UNIVERSITY OF THE ARCTIC

Module 3
Northern Hydrology

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Key Terms and Concepts

- water balance
- precipitation
- evapotranspiration
- surface runoff
- overland flow
- groundwater
- base flow
- active layer
- talik
- stream discharge
- nival freshet
- hydrograph

Learning Objectives/Outcomes

Upon completion of this module you should be able to

1. identify the various components of water balance.
2. develop an understanding of the physical processes that influence precipitation, evapotranspiration, groundwater storage and flow, and surface runoff.
3. distinguish between nival, proglacial, and wetland flow regimes as illustrated in stream hydrographs.
4. practise interpreting hydrographs.
5. provide concise definitions for the key words.

Reading Assignments

Woo (1993), chapter 5, “Northern Hydrology,” in *Canada’s Cold Environments*, 117–142.

Young (1989), chapter 3, “Ice and Snow,” in *To the Arctic: An Introduction to the Far Northern World*, 45–54.

Overview

Snow and ice play a major role in the hydrologic cycle of northern environments. Thawing of snow and ice involves the flux of latent heat; hence the energy and water balances are strongly linked in northern environments (see Module 2). The presence of snow and ice at the Earth’s surface also influences the radiation balance: high albedos reduce insolation in the spring and early summer, allowing for the persistence of cold temperatures in these seasons. For much of the year, water is stored in snowbanks; lake, river, and sea ice; and glaciers. The duration of the snow cover in the Canadian Subarctic is 180 days; in the Canadian Arctic it is approximately 270 days. There is only a short period each year when air and ground temperatures rise above the freezing point ($0^{o}C$), hence most hydrologic processes operate over a much shorter period of the year in Subarctic and Arctic environments than in temperate environments. Given the importance of these atmosphere-surface interactions, it comes as no surprise that Hamelin included measures for snow and ice cover into his calculation of the Nordic Index (see Module 1).

Lecture

Water Balance

Precipitation is delivered from the atmosphere to the Earth’s surface in the form of rain and snow. A portion of this precipitation is returned to the atmosphere through the processes of *evaporation* (i.e., the exchange of water vapour from the ground surface to the atmosphere) and *transpiration* (i.e., the exchange of water vapour from plant tissues to the atmosphere). These two processes are commonly referred to collectively as *evapotranspiration*. Another portion of the precipitation flows across the ground surface as *surface runoff* and contributes to stream flow. Lastly, another portion of the precipitation enters the ground surface under the force of gravity (i.e., *infiltration*) to become *groundwater*. Permafrost strongly influences the movement of groundwater in northern environments: groundwater flow is restricted to the *active layer* and *taliks* within permafrost. The *water balance* describes the various exchanges of water between the atmosphere and the ground surface:

$P = E + R + \Delta G$

where P = precipitation

E = evapotranspiration

R = runoff

ΔG = change in soil moisture

Note that on an annual basis the quantity of water lost from the soil via evapotranspiration (*soil moisture utilization*) is equal to the quantity of water that infiltrates and is stored in the soil (*soil moisture recharge*), so that $\Delta G = 0$. Soil moisture deficits occur when evapotranspiration exceeds the supply of water from precipitation or moisture stored in the soil. Various combinations of evapotranspiration and moisture deficits have been used to define Subarctic and Arctic environments and to differentiate between them (see Module 1).

Precipitation

The processes contributing to the development of precipitation in the Canadian North are examined in Module 2: *cyclonic* precipitation is derived from the ascent of cool, moist air masses along the polar front, while o*rographic* precipitation is derived from the ascent of cool, moist air over a topographic barrier (e.g., a mountain range). High Arctic environments in the Canadian Arctic Archipelago receive less than 200 mm of precipitation annually. Low Arctic environments in northern Canada receive between 200 and 400 mm. Cyclonic precipitation accounts for most of the precipitation in the latter two regions. In contrast, the mountainous western and eastern coastlines of northern Canada receive the largest quantities of precipitation (greater than 300 mm annually); the precipitation received in this region is mostly orographic in nature. The partitioning of total annual precipitation into rain and snow varies from region to region. In the Subarctic zone, the bulk of the precipitation falls as rain, especially in the summer season. In the Low Arctic and High Arctic zones, the bulk of the precipitation falls as snow, particularly in the fall season. See figure 3.1.

