) An entirely reactivated groundwater system as a direct result of this interflow.
- 3) Losses in the catchment resulting from surface flow, evaporation and/or sublimation, and transpiration at maximum rates; and groundwater flow.

The period of equilibrium under these conditions would exist in mid-summer (July and August).

Between these two equilibrium extremes the following conditions would exist:

- 1) A gradually thawing or freezing zone of interflow.
- 2) A gradual reactivation or deactivation of groundwater systems in response to this interflow.
- 3) A gradual increase or decrease in evaporation and/or sublimation, and transpiration at gradually increasing or decreasing rates.

These intermediate conditions would occur from late April or early May to September and October, with one of the two proposed equilibrium conditions occurring before or after this transitory state.

Evaporation

The mass transfer method was used to calculate the reservoir evaporation for East and West Glacier Lakes. This method was selected over other methods because the more extensive data required by these other methods were not available. The mass transfer method uses the formula:

$$E = c(e_o - e_a)(1 + [w/10])$$

where

E = inches/month

c = 14

e_a = saturation vapor pressure at mean monthly temperature in inches Hg

e_o = vapor pressure at mean monthly temperature in inches Hg

w = mean monthly windspeed at 25 ft (mi/hr).

The data used here were obtained from a totalizing anemometer and hygrothermograph located at the Telephone Lakes station and better reflect conditions at Glacier Lakes when compared to other Snowy Range Observatory stations in the area. Factors considered when selecting this station included topography, elevation, and exposure. More recent wind speed data is now avail-

able from the GLEES meteorological tower but was not available for this analysis.

It was assumed that a free surface exists from June 1 to September 30 and that evaporation occurs only during this time interval. It is further assumed that the surface area of the lakes remained constant. The computed total annual loss by evaporation is 9.9 ac ft from West Glacier Lake. Assuming the same surface area for East and West Glacier Lakes, the total evaporation loss from East Glacier Lake is also 9.9 ac ft.

The Blaney-Criddle method was used to determine the evapotranspiration losses for both catchments. As with the mass transfer method, this method was selected because the more extensive data required by other methods were not available. It was assumed that the total evapotranspiration for the season could be reasonably approximated by considering only the losses occurring between June 1 and September 30, which is the period of maximum plant growth. A significant fraction of the watershed areas consists of bare rock with negligible moisture-holding capacity. Evaporation from such a surface would be limited to the drying of a wet surface immediately after a precipitation event. Therefore, the majority of moisture returned to the atmosphere occurs over areas where soil development is sufficient to retain water and support plant life. The evapotranspiration estimate must therefore be adjusted to reflect the percentage of groundcover in the catchment. For computational purposes it has been assumed that 35% groundcover exists in both catchments and that a linear relationship exists between percent groundcover and total evapotranspiration losses. The results of the computations indicate that 288.1 ac ft of moisture is lost via evapotranspiration over the West Glacier Lake watershed and 119.9 ac ft is lost over the East Glacier Lake watershed during the indicated time period.

Water Budget

Using the values computed for surface discharge, evapotranspiration, and precipitation input, a water budget was calculated for East and West Glacier Lakes. Total change in storage is calculated as:

$$S = P - (E + E.T. + Q + G)$$

where

S = change in storage

P = precipitation over watershed

E.T. = evapotranspiration

Q = surface flow

G = groundwater

E = lake evaporation.

The water budget computations for West Glacier Lake indicate that 517.5 ac ft more of water was discharged from the catchment than was being supplied by precipitation input. By these estimates, the snowfield is contributing about 128% more water than is contributed by precipitation over the watershed. It is proposed that this excess moisture is being supplied by the large permanent snowfield at the top of the watershed. This

snowfield straddles the northwestern portions of the East and West Glacier Lakes watersheds and was formed and is maintained by blowing snow deposited on the leeward side of the mountain peaks. This snowfield represents a net moisture input to the catchments that is not recorded by precipitation gages located lower in the catchment.

