 

# HYDRAULIC INFLUENCES ON AUFEIS GROWTH

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## INTRODUCTION

Large aufeis growths on streams in cold regions present an important and perplexing engineering problem for stream control and engineering construction. In addition to the normal complex hydraulic conditions existing in ice covered streams and rivers, the aufeis growth occurs on top of the ice surface, increasing the total thickness of ice. Although streams and lakes are usually covered with ice to a maximum thickness of about 5 feet, in the arctic and subarctic areas of Alaska, aufeis growths may exceed this thickness by 2 to 3 times. The maximum depth of the aufeis is generally controlled by the channel depths as the adjacent flood plain furnishes a large volume of additional storage.

The hydraulic mechanism of aufeis growth is the result of a complex inter-action of open channel, closed conduit, and groundwater flow. Results of a field measurement program on a small stream near Fairbanks, Alaska illustrate rapid and complicated fluctuation of hydrostatic head in the stream and the adjacent groundwater aquifer in conjunction with aufeis growth. Kane *et al.* (1973) reported on the variation in groundwater pore pressure immediately adjacent to the stream; the results of hydrostatic head variation away from the stream at various depths are revealed in this paper. The data indicate a very important role is played by the adjacent groundwater aquifer as a storage reservoir. An understanding of the interaction of groundwater and streamflow is necessary for the development of design criteria where various transportation facilities intersect streams that have a potential for aufeis accumulation.

## PHYSICAL SYSTEM

During the winter a natural arctic stream system is composed of: surface snow cover, aufeis accumulation in the channel and on the adjacent flood plain, streamflow, soil system that includes the zone of seasonal frost and the zone below the seasonal frost and above the permafrost, and the permafrost zone. In addition, the various soil zones may be saturated or unsaturated.

Ground surface topography and the top surface of the aufeis along the centerline of the stream are monitored by level surveys. The depth of seasonal frost is measured at 6 points using frost-tubes as described by Rickard and Brown (1972). The maximum depth of seasonal frost along the stream bank is slightly over 5 feet, while on the average the depth varies from 3-4 feet in these high moisture soils. The soils adjacent to the stream are a mixture of sand and silt, and perenially frozen silts of eolian origin with some partially decomposed organic material can be found in the valley bottoms. The major bedrock unit is schist with a highly weathered contact with the above surficial material.

Goldstream Creek is located in a region of discontinuous permafrost; south facing slopes are permafrost free and the valley bottoms and north facing slopes are underlain with permafrost. In undisturbed areas, the depth to permafrost is approximately 3 feet, depending upon vegetation type. In the vicinity of the stream, the upper surface of the permafrost is depressed by as much as 20 feet. Thicknesses of permafrost greater than 200 feet have been measured in the Fairbanks area.

The drainage area above the Goldstream study site is 74 $mi^2$ with a minimum recorded summer flow of 16 cfs. Twenty-three piezometers were positioned along and transverse to the stream to measure the fluid potential at various depths. The piezometers are 1 1/4 inch diameter galvanized pipe with stainless steel drive-points and a 14 inch screened opening. An antifreeze solution (Mayo, 1972) of methyl alcohol and ethylene glycol is used to prevent freezing of the water in the piezometers. Measurement of water levels in the piezometers are made by manual observation and by water level recorders. Level surveys are also made to monitor the vertical movement of the piezometers.

## MECHANISM OF AUFEIS GROWTH

Streams in this area experience several periods of super-cooling and frazil ice production prior to the development of an ice cover. Large quantities of anchor ice can be found on the bottom and banks of the stream. This anchor ice causes the water surface to rise prior to the formation of an ice cover. With subsequent changes of energy exchange with the atmosphere caused by the ice cover, the anchor ice disappears and the water level drops.

