

NORTHERN HYDROLOGY

Ming-ko Woo

McMaster University, Hamilton, Ontario, Canada

Keywords: Snow, ice, glacier, permafrost, ground ice, snowmelt, active layer, infiltration, evaporation, groundwater, overland flow, runoff, streamflow, lakes, wetlands, reservoir, floods, fill-and-spill, Arctic, Subarctic

Contents

1. Introduction
 2. Physical Setting
 3. Snow Conditions
 4. Glaciers
 5. Active Layer Processes
 6. Groundwater
 7. Runoff Generation
 8. Lakes and Reservoirs
 9. Rivers
 10. Large Basins
 11. Hydrology and Northern Changes
- Glossary
Bibliography
Biographical Sketch

Summary

The Arctic and the Subarctic constitute the North. In this cold region, water commonly occurs in solid and liquid forms, and northern hydrology treats the distribution, movement and storage of freshwater in its different states. The North is subject to increased human activities notably for resource development, and to changes associated with climate warming. Fundamental understanding of northern hydrology better prepares us to cope with these changes and in protecting the environment.

Special to the northern cold region is the prevalence of snow and ice, and the presence of permafrost. Snow accumulation and melt processes dominate northern hydrology in the long winter and the short spring seasons. Glaciers also have a wide occurrence in the Arctic, and their summer melt is a major local water source.

With exceedingly low capability to conduct water, frozen soil including permafrost presents a hindrance to water flow. Infiltration is limited in favor of lateral runoff through surface and subsurface flow routes. Perennially thawed zones in the permafrost called taliks provide conduits for the circulation of deep groundwater, which discharges as springs or through lake bottoms and river beds. The seasonal flow pattern of most northern rivers follows a nival regime in which snowmelt is the principal contributor to total flow, but flows may be supplemented by glacier melt, summer rain, discharge of deep groundwater and outflows from large lakes and reservoirs.

Mega-basins with drainage areas $>0.5 \times 10^6$ km² integrate the flow of their tributary basins, which contribute varying amounts depending on their hydroclimate and physiography. Human-modified river flow, such as for hydropower production, greatly alters the flow regime of the regulated tributary and can even affect the high and low flows of the mega-basin. Good hydrological knowledge enables sound management of northern water resources.

1. Introduction

North, like the word South, is a geographical connotation of locations beyond the mid-latitudes of the planet. Rather than applying locational criteria such as the Arctic Circle to delineate the North, intense coldness is generally considered as a distinguishing feature of the North. Yet coldness is also a foremost characteristic of the far South, such as Antarctica, and high elevation regions in low latitudes, like the Tibetan Plateau. There are differences, however. Unlike Polar Regions, extreme seasonal contrast of extended winter darkness and prolonged summer days do not exist at the temperate and tropical heights; and the South is a continent surrounded by oceans while the North consists of continental and insular areas that enclose an ocean.

Hydrology studies the distribution, storage and movement of freshwater underground, at the surface and in the lower atmosphere. It is an applied as well as a scientific discipline, seeking to understand the processes that govern the occurrence of water and applying the acquired knowledge to manage water resources to address human, ecological and environmental concerns. Northern hydrology is strongly affected by the state in which water occurs (in solid, liquid and gaseous forms). Much of the water in the North is locked in its solid form for various lengths of time, from days to years and decades, even centuries or millennia. Thus, snow, glaciers, lake and river ice are an important parts of the terrestrial landscape. The formation and decay of snow and ice, and the seasonal or long term changes in these forms of storage exert strong influence on the hydrologic cycle. Furthermore, the transformation of water from one state to another involves energy, the gains and losses of which play an essential role in northern hydrology.

The North is sparsely populated but its water resource is considerable and notably pristine. Hydrologic information permits evaluation of flood and drought hazards to the residents and enables assessment of vulnerability of the northern environment. At present, the temperate and tropical regions are more developed relative to the far North, but there is increasing exploitation of resources in the North, including oil and gas extraction, and mining of metals and precious stones, accompanied by the of creation of settlements and transportation routes. These activities and the maintenance of their associated infra-structures necessarily involve the withdrawal and contamination of water, and alteration of the landscape that entails changes in flow and storage (in the forms of water, ice and snow).

