An Investigation Into The Occurrence And Development of Groundwater In Permafrost Regions

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SUMMARY

This report represents a synthesis of information gathered from a review of published literature on the occurrence and development of groundwater in permafrost regions. The ways in which permafrost influences hydrological, hydrogeological, and hydrochemical aspects are briefly discussed. Long periods of cold in northern climates influence precipitation, water storage, infiltration and surface runoff patterns. The permeability of rock and alluvium and the boundary conditions of aquifers are uniquely affected by permafrost. Groundwater chemistry is altered by low temperatures and large thermal gradients near the surface; the term "cryogenous metamorphization" refers to certain chemical changes related to freezing of salt solutions.

The terms supra-, intra-, or subpermafrost water refer to groundwater occurring above, between or below permafrost. Direct evidence of each type includes observation of springs, icings, open reaches in otherwise frozen rivers, and mining and exploration drilling records. Indirect evidence is based on hydrological measurements of base flows in rivers.

Development of groundwater supplies for northern communities involves conducting hydrogeological studies using air photos, geophysical techniques, and test drilling to locate permeable aquifers and delineate permafrost boundaries. Specialized experience in interpretation of these techniques in permafrost regions is essential. Well field development, aquifer testing, and maintenance are also influenced by the presence of permafrost. Some examples of wells in permafrost areas are presented.

Icings form where groundwater emerges from slopes or flood plains; they threaten man-made structures, roads and bridges, although they are often caused by those very structures. Methods of control and prevention are discussed.

Research needs that relate to geotechnical aspects of groundwater in permafrost regions are presented.

TABLE OF CONTENTS

Page No.

LIST OF TABLES

LIST OF ILLUSTRATIONS

AN INVESTIGATION INTO THE OCCURRENCE AND DEVELOPMENT OF GROUNDWATER IN PERMAFROST REGIONS

1.0 INTRODUCTION

Economic expansion into northern regions in the last thirty years has stimulated strong interest in engineering problems associated with permanently frozen ground. One area of investigation that has received considerable attention is that of groundwater occurrence above, within, or beneath permafrost. Reasons for interest in this aspect of the northern landscape include the following:

1. The need to develop year-round water supplies that are free from contaminants and protected from sabotage in areas where surface water may be unavailable or scarce in winter;
2. To understand the causes of the formation of icings on roads, railroads, or adjacent to structures, and to develop ways of preventing them;
3. To expand hydrological, and hydrogeological understanding of permafrost regions.

The fact that groundwater exists in regions of continuous permafrost is surprising to many. However, travellers in northern regions reported phenomena associated with groundwater, such as icings, as early as 1828 (24). The surveyor and explorer for the Canadian Geological Study, J. B. Tyrell, reported on a "peculiar artesian well in the Klondike" in 1903 (13). Explorations for gold bearing gravels in the Yukon encountered groundwater beneath frozen ground, and utilized it whenever possible for placer mining and domestic water supply.

During the Second World War the strategic importance of Alaska and the Canadian North led to extensive research into all features of permafrost terrain. Muller (1944) (1), working for the American Military, conducted a review of the technical literature, including the Russian information that was available at that time. In subsequent years many researchers have studied the inter-action of permafrost and groundwater.

Cederstrom (2), Hopkins and Karlstrom (3) investigated groundwater distribution in Alaska in 1952 to 1954. R.J. Brown edited proceedings of several Canadian permafrost conferences in the late 1950's and early 1960's, which discussed groundwater occurrence. In 1963, Brandon (15) completed a hydrological study of groundwater phenomena in the Northwest Territories. Russian papers date back to the 1920's, with Petrov (1928) (1), and Tolstikhin in the 1930's and later. Today there are numerous researchers in Canada, the U.S. and U.S.S.R. who have published articles on groundwater in conjunction with permafrost. The First, Second and Third International Permafrost Conferences in 1963, 1973, and 1978, respectively, permitted exchange of scientific and engineering experience between all countries concerned with permafrost problems.

This paper consists of a review of major fields of study relating to groundwater distribution and development in permafrost regions. On the basis of the review, the following sections attempt to discuss significant aspects of hydrogeology, hydrogeochemistry, and evidence of groundwater flow, as a basis for understanding the phenomena. Engineering considerations on development of groundwater resources, and prevention of icings are then discussed in detail.

2.0 HYDROGEOLOGIC PRINCIPLES OF GROUNDWATER MOVEMENT IN PERMAFROST REGIONS

2.1 Distribution of Permafrost

Permafrost distribution in northern regions is governed by latitude, altitude, topography and climate. The nature of the interaction between these factors is fully discussed in many books and papers on northern regions, for example, Muller (1). In general, the areal extent and depth of permafrost increases from south to north, unless the climate is altered by some other influence such as a warming ocean current. In the far north permafrost is usually continuous, on high and low ground, in some places extending to 1000 m depth. In Sub-Arctic regions, permafrost may be limited to low lying ground, or to north facing or shaded slopes, and is of limited thickness. The effect on regional hydrogeology and hydrology is directly related to the extent and depth of permafrost.

2.2 The Hydrologic Cycle in Permafrost Regions

In Sub-Arctic and Arctic climates the rate of the hydrologic cycle differs from the cycle rate in temperate climates because the intense cold of winter and the dramatic change from winter to summer results in days of great hydrologic activity after months of hydrologic dormancy. Also, the presence or absence of permanently frozen ground significantly affects the recharge, storage and discharge parameters of the groundwater regime.

Recharge

Precipitation in the form of rain and snow is the fundamental means of recharge. It is usually measured as rainfall plus one tenth of snowfall. The amount of surface water in lakes and rivers, and the amount of water that percolates through pervious surficial deposits is dependent on the amount of precipitation. Throughout much of the Canadian Arctic and Sub-Arctic precipitation is low (18). For example, the mean annual precipitation of the eastern and northern parts of the District of Mackenzie Ranges from 150 to 300 mm per year. South of Great Slave Lake, in the Mackenzie Valley, and throughout most of the

Yukon, precipitation ranges from 250 to 400 mm. Some mountain ranges in the Yukon and Alaska receive much higher precipitation. Most of northeastern U.S.S.R. also has low precipitation (15, 18, 19).

Depsite the low precipitation much of the Arctic landscape appears to be very wet. This is due to the fact that surface runoff of the entire winter's accummulated precipitation occurs during a relatively short thaw season, and because the frozen ground prevents infiltration into groundwater aquifers. The active layer, or zone of seasonally thawing soil, is quite shallow so that it quickly becomes saturated and "swampy". Runoff ponds in numerous shallow lakes, which drain via surface streams, evaporate, or percolate through unfrozen deposits into groundwater aquifers.

Storage and Discharge

After recharge, water moves to storage and discharge. Recharge is not a continuous process, but discharge is, owing to the presence of storage facilities in every drainage basin. The water is stored in lakes, soil-water, groundwater, ground ice and glaciers. The mode of storage may change, as when glacier melt-water flows into a lake, or soil water held by capillary forces in the active layer moves to groundwater. The length of time water is stored ranges from days for stream bank storage, to centuries for glacier or ground ice storage.

The seasonal recharge-discharge relationship for most Arctic environments varies throughout the year. In February, recharge is in the form of snow and is stored on the land surface, lakes and glaciers. Discharge occurs as river runoff approaches a minimum. In May, recharge reaches a peak in the form of melting snow and ice, and rain, which goes into all types of storage. Discharge reaches a peak as snow and ice evaporation is at a maximum, evapotranspiration increases, and river runoff increases.

Recharge in August is in the form of rain and glacier melt. Discharge by evaporation declines, as does river runoff. In November, recharge in the form of snow goes to storage above ground, and evaporation ceases. Soil water freezes, groundwater discharged in springs may freeze in large icings, and river flows draw solely on lake and groundwater storage.

2.3 The Hydrogeology of Groundwater in Permafrost Regions

The Basic Hydrogeologic Model

In temperate regions the groundwater regime is initiated when surface water seeps into surficial soils and rocks under the influence of gravity. Water percolates through porous soils such as sands, gravels, or talus deposits, and through fracture zones, faults, fissures or solution channels in consolidated rock. Topographically high areas are regions of recharge, while topographically low areas tend to be areas of discharge. Thus the geomorphology of the surficial landforms and soil deposits, and the geology of the underlying basement rocks strongly influence the groundwater regime.

Discharge is commonly in the form of springs or overland flow directly into river channels or lakes. The "base flow" or minimum annual discharge rate of a river is often a measure of groundwater storage volume in a hydrogeologic unit (15). Figure 2-1 illustrates this basic model.

Influence of Permafrost on the Hydrogeologic Model

The presence of permafrost has two effects on groundwater flow:

(1) Low temperature increases the viscosity of the water and decreases the rate of flow, and,

(2) The permafrost increases the number of impermeable boundaries within a groundwater flow system (16).

Darcy's law is widely used to describe the rate of flow of a fluid through a permeable medium. It is written:

$$V_z = - k \frac{(dh)}{dz}$$

V_z = rate of groundwater movement (downward)

k = overall permeability

h = the total head, or the sum of elevation plus pressure head

For aquifers in temperate regions, the overall permeability is determined for groundwater at or near 10^{o}C. In cold regions it is necessary to write the more general expression for permeability to correct for increased viscosity at low temperatures.

$$V_z = - \frac{Ko\ Yw}{m} \left(\frac{dh}{dz}\right)$$

Ko = physical permeability constant

Yw = density of water

u = viscosity of water, a function of temperature

In temperate climates,groundwater temperatures range between 10^{o}C and 16^{o}C, with corresponding viscosities between 1.30 and 1.05 centipoise (cp). In Sub-Arctic or Arctic regions shallow groundwaters have temperatures ranging between 0^{o}C and 4.5^{o}C with viscosities 1.79 to 1.55 centipoise (16).

Therefore there is a 27 percent decrease in overall permeability as water cools from 10^{o}C to 0^{o}C, hence a 27 percent decrease in the rate at which cold water moves through equally permeable soils.

The presence of permafrost creates additional boundaries to the groundwater flow. It greatly reduces, and may even eliminate the surface area available for infiltration. In regions of continuous permafrost infiltration must occur through solution channels in karst rocks, through fracture zones, faults or fissures in bedrock, or through unfrozen permeable soils beneath large lakes or river channels (taliks) (7, 13, 15 16). Permafrost adds boundaries that confine flow in otherwise permeable deposits, and thus limits the area available for flow in transmission zones. Groundwater discharge may be restricted in areas that would topographically, be discharge ares.

Besides reducing the percentage of surface water that does infiltrate, the low ground temperature causes the formation of ice lenses within the soil. This increases the storage or retention capability of a hydrogeologic basin. If the permafrost regime is altered the ice lenses may either increase or decrease in size, altering the amount of groundwater discharged or stored. Changes in the rate of flow in an aquifer, as when water is pumped out, can alter thermal conditions, possibly causing the aquifer to freeze. Hydrogeologic conditions become very complex in permafrost regions due to the unpredictable ground thermal conditions and distribution of recharge areas.

Types of Groundwater in Permafrost Regions

With respect to its relation to permafrost, groundwater may be subdivided into three types (4).

(1) Suprapermafrost water which occurs above permafrost, either in the zone of seasonal thawing (active layer), or in unfrozen deposits beneath lakes or rivers. Permafrost serves as an impermeable base.

(2) Intrapermafrost water found between layers of permafrost, in the transmission zone between suprapermafrost water in taliks and subpermafrost water.

(3) Subpermafrost water occurring below permafrost. The permafrost may act as an upper impermeable boundary confining the water under artesian pressure or, the groundwater table may lie at a depth greater than the depth of permafrost.

All three types of groundwater are related to each other to some extent. The degree of interconnection depends on the regional and local geology and the distribution of the unfrozen zones, or taliks.

Taliks

Interconnection of supra, intra, and subpermafrost water occurs through unfrozen zones in the permafrost, called taliks. The distribution of taliks is of major significance in defining the hydrogeologic character of northern landscapes. The Russians have conducted research into the theory of formation of taliks, primarily with regard to their generic classification and the boundary conditions necessary for their formation (5).

Tolstikhin (5) reports that five types of taliks have been distinguished, depending on the nature of the process leading to their formation or preservation. These are: thermal radiation, underwater, chemogenic, technogenic, and vulcanogenic taliks.

Thermal radiation taliks are formed from the heat of percolating atmospheric precipitation. They are typical of areas of discontinuous permafrost, to the extent that their presence is a criterion for distinguishing between continuous or discontinuous permafrost. They usually provide reliable paths for groundwater feed. Thermal radiation taliks are most common in regions of high precipitation and mountainous relief, where high hydraulic gradients aid in circulating the water.

Underwater taliks are the main taliks in regions of continuous permafrost, although they are also present outside this region. Their formation may be associated either with the heating effect of a large body of water without percolation flow (large lakes) or with the effect of percolation flow, as occurs below riverbeds and certain lakes (5, 12, 14).

In continuous permafrost the underwater talik may or may not be connected to deep subpermafrost aquifers. The thermal balance between water temperature and quantity, permafrost temperature, and permeability of underlying deposits, are governing factors in the link between supra and subpermafrost water. Where rivers cut across fracture zones in bedrock, the percolation flow in the riverbed table constitutes a major interconnection between surface and subpermafrost water.

Chemogenic taliks occur as a result of the exothermal reactions of the oxidation of coal, sulfide ores, or other mineral constituents in the rocks (5,13,15). Technogenic (or anthropogenic taliks occur as a result of disturbance of the permafrost regime by engineering activities, such as formation of reservoirs or well construction (1, 20). Volcanogenic taliks are not widespread, but certain mud volcanoes on Alaska's north slope may owe their existence to volcanic heating of deep groundwaters or connate water (22).

The conditions necessary for the formation of taliks are related to size of watershed and quantity of water present, type of surficial soils and rocks, topography, climate, and permafrost conditions. There is an extremely close interdependence between these hydrological, hydrogeological and permafrost factors and the distribution of taliks.

Hydrogeologic Conditions in Continuous Permafrost

The effects of continuous permafrost on the overall hydrogeologic conditions of northern regions prove to be so significant that the Russians (7) have suggested they could form the basis for a subdivision of types of hydrogeologic structures into subtypes. Some of these subtypes include (7):

(a) Artesian basins in which continuous permafrost is not very deep, so that a fresh water zone exists beneath it;

(b) Basins in which the permafrost thickness is greater than the zone of fresh water, with saline water directly below the permafrost;

(c) Basins in which the permafrost thickness exceeds the thickness of the zone of fresh and saline waters, and is underlain by brines.