Map Source: Base Map; Atlas of Canada (www.atlas.gc.ca), Government of Canada. Relief Map: Derived from Gtopo30 DEM – 30 arc second elevation data. These data are distributed by the Land Processes Distributed Active Archive Center (LP DAAC), located at the U.S. Geological Survey's EROS Data Center http://edcdaac.usgs.gov. Data Source: Rainfall, snowfall, and precipitation isolines, Annual means 1951–1980, Environment Canada. Map produced by GIServices, University of Saskatchewan, 2003. Projection: Azimuthal Equidistant. Latitude of Origin 75° N, Central Meridian 90° W. All latitudes north of equator.

Fig. 3.1 Map illustrating the regional variations in total precipitation, precipitation as rain, and precipitation as snow—all superimposed on a physiographic relief map

Evapotranspiration

The presence of permafrost in soils and rocks restricts the exchange of water between the ground surface and *taliks*. The permafrost table serves as an *aquiclude*. This situation means that hydrologic activities are largely restricted to the *active layer* of the permafrost or isolated taliks located beneath some lakes and river beds. Surface waters tend to pond on the ground surface, leading to the development of wetlands. Despite the relative abundance of surface water during the short summer season, evapotranspiration is low, especially in the Low Arctic and High Arctic zones.

Evapotranspiration is generally greatest in the summer when insolation is at its maximum (see Module 2). The flux of water vapour declines northward from the Subarctic boreal forest environment through the Arctic tundra environment (see table 3.1). This situation arises from a decrease in net radiation towards the pole and the nature of the plant communities at the ground surface. Trees and shrubs dominate boreal forest plant communities; these vascular plants actively transpire water vapour to the atmosphere in the summer. Sedges, mosses, and lichens, on the other hand, dominate tundra plant communities; these non-vascular plants do not transpire moisture to the atmosphere.

Table 3.1 The water balance for various northern Canadian locations (adapted from Church 1974)

