Ming-ko Woo

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Prof. Dr. Ming-ko Woo
School of Geography and Earth Sciences
McMaster University
Hamilton, Ontario
Canada L8S 4K1
woo@univmail.cis.mcmaster.ca

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Preface

The word permafrost was coined by S.W. Muller in 1943 and the International Hydrological Decade started in 1965, under the auspices of the United Nations Education, Scientific and Cultural Organization (UNESCO). While valuable observations and cursory measurements had been made in permafrost areas in the early half of the twentieth century, the latter part of the century witnessed expansions in measurement and mapping programs in areas of permafrost that are difficult to access and expensive to operate in. Resource development and environmental assessment provided the added impetus. Concerted effort was made to embark on projects, ranging in scale from experimental plots to small drainage basins, to study the properties, distribution, movement and storage of water as they are directly and indirectly influenced by the presence of permafrost. Investigations in the field and laboratory remarkably advanced permafrost and hydrologic sciences. When the new millennium arrived, a wealth of knowledge had been acquired to consolidate the formal status of permafrost hydrology.

Hydrology is by nature both scientific and applied, as is permafrost investigation. Permafrost hydrology benefits from progress in other disciplines; included among them are atmospheric and climatic sciences, hydrogeology and soil science, geotechnical and environmental engineering, biological and forest sciences, periglacial, fluvial and glacial geomorphology. The interdisciplinary flavor of permafrost hydrology adds to its scientific strength and practical merit while its relevance to these other disciplines is reciprocal. The permafrost domain still encompasses many scientifically uncharted territories with innumerable hydrologic features yet to be discerned, many processes to be understood and pertinent new concepts to evolve. The excitement of discovery will continue to entice future investigators.

This book provides a survey of the status of progress. Through this book I wish to share my experiences with professional and non-professional but interested readers, be they practitioners, researchers or students. The materials are presented in sufficient detail for the instruction of young permafrost hydrologists at a senior level, and broad enough to satisfy the needs of cross-disciplinary researchers and practitioners who can make use of the information without having to delve into the complexity of permafrost or hydrologic sciences. Emphasis is placed on discussion of permafrost and hydrologic processes with the premise that an understanding of the physical processes is fundamental to experimentation, theoretical and modeling work in permafrost hydrology.

I have learned much from published articles on permafrost, hydrology and related or even unrelated subjects, from the work of my colleagues and from discussions with my dedicated research associates and students. For this book, various people have kindly permitted the use of their photographs that uniquely capture a number of hydrologic processes and phenomena: George Brook, Sean Carey, Richard Heron, Ross Mackay, Philip Marsh, Frank Nicholson, Chris Spence, Robin Thorne and Kathy Young. Ross Brown graciously provided snow data I requested specifically for this book. I specially acknowledge the help of my friends Michael Mollinga, Robin Thorne and Laura Brown who improved the manuscript and produced many of the fine maps and diagrams.

Ming-ko Woo

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Chapter 1
Introduction

1.1 The World Cold Regions

The common perception of the world's cold regions are those inhospitable frigid zones extending outward from the north and south poles that are covered (at least for part of the year) with ice and snow, and where one may expect to find vast expanses of frozen ground, glaciers, ice caps, frozen lakes and ice-covered seas. Further away from the poles, climatic conditions generally become less severe, and the ice and snow may disappear for large parts of the year. This advance of milder conditions with decreasing latitude does not occur uniformly, however, being strongly affected by factors such as surface elevation and large scale atmospheric and oceanic circulations. Thus, latitude alone is not the most useful of markers for the boundary between the cold regions and the temperate zones of the mid-latitudes, where sub-zero temperatures occur infrequently. For this reason, researchers have sought a more comprehensive definition of a cold region on the basis of measurable criteria. Since by far the greater part of the Earth's land mass and population are found in the Northern Hemisphere, the northern cold regions have received much of the attention. In an extensive study of northern environmental conditions, Bates and Bilello (1966) suggested that a cold region is one in which at least one of the following criteria is satisfied:

- Average air temperature of the coldest month is <0°C
- Maximum observed snow depth on the ground is >0.3 m (1 ft)
- Average duration of ice that prevents navigation exceeds 100 days per year
- Frost penetration exceeds 0.3 m (1 ft) in at least 1 year of every 10.

By defining cold regions not only on the basis of air temperature but also by taking into account the presence of water in the forms of snow and ice above and below ground, the northern cold regions include nearly all of the land mass north of 40°N latitude. There are significant extensions south of this latitude, most notably in

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mountain ranges and high plateaus. In the Southern Hemisphere the dominant cold region is Antarctica, with a salient that follows the Andean mountain chain in South America. In the subtropics and tropics, cold regions are confined to the highest elevations of mountains and plateaus.

Within a cold region there are often areas where persistent and extremely low air temperatures prevail, and this intense atmospheric coldness, transmitted to and preserved in the ground, gives rise to the perennially frozen ground considered as permafrost. All parts of the world underlain by permafrost therefore possess cold region attributes, making permafrost areas an integral part of the cryosphere (places on Earth where water exists in solid form). Water in its frozen state, either as seasonal ice and snow or as permafrost, has a profound effect on the movement and storage of water on and below the land surface, and these are the concerns of hydrology.

This chapter introduces permafrost and its influence on hydrology, and provides background information on the permafrost environment.