A further subdivision distinguishes between permafrost that has penetrated deeper than the depth of rock fissuring and that which has not. When negative temperatures persist to great depth in crystalline rocks, only regions of extensive tectonic fracturing will prove water bearing.

Water Bearing Characteristics of Rock Types

Hydrogeologic investigation in permafrost regions require an assessment of the permafrost extent and types of taliks likely to be present, as well as the water bearing characteristics of the unfrozen rock and soil that form the taliks. The basic water bearing characteristics of unconsolidated and consolidated rock types are described below.

Unconsolidated Deposits

The two main types of unconsolidated deposits are stream laid deposits (alluvial) and glacial deposits, both of which cover large areas of Canada, Alaska, and the U.S.S.R. (2). Unconsolidated marine deposits are really much smaller and are less important. Eolian deposits such as sand dunes exist in some regions, but groundwater in wells located on eolian deposits is nearly always obtained from alluvium beneath permafrost or from bedrock (17).

Stream Laid Deposits

Alluvium (a stream laid deposit) may be deposited in a variety of topographic forms. In flat-floored, gently sloping narrow valleys, the deposits are generally thin and poorly sorted, and are therefore poor water bearing formations. Some narrow valleys contain a relatively deep fill of alluvium, including sand and gravel which may yield large quantities of water (2). The presence of year-round rivers creates taliks through the permafrost, providing a means of transmission of river water into the underlying unconsolidated sands and gravels. The Tanana Valley in Alaska has alluvial deposits of 250 m depth, and permafrost depths of 81 m in the floodplain adjacent to the river (13). The groundwater resource in this situation is excellent. If the unconsolidated deposits are predominantly silt or till the water bearing characteristics are not nearly as good.

Glacial Deposits

Glacial deposits are extensive in northern Canada. These deposits occur in the Pre-Cambrian Shield area, with thicker deposits on the Mackenzie Plains. As water bearing formations, glacial deposits range from very poor to very good, depending on the distribution of coarser grained sands and gravels in the matrix of fine grained silts, rock flour, and clay (till). Glacial till can create a completely impervious barrier to downward percolation of groundwater. Careful investigation of the specific locality is required to identify deposits of coarser grained material.

Crystalline Rocks

In the igneous and metamorphic rocks groundwater can only exist in fractures, fissures or shattered zones. Thus, granitic rocks, dense basalt, rhyolite, gneiss, slate and schist generally contain little groundwater. In the more brittle rocks (granites and gneisses) fractures at depth remain open and water can penetrate to greater depths than in more plastic schists and slates (2). Impervious glacial tills on top of the crystalline bedrock of the Canadian Shield further reduce the ability of surface water to penetrate the rock. Negative temperatures persist in the rock to great depth in the continuous permafrost regions of northern Canada and Alaska (13). Thus, even in zones of fissured bedrock water is likely to freeze in fissures and prevent active circulation of groundwater. The absence of bedrock groundwater in the Canadian Shield area is demonstrated by the absence of measureable groundwater contribution to the late winter base flow of the rivers (15).

Sedimentary Rocks

Consolidated sedimentary rocks are generally bedded and may contain water in the interstices between the rock grains, in fissures and fractures, or in solution cavities in the rock itself. In northern Canada, active groundwater flow systems in undisturbed sedimentary basins extend to great depths (13, 15). For example, the Mackenzie River Plains Region is composed of flat lying sedimentary rocks consisting mainly of limestones, dolomites and shales. Some of the carbonate rocks contain solution channels through which there is considerable groundwater flow, although most groundwater movement is along joint planes. The overall permeability of sedimentary rocks is higher than the crystalline rocks of the Pre-Cambrian Shield, and groundwater flow occurs at much greater depths.

Fine grained sedimentary rocks such as shale may have a very low permeability and may prevent water from seeping down to the regional groundwater table, thus creating a perched water body. Sandstones and conglomerates that are too tightly cemented may not yield as much groundwater as would be expected of these rocks.

Water may be trapped in sedimentary rocks during the deposition process. This water (connate water) is often saline, especially where the sedimentary rock was deposited in a marine environment. It may exist at great depths, and is generally not part of the active groundwater flow system. Certain springs in the Canadian Arctic Archipelago, such as the Gypsum Hill Springs on Axel Heiberg Island, may be due to the expulsion of connate waters from sediments undergoing compaction (13).

Hydrodynamic Regime

The term "hydrodynamic regime" as used here refers to the piezometric pressure conditions occurring in active systems of supra, intra, and subpermafrost groundwater.

The suprapermafrost water horizons are fed by atmospheric precipitation such as rain, melting snow and ice, which percolates through the active layer during the summer months. If it is not confined by overlying impervious soils it will not be under pressure. During the freezing of the active layer in early winter, suprapermafrost water may be confined between the upper seasonal frost front and the underlying permafrost, and significantly high hydraulic pressures can result (1). The magnitude of the pressure depends on the rate of frost penetration and the elevation and extent of surrounding slopes (1). Further discussion on the icing phenomena associated with such pressure build-up is presented in Chapter 4.

For suprapermafrost water in open taliks beneath rivers, streams and lakes, the piezometric conditions reflect the surface water levels, river stage, etc. Measurement of pore pressures in stream bed deposits is one of the only ways to estimate the direction of flow, flow rate, and volume of water moving through such taliks (12).

Intrapermafrost water may exist in closed taliks beneath frozen lake depressions or river terraces: piezometric levels are normally controlled by the river or lake level before freezing, and post-freezing pressure fluctuations are small. In completely closed taliks of long standing, the water pressure is usually very low. High pressures are generated only when the talik freezes and its thermal and chemical regime is unstable (4).

For intrapermafrost water in transmission zones between supra and subpermafrost waters the pressure regime is complex. If water is descending it will not be under pressure, and piezometric levels will be less than hydrostatic. If water is ascending, it will be under pressure, with piezometric levels greater than hydrostatic (4, 14). This fact was used by Kane et al (14) to demonstrate that subpermafrost groundwater was the source for a central Alaska lake. If the direction of water movement varies the pressure regime will be mixed.

The regime of subpermafrost waters varies. In certain valleys of the Yukon and Alaska water percolates through unfrozen areas on the south facing slopes into aquifers below thick permafrost in the valley bottoms. Artesian pressures may be quite high and may present problems for well construction (20), as discussed in Chapter 5.

In large artesian basins underlying permafrost the measured piezometric head of upper subpermafrost water may be lower than would be expected from the altitudinal relationship between recharge and discharge zones. Tolstikhin (5) suggests at least two reasons to explain these low pressures, namely: the decrease in volume of the groundwater occurring as a result of geochemical alteration of the water (such as incorporation into hydrated mineral forms); and the increase in pore space volume as a result of degradation of the lower boundary of the permafrost. The latter is the probable cause in many cases. The decrease in permafrost thickness has lead to a sharp reduction in stratal pressures of the upper subpermafrost waters. The overall permeability of the subpermafrost strata, as well as the nature of the recharge mechanism and availability of recharge water also influences the piezometric levels measured in large (regional) hydrogeologic basins.

Table 2-1, Classification of Groundwater in the Permafrost Regions, from Tolstikhin (5) summarizes the hydrogeological aspects of mode of occurrence, source of supply, and regime of groundwater systems.

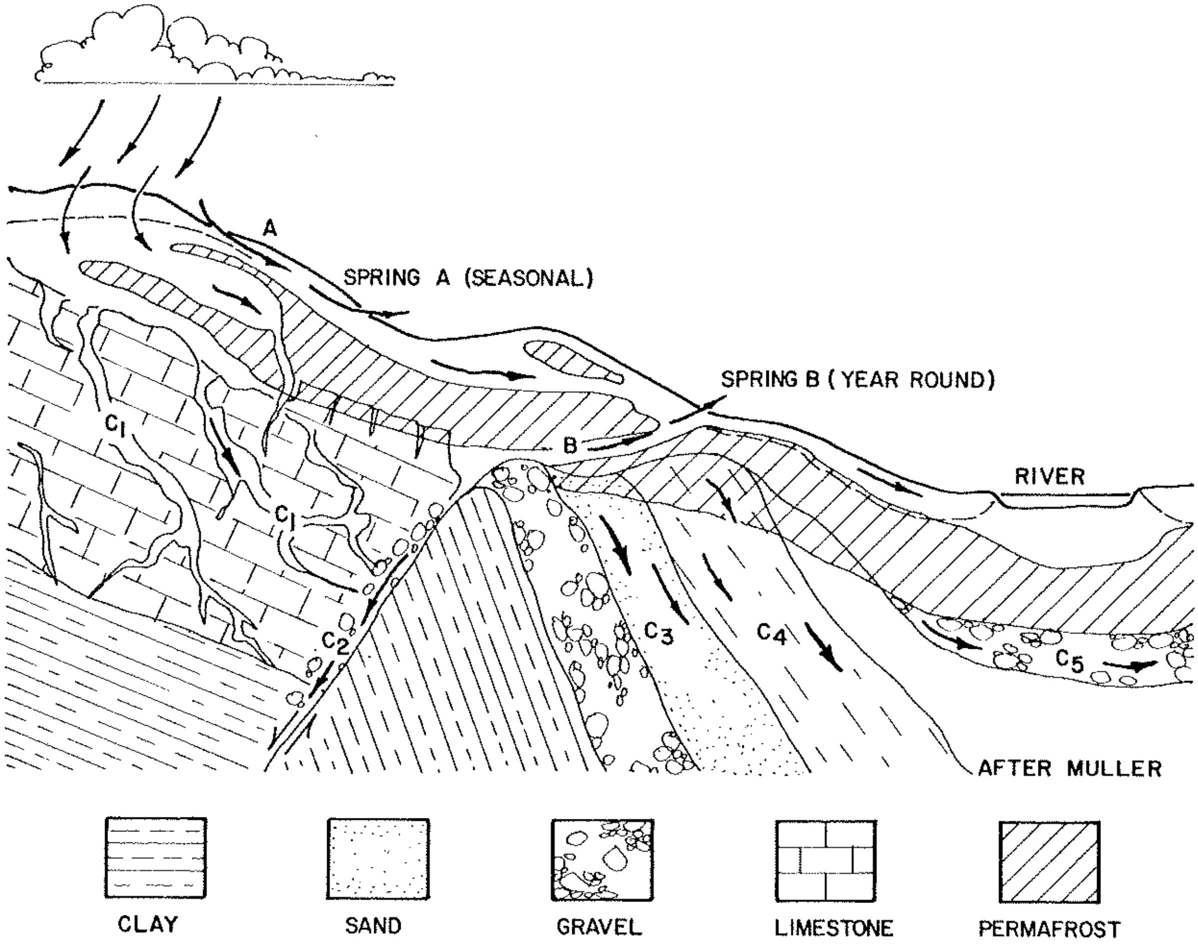
Table 2.1 Classification of Groundwater in Permafrost Regions (after Tolstikhin (5))

Type	Position in cross section	Location of water-bearing rocks	Main Source of supply	Predominating pressures and regime	Temperature
Supra-permafrost	Active layer (vadose water)	Talus deposits and bold mountains	Atmospheric precipitation and condensation	Seasonally frozen, not subjected to pressure, may be subjected to pressure on freezing; descending ground-water	+
		Mountain slopes	Atmospheric precipitation		+
		Flat water divides, plains, river terraces and flood plains	Atmospheric precipitation, river water		+, rarely-
	Active layer and closed taliks	Plains and river terraces, at the foot of moun-tain slopes, floors of lake depressions (above base level of erosion)	Atmospheric precipitation	Undergoes partial seasonal freezing, not subjected to pressure, or subjected to pressure temporarily on freezing; descending groundwater	+, rarely-
	Closed taliks	Alluvial fans	Atmospheric precipitation and surface water (from rivers)	Non-freezing, subjected to weak pressure or no pressure at all (in taliks below lakes and rivers)	+
		Below lakes	Surface water (from lakes)		+,-
		Below riverbeds and low terraces	Surface water and water from open taliks (from their suprapermafrost part)		+
		Sea Coasts	Atmospheric precipitation and sea water	Subject to pressure during freezing only	+,-

Table 2.1 Classification of Groundwater in Permafrost Regions (after Tolstikhin).

Table 2.1 (Continued)

Type	Position in cross section	Location of water-bearing rocks	Main Source of supply	Predominating pressures and regime	Temperature
Intra-permafrost	Completely isolated taliks	Various types of relief and geological structure	No recharge from outside	Subjected to weak pressure or no pressure at all	-
	Closed taliks	Floors of lake and alas depressions which freeze throughout	Surface water	Subjected to pressure	+,-
	Closed taliks	River terraces	Surface water (rivers), less often water from open taliks	Subjected to pressure	+
		Fractured zones cutting across various elements of relief	Surface water (where fractures cut across river valleys)	Non-freezing, subjected to local pressure or no pressure at all	+
	Open taliks	Taliks below lakes	Surface water Subpermafrost water	Subjected to weak pressure Subjected to pressure; ascending groundwater	+
		River valleys (below riverbeds and flood plains), mountains	Surface water or subpermafrost water	Descending or ascending groundwater	+
		Plains	Same	Descending or ascending groundwater	+,-
		Alluvial fans, fractured zones	Subpermafrost water or surface water	Descending or ascending groundwater	+,-
Sub-permafrost	Linked with open taliks	Intermontane depressions		Subjected to fairly stable pressure	+
		Flat mountains and mountain ridges	Surface water	Subjected to changing pressure	+
		Karst Massifs		Subjected to changing pressure	+
	Not linked with open taliks	Plains and platforms	water which occurs at great depths	Subjected to pressure, stable regime.	+,-



---- DEPTH OF SEASONAL FROST

A SUPRAPERMAFROST GROUNDWATER

B INTRAPERMAFROST GROUNDWATER

C SUBPERMAFROST GROUNDWATER

C_1 WATER IN SOLUTION CHANNELS

C_2 WATER ALONG FAULT FISSURE

C_3 WATER IN POROUS ROCK (AQUIFER)

C_4 WATER IN ROCK JOINTS AND FISSURES

C_5 WATER IN ALLUVIAL DEPOSITS

FIGURE 2.1 DIAGRAM SHOWING OCCURRENCE OF GROUNDWATER IN PERMAFROST REGIONS.