An estimate of the size of the snowfield needed to produce the required volume of water can be made by selecting a density value for the snow and calculating the equivalent water content on a volume basis. Then, by selecting various values for the depth of snow, the areal size can be computed. Such computations indicate that for a density of 2.8 pounds/cu foot and a 10-ft uniform depth, the snowfield would have to cover 119 acres. For a 20-ft depth, 59.5 acres would be required. Direct observations of the size of the snowfield indicates that these values are not completely unreasonable as upper and lower size limits and that the largest amount of unaccounted outflow comes from this snowfield. It is observed during the summer season that a large amount of flow into West Glacier Lake and to the outlet of the lake results from melting of the permanent snowfield. Water can be heard running through Long Creek to the west of Cascade Creek, and also in the large boulders in Boulder Creek, a small drainage to the east of Meadow Creek. The boulders in these two drainages preclude flow measurement by flume, thus flow data are not available from Boulder and Long Creeks.

Water not moving through stream channels will flow by subconcentrated surface flow, surface flow, interflow, or groundwater flow. Because there is only one unconfined alluvial aquifer in the area, near surface interflow should not occur until the entire depth of the aquifer is saturated. Assuming that the groundwater and interflow systems can be considered as one system, calculations can be made to determine the volumetric flow rates of groundwater and subconcentrated surface water. These calculations estimate 9.394×10^5 gal/day flows as subconcentrated surface flow, interflow, and groundwater flow in the West Glacier Lake watershed from May 24 to September 30. However, several other quantities can contribute to the outflow in West Glacier Lake, including subsurface flow from East Glacier Lake into West Glacier Lake. The 26.1 ac ft of unaccounted water from the East Glacier Lake water balance could be seeping into West Glacier Lake. The largest problem in this whole water balance effort is the unknown of groundwater movement in the area.

Errors Associated With Water Balance

An excellent summary of the problems associated with water balance studies on lakes is given in a paper by Winter (1981) entitled "Uncertainties in Estimating the Water Balance of Lakes." These same problems exist with trying to do water balance studies on East and West Glacier Lakes and their watershed areas. Winter (1981) estimates errors for the following components of hydrologic measurement:

measuring precipitation in individual storms — 75%
short-term averages — 15–30%
evaporation estimates — 10–15%
stream discharge — 5% +
overland flow — unknown, but can be over 100%.

Accumulation of these errors gives an idea of the difficulty of obtaining precise estimates of watershed water balances. The additional difficulty of obtaining accurate data from remote watersheds in complex terrain such as the Glacier Lakes makes water balance estimates even more uncertain. Nevertheless, we have made preliminary estimates of water balance for the Glacier Lakes that will be further refined as additional measurements of the components of water balance provide more accurate data.

It is difficult to estimate evaporation and evapotranspiration accurately by the methods used. The values obtained could represent 75–100% error. A pan evaporimeter has been installed at the site to obtain more accurate estimates of evaporation.

Streamflow measurements of surface water discharge should generally be within 5% of actual because of the Parshall flumes being used, except during fall freeze periods. On a yearly basis, however, the values obtained should definitely be within 5%, except perhaps for West Glacier Lake outlet. During most of the year, a small amount of seepage occurred at the outlet of West Glacier Lake under the hypalon cutoff liner that could amount to as much as 0.5 cfs during larger flows and approximately 0.25 cfs during the fall period. This leak was repaired in 1989, but some leakage was noted again in 1991.

Groundwater flow was considered to be in balance over a yearly period. This assumption should be approximately true with errors in the range of 5–10%. However, it is believed that seepage does occur from East Glacier into West Glacier, which could account for some of the difference. Any water balance studies done on less than a yearly period would have to account for groundwater movement into and out of the area. The amount of groundwater movement out of the two watershed areas could be sizeable during certain months such as June, July, and August.

It is believed that the largest source of error in the West Glacier Lake watershed is the permanent snowfield that exists along the north and west ends of the watershed divide. It is believed that the accumulation of blowing snow from adjacent watersheds, along with the difference between yearly hold-over storage of the snowfield, can result in over 100% error in estimation of the water balance of West Glacier Lake. It is indicated from the water balance study done that this phenomena is not as pronounced for East Glacier Lake.

Suggestions for Error Minimization

The following ideas and/or suggestions are made to reduce the errors associated with a water balance study on either East or West Glacier Lake watersheds.