1.2 Water in Frozen Soils

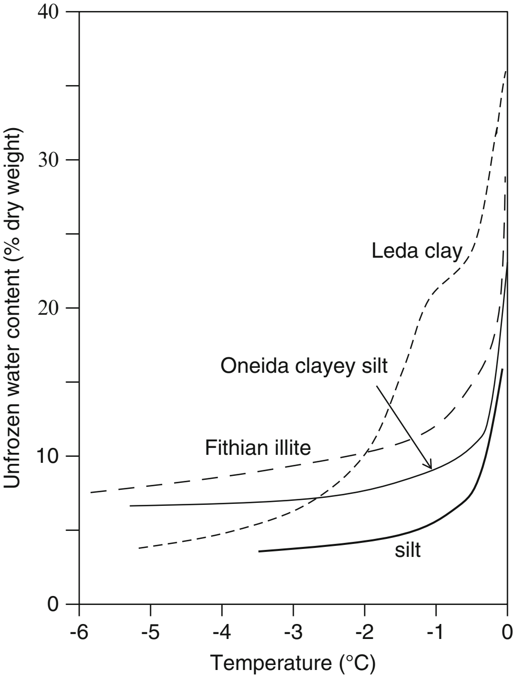
Under saturated conditions, water in the soil pores includes (1) gravitational water that can drain freely, (2) capillary water held against gravitational drainage in interstitial spaces between soil particles, and (3) water adsorbed on the surface of soil particles. Soil freezing under both saturated and non-saturated situations starts with the water farthest from the surface of the soil particles. Gradually the water closer to the grains freezes until a thin layer of unfrozen water remains, even at temperatures considerably below the freezing point of bulk water. Thus, gravitational water freezes first, followed by the capillary water and finally the adsorbed water.

Pure water under one atmospheric pressure freezes at 0°C. However, water in the ground usually freezes at temperatures of a fraction of a degree or even several degrees below 0°C. This freezing point depression occurs in water (1) adsorbed on the surface of soil particles, (2) containing dissolved material, and (3) under pressure, such as deep-seated groundwater. In other words, the amount of unfrozen water in frozen soil depends on solute concentration and confining pressure on the fluid, as well as soil particle size and temperature. Anderson and Tice (1972) developed an empirical relationship

$$\ln \theta_{un} = b + (b_1 + \ln A_s) + (b_2 + {A_s}^c + \ln T_d) \tag{1.1}$$

that relates unfrozen water content (θ_{un}, fraction of dry weight of soil, dimensionless) to the specific surface area of soil (A_s in m^2 kg^{-1}) and temperature below the freezing point of bulk water (T_d, in °C), with b, b_1, b_2 and c being empirical constants. This equation shows that (1) the quantity of unfrozen water decreases

Fig. 1.1 Unfrozen water content for several types of soil, at temperatures below 0°C (Modified after Burt and Williams 1976)



as temperature continues to fall below the freezing point of bulk water, and (2) the finer the soil, the larger the specific surface area and the larger the amount of unfrozen water. Thus, at a given temperature below freezing of the bulk water, clay has a higher content of θ_{un} than silt which in turn has a higher content than sand. Figure 1.1 reproduces Burt and Williams' (1976) laboratory measurement of unfrozen water content for several soils.

Hydraulic conductivity is a measure of the rate at which water can pass through a porous medium. The average rate depends on the (1) size of pores and dilation cracks caused by desiccation or thermal contraction in soils, and the density and dimensions of fissures in rocks, (2) connectivity of pathways in the flow network, and (3) viscosity of the fluid, which is temperature dependent. Table 1.1 provides typical hydraulic conductivity values for unfrozen rock and earth materials. A reduction in temperature below freezing point drastically reduces the hydraulic conductivity (Fig. 1.2) as the unfrozen water content drops and the pores and cracks are increasingly filled with ice.

Moisture can migrate in frozen soil and this is generally attributed to two mechanisms. One is the movement of fluid through the film of interconnected unfrozen water on the surface of the soil particles. The second is related to heat transfer associated with phase change. As the freezing front advances, latent heat is released by freezing of water at the front. This heat is conducted through the ice lens

Table 1.1 Hydraulic conductivity of saturated rocks and earth materials

Material	Range of hydraulic conductivity [m s^{-1}]
Rocks	
Plutonic and metamorphic rocks	
Unfractured	10^{-10}–10^{-14}
Fractured or weathered	10^{-4}–10^{-8}
Basalt	10^{-2}–10^{-7}
Sandstone	10^{-6}–10^{-10}
Shale	10^{-9}–10^{-12}
Unconsolidated Materials	
Gravel	10^{0}–10^{-4}
Sand	10^{-3}–10^{-6}
Silt and loess	10^{-5}–10^{-9}
Clay	10^{-9}–10^{-12}
Glacial till	10^{-4}–10^{-12}