3.0 HYDROCHEMISTRY OF GROUNDWATER IN PERMAFROST REGIONS

Certain chemical reactions occur between mineral elements in the soil or rock and water percolating through the pore spaces that strongly influence the quality of groundwater. Quality is defined in terms of the quantity and type of dissolved minerals, the chemical reactivity of the water (acidic or basic), and the taste, odour, colour and turbidity of the water. In depth discussion of topics relating to hydrochemistry of groundwater may be found in any text on groundwater hydrology, such as Todd (1959) (27) or the Unesca publication (1977) (26). The following paragraphs briefly review some fundamentals of groundwater hydrochemistry, but stress those aspects that illustrate the influence of permafrost on water quality.

General Hydrochemistry

The basic factors that influence groundwater quality, regardless of climatic conditions, are:

1. The chemical nature of the source water;
2. The chemical nature of the rocks and soils of the aquifer;
3. The altitude, extent, depth, and permeability of the groundwater flow system.

The degree of mineralization is one measure of water quality. It is measured as the mass of dissolved solids per unit volume of solution (milligrams per litre). Dissolved solids are primarily salts of calcium, magnesium, sodium and potassium cations with carbonate, bicarbonate, sulphate, chloride and nitrate anions. Less abundant minerals include iron, manganese, and others, as listed in Table 3.1. Depending on to what degree certain minerals predominate, the water can be described as "hard", referring to calcium and magnesium content, "alkaline" referring to carbonate, bicarbaonte and hydroxyl anion content, or "saline" referring to chloride content. Excessive amounts of any minerals may preclude use of the water for domestic or even industrial use without treatment.

The presence of ions imparts electrical conductivity to mineralized water, so that measuring the conductance of a water sample is a rapid means of measuring degree of mineralization. Laboratory chemical analysis is still required to determine the type of ions in solution. Since groundwater is invariably more mineralized than surface water, conductance measurements are used to indicate the magnitude of groundwater contribution to a river. The hydrologist must simply know the average conductance readings of undiluted groundwater in a region, and then compare those values with readings obtained from more dilute river water. Brandon (15) used conductance measurements to determine the groundwater contribution to rivers in the Yukon and Northwest Territories.

Near-surface or suprapermafrost groundwater may have high levels of organic compounds, such as humic acid, as well as abundant oxygen and carbon dioxide. Such water may be relatively aggressive or acidic, and will act quickly to dissolve minerals in the weathered surface rock. Salts are precipitated out of solution during freezing of groundwater in icings, but are quickly redissolved by such aggressive surface water. Thus the quality of the surface water influences the quality of groundwater.

The chemical nature of the rock or soil also influences groundwater quality. Limestone and dolomite rocks yield easily soluble carbonates and calcium, and produce "calcic" water. If pyritiferous minerals are present, as they may be in limestone, shales or granites, sulphate mineralization occurs, sometimes producing enough heat in the exothermic reactions to result in hot springs. Water percolating through saline rock types, through gypsum or mineral deposits will take the corresponding minerals into solution. The degree of mineralization will depend partly on the length of time water is in contact with the rock.

Tolstikhin (4) presents data that demonstrates that there is a change in relative abundance of certain salts with altitude in mountainous regions, as shown in Figure 3.1. At higher elevations sodium and chloride ions are more common, while at lower altitudes calcium, carbonates and sulphates predominate. An explanation may be that water at lower elevations has had more time to dissolve the less soluble salts of calcium and magnesium while at higher elevations the easily soluble sodium salts predominate.

Brandon (15) was able to distinguish which rock formation of several possibilities was the aquifer for certain springs by comparing groundwater mineral content with the predominant minerals in the formations. Knowledge of the extent and depth of the rock formations then leads to an estimate of the flow rates through the aquifer.

Influence of Permafrost on Groundwater Quality

The mineralization of groundwater is affected by the presence of permafrost and seasonal freezing of aquifers in the following ways (13, 25):

1. Increased residence time for reactions between groundwater and the enclosing rocks;
2. Reduced temperatures retard chemical reactions, with the exception of increased solubility of CO_2 at lower temperatures, which allows for somewhat higher saturation concentrations of calcium and magnesium bicarbonate. Solubility of gypsum (anhydrite) also increases with decreasing temperature, although reactions are retarded (13).
3. The physical interruption of mixing waters of different chemical composition, such as seawater and fresh groundwater.
4. Change in the mineralization and composition of groundwater under the influence of freezing or thawing, referred to as "cryogenous metamorphization" in the Soviet literature.

Williams and van Everdingen (13) report that the role permafrost plays in influencing groundwater quality is probably minor. In contrast, Anisimova (25) states that the process of freezing of mineralized groundwater in the soil matrix of the active layer, or in spring icings, is responsible for definite chemical changes in groundwater, and in the subjacent permafrost.

There is marked seasonal variation in water quality due to seasonal reduction in fresh recharge and possibly because of fractionation by freezing of a part of the aquifer. Water quality measurements taken in sub-riverbed aquifers in Alaska reveal marked increases in dissolved mineral content when recharge ceases in the fall. During the winter, the concentration of dissolved solids increases in the unfrozen part of the aquifer as seasonal frost penetrates; in the spring, renewed dilution by infiltration of snow-melt reduces the concentration to summer levels (13). Anisimova (25) notes an exception to the latter statement. In some springs, salts are precipitated out of solution during the freezing period, and are redissolved during the beginning of the thaw runoff. Thus the mineral concentration in the early runoff increases as the flow increases, until excess salts are removed by solution or washed away as solids.

According to Anisimova (25), the increased mineralization of suprapermafrost groundwater during the seasonal freezing is also partly due to the migration of salt ions from the freezing front down toward the warmer layers of water. A persistent downwater migration occurs under the effects of gravitational and thermal gradients and diffusion. Thus, sodium, calcium and magnesium chloride salts gradually accummulate in the unfrozen pore water in the subjacent permafrost. Increased solute concentration depresses the freezing point of the pore water so that the soil thaws at a negative temperature. In geologic time, pockets of highly saline negative temperature water, called "cryopegs" form within a body of permafrost (5, 25, 28, 29). Anisimova (25) and Tolstikhin (5) report that borehole drilling records clearly demonstrate this salt enrichment of the upper permafrost zones. Studies done by Pisarskiy et al (9) confirmed the relative increase in sodium ions in lower ice layers of a naled (icing).

A reverse movement of chloride salt ions from the subjacent permafrost back into the active layer pore water during the thaw season only occurs under very warm conditions, and is probably insignificant (25).

Mineralized groundwater undergoes some chemical changes when it freezes as part of a spring icing. As its temperature drops the least soluble salts are precipitated out of solution as distinct crystals. In this way, icings at groundwater discharge points act as chemical barriers, preventing the passage of salts into surface runoff. Estimates of the quantity of salts precipitated annually in Yakutia, U.S.S.R., are substantial, ranging from 2×10^3 to 15×10^3 tons/year (25). These precipitates later redissolve in the surface runoff over an extended period. If measurements of river water mineralization are used to estimate groundwater contribution to total discharge, the effects of precipitation and resolution near icings should be considered, especially if quantities of precipitates are as large as the Russian literature suggests.

The process of cryogenous metamorphization described above is probably insignificant in deep subpermafrost aquifers. However, subpermafrost groundwater quality is indirectly affected in that the aquifer must be recharged from suprapermafrost or surface water.

MAJOR CONSTITUENTS		MINOR CONSTITUENTS
COMMON CATIONS	COMMON ANIONS	
Calcium (Ca)	Carbonate (CO3)	Iron (Fe)
Magnesium (Mg)	Bicarbonate (HCO3)	Aluminum (Al)
Sodium (Na)	Sulphate (SO4)	Silica (SiO2)
Potassium (K)	Chloride (Cl)	Boron (B)
	Nitrate (NO3)	Fluoride (F)
		Selenium (Se)

Table 3.1. Chemical constituents of groundwater, from Todd, (1959) (27).

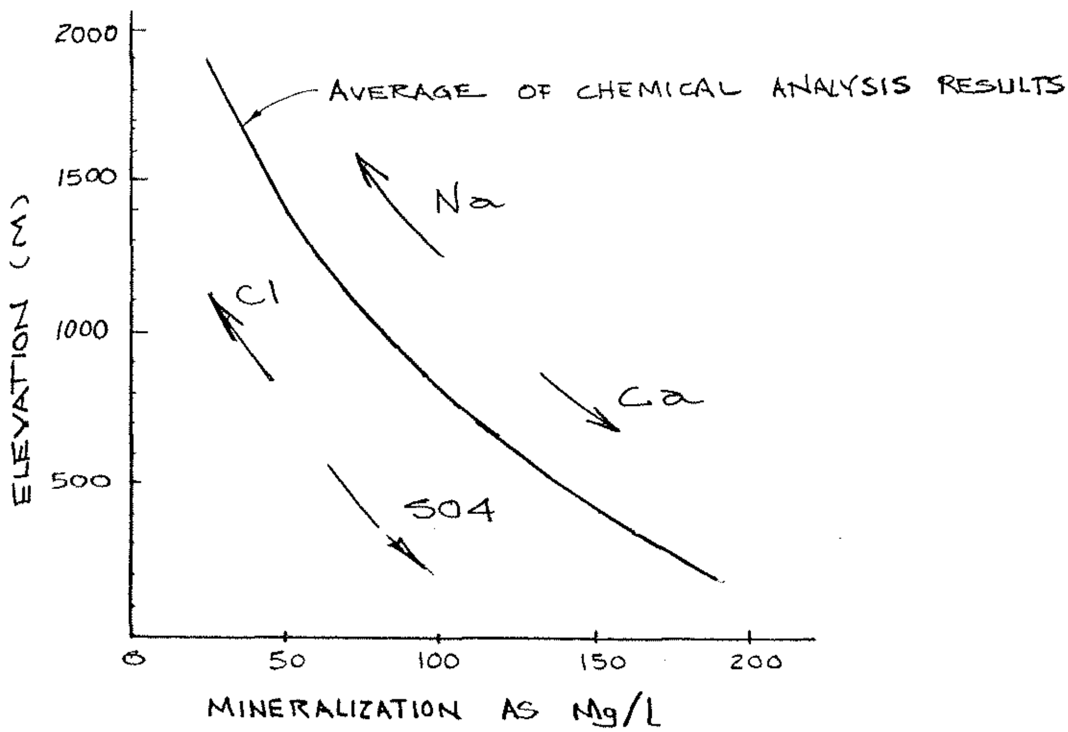


Figure 3.1. Changes in mineralization and composition of groundwater with elevation, after Tolstikhin (1974) (5).

4.0 EVIDENCE OF GROUNDWATER IN PERMAFROST REGIONS

The fact that groundwater flow systems exist in regions of permafrost can be illustrated by the following: (13, 16)

a) Direct observation of springs and their associated icings;
b) The presence of salt mineral deposits and halophytic plants in places where mineralized ground water emerges;
c) The presence of open water in otherwise frozen rivers;
d) Contribution to base flow and dissolved mineral contents of streams, and;
e) Mining and drilling records.

The number of manifestations of groundwater movement decreases from south to north, but even in the continuous permafrost of the high Arctic there are occurrences of springs (3, 7, 11, 13).

Springs and Associated Icings

In permafrost regions the occurrence of freshwater springs is related to the freezing or thawing of the transmission zones. They may be fed from either suprapermafrost or subpermafrost aquifers. Two major types of springs may be defined on the basis of their location and conditions of discharge, namely: subaqueous springs in riverbeds or lakes; and springs at the foot of terraces, alluvial fans, or on piedmont slopes. A third distinction may be made on the basis of temperature, i.e., thermal spings (1, 4, 5, 7, 13, 15).

Subaqueous Springs in Riverbeds

These springs are the most commonly encountered type of spring. River channels and lakes are the lowest points (locally) in hydrogeologic basins, and the above zero temperature of the water protects the outlet from freezing. Tolstikhin (4) and other authors (1, 13, 24) suggest three causes of subaqueous springs:

a) A change in the cross-section of the sub-bed groundwater flow because of an abrupt reduction in the thickness or permeability of the alluvium (see Figure 5-4).

b) A discharge of water ascending in a fault or fissured water bearing zone; or

c) An abrupt change in bedrock and permafrost conditions in the riverbed.

In summer, subaqueous springs are noticeable as the cause of a sudden increase in river discharge, or a lake or bog with no surface water inflow. In winter they may create open water reaches in otherwise frozen rivers. An example of this is the large spring on the Fishing Branch of the Porcupine River north of the Ogilvie Mountains, Yukon Territory, which issues water at 4.5°C, with an ice-free reach extending 30 km downstream (13). The above freezing temperature of the water suggests that the subsurface path of the water must pass well below the base of the permafrost. The warmed subpermafrost water rises through carbonate rocks and coarse alluvium.

Less powerful subaqueous springs will form an ice-free pool surrounded by ice. If suprapermafrost water is flowing through pervious alluvium in the stream bed, and is forced to rise by a change in the bedrock or permafrost profile, it will emerge from the most permeable spots in the floodplain. Numerous small icings and ice mounds appear, which eventually coalesce into a single icing. River icings of this sort may grow to enormous size and engulf bridges or even towns (1, 8, 9, 10, 12, 23, 24). Their severity increases in colder weather as deep freezing of the alluvium forces more water to rise to the surface.

Kane and Slaughter (14) demonstrated that a bog lake in a swampy area in central Alaska was fed by subpermafrost water rising under artesian head through taliks beneath the lake. Recharge of the subpermafrost aquifer was accomplished through thermal radiation taliks on the south facing mountain slope above the valley. The researchers measured piezometric pressures at various depths beneath the lake. If a lake is entirely underlain by permafrost, there can be no vertical flow component and fluid potential will not vary with depth; if a difference in fluid potential exists, fluid must flow from zones of higher potential to zones of lower potential, and a thawed transmission zone is indicated.

If the discharge rate is small and no distinct channel or pond forms for the runoff, the term "seepage" rather than spring is used. The ground may become saturated during the summer months, as evidenced by an abundant growth of hydrophylic plants. However, if the rate of evaporation exceeds the rate of groundwater inflow, an accumulation of precipitated salt mineral develops in the soil, and only halophytic plants, for example, horsetails, will grow (15). In winter, seepages give rise to the formation of ground icings, which are formed by the successive build-up of thin layers of ice. Ice mounds or hydrolaccoliths may also develop, although that phenomenon is also associated with other types of springs.

Springs at the Bases of Slopes

On long gentle slopes suprapermafrost water percolates through the active layer in the summer. Depending on local topography, soil permeability, and variations in the thickness of the active layer, water may be focussed into general discharge areas, forming springs. If permafrost on slopes (usually south facing) is discontinuous or shallow, water may circulate through relatively deep taliks and transmission zones before exiting at some lower elevation on the slope, either seeping from a large area or concentrating in a single spot. The discharge location will be related to the freezing and thawing of the transmission areas. Springs on slopes usually occur above the base erosional level: their discharge rates may fluctuate, or cease entirely during the winter.