The process of aufeis growth starts shortly after this initial ice cover develops on the stream. The first aufeis formation on the surface is caused by the added weight of snow accumulation. This additional surcharge increases the potential water level within the ice cover. Due to the difference in the specific weight of water and ice, water will reach an equilibrium elevation of 0.9 times the total thickness of the floating ice. Adding a surcharge on the top surface of the ice causes this level to approach the surface level of the ice. If fractures are present in the ice cover, this water will flow onto the ice surface and through the snow pack where it will eventually freeze. Michel (1971) present the following equation to describe this event:

$$h_w = \frac{(\lambda_w - \lambda_i)}{\lambda_s} h + \frac{(\lambda_w - \lambda_i)}{\lambda_s} (1-e)(h_s - h_w)$$

$h_w$ = Thickness of unsaturated snow [ft]

$h_s$ = Total thickness of saturated and unsaturated snow [ft]

$h$ = Thickness of ice cover [ft]

$\lambda_w$ = Specific weight of water [#/ft$^3$]

$\lambda_i$ = Specific weight of ice [#/ft$^3$]

$\lambda_s$ = Specific weight of snow [#/ft$^3$]

$e$ = Porosity of the ice pan, ratio of volume of voids filled with water to the total volume of the ice pan

Discretion must be used when applying this equation to river conditions because this equation was developed for floating ice covers. In narrow channels generally some support is afforded by stream banks and exposed bars, but for wide rivers and narrow streams with thin ice cover this equation is suitable. The depth of snow at various densities required before the water level will reach the snow-ice interface for the case when no snow-slush is present ($h_w = (\lambda_w - \lambda_i)(h)/\lambda_s$) is shown in Figure 1.

The ability of ice to resist deformation caused by transverse forces increases as the ice thickness increases and as the bond to the stream bank strengthens. This allows the ice cover to resist deformation when the hydrostatic pressure in the stream increases. This resistance to upward vertical movement holds the ice in place and allows overflow to occur on top of the ice. On large rivers with wide spans, the ice will yield to uplifting forces and no overflows occur.

The variation in the hydrostatic head in a piezometer located near the stream bank for two winter periods and one summer period is shown in Figure 2. The cause of these pressure fluctuations is not known. Two possibilities exist: an increase in pressure resulting from increased resistance of flow due to the downward freezing of the ice-water interface; and, an increase in pressure due to unsteady flow conditions in the stream. The hydrostatic head measured 140 feet away from the stream during one winter is shown in Figure 3. A comparison of this curve to the previous curve indicates the stream is the source of major pressure changes and the adjacent aquifer only responds to these pressure fluctuations.