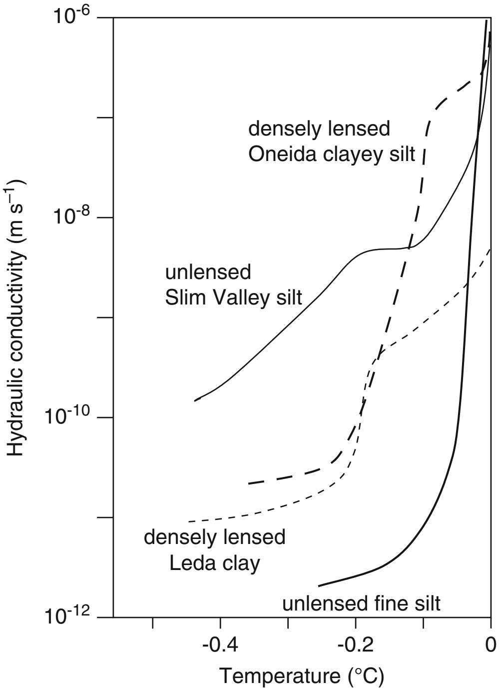


Fig. 1.2 Logarithmic decline in hydraulic conductivity of several types of soil as temperature falls below 0°C (Modified after Burt and Williams 1976)

toward the cold side. Melting of the ice then occurs at the cold side of the ice lens. With this process occurring across each lens and between lenses, the net effect is a transport of water in the unfrozen films.

1.3 Permafrost

1.3.1 Definitions

Permafrost is ground that remains at or below 0°C for at least two consecutive years. It was originally conceived as perennially frozen ground (Muller 1943), but the currently adopted definition is based on temperature and not on the freeze-thaw state of water in the host medium.

Two parallel sets of definitions apply to cold grounds (Fig. 1.3) based on intersections of the maximum and minimum ground temperature profiles with the 0°C isotherm and with an isotherm that defines the freezing point depression (or sub-zero temperature at which most of the soil water freezes). Perennially cryotic ground is equivalent to permafrost (with temperature at or below 0°C, regardless of whether its water is in a solid or a liquid state) while perennially frozen ground refers to the zone where most of soil water is frozen. The top boundary of the permafrost is the permafrost table.

An active layer is the top layer of the ground in a permafrost area, subject to seasonal freeze and thaw conditions. It is somewhat deeper than the seasonally cryotic zone due to freezing point depression. For the same reason, there is a layer at the base of the permafrost, known as the cryopeg, which has temperature below

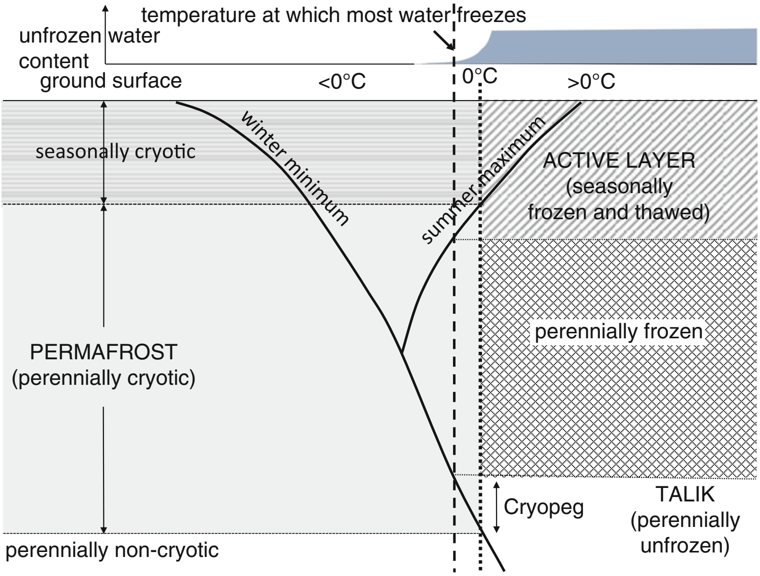


Fig. 1.3 Definition of permafrost and associated features based on intersections between 0°C line and annual maximum and minimum ground temperature profiles. Frozen zone is defined on the basis of intersections of the annual maximum temperature profile with the temperature of ice nucleation, which is usually <0°C and varies with soil type

0°C but with water remaining unfrozen. Talik or perennially unfrozen zone is found below the permafrost, but may also be located within or above the permafrost.

1.3.2 *Distribution*

Permafrost occupies about 22% of the exposed land surface in Northern Hemisphere (Brown et al. 1997) (Fig. 1.4). In Antarctica, permafrost is found in almost all the ice-free areas which constitute only 0.35% of the region (Bockheim et al. 2008). At the same latitude in both Hemispheres, permafrost tends to be thinner under maritime influence than under a continental climate, and high altitudes are required for permafrost to exist in temperate and subtropical latitudes.

Continuous permafrost is considered to exist where 90% or more of the area within a geographic region is underlain by permafrost, with taliks found only in isolated locations such as beneath a deep lake or along the vent of a geothermal spring. Permafrost is discontinuous where it occurs in a geographic region with other areas being free of permafrost (Permafrost Subcommittee 1988).