During the winter, icings form at the site of these springs, and the discharge zone may migrate as freezing seals off successive outlet areas. The presence of the ice actually prevents the talik or aquifer from freezing back into the slope. Water emerging at the base of a slope, say adjacent to a stream floodplain, may continue to flow under the seasonal frost in the active layer of the floodplain. The distance travelled depends on the temperature and pressure regime of the spring. An ice lens may form at the new freeze point, which will continue to grow as long as water continues to seep past the normal discharge point. The lens may force overlying soil up in a small dome or blister, causing vegetation to lean in all directions. These relatively small seasonal mounds are termed hydrolaccoliths (23).

Open system pingos are another manifestation of the presence of groundwater adjacent to permafrost. They differ from hydrolaccoliths only in that they persist through two or more winters, and may grow quite large. A prime requirement for the formation of open system pingos is a restricted groundwater flow; too large a flow would prevent freezing of the pingo (13).

Another phenomenon associated with groundwater on long slopes occurs when water in the active layer becomes confined beneath seasonal frost in early winter and hydrostatic pressures increase at lower elevations on the slope. Muller (1) describes how the presence of a heated building, or even a sunwarmed barrel, may thaw a "window" through the confining frost layer, so that water rises under pressure into the building or around the barrel, as illustrated in Figure 4-1. Houses have been filled to the eaves with ice by this kind of spring.

Thermal Springs

Water issuing from most springs in permafrost areas ranges in temperature between $0^{\circ}C$ and $4^{\circ}C$. For example, subpermafrost water in the Fairbanks area is usually around $1.7^{\circ}C$ (14). Thermal springs are those in which the water temperature is higher than normal, i.e., about $4^{\circ}C$. Brandon (15) defines a "normal" thermal spring as one in which the water is warmed by deep circulation where the geothermal gradient accounts for the heat input. Thus, the large spring on the Fishing Branch of the Porcupine River, with a temperature of $4.5^{\circ}C$ would be a normal thermal spring. Much warmer spring waters result from exothermic reactions of water with minerals in the rock, such as coal or pyrites, from the residual heat content in active tectonic fault zones, or from relatively young igneous intrusions or volcanic activity (5, 13, 15). Where the geologic structure does not allow for deep circulation, anomalously high groundwater temperatures are most likely due to exothermic reactions in the rock.

The dissolved mineral content of thermal spring water is often very high. Upon cooling, certain minerals precipitate out of solution. Thus, deposits of travertine (calcite) and sulfates often mark the location of these springs. Brandon lists numerous examples of thermal springs in the Yukon and Mackenzie Districts (15).

Hydrological Evidence of Groundwater Flow

The contribution that groundwater discharge makes to the river flows in Arctic Regions is measured in two ways:

a) Hydrograph records of winter base flow;

b) Chemical analyses of river waters.

The lowest annual flow rate in a river occurs during late winter, when surface water input is non-existent. The flow that remains is derived from lake storage and groundwater storage. An analysis of the physiographic features of a hydrogeologic basin must be made to determine what percentage is due to groundwater. Thus, in the dense crystalline rocks of the Canadian Shield, where lakes are numerous and springs rare, it is safe to assume that winter base flow rates are primarily due to lake storage. In areas where there are fewer lakes but evidence of springs or icings, it is evident that most of the base flow must come from groundwater storage. Brandon (15) used the above approach to establish that groundwater contributes little to base flows in the Canadian Shield Rivers, but contributes significantly to base flows in the Mackenzie Plains and Cordillera Rivers.

If chemical analyses are made at frequent intervals throughout the year it is possible to note the change in dissolved mineral content of the river water. Dissolved mineral content will be highest when the groundwater component is least diluted by less mineralized surface water. The most direct method of measuring dissolved mineral content is to measure the conductance (15). If the hydrologist knows the approximate conductance of groundwater in the area, he can compare that value with the river water readings, and arrive at an estimate of the proportion of flow that is due to groundwater discharge.

A significant volume of groundwater is retained in icings, and only large subaqueous springs will maintain year round flow in excess of the volume of water held as ice. Therefore the actual groundwater reserve in a watershed may be much larger than is apparent from either the river base flow or mineral content. It is necessary to consider the amount of change over the year. For example, if the dissolved mineral content changes little, then there is little groundwater contribution to river flow. An aerial reconnaissance conducted in winter will provide an assessment of the number of icings, hence the relative abundance of groundwater in the region.

Drilling and Mining Records

The presence of groundwater flow systems can be conclusively established by the drilling records. Drilling for gold and mineral exploration was conducted in the Yukon Territory and Alaska early in this century (2) and, more recently, extensive drilling for oil and gas has been conducted in the Mackenzie District. The geological and cryological profile can be established and water bearing horizons noted. As early as 1904 drillers had noted the presence of artesian water beneath permafrost in the Yukon (13). In some cases, the artesian pressures creates serious problems for drilling, with risk of uncontrolled flow occurring (2). Extensive drilling in the Fairbanks Area of Alaska has delineated the local geology and permafrost distribution and led to an understanding of the hydrogeology of a region can not be obtained without some drilling to supplement information obtained in other ways.

Information on the presence of groundwater can also be obtained from mines. For instance, water is not found in the upper drifts through permafrost on the Con Mine in Yellowknife, but is found at deeper levels beneath the lake, where water descends through unfrozen fissures in the rock (15). In the Razdel'ny Mine of Vaigach Island, U.S.S.R., a small horizon of saline intrapermafrost water was exposed at a depth of 49 m. The inflow of water was at first insignificant, but movement of the water caused the flow channel to expand by melting ground ice, and the mine was eventually flooded. Thus, mining experience and exploration programmes can yield useful information on groundwater conditions in the region being studied.

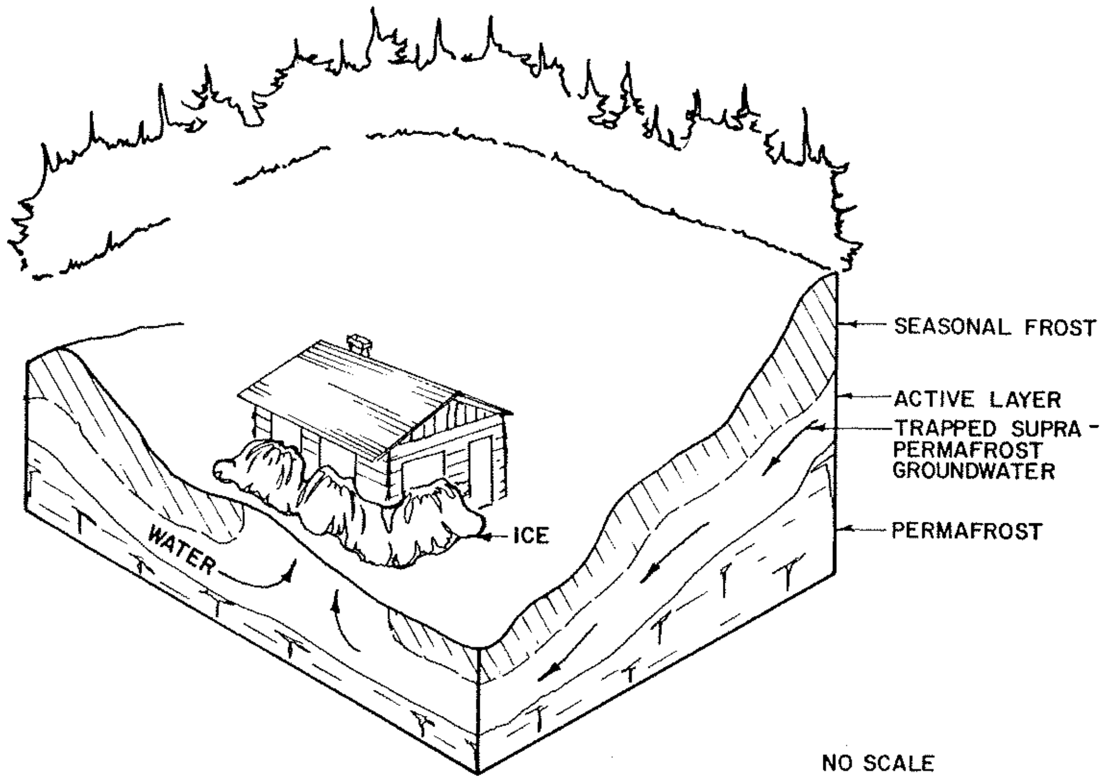


FIGURE 4.1 DIAGRAMMATIC SKETCH OF ICING CAUSED BY FREEZING OF THE ACTIVE LAYER, WITH WATER BEING FORCED THROUGH UNFROZEN ZONE BENEATH HEATED BUILDING. AFTER MULLER (1947) (1).

5.0 ENGINEERING PROBLEMS RELATING TO GROUNDWATER IN PERMAFROST REGIONS

The fact that groundwater is present even in the severe climatic conditions of the far north is both an advantage for engineering development and a source of serious problems. It is an advantage in that groundwater may provide good quality water for individual homes, small communities, remote construction camps or major industries. Even groundwater of poor quality may be useful for industrial or mining uses, or for emergency fire protection supplies. Problems arise when groundwater emerges where it is not wanted and forms very large icings which may cover roads or bridges, making them impassable or possibly destroying them. In the last three decades Russian, American and Canadian engineers and scientists have accumulated considerable practical experience in development and control of groundwater in regions of permafrost.

5.1 Development of Groundwater Supplies

Despite an apparent abundance of surface water in Arctic Regions, it is often preferable to develop groundwater supplies. Many of the lakes and rivers freeze to the bottom in the winter, and even when they do not the stagnant water below the ice may be unsuitable for domestic use, or of limited quantity. Even near major rivers such as the Tanana and Yukon Rivers in Alaska, or the Mackenzie River in Canada, the heavy silt load (turbidity) makes the water unsuitable unless it is extensively treated. Water intake structures in rivers are expensive and must be protected from freezing and ice damage. Groundwater supplies have the advantages of: (1) constant temperature greater than $0^{\circ}C$; (2) lower construction and maintenance costs because intake structures, filtration plants, and (if the wells are spaced carefully) lengthy pipelines are often unnecessary; (3) they are less vulnerable to sabotage or vandalism and are usually safer bacteriologically. Disadvantages include: (1) excessive mineralization of groundwater causes corrosion problems in piping, and (2) location, development and freezing problems.

Development of a groundwater supply involves three phases:

(1) Location of an aquifer;

(2) Quantitative and chemical testing of the acquifer;

(3) Well field development.

Each phase is equally important. In permafrost regions each phase has unique problems directly influenced by the presence of permafrost.

Location of an Aquifer

The search for groundwater in permafrost regions requires that a complete geologic assessment of the site be conducted by a geologist who is experienced in permafrost phenomena. Three types of investigation may be required (3):

(1) Reconnaissance Survey - a brief trip through the area to observe the major topographic and geologic features and to note any existing wells or groundwater discharge evidence, and to interview local engineers and others;

(2) General Survey - topographic and geologic mapping, determination of permafrost distribution, recording water levels in existing wells, and making a detailed inventory of springs and associated icings;

(3) Field Techniques and Special Problems - development of the water supply may require long term pumping tests and special methods to avoid freezing problems.

The object of the survey is to establish an understanding of the bedrock and surficial geology, and the extent and thickness of permafrost, in order to develop a probable hydrogeologic model for the region. The model then forms a basis for selection of areas worthy of further investigation using geophysical techniques and test drilling.

The first step in developing the hydrogeologic concept is similar to groundwater investigation in any climate, and that is to learn all that is known about the region from published (or unpublished) records. Such records include geological, hydrogeological, hydrological and geophysical reports and papers, geological, hydrogeological and topographical maps, logs of drillings of all kinds, chemical analyses of water, and hydrological data from existing observations and other wells.

Material of this sort may be found in the archives of geological surveys, water authorities, waterworks, water management offices, mining industries, oil and gas industries, firms concerned with geophysical research, drillers and local people.

Unfortunately there are vast regions of the northern countries, especially in Canada, for which such easily available information is very sparse. For example, the Hydrogeological Atlas of Canada (1978) (18) shows six hydrogeologic regions of Canada in which groundwater monitoring stations have collected information on possible yields and water quality. The Northern Hydrogeological Region, which includes at least fifty percent of Canada, is simply described as "unknown". The authors (18) admit that little has been done to monitor groundwater in the north, although this is changing as mineral exploration increases.

If topographic maps of accuracy and suitable scale do not exist, all operations must commence with the preparation of such maps (26). In unexplored remote regions air photogrammetric maps are the most easily made. Air photos can also provide useful information on geology, permafrost extent, and groundwater phenomena.

Use of Aerial Photography

Certain indicators of the extent of permafrost are evident in air photos. Typical indicators are: vegetation associations (such as Black Spruce), beaded drainage, string bogs, solifluction lobes on slopes, frost mounds and polygonal microrelief patterns, pingos, and thermokarst lakes or other thaw induced features (3, 37). Direct evidence of groundwater discharge in the form of icings, frost blisters or hydrolaccoliths, or unfrozen reaches in rivers may be obtained from air photos taken during the winter or early spring.

Hopkins et al (1954) (3) gives a detailed description of permafrost and groundwater indicators in aerial photographs. However, he concludes that reliable interpretation of air photos requires trained, experienced individuals, and that even then their limitations are severe. In the 1970's interpretive experience and ability has expanded, with the development of multispectral photographs, false color to enhance vegetation differences, and infrared film to take advantage of thermal differences at groundwater discharge points. However, limitations still exist. For example, it is impossible to estimate the depth of permafrost, yet that information is essential for evaluating the hydrogeologic regime of the area.

After having reviewed geological information, obtained topographical details and other information from aerial photographs, and using notes from the initial reconnaisance survey, the engineer should be able to select the most promising areas for futher testing and mapping. More detailed localized studies may utilize geophysical methods or actual drilling of testholes. Geophysical mapping techniques provide information intermediate between air photos and test drilling, but they may provide valuable additional information at less cost than drilling.

Use of Geophysical Methods

Certain physical properties of soils and rock can be used as indicators of the substrata. For example, Soviet geophysical mapping programs using dc resistivity techniques have shown that three important objectives can be met using ground resistivity: measurement of depth of permafrost; mapping of frozen sections in discontinuous permafrost; and mapping of high ice content ground (34, 36). Seismic refraction methods are also utilized to map permafrost extent and depth in surficial materials (3). Thermistor cables are used in deep wells to monitor ground temperatures (21) but the data obtained relates to a relatively small zone around the well and is not useful to large scale rapid mapping of permafrost. Piezometers are also used to measure piezometric levels in taliks and subpermafrost aquifers, and are a useful tool for interpreting the hydrogeologic regime of the area under study.