It is generally acknowledged that as global warming intensifies, the northern climate is particularly prone to change. Furthermore, environmental disturbances in high latitudes produce feedbacks that can have global implications. A sound assessment of the hydrological consequences requires appropriate understanding of northern hydrological

processes. While it is beyond the scope of this chapter to discuss the impacts of climate change, the materials presented provides a survey of basic principles essential for the appraisal of hydrological responses to external forcing, both natural and human induced.

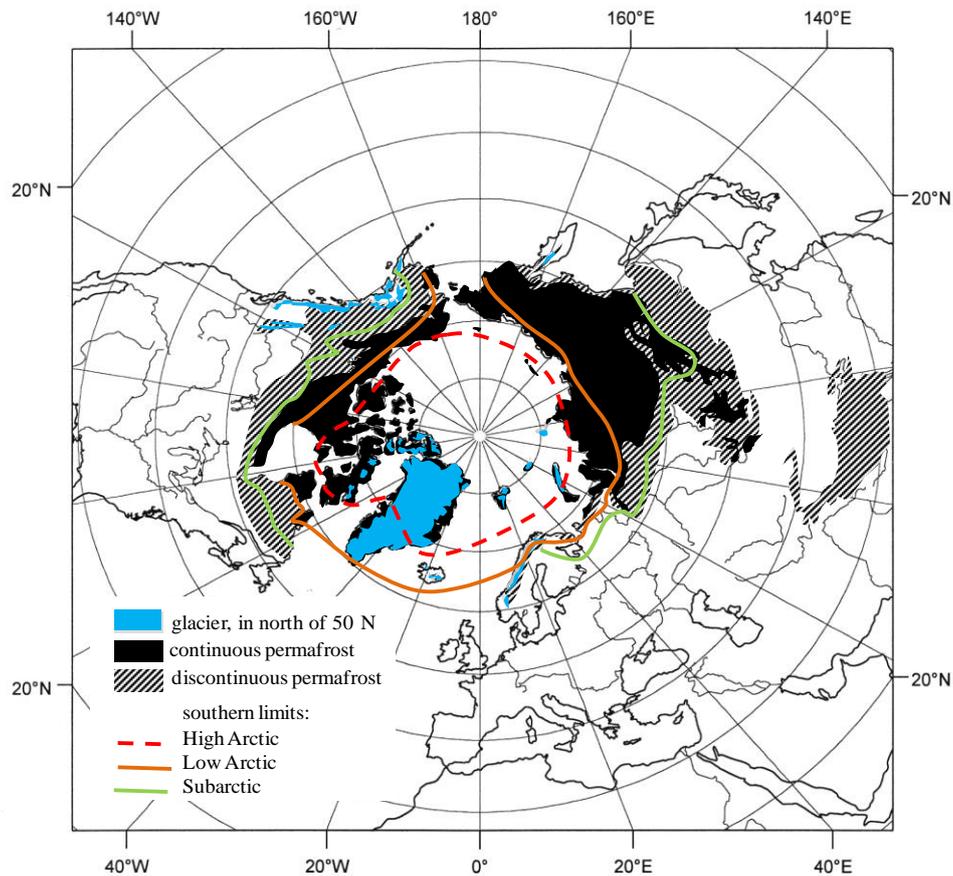


Figure 1. Location of Arctic and Subarctic and distribution of permafrost in Northern Hemisphere. In the map, areas with sporadic presence of permafrost are included under the discontinuous permafrost category.