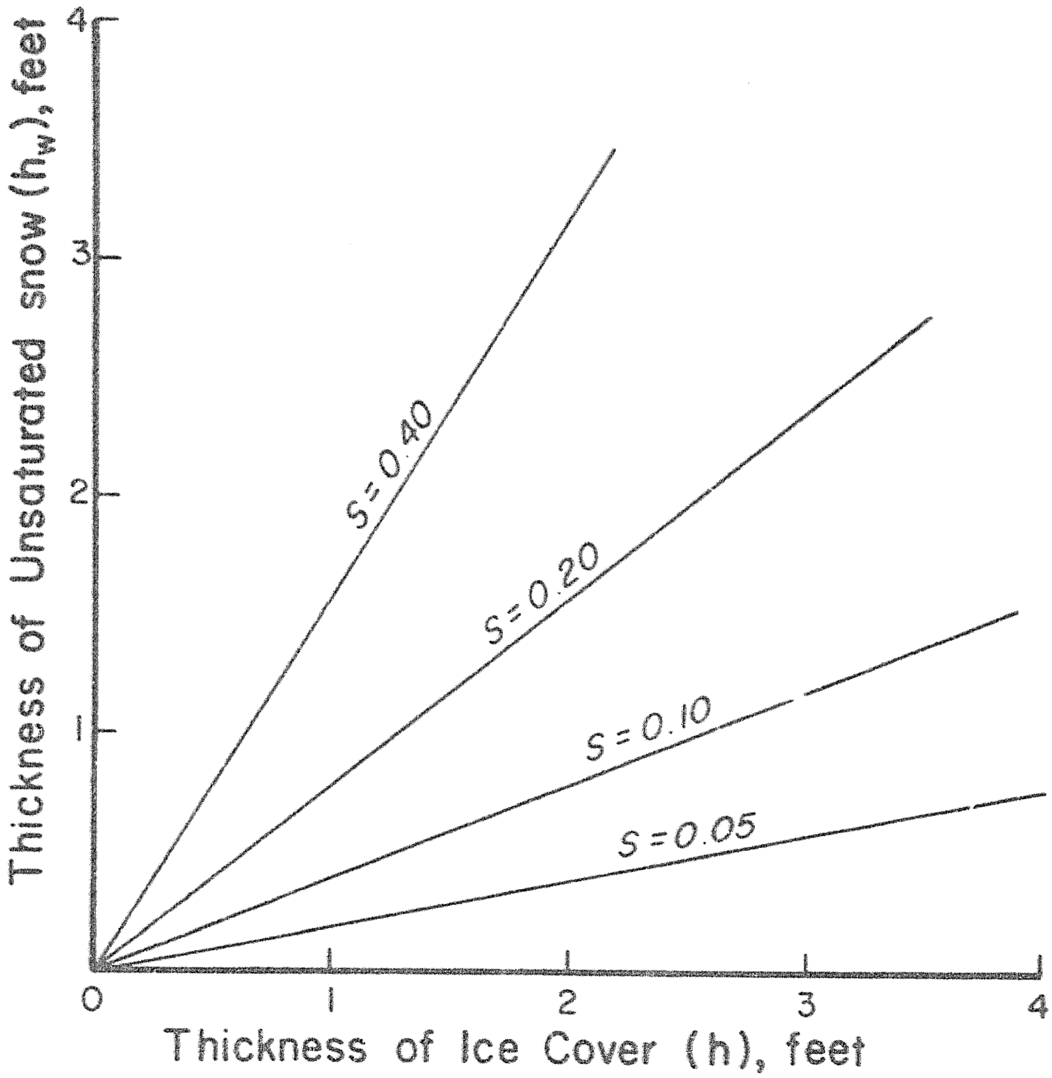


Figure 1. Relationship between overlying snow cover ($h_W$) with various specific gravities (S) and a given ice thickness (h) such that the equilibrium elevation of the water is at the snow ice interface.