The terms widespread, sporadic, isolated and island permafrost have been used to describe discontinuous permafrost that occurs in various proportions of the total land area. This book distinguishes only continuous and discontinuous permafrost (which encompasses all permafrost areas where the permafrost is not continuous) categories mainly on the basis of their hydrologic functions. Discontinuous permafrost is where the presence of permafrost does not significantly impede recharge,

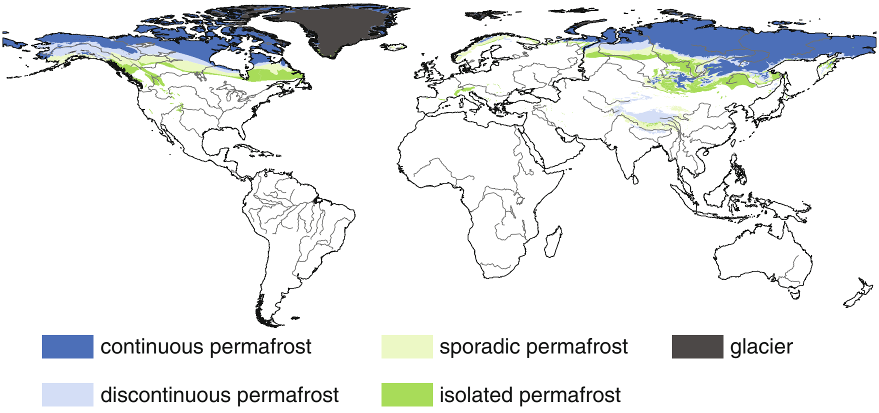


Fig. 1.4 World distribution of permafrost, showing areas with continuous, discontinuous, sporadic and isolated permafrost. The extent of discontinuous permafrost in the Northern Hemisphere is also shown in Fig. 1.22. Permafrost in Antarctica is not shown. Elsewhere in the Southern Hemisphere, permafrost occurs sporadically and their size is too limited to appear on the map. For most of this book, distinction is not made among discontinuous, sporadic and isolated permafrost but are lumped under the general label of discontinuous permafrost

circulation and discharge of the regional groundwater flow systems that exist above, within and below the permafrost. Discontinuous permafrost stretches to the southern limit of permafrost occurrence in lowlands of the Northern Hemisphere. In ice-free parts of Antarctica, discontinuous permafrost and non-permafrost conditions are restricted to coastal lowlands of the maritime Antarctic Peninsula and its offshore islands.

Alpine or mountain permafrost and plateau permafrost are locational designations, referring to permafrost found at high altitudes in middle and low latitudes. Subsea permafrost, as the term implies, is found underneath the sea bed. Although important in its own right, and though there may be groundwater discharge from beneath the sea beds, subsea permafrost is excluded from the present hydrologic considerations.

1.3.3 Factors Influencing Permafrost Occurrence

Regional and local conditions affect the development of permafrost and influence the thickness of the active layer.

1.3.3.1 Location and Topography

Latitude, elevation and continentality are the major determinants of permafrost occurrence on a global scale. Permafrost occurs prevalently in circumpolar areas. Most of Antarctica is under ice, however, and insufficient is known about the permafrost beneath the glaciers. In temperate and subtropical zones, it has a preference for high elevations including the Tibetan (Qing-Zang) Plateau and mountain ranges in the temperate zone such as the Alps, the Andes, the Western Cordillera of North America, and mountains that extend from Central Asia, through Mongolia to southeastern Siberia and northeastern China. Another regional factor is the oceanic effect. Areas under maritime influences have milder climates than their continental counterparts and the warmer conditions restrict permafrost development. With the Gulf Stream bringing heat and moisture to northeastern Atlantic, for example, permafrost is not found at low elevations on coastal Norway, even above the Arctic Circle (Fig. 1.5a). Similarly, maritime influence renders the permafrost to be discontinuous in coastal lowlands of the Antarctic Peninsula and its offshore islands (Fig. 1.5b). At a local scale, reduced temperature and frequent cloudiness at high elevations of the temperate or even tropical areas enable sporadic occurrence of permafrost. In sub-polar and temperate zones, permafrost patches are formed in topographic hollows and beneath slopes that frequently lie in shadows. Thus, permafrost underlies north-facing slopes in the subarctic but many south-facing slopes are free of permafrost.