2. Physical Setting

The land area of the northern circumpolar region consists of the Arctic and the Subarctic, which together represents the far North (Figure 1). Northern seas and oceans are excluded from the present consideration as our focus is on terrestrial hydrology. The Arctic is a treeless region. In the extreme north is the High Arctic (Figure 2a) where the ground is largely barren and the surface has 10% or less of tundra vegetation, which includes lichens and mosses, herbaceous plants and prostrate arctic willow. The Low Arctic has a dense cover of tundra vegetation, together with varying percentages of erect shrubs that include willow, birch and alder. The Arctic is separated from the Subarctic by the tree-line which is a narrow belt with a mixture of shrubs and stands of trees (Figure 2b). Tree growth in the Subarctic ranges from open woodland at the northern fringes, to dense covers of boreal forest further south. Spruce and larch are common, as are aspen and birch.



Figure 2, (a) High Arctic polar desert landscape with predominantly barren ground interspersed with moist patches that support tundra vegetation growth, Resolute, Cornwallis Island, Canada. (b) Forest margin with tundra-shrub at Salekhard in Siberia, Russia. The forest consists of spruce, larch and birch, and undergrowth of shrubs.

The North includes large land masses of northern Eurasia and North America, as well as islands of various sizes juxtaposed with ocean straits and sea inlets, most of which acquire an ice cover in part or most of the year. All major rock types are represented in the North, from strongly metamorphosed Precambrian rocks of 0.6 to >2.5 billion years in age, to volcanic and sedimentary beds that continue to form. Topography is highly varied, encompassing large plains that rise from the Arctic coast to considerable

elevations inland, rolling terrain with rounded hills, intermontane plateaus, high mountains and ridges of strong relief, often soaring to heights of over 3000 m.

Northern areas share the common trait of experiencing at least half a year with sub-freezing air temperatures. There are, however, zones that are anomalously warm for their high latitudes, including coastal location where intense coldness is ameliorated by mild maritime influences, such as the southern coast of Alaska and the northern coast of Norway. Overall, seasonal change in air temperature is largely driven by the solar radiation regime. Owing to polar positions, the annual supply of radiation energy is more limited than at the lower latitudes. Available energy is concentrated in the summer with its long hours of daylight while winter is a period of prolonged darkness, accompanied by heat loss and continuous cooling at the land, water, snow and ice surfaces. Precipitation varies greatly within the vast northern region. Areas of very low annual precipitation (<100-300 mm per year), known as polar deserts, are found in the Arctic Islands. On the other extreme are coastal belts where moisture-bearing onshore winds encounter topographic barriers to deposit heavy orographic precipitation.

Persistent and intense coldness leads to the occurrence of permafrost, defined as earth materials with temperature at or below 0°C for at least two consecutive years. Note that permafrost is defined on the basis of temperature and not on the freeze-thaw state of water. The ground can be labeled as permafrost with temperature being perennially below 0°C but freezing may be prevented by freezing-point depression (due to large pressure imposed by an overburden such as a thick glacier, or an abundance of impurities in the water) that maintains the soil water in a liquid state. Permafrost may be rich in ground ice or the ice content can be negligible. Above the permafrost lies the active layer, a layer that is subject to freezing in winter and thawing in summer. There are also zones located above, within or below the permafrost, known as taliks, that are kept unfrozen year-round by geothermal heat or by groundwater circulation. In some cases, taliks stay unfrozen because they are relicts left from a past period with above-freezing conditions. Figure 3 provides a simplified representation of permafrost, talik and active layer in a cold region setting.

Permafrost is continuous and underlies all land in the Arctic, but it becomes discontinuous and sporadic in the Subarctic (Figure 1). Permafrost thickness reaches 400 m in Svalbard (at about 80°N, north of the Scandinavia mainland), 600 m in the Canadian Arctic Islands and >1000 m in eastern Siberia, whereas the thickness drops to only tens of meters in the discontinuous permafrost zones, and permafrost becomes only sporadic in occurrence in the transition to non-permafrost terrain. A southward decrease in permafrost thickness is accompanied by an increase in active layer thickness from about 0.3-1.0 m in the Arctic, to > 2 m in the Subarctic. Locally, the active layer is thinner on north-facing than on south-facing slopes, under peat and vegetation mats, and in fine-grained materials.