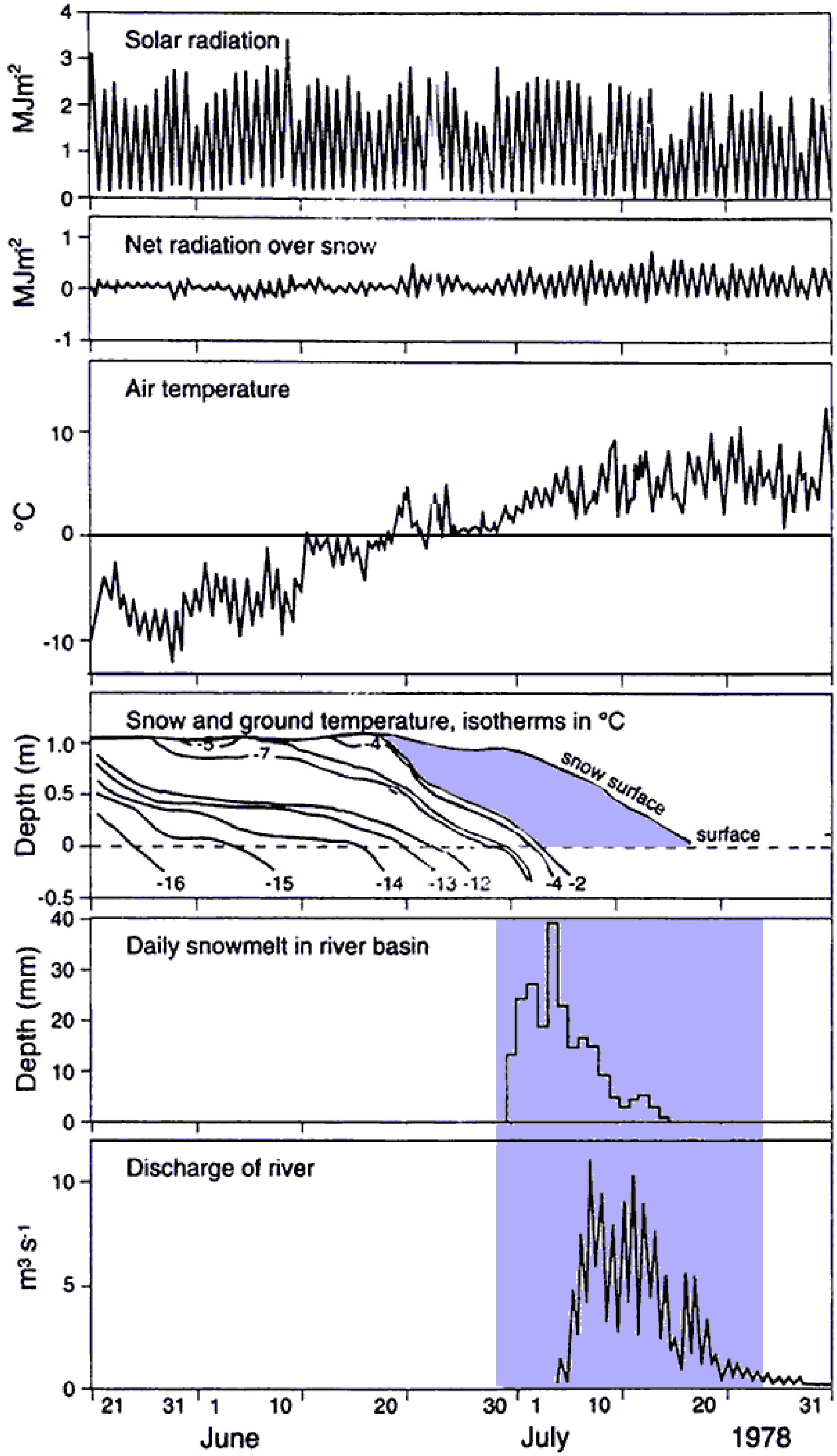
Watershed	Lat. (^oN)	Long. (^oW)	Vegetation	Precip. (mm)	Evapotrans (mm)	Runoff (mm)
Knob Lake, Schefferville, Quebec	55	67	Open lichen woodland	915	280	635
Boot Creek, Inuvik, NWT	68	134	open lichen woodland	285	75	210
Decade River Baffin Island, Nunavut	70	70	grass-sedge tundra; 68% glacierized	460	10	450
Lewis River, Baffin Island, Nunavut	70	75	grass-sedge tundra; 89% glacierized	550	50	500

Surface Runoff

The thawing of snow and ice involves the flux of latent heat; therefore, the generation of surface runoff is strongly linked to the energy balance in northern environments (see fig. 3.2). The presence of permafrost inhibits the infiltration of meltwater into soils and rocks, leading to the saturation of the active layer and the generation of surface runoff (i.e., saturated overland flow). The flow of water across the ground surface occurs from a variety of sources:

- the melting of seasonal and semi-permanent snowbanks
- the melting of ice caps and glaciers
- the flow of water from wetlands

The source of the meltwater influences the magnitude and timing of the *nival freshet* and the duration of stream flow.


Solar radiation
MJm^2
Net radiation over snow
MJm^2
Air temperature
°C
Snow and ground temperature, isotherms in °C
Depth (m)
snow surface
surface
-16
-15
-14
-13 -12
-4 -2
Daily snowmelt in river basin
Depth (mm)
Discharge of river
m^3 s^{-1}
21
31
1
10
20
30
1
10
20
31
June
July
1978

Source: Woo (1993)

Fig. 3.2 Generation of meltwater in McMaster River, Resolute, Cornwallis Island, Nunavut

Let us look at the data presented in figure 3.2 in more detail. The data recorded at this station in the Canadian High Arctic can be divided into two periods: a pre-melt period extending from May 21 to July 1, and a melt period extending from July 1 to July 31.

Pre-Melt Period

The first figure illustrates the diurnal variation in solar radiation received at the Earth's surface. Maximum values correspond to solar noon; and minimum values correspond to midnight.

The second figure illustrates the daily variations in net all-wave radiation. Net radiation is consistently low throughout the pre-melt season. Most of the incoming solar radiation is reflected off the highly reflective snow surface. The energy that is absorbed at the surface is used to raise the temperature of the air and snow cover.

The third figure illustrates the gradual increase in air temperatures during the pre-melt season.