Resistivity surveys and seismic testing conducted during a ground reconnaissance are relatively expensive and time consuming. Considering the remoteness of most northern development projects it is desirable to take geophysical measurements from aircraft, without the use of a ground crew. Hoekstra (1973) (34) and Hoekstra et al (1975) (33) have investigated the use of airborne low frequency electromagnetic sensors to map the electrical resistivity of the ground. They demonstrated that very low frequency (VLF) E-phase resistivity (31, 32) measurements showed the best correlation between resistivity and surficial geo-ogy, at least in the highly discontinuous permafrost near Fairbanks, Alaska. However, a short survey conducted by the Geological Survey of Canada near Thompson, Manitoba, failed to delineate permafrost because of active layer complications and because only a single frequency (VLF) was used. Resistivity measurements should be taken when the active layer is frozen, and several frequencies should be used to aid interpretation when results at one frequency are ambiguous (34). Furthermore, Hoekstra concluded that considerable "ground truth", i.e., confirmation of geophysical results with drilling records, is required. Airborne resistivity measurement techniques are still in the development stage.

Seismic refraction techniques are capable of delineating areas of discontinuous permafrost. Hunter (30) and Garg (32) discuss the physics of seismic refraction, and recommend it as an effective means of measuring in situ properties of surficial soils. Seismic testing must be conducted on the ground by an experienced survey party, but it is still less expensive than the drilling of test holes. Hunter (30) cautions that in the discontinuous zone seismic profiling should be done during the summer when the active layer is thawed. Otherwise the frozen surface layer, which transmits seismic waves at higher velcities, may mask an underlying low velocity unfrozen soil deposit.

Resistivity surveys may also be conducted on the ground, using arrays of electrodes or down-borehole techniques. The choice between surficial mapping by seismic or resistivity methods will be largely governed by the seasonal limitations of the methods (resistivity in the winter, seismic in the summer). A prospecting program for reliable groundwater aquifers should include a survey taken during the so called "critial period" i.e., during late winter when frost penetration is greatest and discharge zones at their smallest. For this reason a resistivity survey may be more practicable than a seismic survey. Rennie et al (38) found that a resistivity survey conducted near Fort Simpson in the Northwest Territories was successful in delineating boundaries of discontinuous permafrost, as well as providing an estimate of permafrost depth.

Despite some limitations in the information obtained with seismic and resistivity measurements, they are more economical than drilling. Once an area has been selected for exploration by drilling, the geophysical survey results help "fill in" information between boreholes. Geophysical techniques, when combined with drilling for verification, are a very effective means of evaluating the dimensions and boundary conditions of an aquifer.

A good example of how geophysical methods may be used in groundwater exploration is reported by Shcheglov and Dmitriyev (1973) (39). A geological assessment of a region in central Yakutia, U.S.S.R. established that the only promising groundwater source was from unfrozen taliks beneath thermokarst lakes and bogs. They utilized a combination of downhole vertical resistivity soundings, surface resistivity profiling, and information from the drilling record, to measure dimensions and volume of the taliks. Geophysical measurements also provided information on rock type and permeability.

Piezometric levels in existing wells or in test wells give useful information about the hydrogeologic regime. An interesting example of the use of piezometers is presented in Kane and Slaughter's (1973) article (14) and is discussed in chapter 4. Piezometers are subject to freezing problems, and must therefore be installed only in unfrozen ground.

Temperature measurements with depth are sometimes taken by oil exploration drilling crews (21) and are a useful guide to regional permafrost depths. At least one water exploration test hole should be instrumented to determine the vertical variation in temperature of the permafrost, as this information is necessary for evaluating potential freezing or excessive thawing problems around well casings.

Groundwater Occurrence

Reconnaissance survey results will indicate which of supra, intra, or subpermafrost aquifers are most probable sources of groundwater.

In regions of continuous permafrost suprapermafrost water may be found in unfrozen alluvium beneath lakes, stream beds, flood plains of large rivers, or even in man-made thermokarst depressions in the permafrost table. Springs are sometimes fed by suprapermafrost water, but, if so, such springs seldom flow year round and do not constitute a reliable water supply. Aquifers in unfrozen river alluvium are often the best, and only, water sources in continuous permafrost areas.

Intrapermafrost groundwater occurs in thick alluvial deposits near rivers or old river channels, and sometimes in rock fissures, joints, faults, veins and dykes. In places where subpermafrost water is rising to the surface, as under a natural lake or around an artesian well, water may thaw irregular and unpredictable horizontal lenses within the surrounding permafrost, hence becoming intrapermafrost water. Groundwater may flow freely through a pipelike fissure in permafrost and is classified as intrapermafrost water, even though it originated in supra or subpermafrost aquifers. If this type of "pipe" is tapped for water, care must be taken not to interrupt or retard the flow, which may cause the transmission zone to freeze. Intrapermafrost water is often heavily mineralized or saline and not suitable for domestic supply; it is also difficult to locate.

Subpermafrost groundwater usually has the highest yield and best quality. As discussed in Chapter 2, a deep flow system must be geologically possible and the permafrost depth must not be greater than 50 to 80 m. The subpermafrost soils must also be permeable to permit groundwater movement. Water from the deepest aquifers is warmer than water directly beneath the frozen zone, and is preferable because it is less susceptible to freezing in the well casing.

Drilling

The drilling program will should be arranged according to the type of groundwater being sought. If a spring is to be investigated to determine its source and regime, it may be necessary to drill back from the discharge point in order to intercept groundwater at a subsurface location. A suprapermafrost water aquifer beneath a lake or river may be explored by drilling from the ice in winter. If there is no surface evidence of groundwater, but a subpermafrost aquifer is geologically possible, a drilling program must be devised that systematically explores all possible subsurface formations.

The local topography influences the organization of drilling. In searching for subpermafrost water in thick alluvial deposits of east-west trending valleys,drilling should proceed from the foot of the south facing slope to the middle of the valley. Test holes drilled along north facing slopes generally give negative results (1). In valleys trending north-south, test drilling should start near the river channel and proceed toward the side of the valley that receives the most solar radiation, unless visible springs make the choice of drilling locations more obvious. Muller (1) recommends spacing of drill holes at 50 m to 200 m intervals in a transverse line along the valley, followed by additional drilling at 500 to 1000 m spacing in other directions to delineate the areal extent of the alluvial unfrozen zone.

In regions of statified bedrock below permafrost drilling should be determined on the basis of the structural geology. For a synclinal structure, test holes are placed along the axis of the syncline as well as across it. Test wells should be drilled in the centre of a structural depression. The dip of stratified bedding should also be considered in placing test wells so that they penetrate the permeable beds below permafrost level.

In crystalline rock drilling is directed toward determining the depth and spacing of rock fissures and joints, and then intersecting the joint systems at depth, either beneath the permafrost or at least in an unfrozen transmission zone. Fissures that exceed permafrost depth act as important hydraulic connections between surface water and subpermafrost aquifers. If permafrost depth is greater than the depth of fissuring, the existence of subpermafrost water will be unlikely. Joint systems on crystalline rocks are not always interconnected, so that water in different joints acts independently. A small charge of dynamite is sometimes used to fracture the rock sufficiently to connect several joint systems and allow freer movement of water.

As an example of the variability in the occurrence of groundwater in crystalline rocks, it is known that water penetrates fissures in the crystalline bedrock beneath Great Slave Lake, and is encountered in mine drifts at the Con Mine at Yellowknife, Northwest Territories. At Rae, also on Great Slave Lake, a diamond drill hole was put down to a depth of 215 m, but it showed that the granite was too massive to permit the movement of groundwater (15).

In areas of discontinuous permafrost and mountainous terrain, permafrost is commonly limited to the low lying areas between divides. Drill holes placed at the foot of south facing slopes in fissured rocks almost always produce water (1).

Solution channels in dolomite or limestone bedrock in the discontinuous permafrost zone often yield abundant quantities of good quality groundwater. Drilling must establish whether solution channels extend beneath the permafrost, and if there is a connection between solution channels at depth and the surface. If drill holes do not encounter water, it may simply be because they missed the solution channels, which are irregularly distributed in the limestone. Muller (1) recommends using a dynamite blast, as a last resort, to fracture the rock and link the well to nearby water bearing channels.

Quantitative Assessment

Quantitative testing to determine the maximum, minimum and safe yield from an aquifer is discussed in such texts on groundwater hydrology, as, Todd (1959) (27) and the Unesco publication (1977) (26). Testing in permafrost regions is the same as in temperate areas, namely to conduct pumping tests in test wells while recording drawdown in observation wells and changes in the regime of springs or other natural groundwater phenomena. Careful evaluation of the flow rates, drawdown, and range of influence, leads to an estimate of the aquifer size, storage capacity and transmissivity. Precautions must be taken to protect equipment from freezing when pump tests are done in winter.

A study of the maximum yield of a suprapermafrost aquifer should be carried out in September or October when the active layer is thawed to the maximum depth. Drilling or geophysical methods may be required to estimate the volume of the surficial talik at that time. Minimum yield should be assessed in late winter, when the extent of freezing is greatest and recharge is minimum. Samples should be taken for chemical analysis: water trapped in lake or river bottoms is sometimes stagnant and undesireable for domestic use, although it may serve as an emergency fire protection supply.

It is difficult to evaluate maximum or minimum yields of intra-permafrost water unless the size, shape and means of recharge is known. This is seldom the case. If the intrapermafrost aquifer is closed, i.e. not connected to any supra- or subpermafrost water, its quality may be very poor, and the water only fit for emergency use.

Determination of the yield of an aquifer in stratified bedrock requires a thorough familiarity with the regional geology. Pore space volume and rate of percolation must be calculated. Unless the aquifer is known to be fed by an outside source it is safer to assume it has a limited yield.

There will be a lag between changes in surface water conditions and changes in piezometer levels in an underground aquifer. If this lag is small, there must be a fairly direct hydraulic connection for recharge of the aquifer, and the safe yield estimate can be increased accordingly. Minimum yield should be checked during late winter when such recharge is minimal.

The presence of permafrost complicates the quantitative testing of the aquifer. Permafrost boundaries to the unfrozen zone change on a seasonal basis and cannot be considered equivalent to lithologic boundaries (33). Pumping water from beneath the permafrost may cause the soil or rock to freeze even deeper. Conversely, increased flow rates may bring in more heat, thaw the overlying permafrost, and increase the size of the aquifer. Brandon (15) and Cederstrom (2) recommend maintaining the piezometric level of the aquifer as close to the undisturbed level as possible in order to avoid possible freeze up and loss of the aquifer. Consequently the permissible drawdown for pumping at capacity is quite small, a fact which limits the safe yield of an Arctic groundwater system. This problem is less restricting in discontinuous "warm" permafrost where disturbance is more likely to cause thaw than freeze-up. An increased thawed area would be a disadvantage in thaw unstable soils. However, in thaw stable gravels, thawing of permafrost boundaries would increase the storage capacity of the aquifer.

Winter pumping should continue for a minimum of 10 to 15 days, but preferably 1 or 2 months to obtain a "steady state" condition (1). Hydrological texts (27) present expressions for non-steady state evaluation of pumped wells, but discussion of such hydrological calculations is outside the scope of this paper.

Chemical Testing

Chemical testing is required to determine water quality, possible treatment required, and as a means of verifying the subsurface origin of the groundwater. Suprapermafrost or surface water is generaly less mineralized than deep circulating groundwater. It can have a high organic or humic acid content, iron content, it may have poor colour or taste, or be turbid. Bacterial contamination from septic tanks, sewage lagoons or refuse dumps occurs frequently near villages or small towns.

Subpermafrost water may be less turbid due to natural filtration, but it may have high total dissolved solids content, as discussed in Chapter 3. The dominant mineral constituents are indicators of the rock or soil type of the aquifer. If there is ambiguity about which rock formation is acting as a transmission medium, chemical test results will reduce or eliminate the uncertainty. For example, Brandon (15) determined that the "Saline River" formation, not the "Bear Rock" formation was the aquifer for certain saline springs along the Mackenzie. Knowing the regional geology, he was then able to pinpoint the correct recharge area.

Natural or artificial isotopes in groundwater are used to determine its age, flow velocity and direction, inter-relations between surface waters and ground waters, possible interconnections between aquifers, local porosity and transmissivity (26). Brandon (15) reported using the natural isotope of water, tritium, to determine the age of water in the "Roche-Qui-Trempe a ℓEau" springs in the Northwest Territories as 30 $\pm$ 10 years. Since the recharge region was approximately 40 kilometres to the east, an approximate measure of the flow velocity through the aquifer was obtained.

Well Field Development

Well field development involves the drilling of wells, installation of well casings, grouting to control unwanted discharge around the casing, gravel packing if necessary, installation of well screen, and surging techniques to wash all fines away from the well screen. Submersible pumps of suitable capacity are lowered into the well, and piping is connected to the water storage or distribution system. Special heating elements or return circulation lines may be required to prevent freezing or allow thawing of the well. Proper well development is equal in importance to the exploration program and warrants full attention of the engineer.

Well drilling techniques in permafrost regions vary. Brandon (15) lists the following:

(a) Rotary drilling with mud - a successful method in sedimentary rocks, but impractical in heavy boulders or crystalline rocks;

(b) Percussion drilling with cable tool drill, a method that is certain of making a hole in any ground;

(c) Reverse circulation drilling, which drills large diameter wells in alluvium or glacial drift;

(d) Jet drilling, which is satisfactory for installing shallow sand points in unfrozen alluvium;

(e) Diamond drilling, which is only satisfactory for wells in jointed rock where a small domestic supply is required, and where a special small diameter pump is available.

Cederstrom (1954) (2) and Brandon (1964) (15) reported that cable tool percussion drilling (also called churn drilling) is most adaptable to drilling in permafrost, and is the preferred method for water well drilling. The drilling fluid should be as cold as possible to minimize the effects of thawing of the surrounding soil. A brine solution is used sometimes, but only enough drilling mud is used to operate efficiently and to keep the hydrostatic head from forcing the brine into the aquifer. The aquifer must be pumped to flush out any remaining brine solution. Compressed air has been used to replace brine solution in extremely cold weather drilling. In winter drilling a "parka" or some sort of heated enclosure of the drill rig is desireable to protect the drilling crew and ease problems in handling wet tools.