Myriad lakes of different dimensions are scattered in the North, ranging in size from tundra ponds that measure several meters across to some of the largest lakes in the world, including Great Bear Lake, Great Slave Lake, Lake Athabasca and Lake Baikal. Immense stretches of wetlands and peatlands spread across the northern plains of Siberia and western Canada, together with less sizable ones on Arctic coastal plains,

river deltas and flood plains, and mere patches clustered in the semi-arid High Arctic. Five mighty rivers and their tributaries dominate surface drainage: Ob, Yenisei, Lena, Mackenzie and Yukon, but there are also many rivers of medium and smaller sizes that empty directly or indirectly (e.g. via Hudson Bay) to the Arctic Ocean.

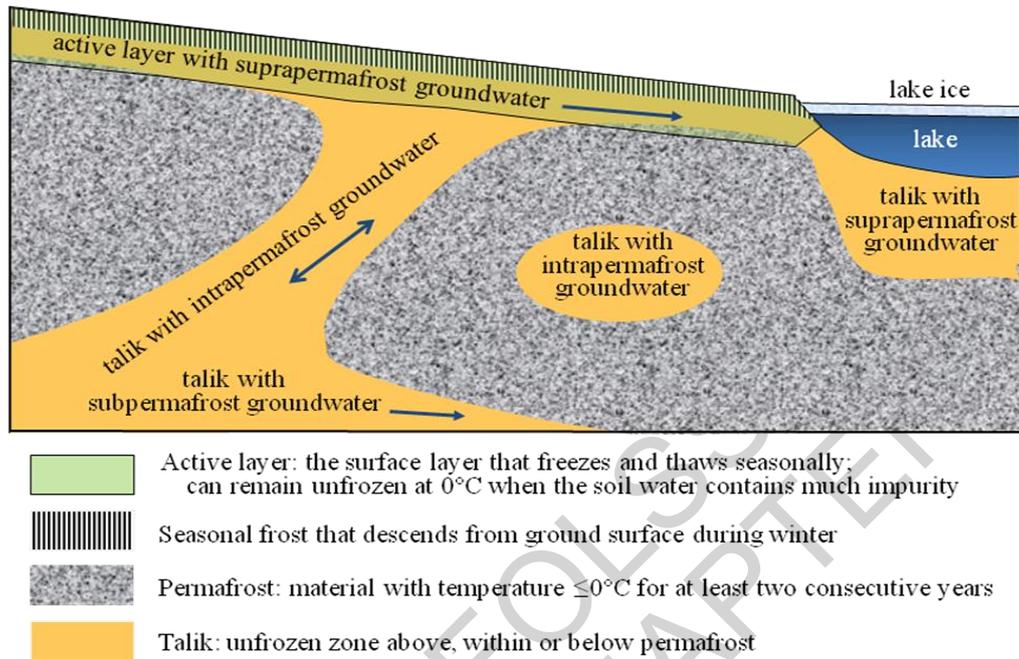


Figure 3. Definition of permafrost, talik and active layer, and groundwater occurrence in permafrost terrain.

3. Snow Conditions

3.1. Accumulation and Distribution

In the Arctic, snow accumulates over many winter months without melt interruption, but the Subarctic experiences occasional mid-winter melt events. The snowpack is typically stratified, partly because of differences in the snow deposited by individual events, and also due to the presence of ice layers produced by refreezing of water from mid-winter melt and from rain-on-snow. Drifting and re-deposition of snow produces hard wind-packed layers, while compaction of the snow under its own weight increases the snow density. Vapor flux through sublimation and condensation within the snowpack yields depth hoar which has low density and lacks cohesion.

The Arctic is frequently windswept to cause scouring of the snow on exposed sites. Blowing snow is prone to sublimation, which converts the snow from solid to vapor state and is then lost to the atmosphere. The snow that blows and drifts is eventually deposited in sheltered areas. Re-distribution of snow through scouring and deposition produces a highly uneven snow cover at the end of winter, leaving thin snow on exposed hill-tops and completely or partially filling topographic hollows, valleys and gullies with deep drifts (Figure 4a), superimposed with surface patterns such as vortices,

dunes and sastrugis. Tundra vegetation and shrubs in the Low Arctic are often partly or wholly buried by the snow.