Precipitation gages should be checked to make sure that they are operating correctly and the weighing mechanisms are accurate to within the limits of the instrumentation as indicated by the manufacturer. All precipitation gages should be shielded from the wind since much of the area is subject to high winds during the winter period. Additional precipitation and snow survey data have been collected (in 1989 and 1990) since this analysis was made (for 1988), which indicate that the precipitation collectors are inefficient collectors of snow. In addition, the location of the SRO precipitation collector at Glacier Lakes is on a ridgetop where deposition is considerably lower than that in other portions of the East and West Glacier Lakes watersheds.

A land evaporation pan has been installed within the entire watershed area so that the estimates of evaporation and evapotranspiration can be made more accurately than was done under this study of water balance. This data was collected beginning in 1991.

A detailed snow survey of the two watershed areas is necessary in late April or when the snowpack is close to being ripe to determine the actual amount of water stored during the winter period as a result of precipitation and blowing snow accumulation from adjacent watersheds. This task could be very difficult on the West Glacier Lake watershed because of the cornices that are formed as a result of the blowing snow.

The permanent snowfield needs to be measured in the fall of each year near the end of the melt period for the snowfield. The change in volume each year can then be determined. It will be necessary to get a reasonably accurate estimate of the density of the snowfield at this time also.

Any water balance studies made over a shorter period than one year will need to include runoff occurring either as overland flow directly into the lake or unmeasured surface inflow that cannot be obtained due to boulder fields. Both of these estimations (groundwater movement and unmeasured surface flows) on these two watershed areas can reflect as much as 100% or greater errors in the water balance. No easy solution to these problems exist. Physical measurement techniques to quantify the amount of water input to or output from the given lake water balance in these two watersheds is almost impossible without an undue amount of land disturbance.

Groundwater movement can be estimated by placing piezometers at selected locations throughout the watershed area to determine groundwater gradients. Using an estimate for hydraulic conductivity that can be done either by estimation from soil type and structure or in-field tests (several available including pumping), Darcy's Law can be applied to a cross section of the area to determine flow. Cross sections can be obtained in these areas using surface geophysical techniques.

Finally, the hypalon liners of the flumes should be periodically checked to prevent as much seepage as possible from under the liner.

Depth Measurement of Unconsolidated Material

In order to get a better feel for possible groundwater movement in the East and West Glacier Lake watersheds, a number of cross sections were selected to obtain the depth of unconsolidated material available for groundwater flow throughout the watersheds. A surface geophysical technique known as seismic refraction was performed using a hammer to create the sound wave and several geophones to detect the sound wave movement to determine the depth to bedrock material.

Eight different cross sections were obtained using the seismic refraction technique. Figure 9.1 has a map that indicates the location of the eight cross sections. Each of the eight cross sections is schematically shown (figs. 9.2–9.8) as determined from the seismic refraction data.

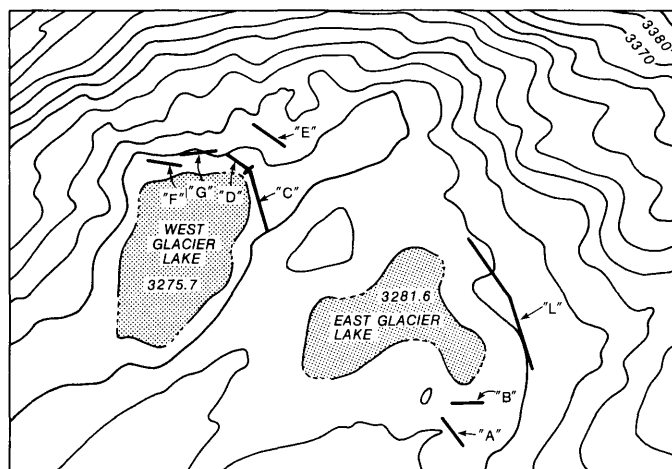


Figure 9.1.—Map showing locations of cross sections used to determine depth of unconsolidated material.