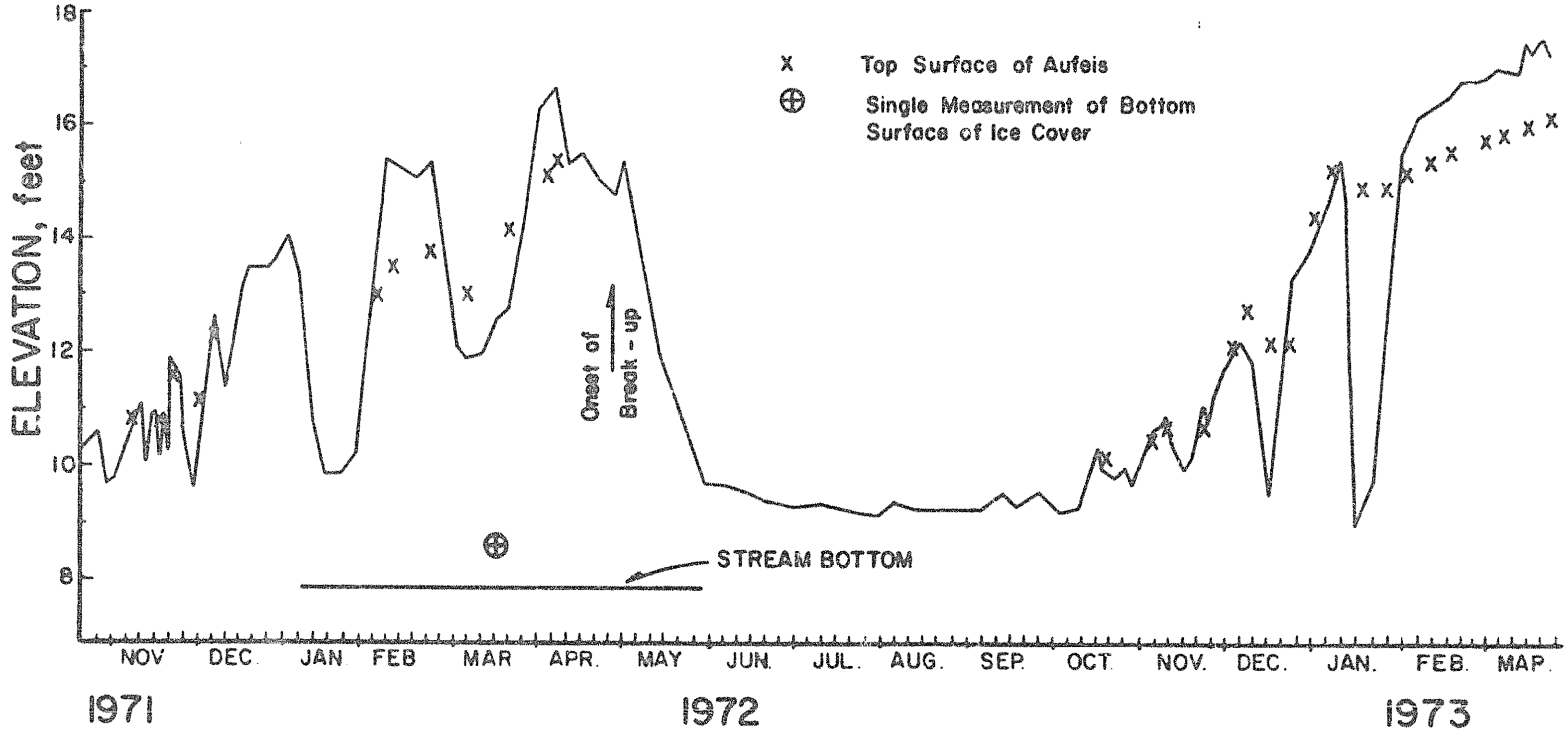


Figure 2. Measured hydrostatic head immediately adjacent to Goldstream Creek (Piezometer #3).