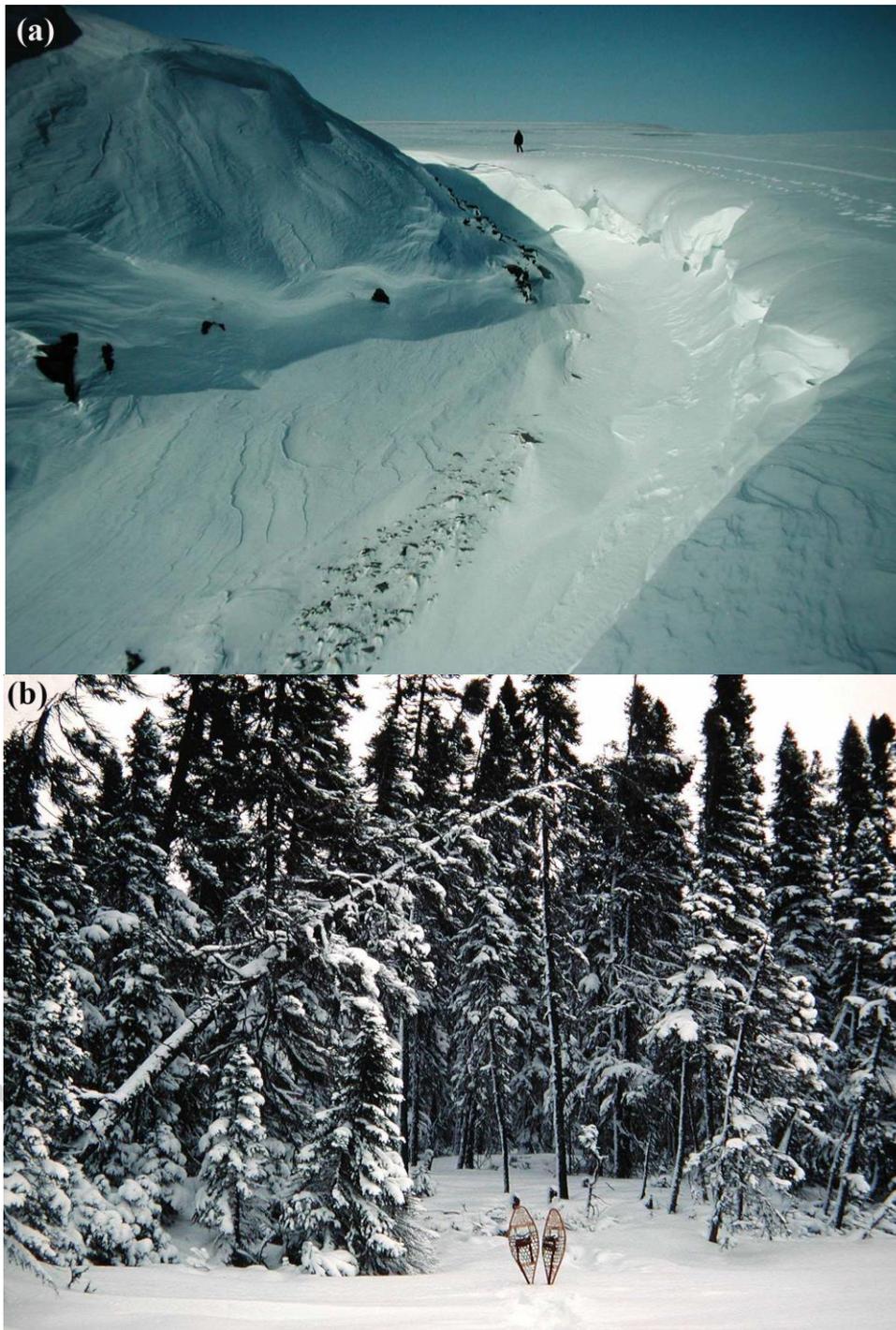


Figure 4. (a) Arctic snow re-distributed by wind to form an uneven cover, with some areas swept free and other areas producing large cornices. (b) Snow intercepted by Subarctic tree canopy. Intercepted snow may subsequently fall off the trees but it is also subject to sublimation loss.