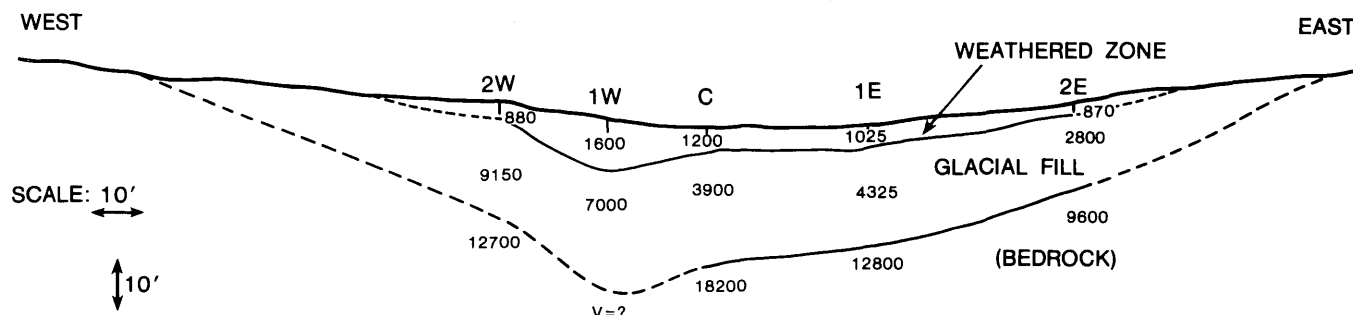


Figure 9.2.—Cross section A. Depth of unconsolidated material.

SCALE: 10'

10'

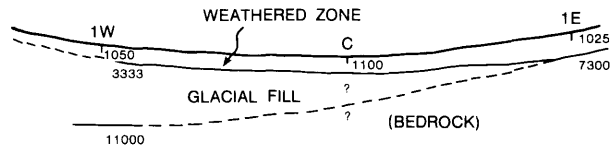


Figure 9.3.—Cross section B. Depth of unconsolidated material.

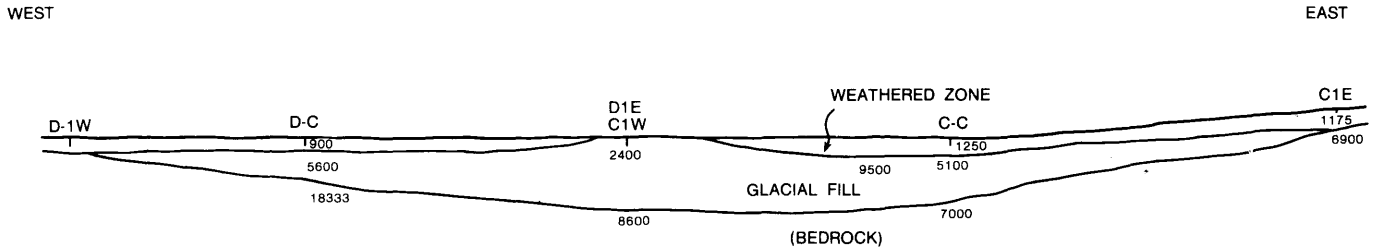


Figure 9.4.—Cross sections C and D. Depth of unconsolidated material.

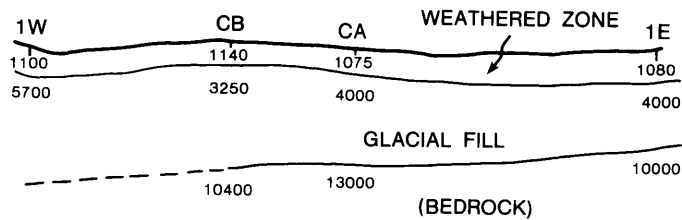


Figure 9.5.—Cross section E. Depth of unconsolidated material.



Figure 9.6.—Cross section F. Depth of unconsolidated material.

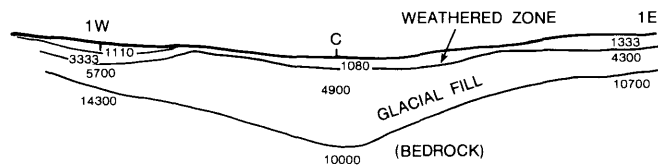


Figure 9.7.—Cross section G. Depth of unconsolidated material.