In permafrost, casing may only be required for the upper few metres of hole through the active layer. The final casing is then driven into the hole in one continuous operation, thus avoiding the problem of the upper part of the casing freezing to the sides of the hole during interruption in drilling. It is essential to have a boiler handy to apply steam or hot water to free a frozen casing or tool train. Experienced contractors organize drilling teams for 24 hour operation so that the drilling mud does not have to be bailed out at the end of a drilling shift.

The outside diameter of the collars on the casing should fit tightly into the borehole. Once installed, the annulus between the outside of the pipe and the wall of the borehole must be cement grouted. Low ground temperatures retard setting of the cement, a problem that is overcome by using special cements, adding calcium chloride to the cement, or adding heat until the cement sets. A delicate balance must be drawn between causing excessive thaw of surrounding permafrost (by either the heat of hydration of cement or by added heat) and not enough heat to prevent freezing of the grout. Figure 5-1 illustrates the relationship of thaw diameter to casing diameter in permafrost.

In thaw unstable soils excessive thaw around the casing may cause blowout or failure of the well. Linnell (1973) (20) presents a case history of an uncontrolled artesian well drilled in permafrost near Fairbanks, Alaska in 1946. A 12.7 cm diameter hole was drilled through approximately 33 m of frozen alluvium into a subpermafrost artesian aquifer. As soon as the drill penetrated the aquifer a strong upward flow began which started to enlarge the well diameter by erosive action and thaw of the surrounding permafrost. An 11.4 cm od. well casing was quickly assembled and lowered into the hole, but because the outside diameter of the casing was smaller than the drilled diameter of the well, and because of thaw enlargement of the hole, water flowed to the surface both around and through the casing. This flow was now uncontrollable and a progressively enlarging hole was formed at the well head. Numerous attempts to stop the flow were made with at best only temporary success. It was not until four years later that the well was finally stopped by installing freeze probes around the well location and circulating refrigerant brine until the area was completely refrozen and the continuity of the permafrost re-established. The well was then abandoned.

Possible consequences of uncontrollable flow from artesian wells in permafrost include formation of a constantly enlarging thaw and erosion pit at the well, permafrost degradation and terrain damage in the area exposed to the surface and subsurface discharge from the well, ice-fog and ground-ice in winter, development of frost mounds, and waste of expensively developed water.

The risk of uncontrolled flow from wells may be reduced by using tightly fitting casings, but the ultimate controlling factor may be the soil type. Linnell (20) makes the following remarks: "When permafrost materials are thaw stable soils, free of excess ice, the relative safety against flotation, piping and blowout in a thaw zone surrounding the casing can be evaluated using standard soil mechanics methods, using critical hydraulic gradients or creep ratio approaches, since such soils when thawed will have the characteristics of unfrozen soil. In ice rich soil or rock the degree of safety may be indeterminate". Table 5-1 from Linnell's article presents a summary of well stability conditions in four combinations of soil-ice conditions.

When water rises through a permafrost zone, either the water may freeze in the casing or the surrounding permafrost will thaw. Whichever happens depends on the water temperature, permafrost temperature and thickness, and the rate and duration of flow. Larger diameter well casings are recommended because they take longer to freeze than small diameter casings (42). If water demand is low, thermal insulation, introduction of heat, periodic mechanical removal of ice, or continuous pumping to waste, storage or back into the well may be required to prevent freezing. In some private wells hot water from the house hot water tank can be pumped down the well (2). Page (44) suggests the use of wind operated generators to power electrical devices to heat or thaw wells. Continuous pumping at a low rate of 1 to 2 gpm and introduction of warm water (5°C) are commonly used methods in Alaska (42).

In thaw unstable soils and under artesian conditions it is very important to prevent thawing of the surrounding permafrost and consequent loss of control of the well. Under such conditions pumping may be limited to one or two months, allowing time for the permafrost to refreeze between pumping periods. The critical time will be immediately after a pumping period, when thaw is at a maximum, and artesian pressure is increasing due to cessation of pumping. Careful thermal analysis of the rate of thaw is required in such cases, for which soil type, ice content, and soil and water temperatures must be known.

Installation of well screens, gravel packing, surging to cleanse the well of fines, and disinfection procedures do not differ significantly between temperate and permafrost regions. Information is available in most texts on groundwater development.

Whether continuous or intermittent pumping is employed, some form of water storage should be provided. If pumping is continuous, it is more economical to store water than to waste it; if pumping is intermittent, storage is required to supply water to users between pumping periods. For domestic water supply a proper storage facility allows convenient control for treatment of the water and provides emergency water for fire fighting. Storage methods include elevated, heated tanks, buried tanks, open surface ground reservoirs, or artificial lakes. Buried tanks require less heat input than elevated tanks, and if large enough, may require no additional heat input (45). An uncovered ground reservoir must provide the required volume of water beneath the expected ice thickness.

An insulated and heated building should be constructed over the well head to protect piping and other equipment from freezing and other damage. A heated building is especially necessary during winter pumping tests. Piping should be arranged so it is easily accessible for draining, thawing, or removal, without the need for excavation in frozen gound. Connection to the water storage and distribution system may be made using utilidors, insulated buried pipes, or insulated surface pipes. It may be necessary to supply heat to the water before pumping into the distribution system. If so, a furnace or steam plant must be constructed by the storage facility to provide heat. Detailed information on water storage and distribution in cold climates is available in the Environment Canada publication (1979) "Cold Climate Utilities Delivery Design Manual" (47).

Examples of Developed Groundwater Supplies in Northern Communities

Residents of northern communities have made use of groundwater for domestic water supply for many years. In the southern fringe of the permafrost zone the techniques of water well development differed little from southern more temperate areas, i.e., shallow wells were hand dug or drilled in water bearing alluvium above or between permafrost areas, or springs were utilized where possible. In the last three decades development has advanced northward into continuous permafrost regions, where the difficulties and costs of locating and developing groundwater sources are much greater. The following examples of developed water supplies were chosen to illustrate these levels of development from inexpensive individual supplies to more costly supplies for far northern camps.

Wells in Unfrozen Alluvium

Early settlers in Anchorage, Alaska, dug shallow (10 to 15 m) wells into a gravel mantle overlying silts and clays in the area. The gravels were free of permafrost. As the population increased septic tank effluent seriously contaminated the gravels; wells were drilled into a deeper water bearing zone at the 50 m depth below the silts. That level also has become contaminated from septic tank effluent, so that wells must now be drilled to the 130 m depth just above bedrock. Contamination of shallow hand dug wells is extremely difficult to avoid. Brandon (15) describes a 4 m deep well in frozen clay at Jean Marie

River, N.W.T. as almost dry, and, in August, frozen to the bottom. Such wells are little more than cisterns.

Some towns in the discontinuous permafrost areas obtain water from wells excavated, drilled, or driven in permeable alluvium adjacent to large rivers. Water flowing through riverbed alluvium does not freeze during winter, and natural filtration removes excessive silt. For this reason water obtained from such wells is preferable to water taken directly from the river. Examples include the towns of Whitehorse, Dawson, and Mayo in the Yukon Territory.

Whitehorse takes its water from both a river intake and a well field which is located in coarse grained alluvium on the east side of the Yukon River. Three wells yield from 910 to 1460 litres per minute at a temperature of 3.5° to $4.5^{\circ}C$. This is warmer than the river water, which allows a saving in the cost of heating the water before it enters the distribution system.

The town of Dawson is located on the Yukon River below its junction with the Klondike River. Discontinuous permafrost is widespread. Water is obtained from two shallow wells (one is 12 m deep) in sand and gravel alluvium near the mouth of the Klondike River. Water is heated to a temperature of $2.8^{\circ}C$ by steam injected directly into the well. The distribution system was constructed of wood stave pipe buried approximately 0.3 m below the surface, but above the permafrost. Water is kept from freezing by injection of heat at the wells and at selected points in the distribution mains, and by maintaining continuous flow by bleeding to waste at every outlet in the system. Although wasteful, the Dawson water system has worked well for many years.

Mayo is located on the north side of the Stewart River in the Central Yukon. Silt and sand alluvium underlies the area, (with some areas siltier than others) and permafrost is present in some locations. Most of the wells are sand-points which have been hand driven through the alluvium. Domestic supplies are adequate and of good quality. The small diameter hand driven wells may suffer freezing problems in winter, so that wells may have to be pumped continuously or provided with heat tracing.

Unfrozen alluvium beneath permafrost is a major source of water supply in the Tanana River Valley near Fairbanks, Alaska. The hydrogeologic situation that leads to the development of artesian pressures beneath approximately 50 m of permafrost was discussed in Chapter 2, but is illustrated again for clarity in Figure 5-2, which shows a typical profile near Fairbanks, Fort Greely, and Clear Air Force Base, Alaska. High production industrial wells have been developed at Clear Air Force Base and at Fort Greely along the Tanana River. At Clear Air Force Base the wells were driven 25 to 30 m though permafrost to unfrozen water bearing gravels, while at Fort Greely the best aquifer is 76 to 106 m deep (42). A developmental nuclear power plant was constructed at Fort Greely using a high capacity well, with water at 1.1^{o} to $4.5^{o}C$, for cooling water. The water is put through a condenser and returned to ground water through a recharge well. The wells were spaced to prevent recirculation and tests were conducted with tracer dyes to check this possibility.

It is of interest to note that in southern regions major insurance companies seldom recognize direct pumping from a well field as a reliable water supply for fire protection, because of the possibility of pump failure. A storage system is preferred so that water is available under gravity feed, if the pumps should fail. However, the nuclear reactor at Fort Greely appears to be dependent on pumped water for cooling the reactor core. Failure of the pumping system or even reduction in its capacity would have serious and dangerous consequences, as evidenced by the recent Three Mile Island nuclear accident in Pennsylvanie, U.S.A.

Groundwater is used to dilute mildly radioactive waste water from the Fort Greely reactor before it is released into a nearby stream at flood runoff time.

Several American military bases in Alaska utilize groundwater supplies. Galena is supplied from a groundwater aquifer 60 m beneath permafrost; this water is of poor quality, with obnoxious gases, high iron and manganese content, and excessive hardness, and it requires considerable treatment. A well at Bethel Air Force Base penetrates 180 m of permafrost to obtain good quality water from sands at that depth.

On the Arctic coast of Alaska, permafrost is generally at least 300 m thick, so that unfrozen water-bearing alluvium at depth is very rare. The only groundwater that is found exists in shallow unfrozen alluvium beneath the larger lakes (more than 2.5 m deep and 600 m wide) (3) and beneath major streams or rivers.

A water supply was developed in an unfrozen gravel beneath the Sagavanirktok River for an oil camp near Prudhoe Bay, Alaska (46). A thorough investigation of the extent of unfrozen areas beneath the river indicated that an infiltration gallery installed beneath the channel would provide an acceptable water supply. A nearby pond was used as an emergency supply by pumping river water into it. The infiltration gallery operated satisfactorily between June 15 and December 15, 1970, at which time it failed due to silting of the intake line and surrounding aquifer material. A temporary pump intake was suspended in water through a hole in the river ice for the remainder of the winter. During break-up the emergency water in the nearby pond was used to supply the camp. In 1971, a steel pier was constructed and the water intake line suspended directly in the river. In this case development of the unfrozen alluvium as a groundwater supply was unsuccessful.

Wells in Fissured Rock

A water bearing fracture in a granite formation near Northway on the Alaska Highway was tapped to provide water for an important oil pipeline pumping station. A 125 mm borehole was drilled to intersect the fracture at a depth of 67 m. The hole was cased and grouted as shown in Figure 5-3 (46). Special sealing methods were used to prevent contamination of the water, since surface water penetrated the rock fissure without the natural filtration that occurs in granular aquifers.

5.2 PROBLEMS ASSOCIATED WITH GROUNDWATER IN PERMAFROST REGIONS

Groundwater discharge during the severe Arctic winter contributes to a number of problems, most significant being the formation of icings adjacent to roads, railways or engineering structures. Problems arise during the summer, when suprapermafrost groundwater saturates the active layer on a mild slope, turning the soil into a slurry that creeps downhill (solifluction), sometimes threatening roads. Pore pressures play a similar role in mass wasting to what they do in more temperate regions. However, icings are the most difficult to prevent or control and are worthy of special comment.

Icings

Each winter many millions of dollars are spent by highway departments of Alaska, Canada and the U.S.S.R. in repairing damage done to roads by the formation of icings. Icings, called "aufeis" or Naleds, are formed when ground water seepage continues throughout the winter, and freezes to form a large mass of stratified ice. Successive sheets of ice may attain a thickness of several metres, with an areal extent of several square kilometres. The damage done to roadways can be dramatic. Under certain conditions the discharge may be sealed by ice until it is released by a sudden explosive rupturing of the ice. Metres thick slabs of ice have been thrown across roadways by this process, and the sudden release of trapped water can wash out road embankments and even bridges (7). The following is a review of the processes that govern the formation of icings, their effects upon roads, and methods of prevention.

Causes of Formation of Icings

Depending on origin, icings can be divided into three main groups (24): spring; river (from surface water of permanent and temporary streams): and ground (supraperamfrost water). Icings may form under natural conditions, or artificial conditions, i.e. due to disruption of the natural ground water regime by construction. They can form on slopes of varying steepness, on the edges and bottoms of ravines or valleys of creeks and rivers, and on the slopes and crests of depressions.

Conditions favourable to the formation of icings are:

(1) A source of water; subpermafrost water rising in springs, or suprapermfrost water in the active layer;
(2) Low temperatures in the air and only a thin cover of snow during early winter;
(3) Proximity of the permafrost table to the surface;
(4) Thick cover of snow during the latter part of the winter.

Icings are largest at the end of the winter, when snow cover is maximum. Snow acts as an insulating layer to preserve low ground temperatures which were caused by the earlier frosts and minimum snow cover.

The existence of springs in regions of permafrost depends on the local hydrogeology. The geology must be such that surface water can penetrate surface materials and remain unfrozen while it moves to a discharge point. If the groundwater source is from beneath the permafrost (subpermafrost water), springs may flow year round, forming extremely large icings, with ice volume measured in cubic kilometres. From the point of view of road construction major year round springs can usually be identified from aerial photographs or ground reconnaissance, and avoided.

River icings form when water flowing through pervious deposits in river channels is blocked and forced to rise to the surface. Possible mechanisms to cause such blockings are: (1) an outcrop of bedrock in the stream channel, or (2) freezing of a shallow portion of the stream so that upstream flow is impeded. These modes are illustrated in Figure 5-4.