In the Subarctic with trees and tall shrubs that protrude above the snow field, vegetation intercepts the falling snow (Figure 4b). While some of the intercepted snow later falls off the vegetation, part of the snow is retained on the vegetation canopy or is lost through sublimation. Re-distribution of snow by wind is possible in open woodlands but not so underneath a dense vegetation canopy that remains calm in most days. Snow depth on the floor of dense forests is rendered uneven by the underlying shrubs and fallen logs, and by irregular shedding of the snow from tree crowns.

-
-
-

TO ACCESS ALL THE 44 PAGES OF THIS CHAPTER,
Visit: <http://www.eolss.net/Eolss-sampleAllChapter.aspx>

Bibliography

French H.M. (2007). *The Periglacial Environment*, Wiley, Chichester, 3rd Ed. [This is a standard text that describes and explains various landform features found in permafrost terrain].

Gray D.M., Male D.H. (1981) *Handbook of Snow: Principles, Processes, Management and Use*. Pergamon Press, Toronto. [This is a comprehensive treatise on different aspects of snow, including its physical attributes and processes, and the management and use of snow in relation to human activities and livelihood].

Hinzman L.D., Destouni G., Woo M.K. (2013). Preface: Hydrogeology of cold regions. *Hydrogeology Journal* **21**: 1-4. [The three guest-editors compiled this special issue with 21 articles that span over 300 pages, dealing with groundwater in various permafrost regions of the world, including field investigations and modeling studies].

Kane D.L., Yang D.Q. (2004). Northern research basins water balance. *International Association of Hydrological Science Publ* **290**. [The editors have produced a compendium of results from water balance investigations undertaken in different northern research basins, with unique sets of information that allow comparisons of hydrological status among circumpolar areas].

Proceedings of International Conferences on Permafrost (1966 to 2012). [This set of 10 conference proceedings offers a historical perspective on the past and current advances in permafrost-related sciences, including hydrology, in the past half of a century].

Serreze M.C., Barry R.G. (2005). *The Arctic Climate System*. Cambridge University Press, Cambridge. [This book provides details on the climate of the circumpolar region, which gives useful background information for northern hydrology].

Singh P., Singh V.P. (2001). *Snow and Glacier Hydrology*. Kluwer, Dordrecht. [This is a general text that provides a broad background on the hydrology of snow and glaciers].

Woo M.K. (2012) *Permafrost Hydrology*. Springer, Heidelberg. [This book synthesizes materials on the hydrology of permafrost regions published in the last 50 years, and can serve as a reference, or as a text for senior level students].

Biographical Sketch

Ming-ko Woo is a Professor Emeritus in the School of Geography and Earth Sciences at McMaster University. He is a Professional Hydrologist of the American Institute of Hydrology, a Fellow of the

Arctic Institute of North America and of the Royal Canadian Geographical Society. After studying Geography and Geology at the University of Hong Kong, he specialized in snow hydrology for his doctoral work at the University of British Columbia. His primary research relates to the hydrology of permafrost, snow and wetlands, as well as to climate variability. For over three decades, he carried out field investigations in a range of cold environments, from the Arctic, Subarctic, subalpine to extensive wetlands in Canada, to alpine area in Tianshan. In addition, he has worked on soil erosion in South China and drought problems in Sahelian Nigeria. He received the Award for Scholarly Distinction from the Canadian Association of Geographers in 1992, and the President's Service Award from the American Society of Wetland Scientists in 1996. In 2008, he was bestowed the Tuzo Wilson Medal, the highest honor conferred by the Canadian Geophysical Union, which also established the M.K. Woo Hydrology Lecture Series in recognition of his contribution to Canadian hydrology. Over the years, he has produced four generations of graduate students, with most of his first-generation students now being established as academics and senior scientists and successful administrators.