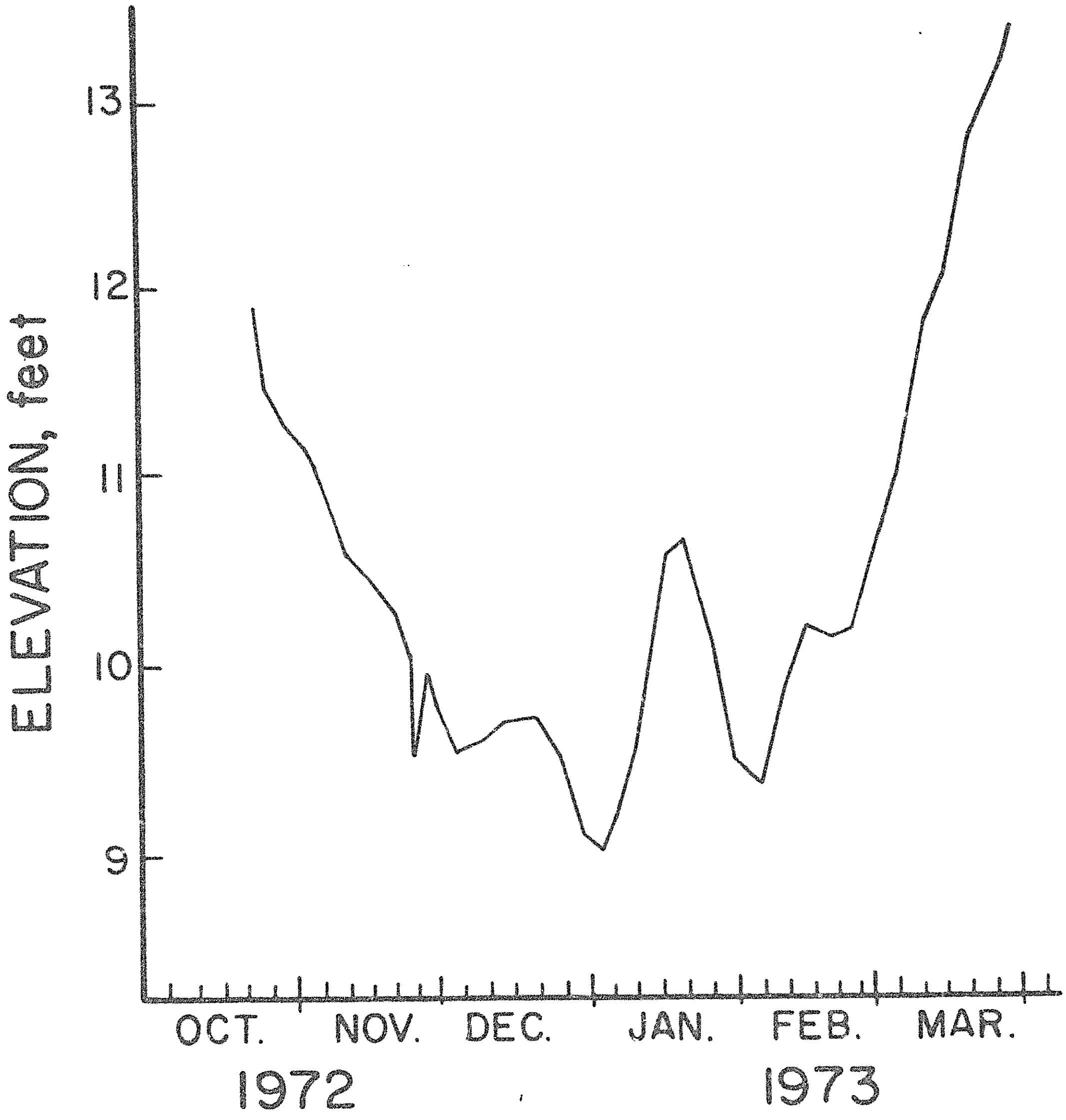


Figure 3. Measured hydrostatic head 140 feet away from Goldstream Creek (Piezometer 1-2).

Associated with these pressure changes is a vertical movement of the ice cover in the stream and of the adjacent ground surface. The elevation of the top surface of aufeis at the centerline of the stream for selected dates is shown in Figure 2. Note the drop in the ice surface when lower pressures prevail. This same movement is apparent on the stream banks, gradually decreasing in magnitude away from the stream. The net upward movement adjacent to the stream has exceeded 1 foot in 1973. Apparently the seasonal frost zone has a very low permeability, thus confining the groundwater flow. Since the adjacent soil material is unconsolidated, separation occurs at the freezing front of the seasonal frost and a wedge of ice forms. After the spring snowmelt runoff, this wedge is exposed to the warmer stream water and melts from the stream into the bank. The overlying material is left unsupported and may slump into the stream.

As the winter season progresses, the water moves from the stream into the adjacent unfrozen aquifer increasing the bank storage. This process is analogous to changes in bank storage during a flood-wave progression. At a point in time when the streamflow is at a minimum, the flow is further decreased by bank storage. When the spring flood event occurs, the banks are already saturated. After the spring peak runoff, the bank storage increases low water flow. The volume of bank storage is a function of hydrogeologic conditions and the distribution of permafrost along the stream.