Icings may develop anywhere in alluvial flood plains adjacent to rivers, depending on the unpredictable arrangement of pervious and impervious zones. River icings may grow to enormous size, due to the large quantity of water present in the river bed. They pose significant problems at river crossings, where bridges or culverts may be destroyed if the icing develops on the upstream side. An embankment built across a stream channel may cause permafrost to extend into the channel, blocking the flow of water through the stream bed and causing it to rise to the surface, where it freezes and forms an icing.

Icings are formed when the winter freezing of ground penetrates down to and merges with the permafrost. The ground water in the active layer is forced to the surface along a path of least resistance, spilling over and freezing. On long gentle slopes, especially if the strata dip parallel to the slope, seasonal frost creates an upper boundary to groundwater in the active layer, so that a confined aquifer is formed. Significant artesian pressures may develop.

Disturbance of the active layer on a long gentle slope will contribute to formation of an icing. An embankment constructed transversely to the slope direction will compress the active layer, and cause the permafrost table to rise. Such disturbance creates a barrier to downslope percolation of water, so that icings form along the uphill side of the embankment, as shown in Figure 5-5 (1, 24).

In mountainous regions road construction may require cut sections through bedrock, exposing jointed rock surfaces. Groundwater may be transmitted through the rock joints and form large icings on the rock face, and even on the road itself.

Methods for Control of Icings Adjacent to Roads or Structures

Road construction is a major cause of icing formation in perma frost regions. The Russians have noted that icings form a remarkable alignment with roads or railroads, which clearly indicates that the construction of the road was the prime cause of the icing. The following approaches have been taken to control icings: (1, 24)

(1) Transfer of location. The route, structure or installation may be transferred to a new location where icings do not occur. This is a very costly solution, but for new projects the location should be chosen so as to minimize or avoid potential icing problems. The mechanisms for icing formation must be well understood before this selection can be made.

(2) Raising Grade. Another approach is to raise the grade of the route or structures to at least postpone the seasonal encroachment of icings. This approach is costly and depends on the availability of large quantities of fill material. Associated hazards include washouts due to ice-blocked drainage facilities, and undesireable seepage effects.

(3) Numerous large drainage structures. Culverts with large vertical dimensions, or small bridges instead of culverts may be designed so that the openings accommodate significant icing volumes; this results in openings larger than required to pass the design flood.

(4) Provide storage space. A ponding basin of approximate dimensions is excavated, or a cut face is moved back farther than the normal setback.

(5) Dams, dikes or barriers. These include devices known as ice-fences or frost-belts. Dams or dikes are permanent structures placed between the source of the icing and the structure to be protected. Barriers or ice fences may be temporary or permanent. Permanent barriers are commonly made of logs or lumber, while temporary barriers may be built of snow fencing or wire fencing faced with plastic sheeting, tar paper or other materials.

Temporary fences must be only strong enough to withstand local winds, since only a few inches of water is impounded at any one time during icing growth. A second or even a third fence can be placed over the first as the icing grows higher.

Icings create drainage problems by blocking normal drainage facilities. Carey (24) presents several techniques for controlling such drainage problems. These include culvert closures, installation of staggered culverts, or direct application of heat to thaw ice inside culverts. Culvert closures involve blocking off the culvert in the fall, so that it does not become filled with ice in the winter and prevent drainage during the thaw season. Culverts may be staggered, with one culvert placed higher than another. The lower culvert becomes ice plugged, but the higher culvert will be ice free in the spring runoff: water levels rise until they reach the level of the higher culvert. Figure 5-6 illustrates the use of staggered culverts.

Another concept is to construct an embankment of large boulders. Water passes freely through the voids in the embankment until freeze-up. The core remains ice free during the winter, and in spring the outer shell of ice thaws rapidly, allowing water to pass through the boulder dike. However, such dikes are most suitable to sub-Arctic regions.

Heat is used to establish or maintain drainage channels in the ice to facilitate drainage and spring runoff. Steam is generated on truck mounted boilers and fed into culverts to maintain an ice free passage. Other methods include the use of fire pots or electrical cables, although the latter method may be costly.

Methods of Icing Prevention

The preceding techniques are suggested for control of icings. In some cases it may be possible to prevent icing formation. For example, river icings may be prevented by channel modification to remove the cause of the upsurging water (Figure 5-4). A common method is to excavate a narrow deep trench to carry water through the critical region.

Ground icings may be prevented by providing drainage of subsurface water or by construction of a frost belt. Subsurface drainage systems are recognized as effective in preventing ground icings. Tiles are laid in trenches in the active layer, or below the depth of seasonal frost penetration. This expensive method is not well suited for true permafrost regions, due to the vulnerability to freezing of the tiles (24).

When route location is unable to avoid conditions that contribute to icing formation, construction of an interceptor trench or "frost-belt" may provide a satisfactory corrective measure. The frost belt consists of a trench excavated away from the road, which promotes an early complete freezing of the active layer far enough from the road, so that icing will not damage the roadway. Figure 5-7 illustrates the concept of the frost belt.

Muller (1) gives recommended dimensions for frost belts. It should be located 50 to 100 metres upslope from the road and slightly longer than the length of the icing to be eradicated. It may be 5 to 10 metres wide and between 0.5 and 1 metre deep. Spoil should be piled on the downslope side of the frost belt, and snow in the early part of the winter should be scraped off and piled on the upslope side. This will allow the frost to penetrate the active layer faster.

If large ice mounds form above the frost belt they should be punctured and drained before they explode and cause damage. It should be stated that the frost belt is only effective for surficial or suprapermafrost water. If subpermafrost water exists on the slope, such as in springs, diversion trenches may be preferred. A careful survey of the icing is necessary to determine the true water source.

A disadvantage of the frost belt is that after a year or two of operation a depression is created on the permafrost table. Water percolating through the deepened active layer proceeds unchecked to the fill of the road bed. One way to avoid or delay this is to fill the trench with an insulating mat in the spring, to prevent thawing. However, this increases the cost of maintenance.

Cribbing or sheet piles may be placed on an excavated trench and covered with an earth mound up-slope from the structure to be protected. The cribbing forms a barrier to water percolating through the active layer, as in Figure 5-8. The icing is then forced to develop behind this barrier, not at the road or structure.

The methods for control or prevention of icings are derived from an understanding of the origins and the factors affecting their formation. If they are applied without regard to specific conditions at a site they may not work. Improper understanding of the nature of icing phenomena has led to misapplication of certain techniques. Consequently, these efforts have been unsuccessful, and those counteractive measures have gained undeservedly poor reputations.

Table 5.1. Stability of wells under Artesian Flow for four combinations of conditions (from Linnell, 1973) (20)

Case No.	Type of Permafrost	Type of Casing Installation	Well Stability Condition
1.	High-ice-content, thaw-unstable permafrost (extreme condition would be soil-free ice, as in drilling through a glacier)	No casing in permafrost zone or casing incompletely sealed to permafrost	Unstable; although a situation can be visualized in which flow is so slight that ice buildup occurs instead of thaw, conditions at the bottom of permafrost, where temperature is borderline, will tend to be unstable
2.		Casing to bottom of permafrost zone or lower	Unstable unless thaw outside the casing is prevented. Even though penetration of casing into underlying unfrozen ground is sufficient for safety against piping or blowout within that zone and casing is in tight contact with permafrost, thaw of ice around casing by flow of warm fluid within it may allow the artesian pressure at the base of permafrost to break through
3.	Thaw-stable permafrost, no excess ice	No casing in permafrost zone or casing imcompletely sealed to permafrost	Unstable unless permafrost zone is thaw-stable bedrock. Frozen soils will be subject to erosion when flow thaws ice bond
4.		Casing to bottom of permafrost zone or lower	Stable, provided total casing imbedment is sufficient for safety against piping or blowout

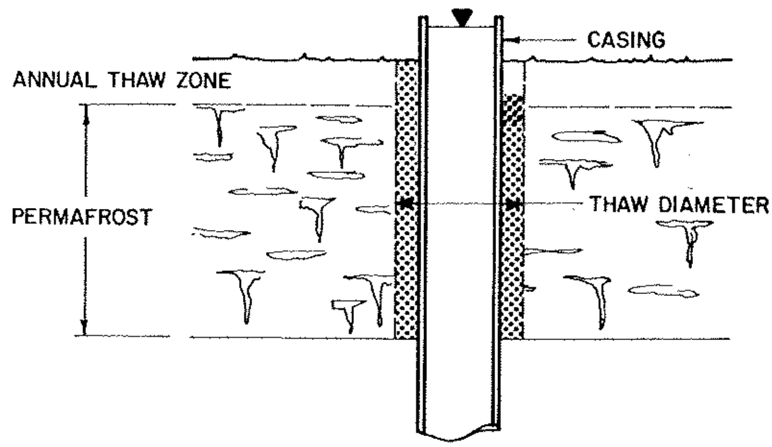


FIGURE 5.1 THAW AROUND WELL CASING.

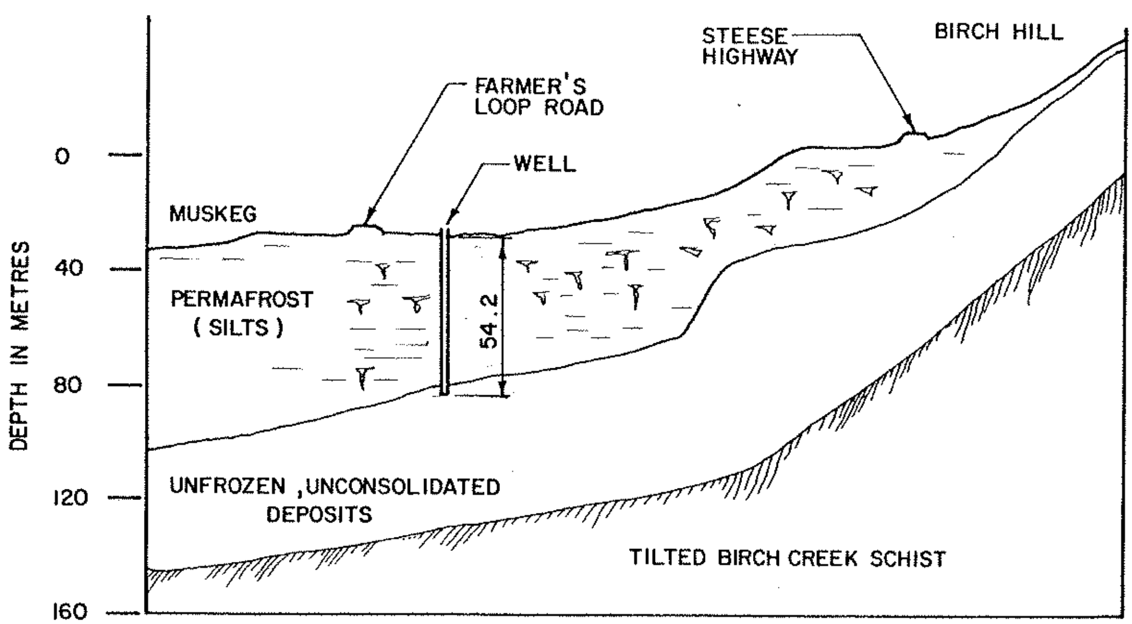


FIGURE 5.2 CROSS SECTION OF ARTESIAN SUBPERMAFROST AQUIFER NEAR FAIRBANKS, ALASKA.