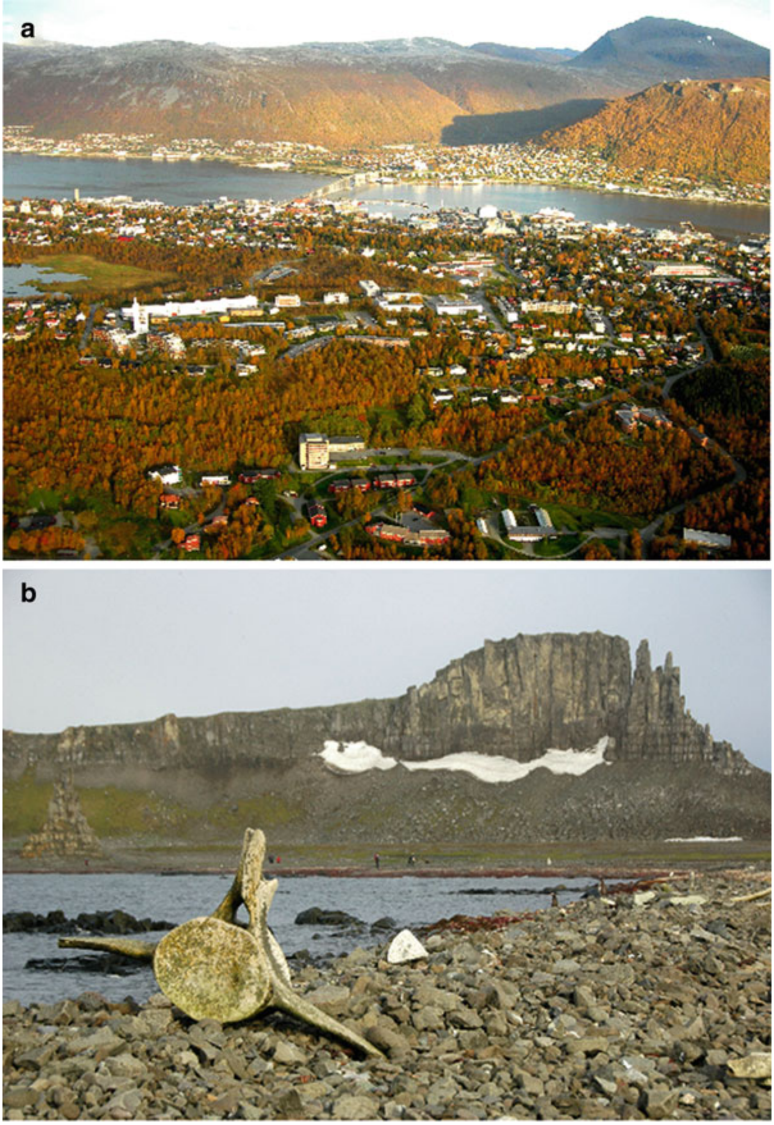


Fig. 1.5 (**a**) Absence of permafrost on coastal lowlands around Tromsø, Norway, above the Arctic Circle attributed to maritime influence. Permafrost is restricted to high elevations on the mountains. (**b**) Maritime influence renders permafrost to be discontinuous in coastal lowlands of Antarctic Peninsula and its offshore islands. Picture shows Aitcho Island with basaltic cliff above talus slope materials, and foreground with raised beach boulders enclosing a freshwater lagoon. The otherwise barren ground is vegetated by only mosses and lichens

1.3.3.2 Snow Cover

The presence of a lingering snow cover delays ground warming in the spring. However, considered over a year, the cooling effect due to reduction in snow-free days is counteracted by the effectiveness of snow insulation against atmospheric coldness. Snow is an excellent insulator against winter heat loss from the ground. Such a role of snow has long been confirmed by field observation and modeling. Nicholson and Granberg (1973) found that snow of about 0.7 m thickness prevents permafrost development on the Canadian Shield near Schefferville, Quebec. Goodrich (1982) showed through modeling that a combination of snow cover and latent heat release associated with freezing of moisture-rich soil results in higher ground temperature than due to snow insulation alone.

1.3.3.3 Water Bodies and Water Flow

Water bodies, including the ocean, lakes and rivers, inhibit or warm the permafrost in their immediate vicinity. The sea and lakes that do not freeze to the bottom in winter maintain a talik at the sea floor and the lake bed. In addition to its influence on permafrost development, surface water has large effects on ground temperatures. Jorgenson et al. (2010) noted that the mean annual temperatures of sediments on the bottom of a shallow and a deep lake in Denali National Park, Alaska, were about 8°C, which is 10°C warmer than the mean air temperature. Heat from water bodies is also transmitted laterally to warm or deplete the permafrost at the shore zones. Kristensen et al. (2008), for instance, obtained significantly higher permafrost temperature from a borehole drilled 6 m from the shore of an ice-cored moraine in Svea, Svalbard, compared with another borehole 145 m from the water bodies (Fig. 1.6). Permafrost development is also hindered by flooding, which may add heat to the soil and may also deposit sediments that destroy any insulating cover of lichen and moss (Viereck 1973).

Groundwater flow carries heat and if the flow is continuous throughout the year, taliks are maintained in the permafrost (Sect. 3.1.2). In the discontinuous permafrost area of Schefferville, Nicholson and Thom (1973) found that large valleys have talik zones due to a combination of deep snow and groundwater movement that convects heat to keep the valley floors from freezing.

1.3.3.4 Vegetation

Vegetation directly influences heat transfer to the ground by altering the bare-ground albedo. In forested environments that include an understory of shrubs and a forest floor with lichen and moss mats, the trees and shrubs in summer provide shade to moderate heating of the ground, and in winter modify the distribution of snow. Of particular significance to the ground thermal regime is the moss and lichen layer which tends to have a high porosity (Fig. 1.7). Saturated moss and lichen do

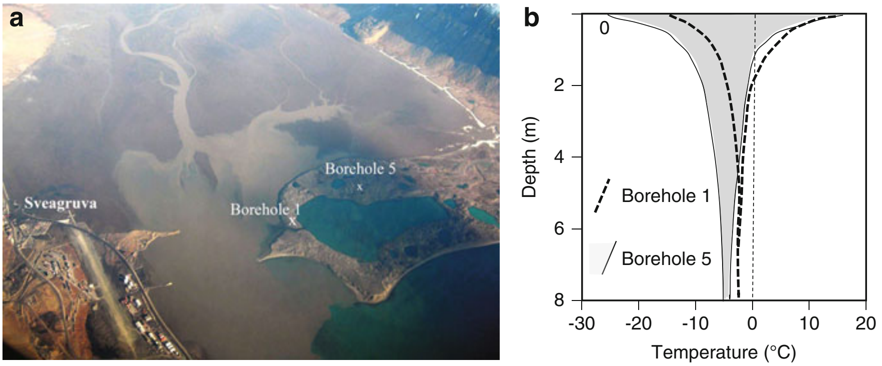


Fig. 1.6 (**a**) Location of two boreholes in an ice-cored moraine that forms a peninsula across a fiord in Svalbard, opposite to the coal mining settlement of Svea seen on the lower left. (**b**) Annual maximum and minimum temperature profiles show that Borehole 1 is warmer than Borehole 5 due to its closer proximity to water bodies, and its depth of zero annual temperature amplitude is about 6 m