The flow conditions in the aquifer change drastically from a late summer situation to a winter situation during aufeis growth periods as shown in Figures 4 and 5. The direction of flow is reversed and the stream has changed from a point of low fluid potential to a point of high fluid potential. This clearly shows that subarctic and arctic streams receive water from sources other than the adjacent bank storage during the winter months. From visual observation, most small streams do have flow throughout the winter. Aufeis accumulation, springs, and ice free reaches of rivers all indicate that flow, both surface and subsurface, does exist. Since the adjacent unfrozen zone and suprapermafrost groundwater does not appear to be contributing flow, subpermafrost groundwater is the most probable source.

The volume of subpermafrost groundwater discharged into the stream could be determined by accounting for the stream discharge, increase of bank storage and the volume of the aufeis accumulation. The difficulties of measuring discharge in a small stream are numerous; the depth of flow is often less than 1 foot, while the ice cover may exceed 5 feet or more. Penetration of access holes through the ice at times of high pressure results in vertical flow up the access holes and out onto the ice surface. Several discharge measurements on Goldstream Creek have been made but only during the summer and shortly after freeze-up. The discharge

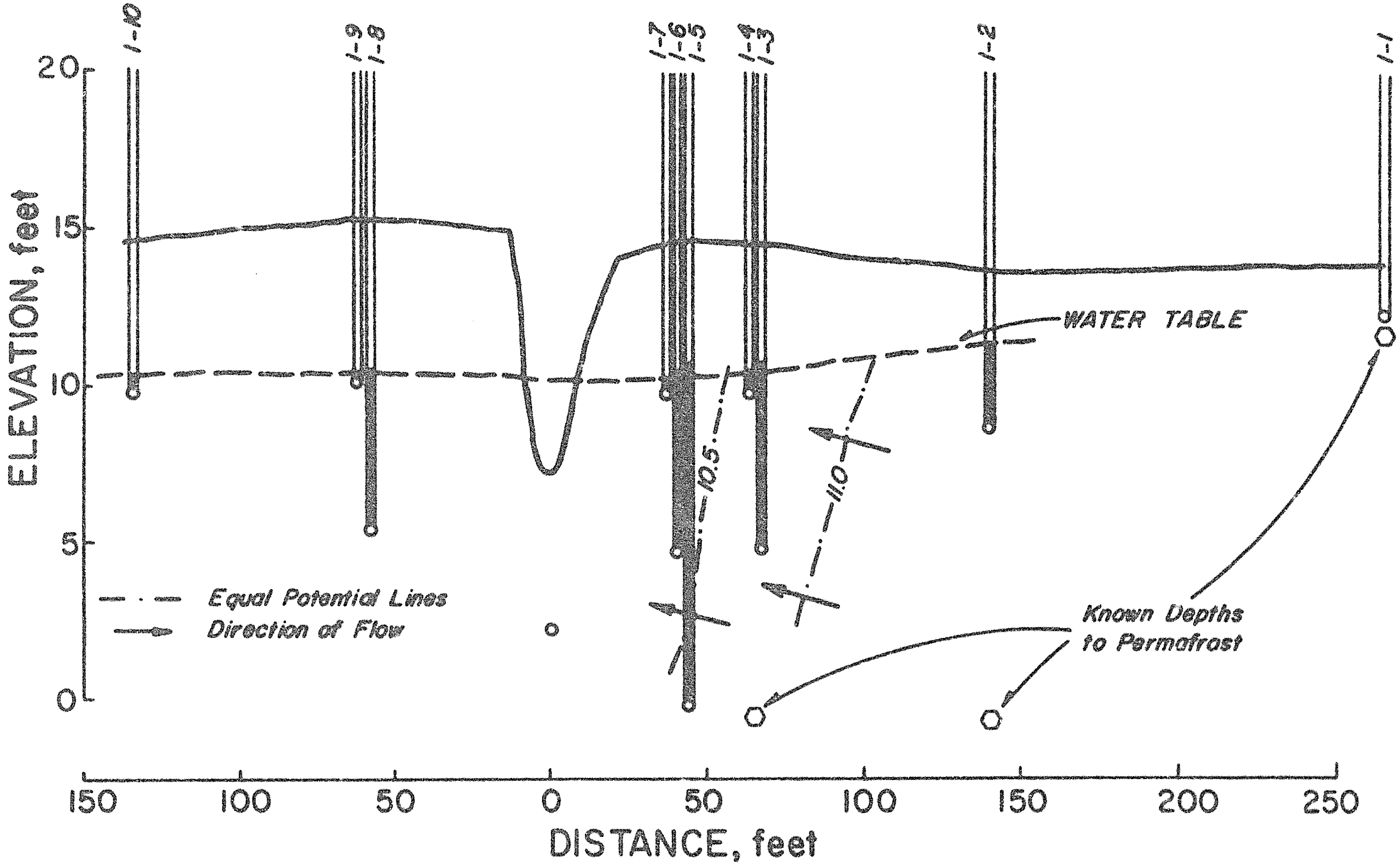


Figure 4. Cross-section showing the location and depth of piezometers, plus late summer flow conditions.