The fourth figure illustrates the rapid warming of the snowpack during the pre-melt season. Warming of the snowpack is accompanied by the generation of meltwater. Some of this meltwater will infiltrate the snowpack and the underlying frozen soil. As this meltwater refreezes within the snowpack and soil, latent heat (specifically the latent heat of fusion) is released. This heat serves to rapidly raise snow and soil temperatures. A basal ice layer develops at the snow-soil interface. Meltwater generated during this period is stored within the snowpack; hence it is unavailable to support stream flow. This situation is reflected in the last two figures.

Melt Period

The first figure illustrates the diurnal variation in solar radiation received at the Earth's surface. Maximum values correspond to solar noon; and minimum values correspond to midnight.

The second figure illustrates the daily variations in net all-wave radiation. Net radiation is consistently greater than in the pre-melt season. This situation reflects a change in the surface albedo. The generation of meltwater at the surface serves to lower the surface albedo, allowing more solar radiation to be absorbed. More energy is available to raise the temperature of the air and snow cover.

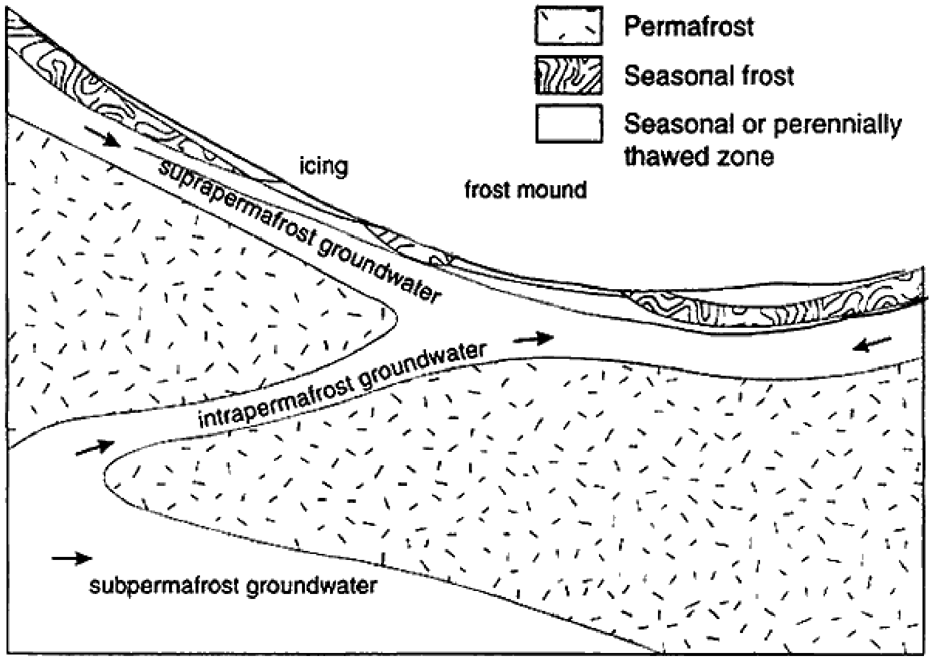
The third figure illustrates the rapid increase in air temperatures as the surface warms during the melt season.

The fourth figure illustrates the rapid warming of the snowpack during the melt season.

The fifth figure illustrates that as temperatures in the snowpack rise above the freezing point (0^oC), snow melt proceeds rapidly. Meltwater is unable to infiltrate through the basal ice layer and is forced to flow across the ground surface towards stream channels. The rapid influx of meltwater results in the rapid increase in stream discharge; this event is known as the *nival freshet*. This event is illustrated in the sixth figure.

Groundwater

The contribution of groundwater to support stream flow is largely influenced by the presence of taliks, which allow for the movement of groundwater through permafrost to stream channels. *Suprapermafrost groundwater* is held within the active layer or in isolated taliks beneath lake beds and river channels. The seasonal thawing and freezing of the active layer governs the supply of suprapermafrost groundwater to stream channels. Discharge of groundwater from the active layer is greatest in the summer—when water can infiltrate soil and rock—and ceases when the water stored in the active layer is depleted or frozen. *Intrapermafrost groundwater* occurs within taliks that are sustained by the flow of warm water through them. *Subpermafrost groundwater* occurs in taliks below the *permafrost table*. Owing to the dearth of connecting intrapermafrost taliks within deep permafrost, groundwater seldom reaches the surface in the continuous permafrost zone. However, where taliks connect subpermafrost groundwater to the surface, base flow in stream channels can be sustained throughout the year. (See fig. 3.3.)