Fig. 1.7 Examples of mosses (**a**) *Ditrichum flexicaule*, (**b**) *Racomytrium langinosum* (some mosses are ripped and laid out on the left to show their vertical elongation), and lichens (**c**) *Cladonia rangiferina* (reindeer lichen), (**d**) *Dactylina arctica* (Arctic finger lichen). High porosity of moss and lichen mats offers good insulation and facilitates water infiltration

not transpire and evaporation loss is limited to moisture drawn to the surface through wicking. With suppressed evaporation, the surface becomes dry and warm, but the large amount of air in dry moss and lichen is an effective insulator, leaving the bottom layer wet and cool. This mechanism buffers the ground from summer heat and maintains a thinner active layer than would be found beneath bare ground. The forest ecosystem undergoes vegetation succession change after disturbance. A shift from deciduous to coniferous forest (1) increases the amount of snow interception on tree branches and leaves, (2) reduces litter fall and slackens accumulation of organic horizons but (3) encourages growth of mosses on the forest floor, (4) increases soil moisture that reduces summer heating and enhances winter heat loss due to differences in thermal properties between water and ice (Jorgenson et al. 2010).

1.3.3.5 Soils and Rocks

Different bedrock and soil materials have different surface albedo, thermal conductivity and heat capacity, though the intrinsic differences are not large. However, when considered in conjunction with the amount of fissures and pore space in the material, and their moisture or ice content, the thermal properties vary considerably. This results in significant variation in the thickness of the active layer and may even determine whether permafrost is present or absent in discontinuous permafrost zones. Peat as a soil material is particularly effective in maintaining a cold substrate. Depending on the degree of decomposition and compaction, the insulating and moisture absorption capabilities of peat vary but in general, peat has high porosity relative to most mineral soils. Peat usually has high water content when wet and high air content when dry. Brown (1963) reported a dry peat that has a thermal conductivity of 0.07 W m^{-1} C^{-1}. When saturated and thawed, the thermal conductivity rises to 0.46 W m^{-1} C^{-1}, but when this saturated peat is frozen, its thermal conductivity reaches 2.3 W m^{-1} C^{-1} (cf. thermal conductivity listed for peat in Table 2.1). Large difference in thermal conductivity between icy peat and unfrozen saturated peat results in large heat loss from the ground in winter and insulation against ground heating in summer.

1.3.3.6 Fire

Wildfire, usually initiated by lightning activity, is a common summer feature in boreal forests and can sweep across large areas. It is a recurrent feature and causes frequent renewal of plant succession (Fig. 1.8). Despite its devastation of the above ground vegetation, the heat produced by wildfire has limited effect in thawing the permafrost. Kasischke et al. (2010) further noted that shallow thaw depth in permafrost terrain and poor drainage that is facilitated by efficient moisture retention in a *Sphagnum* moss cover, render some wet black spruce forest sites resilient to wildfire. After a wildfire, there are several consequences that alter the

Fig. 1.8 Growth of aspen (*Populus tremuloides*), shown in middle of picture, after a black spruce (*Picea mariana*) cover was burnt, Chena River, Alaska. Leaning trees are an indication of permafrost degradation, which weakens the support for the trees

ground thermal conditions (Viereck 1973). These include (1) change in surface albedo, with the charred vegetation and burnt surfaces absorbing more radiation, (2) removal of vegetation and the insulating organic mat that covers the forest floor, and (3) reduction in interception of precipitation as leaves and branches are burnt off, enabling deeper snow accumulation for ground insulation, (4) earlier and more rapid snowmelt that exposes the burnt areas to surface heating for a longer period, and (5) deeper thaw at the burnt site, leading to subsidence of locally ice-rich soils. Where water fills the depressions thus created, the thermal regime is altered through the low albedo and large heat absorption by the water, though much heat is lost to evaporating the water in the summer (Jorgenson et al. 2010).

1.3.3.7 Geothermal Heat

Geothermal heat warms the permafrost from the bottom, and the geothermal gradient influences the thickness of the permafrost as well as its temperature. Climatically cold areas such as Iceland and Kamchatka Peninsula have limited areas with permafrost due to pronounced geothermal heating and volcanic activity. In other permafrost regions, geothermal activity along faults and the occurrence of hot springs give rise to local taliks. Many such features can be found in tectonically active areas such as the Tibetan Plateau (Fig. 1.9).

Fig. 1.9 Fault-lines and other zones of structural weakness offer preferred conduits for geothermal heat flow that leads to talik formation in permafrost. At Yangbajing on Tibetan Plateau, geothermal heat has been tapped for decades as an energy source for power generation

1.4 Permafrost and Hydrology

Central to hydrology is the water cycle, that is, the circulation of water on and near the Earth's surface (Chow 1964, pp 1–2). Hydrology as a scientific or applied discipline is concerned with the distribution, movement and storage of water in this hydrologic cycle.

Distinct from meteorology and climatology, which deal with moisture in the atmosphere, and oceanography, which concerns water in the seas and oceans, hydrology focuses on water on and near the land surface. Freshwater (though freshness is not taken in the strictest sense as most water has some minimal concentration of dissolved substances) rather than saline water is the medium under consideration. Furthermore, this book concerns physical hydrology. Water quality, though of great significance in a scientific and an applied sense, is left to other publications. Excluded also from hydrologic considerations are the mechanical behavior and the force of water, which are in the realm of hydraulics.