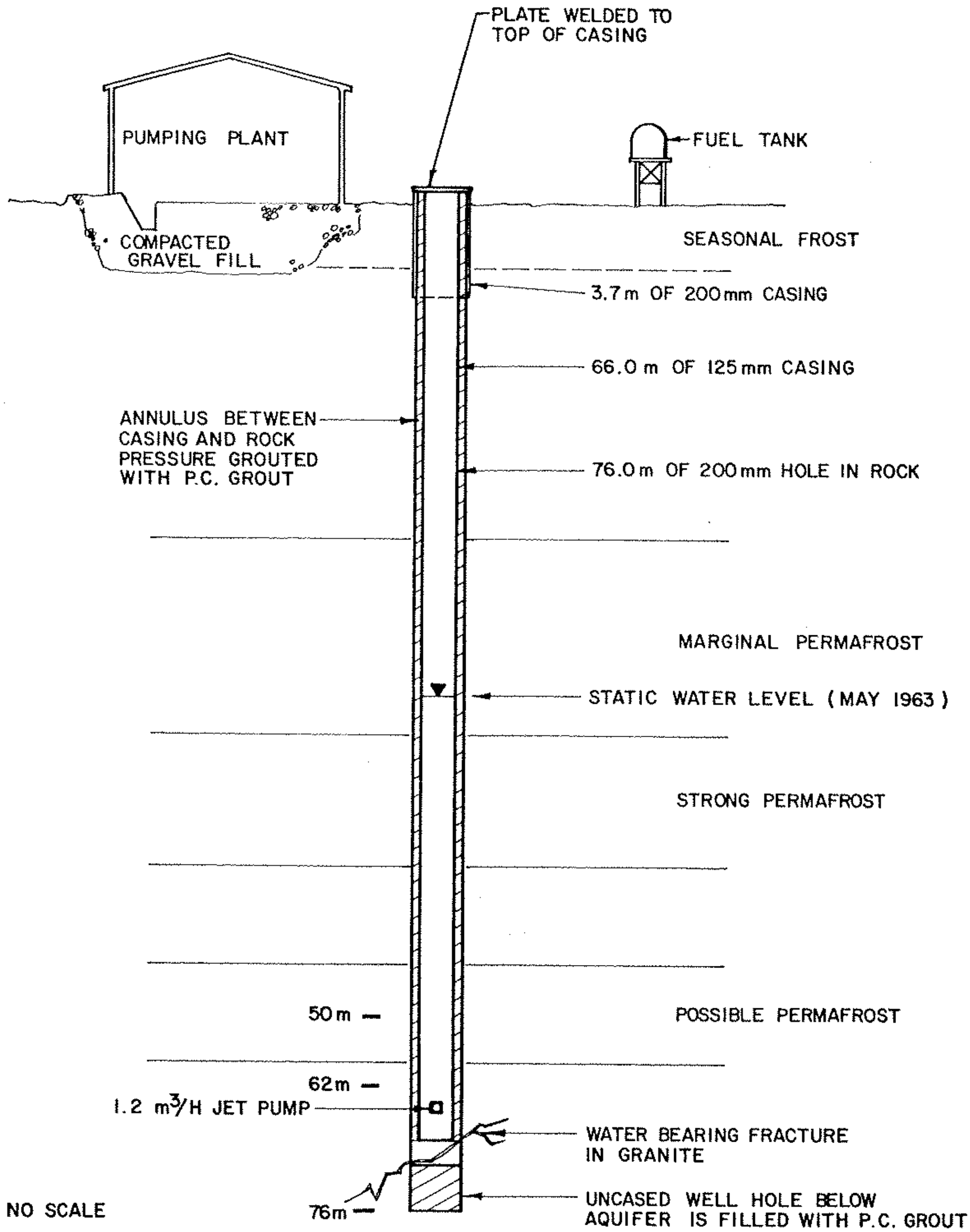
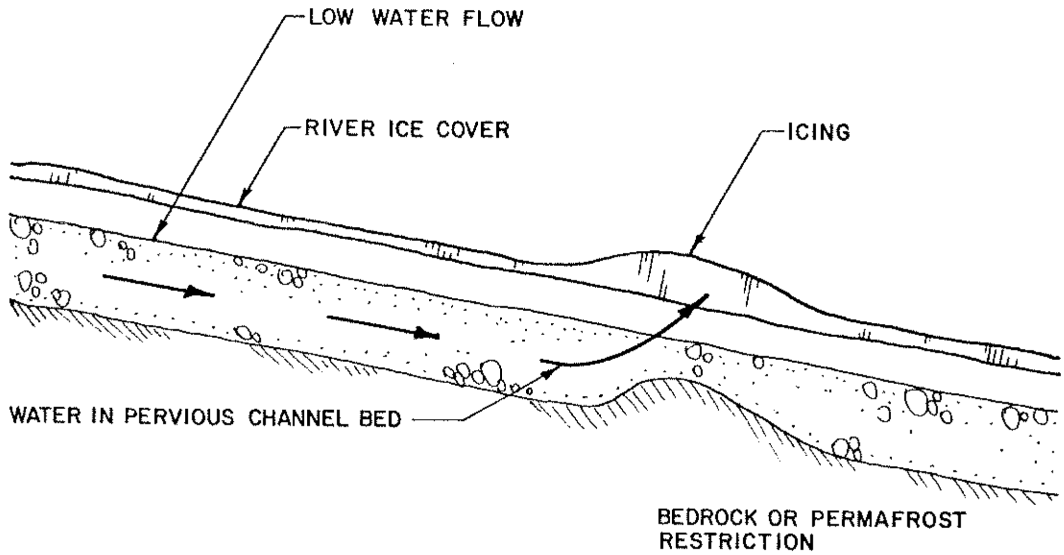
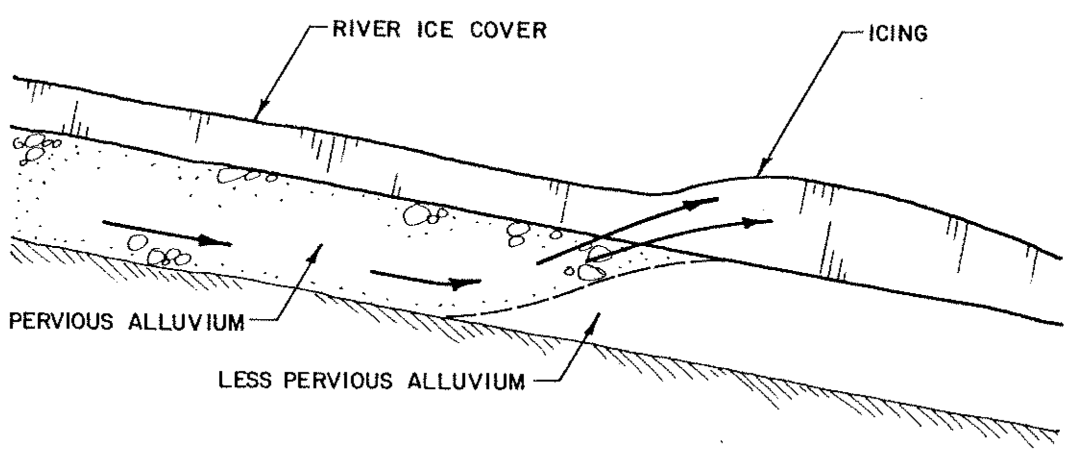


FIGURE 5.3 DIAGRAMMATIC SKETCH OF WELL IN GRANITE (AT NORTHWAY, ALASKA). FROM W. GEORGE (42).



(a) RIVER ICING FORMED DUE TO OBSTRUCTION OF FLOW IN STREAM BED.



(b) RIVER ICING CAUSED BY CHANGE IN PERMEABILITY OF SUB - BED ALLUVIUM.

FIGURE 5.4 RIVER ICINGS.

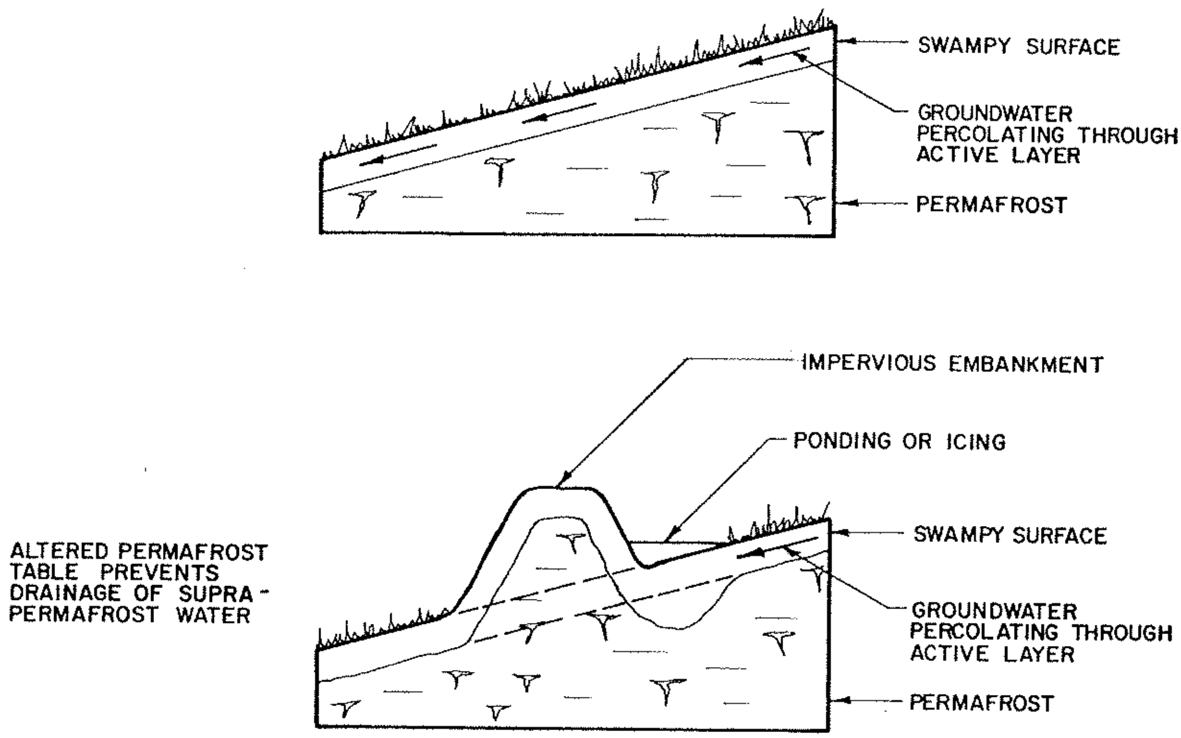


FIGURE 5.5 FORMATION OF AN ICING OR PONDING DUE TO DISTURBANCE OF THE ACTIVE LAYER BY EMBANKMENT CONSTRUCTION.

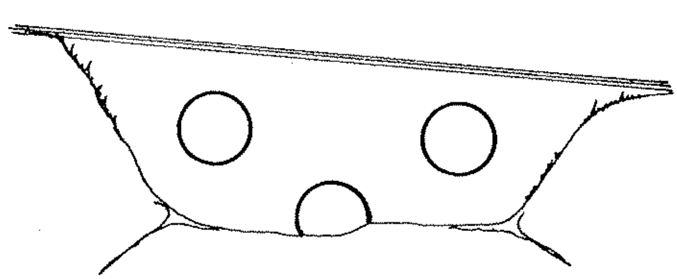


FIGURE 5.6 STAGGERED CULVERTS IN ROAD EMBANKMENT TO PASS SPRING RUNOFF.

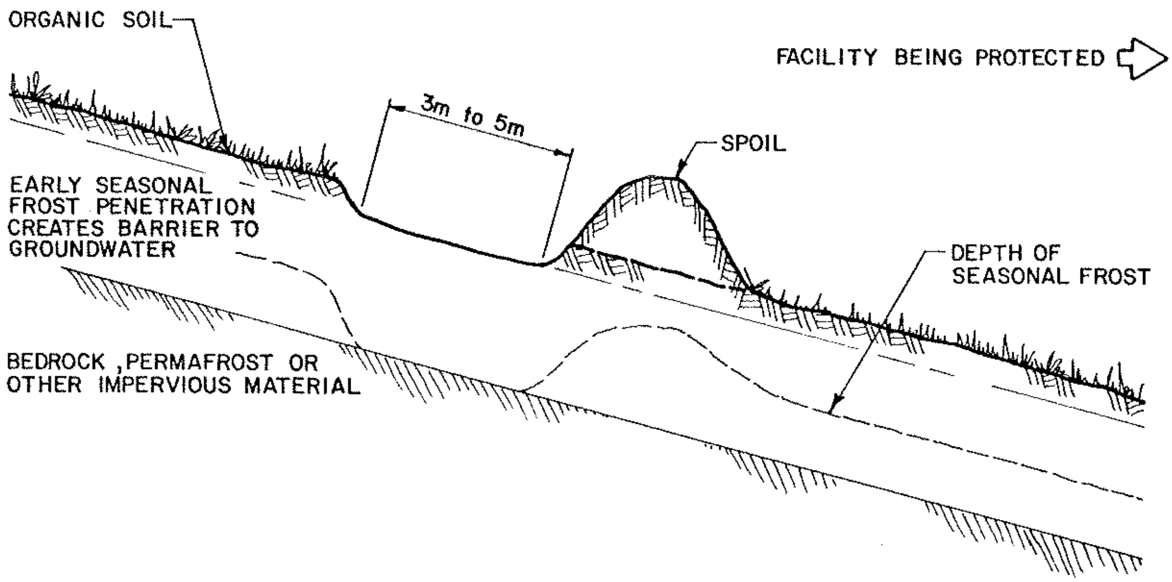
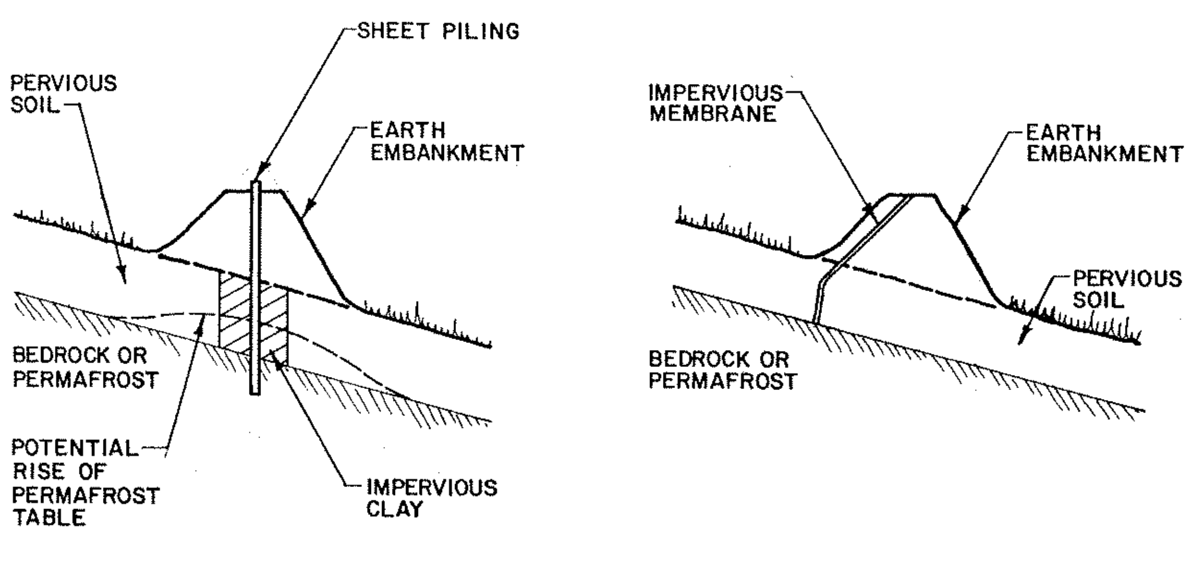


FIGURE 5.7 TYPICAL CROSS SECTION OF A FROST BELT INSTALLATION TO CONTROL LOCATION OF ICING.



(a) SHEET PILING BARRIER

(b) PLASTIC MEMBRANE USED AS BARRIER

FIGURE 5.8 EARTH EMBANKMENTS WITH IMPERVIOUS BARRIERS.

6.0 RESEARCH NEEDS

Further research is required to improve understanding and knowledge of groundwater hydrology and hydrogeology in permafrost regions. Williams and van Everdingen (13) present a thorough list of recommendations for further research, some of which are listed below:

1. Application of the theory of irreversible thermodynamics to the problems of coupled flow of energy (heat), and mass, (water and salts) in a porous medium subject to freezing, in order to improve understanding of the interaction between permafrost and moving groundwater. Develop analytical solutions to steady-state and non steady-state differential equations for flow in porous media with thermally changing boundary conditions.
2. Study of the effects of transient pore pressures in riverbed alluvium and the decrease of available discharge area during freezing and their possible effects on the stability of riverbed material and on the formation of icings.
3. Investigate the influence of low temperatures, permafrost barriers, and seasonal freezing and thawing of aquifers on groundwater chemistry.
4. Expand studies of large northern springs to determine recharge areas, seasonal changes in rates, temperature, and chemistry: investigate associated icings to determine winter discharge rates, and their contribution to spring runoff.
5. Continue work to broaden geological information on remote areas, and to develop mathematical models of hydro-geologic factors to arrive at quantitative assessment of recharge, storage and discharge of groundwater. Hydro-logical studies on stream flow from various basins should continue, and groundwater monitoring wells should be developed.

Investigations in the areas listed above will be aided by further development of geophysical methods to delineate permafrost extent and soil type, especially by airborne equipment. Specifically, remote sensing of either geophysical properties (resistivity) or thermal (infrared) differences between groundwater and surface water, or visual interpretation of plant types or geomorphic features, will greatly reduce the costs of exploration for groundwater in permafrost regions.

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