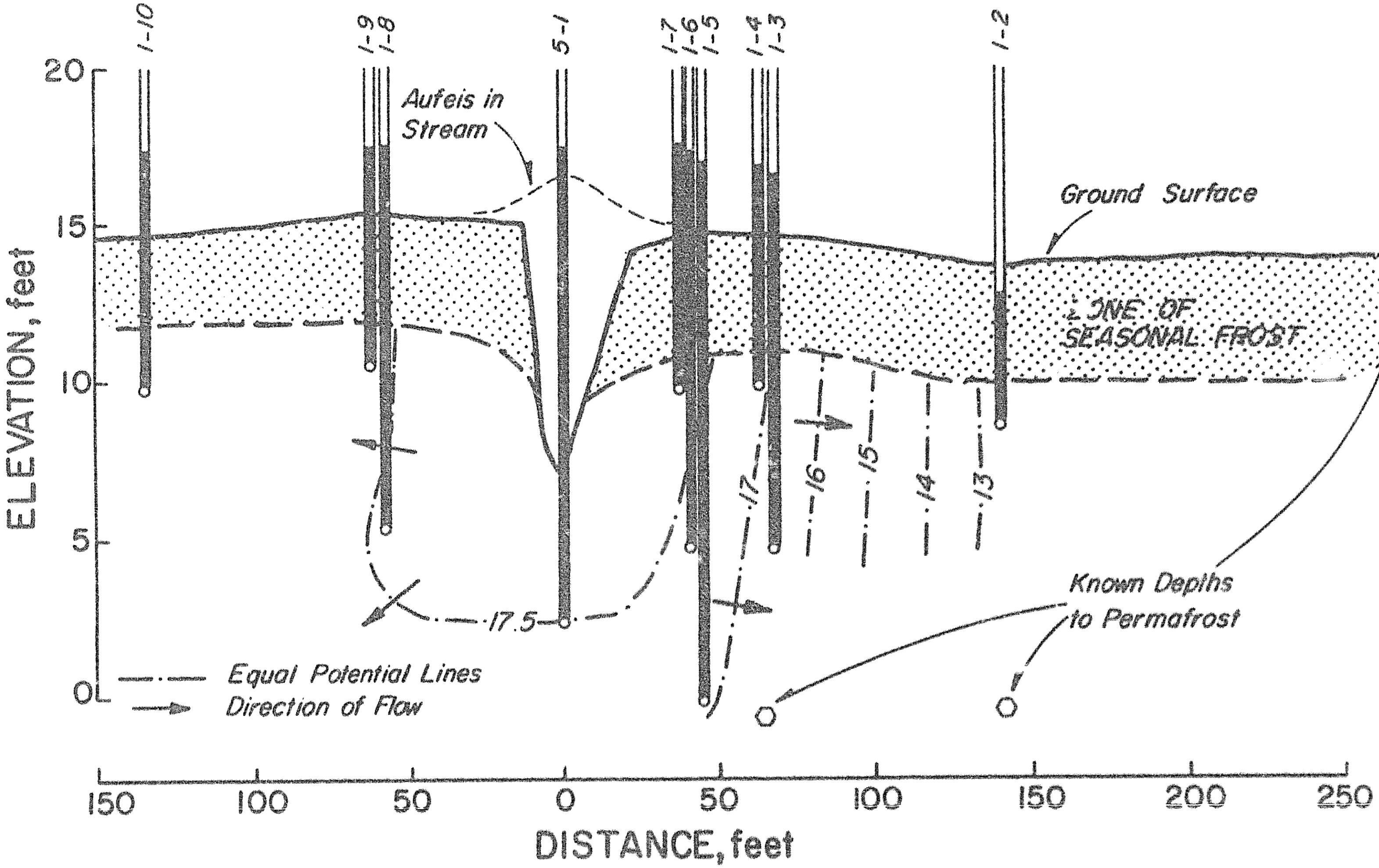


Figure 5. Same cross-section as in the previous figure except showing late winter flow conditions and the seasonal frost depth.

measured with total surface ice cover on 6 November 1971 was 22 cfs and on 3 November 1972 was 16 cfs. The discharge during the remaining period of ice cover would be less because of the increase in bank storage and the increase in the aufeis. For a small stream near Fairbanks, Kane and Slaughter (1972) estimated that the aufeis deposits along that stream constituted 40% of the winter streamflow. No estimate was made of the increase in bank storage.

Measurement of the unfrozen area available for channel flow below the aufeis cover was made on 17 March 1972, at two cross-sections. The area on a shallow reach of the stream showed a reduction of about 90% over the flow conditions that prevailed just prior to the development of an ice cover. No measurements were made of changes in the stream channel bottom.

## ENGINEERING SIGNIFICANCE

Although aufeis growth occur naturally, man's activity in an area will cause new icing growths or influence the size of existing icing growths. These icings completely fill culverts and stream channels and may flow onto the adjacent flood plain or over roadway surfaces. This hazard is not restricted just to the winter season. At the time of spring break-up, man-made drainage structures are either partially or completely filled with ice and no longer do they have the full designed capacity. Large areas upstream from crossings become flooded and eventually this water may spill over the roadways. Several thousand dollars are spent annually on the maintenance of roads in Alaska because of aufeis related problems.

To adequately design stream crossings such that aufeis growths are minimized or eliminated, the hydraulic flow conditions of the stream and the adjacent aquifer need to be considered. The results of this study show that the adjacent bank has a net increase in the volume of water stored during the winter and that flow in the stream is the source of this water. Generally, the largest values of hydrostatic head were measured near the stream; these values decreased at distances away from the stream. This indicates that there is a restriction of the flow in the channel resulting in increased pressures. Whether this fluctuation of pressure is due to an actual reduction in the cross-sectional area available for channel flow or unsteady flow conditions in the stream is unknown at this time. Likely, it is a combination of both.

Design criteria are needed such that the natural drainage of water, both surface and subsurface, can occur across an obstruction imposed by a crossing. In general, this means that crossings have to be designed to pass winter flow and to minimize the depth of the 0°C isotherm penetration within the drainage structure. The present practice now applied for small drainages is the installation of one culvert where the design is based on the peak discharge of a given flood event. During the winter these culverts flow partially full and are exposed to an atmosphere of extremely low temperatures.

New structures should be designed to carry the low winter flow and be protected from the extremely low ambient air temperatures. Elevated culverts can be used to carry peak flows. As long as structures impair the movement of water, increased pressure will develop and aufeis growths will occur.

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