Source: Woo (1993)

Fig. 3.3 Occurrence of groundwater in permafrost

Stream Flow

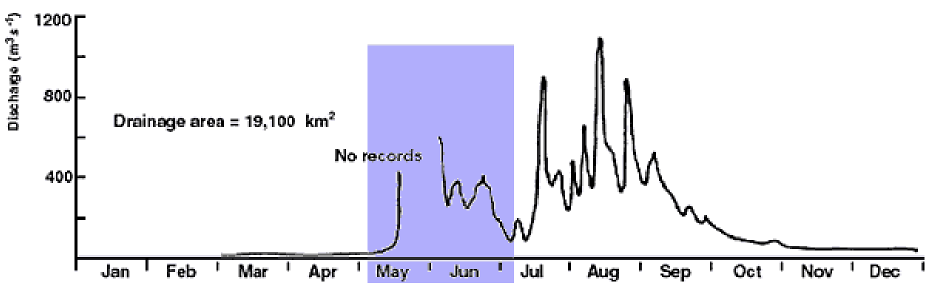
A stream is a body of water flowing down a slope within a defined channel. Water is supplied to the stream from surface runoff (*overland flow*), groundwater (*base flow*), and direct precipitation as rain. Hydrologists employ *hydrographs* to study the relationship between the input of water from these various sources and the discharge of water in stream channels. A hydrograph illustrates how stream discharge, measured in units of cubic metres per second (m^3/s), varies over a given period of time. Hydrologists recognize several different hydrologic regimes:

- Arctic nival
- Subarctic nival
- proglacial
- wetland/muskeg

The nival regime represents stream flow derived from melting snow, thawing of the active layer, and direct precipitation. The proglacial regime represents stream flow derived from the melting of snow and glacier ice, and direct precipitation. The wetland regime represents stream flow through wetlands.

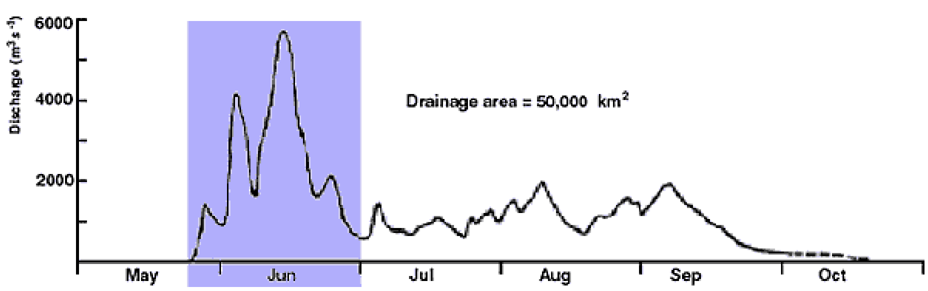
Nival Regime

The processes contributing to the nival freshet in this hydrologic regime are presented above in association with figure 3.2. In figure 3.4 and figure 3.5, the period of the nival freshet is indicated by the shading. Note that the freshet occurs several weeks later earlier in the Subarctic environment (see fig. 3.4) compared to the Arctic environment (see fig. 3.5); this is because the greater amounts of insolation at lower latitudes warms the air and snowpack earlier. Subsequent peaks in stream discharge in the summer period following the nival freshet largely reflect the input of water from direct precipitation augmented by inputs of groundwater. In the fall season, precipitation changes from rain to snow and the active layer refreezes as air temperatures drop, causing stream flow to cease.