1.4.1 Permafrost Hydrology

Permafrost hydrology is that branch of cold region hydrology that is concerned with the direct or indirect effects of perennially frozen ground on the properties, occurrence, distribution, movement and storage of water.

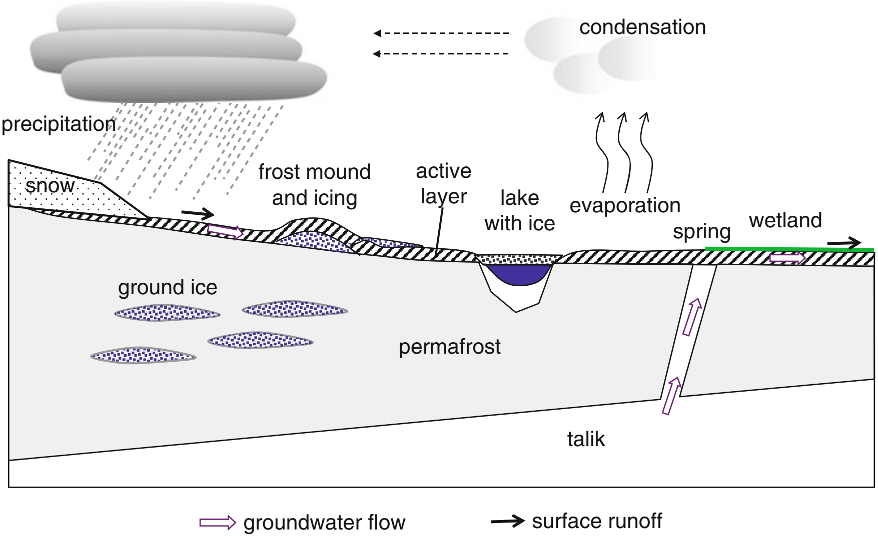


Fig. 1.10 Conceptualization of the circulation and storage of water in permafrost regions, with emphasis on the effect of coldness

Figure 1.10 is a conceptualization of the circulation and storage of water in permafrost terrain. The effect of coldness is emphasized. Precipitation arrives mainly in the forms of snow in winter and rain in summer. Snowfall accumulates seasonally over the long winters or perennially in snowbanks or as glaciers. In spring and summer, rainfall and snow meltwater saturate the thinly thawed soil and any excess that cannot enter the ground runs off to feed rivers, wetlands and lakes, which may retain this surface water for various lengths of time. The stored surface water may subsequently evaporate or infiltrate or support lateral flow. Below the surface, water is kept as ground ice, either seasonally or for long durations of decades to millennia; but ice melt is also a source of runoff. Some water may percolate deeper to recharge the groundwater reservoirs that lie above, within or below the permafrost. Groundwater discharge, if it occurs in winter, freezes above ground or within the active layer. Otherwise, it emerges as springs or feeds the streams, wetlands, lakes and the sea. Evaporation from the land and water bodies returns moisture to the atmosphere but in winter the evaporative flux is curtailed by a cover of snow and ice, and limited by low to negligible supply of energy. Finally, condensation of atmospheric moisture, formation of clouds, and precipitation processes complete the hydrologic cycle.

An examination of the hydrologic cycle of permafrost areas evidently finds snow, glaciers and various other forms of ice to play a major role in the hydrology of cold regions. Glacial hydrology is beyond the scope of this book while snow hydrology is a vast field and only several facets of it are treated here. Of the many characteristics of surface (river and lake) ice and ground ice, only those of direct relevance to hydrology are considered.

1.4.2 Hydrologic Behavior of Seasonal Frost and Permafrost

Frozen ground is naturally not restricted to permafrost regions. Large parts of the temperate zone are subject to recurrent or occasional soil freezing and there are many similarities and differences in the hydrology of the seasonally and the perennially frozen ground.

The active layer in permafrost regions, subject to seasonal freeze and thaw, is equivalent to the layer with seasonal frost in non-permafrost areas. Cold regions with or without permafrost exhibit several similar hydrologic traits.

- Unfrozen water content in frozen soil drops markedly as temperature falls further below freezing.
- Ground ice tends to seal openings in soils and rocks to render the frozen materials impervious and behave as an aquiclude (Chap. 3).
- Hydraulic conductivity and liquid water storage capacity are therefore temperature dependent and are reduced sharply as the soil freezes.
- Heat and moisture fluxes are closely coupled and are often interdependent (Chap. 2).
- Seasonal freeze-thaw is experienced at the top soil layer, and the active layer behaves like the seasonal frost zone in non-permafrost areas.
- The hydrology of frozen soils is closely linked to snow hydrology.

Dissimilarities also exist between permafrost and non-permafrost areas in terms of their hydrology and hydrology-related conditions.

- The distinguishing feature is the duration of freezing. For permafrost, the ground must be at or below 0°C for at least two consecutive summers, but is usually so for longer durations.
- Multi-year ice and semi-permanent snowbanks can only be found in permafrost areas.
- Prolonged subfreezing condition in permafrost has long-term consequences that affect the hydrology.