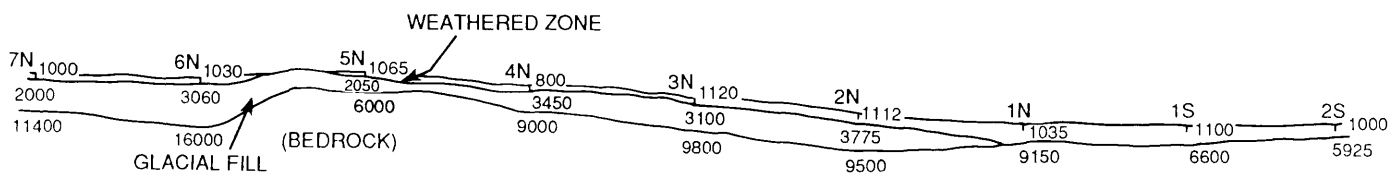


Figure 9.8.—Cross section L. Depth of unconsolidated material.

SCALE: 10'

10'

Most of the depths to the base of the weathering layer (velocity 200–500 fps) are quite reliable. The layer with velocities in the range from 200–4,000 fps is probably glacial material. Velocities above 4,000 fps and up to 7,000 fps are at a higher velocity than would be expected for glacial debris, but it is possible. The cross sections drawn are, therefore, the author's interpretations. The granite bedrock material was expected to have a velocity around 16,000–18,000 fps. Since these velocities were not measured that often, it could be possible for the glacial material to be as much as 20 feet thick (as is shown on most of the cross sections) on a highly disturbed bedrock surface, which would account for the slower velocities measured in several instances.

A crude estimate of hydraulic conductivity was determined using information from the water balance study and the seismic refraction cross-sections. Values for the hydraulic conductivity were found to be between 25 and 146 gpd/ft². Conductivity (K) can be calculated from the formula:

$$Q - KIA = >K = Q/IA$$

where

Q = Volumetric flowrate gal/day

I = Hydraulic gradient

A = Area perpendicular to flow

K = Hydraulic conductivity.

For West Glacier Lake watershed assume:

- 1) All nonchanneled flow moves in the groundwater aquifer, i.e., no subconcentrated surface flow.
- 2) Q = 939,400 gal/day.
- 3) The hydraulic gradient is unity, i.e., 1 ft/ft.
- 4) The area perpendicular to flow can be completely accounted for from the seismic profiles. For WGL shot lines "C-D," "F," and "G" the entire thickness is saturated.

$$5) K = \frac{939,400 \text{ gal/day}}{(1 \text{ ft/ft}) (6,425 \text{ ft}^2)}$$

$$6) K = \frac{146.2 \text{ GPD}}{\text{ft}^2}$$

Evaluation of Hydraulic Conductivity Analysis

The hydraulic conductivity calculated falls at the upper limit of conductivities for glacial tills (10⁻⁶ to 10²). The problem with the analysis is that none of the assumptions used in performing the calculation can truly be justified. There is no reason to believe, for example, that all of the nonchannelized flow moves in the groundwater system or that the hydraulic gradient is unity. The area perpendicular to flow is certainly much greater than that calculated from the refraction survey as the shot lines cover only a fraction of the potential contributing area.

However, in spite of these shortcomings, the K value calculated may not be totally erroneous when the following observations are taken into account:

- 1) If the fraction of nonchannelized flow entering the groundwater system is only 10% of the total nonchannelized flow (93,940 gal/day) the resulting conductivity is only decreased by one order of magnitude.
- 2) Although the hydraulic gradient is most likely some fraction of unity, it is definitely known that the aquifer area perpendicular to flow is much greater than the 6,425 ft² value used. Therefore, the effects of decreased gradient and increased area will tend to offset each other resulting in minimal changes in the conductivity. For example, if I = .5 ft/ft and 2A = 12,850 ft², there will be no change at all in the conductivity.

In conclusion, although the individual assumptions may not be justifiable, the overall affect may be negligible. Therefore, the hydraulic conductivity value of K = 146.2 GPD/ft² for this aquifer may be very close to the true value, which can only be determined with further and more extensive study.

Reference

Winter, T.C. 1981. Uncertainties in estimating the water balance of lakes. Water Resources Bulletin. 17(1): 82–115.