Source: Water Survey of Canada Records (Church 1974)

Fig. 3.4 Subarctic nival regime. large river; Arctic Red River near Martin House, 1971

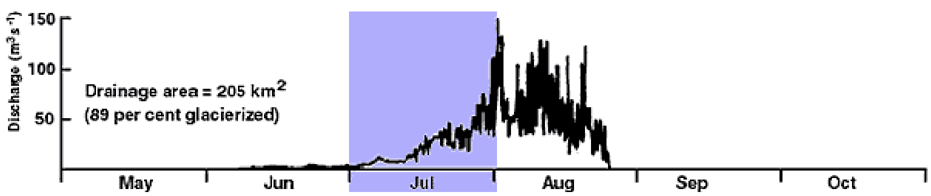


Source: Church (1974)

Fig. 3.5 Arctic nival regime, large river; Colville River, 1962

Proglacial Regime

Surface runoff from glacierized landscapes is controlled largely by the energy budget that contributes to the melting of snow and glacier ice. Net all-wave radiation is consistently low throughout the pre-melt season. Most of the incoming solar radiation is reflected from highly reflective snow and ice surfaces. The energy that is absorbed at the surface gradually raises the temperature of the air and snow cover. As the snowpack warms, meltwater is generated. Some of this meltwater infiltrates the snowpack and the underlying glacier ice. As this meltwater refreezes within the snowpack and glacier, latent heat (specifically the *latent heat of fusion*) is released. This heat rapidly raises air, snow, and ice temperatures. A basal ice layer develops at the snow–glacier ice interface. Meltwater generated during this period is stored within the snowpack or in the network of small-diameter channels within the glacier (i.e., the intergranular network); therefore, it is unavailable to support stream flow. This situation is reflected in the hydrograph for May, June, and early July illustrated in figure 3.6.

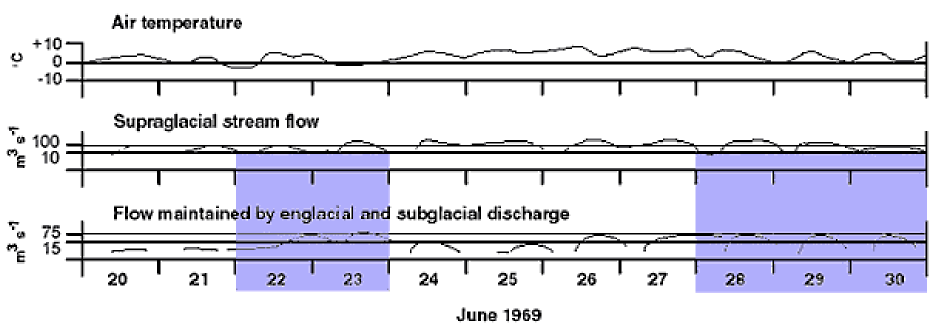


Source: Church (1974)

Fig. 3.6 Proglacial regime; Lewis River, Baffin Island, 1963

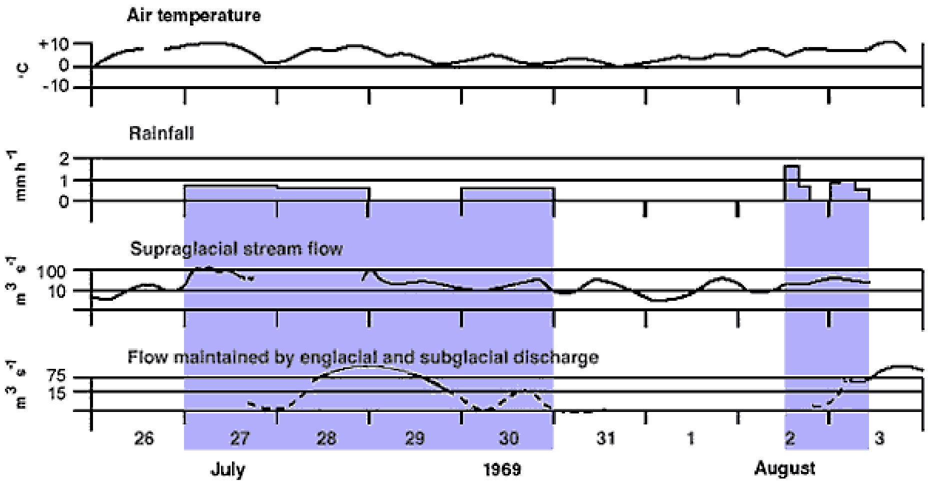
Net radiation is consistently greater throughout the months of July and August (the melt season) than in May and June (the pre-melt season). This situation reflects a change in the surface albedo. The generation of meltwater on the glacier surface and the exposure of sediment-laden glacier ice serve to lower the surface albedo, allowing more solar radiation to be absorbed. More energy is available to raise the temperature of the air, snowpack, and glacier surface. As temperatures in the snowpack and glacier ice rise above the freezing point (0^oC), melting proceeds rapidly. Meltwater begins to flow across the glacier surface in *supraglacial channels*. In cold-based glaciers, all of the meltwater generated on the glacier surface is transferred to the ice margin in these channels. In contrast, meltwater generated on the surface of warm-based glaciers flows within supraglacial, englacial, and subglacial channels. *Englacial channels* are derived from the intergranular network. Meltwater flowing through the intergranular network gradually expands these conduits, facilitating the flow of water through the glacier towards the bed. Meltwater transferred to the glacier bed flows in a variety of *subglacial channels* towards the ice margin and is eventually discharged into *proglacial stream channels*. Rapid snowmelt combined with the expansion of the internal drainage network within glaciers contributes to the nival freshet in proglacial stream channels. The period of the nival freshet is indicated by the shading in figure 3.6. Note that the nival freshet occurs 4 to 6 weeks later in the proglacial regime than in the nival regime.