  1. A special suite of frost-related geomorphic features is developed in permafrost terrain, which in turn affects surface and subsurface water movement (Sect. 6.1.4).
  2. The soil is subject to disturbance by freeze-thaw processes; organic matters are preserved against rapid decomposition; peat formation is favored by short seasons of decomposition.
  3. Ground ice, when incorporated as part of the permafrost, does not melt after its formation (until the permafrost is eventually degraded).
  4. Groundwater from below the permafrost seldom reaches the surface and there is much less mixing between near-surface and deep-seated groundwater in permafrost than in non-permafrost zones.
  5. Similarly, most surface water runs off or is stored in the active layer and does not recharge the deep groundwater reservoir.

- Vegetation has shallow roots since downward growth is prevented by the permafrost; water uptake for evapotranspiration is consequently limited compared to plants with deep root mass.

1.5 Environments of Permafrost Regions

1.5.1 Hydroclimatology

Low temperature is the unifying variable for all permafrost areas. Precipitation, though, is highly variable across permafrost areas, both in terms of magnitude and timing. There is notable seasonal variation in temperature and in most cases, precipitation as well. Several factors are responsible for the regional and seasonal variations of temperature and precipitation in permafrost regions.

Latitudinal position plays the dominant role. There is a poleward increase in coldness, though factors such as continentality, planetary circulation and air mass patterns give rise to regional deviations from this overall trend. Aridity also increases poleward. The zone of low precipitation (<250 mm per year) is regarded as the polar desert.

Permafrost areas in the interior of large land masses, such as the Mackenzie and Keewatin districts of northern Canada and large parts of Siberia, have a continental climate with very cold winters (<−25°C in January) and summer temperatures rising to 15°C in July. These areas have moderate to low precipitation, most of which comes in summer.

A maritime setting with open water conditions has a moderating effect on temperature (Woo 2010). This maritime influence is experienced in the permafrost areas of southern coastal Greenland and in several narrow strips of land that fringe Antarctica. However, Arctic islands and Arctic coast adjacent to a sea with an ice cover do not benefit from such effects. Compare, for example, two sites at about 80°N: Longyearbyen in Svalbard, where a warm ocean current generally inhibits sea ice formation, and Eureka in Ellesmere Island, with a sea ice cover for >9 months. Both sites have similar July temperatures of about 6°C but their respective January temperatures are −15°C and −37°C.

On a continental scale, land-sea contrasts in heating and atmospheric pressure differences give rise to monsoons. The East Asiatic monsoon exerts large influence on the climate of southern Siberia, the Amur region, Mongolia and northeastern China. In winter, cold and dry air flows out of the continental interior. Precipitation comes mainly in the summer when landward airflow draws in moisture from the Pacific. For the Tibetan Plateau, the Indian monsoon brings heavy summer precipitation to its southeast. However, other parts of the Plateau are shielded from this moist airflow by the Himalaya and other high ranges and are consequently arid or semi-arid.

Westerlies arising from atmospheric circulation on a planetary scale are another mechanism that brings moisture from the oceans to the land in subarctic and subantarctic regions. The storms that accompany the westerly airflows deposit precipitation in western Siberia but the amount declines in eastern Siberia where the Asiatic monsoon strengthens. In North America, winter storms follow the track of the eastward moving jet stream, which is often deflected by the lofty Cordilleran mountains northward to Alaska where they deposit much of their moisture on the windward slopes. Areas east of the mountains are left relatively dry. In summer, storms spawned in the subtropics occasionally bring in precipitation from the south.

Mountains oriented perpendicular to the flow direction of moisture-laden air strongly affect the distribution of precipitation, with higher amounts falling on windward slopes and at high elevations. With decreasing temperature at high elevations, snowfall becomes a major form of precipitation. The change in temperature and precipitation with height gives rise to marked vertical zonation of climate, particularly in temperate and tropical latitudes. For mountain complexes in temperate regions, permafrost may occur preferentially on shaded slopes and those with a thin snow cover.

In permafrost areas, snow accumulation and ice formation are important hydrologic responses to the coldness, retarding water entry to the ground and delaying lateral runoff. On the other hand, prolonged presence of a seasonal or perennial snow and ice cover has strong feedbacks on the hydroclimate: much of incoming radiation is reflected, with the result that the lower atmospheric layer is kept cool during the warm seasons and surface evaporation is inhibited.

1.5.2 Geology

All major types of rock are represented in permafrost regions, from very ancient Precambrian rock (older than 600 million years and often older than one billion years) to recently formed strata resulting from volcanic activities. Various rock types can have separate attributes that influence hydrologic behavior. Rocks are riddled with fissures of various dimensions, which may be in the form of laminae, bedding planes, joints or faults. Structural deformation causes the rocks to fracture and distort; extreme heat and pressure alter and remold the original earth materials.

Sedimentary rocks are made up of sediments deposited in layers and subsequently hardened into rocks. They can form flat-lying and gently dipping beds but can also be deformed into folds and fractured and steeply sloping beds. Sedimentary rocks that have high rock solubility (e.g. carbonates and gypsum) hold a special place in hydrology (Fig. 1.11). They contain solution conduits (natural tunnels and other openings) that offer passages for groundwater flow, and caves and sinkholes enhance the capacity for surface retention and groundwater storage (Ford and Williams 1989).

Plutonic rocks are formed when magma (molten rock material) cools and crystallizes deep in the Earth's crust. Magma also injects into existing rocks and