The hydrologic response of a high-latitude glacier to daily variations in insolation is illustrated in figure 3.7 and figure 3.8. Diurnal variations in insolation are reflected in the day-to-day variations in air temperatures; the warmest air temperatures occur in the mid-afternoon, shortly after daily maximum of insolation at solar noon and the coldest air temperatures occur in the early morning, shortly after the daily minimum of insolation at midnight. Note that there is lag between the timing of the warmest temperatures of the day and the peak discharge of meltwater in supraglacial, englacial and subglacial channels (highlighted); peak discharges are recorded several hours after the warmest temperatures of the day. This lag represents the time required to absorb insolation, melt snow and ice, and deliver the meltwater to channels.



Source: Woo (1993)

Fig. 3.7 White Glacier, Axel Heiberg Island, Nunavut; non-rainy period, June 1969



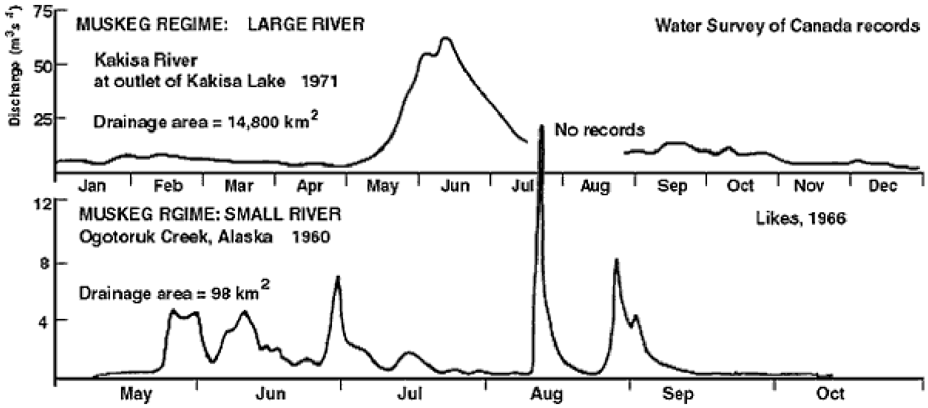
Source: Woo (1993)

Fig. 3.8 White Glacier, Axel Heiberg Island, Nunavut; rainy period, July to August, 1969

The sustained high-stream discharges recorded in proglacial streams in the late summer (snow-free season) reflect the inflow of meltwater from glaciers supplemented by direct precipitation. In the fall season, precipitation changes from rain to snow as air temperatures drop, causing stream flow to decrease or cease.

Wetland Regime

This hydrologic regime is associated with poorly drained lowlands, characterized by the accumulation of organic materials consisting largely of mosses and sedges. Mosses, in particular, possess a high water-retention capacity. The abundant vegetation also creates resistance to the flow of water. The combination of these factors reduces high stream flows through these areas during the summer season. A pronounced nival freshet may occur in late spring when the organic materials are frozen and unable to absorb the meltwater released by melting snow (see fig. 3.9).



Source: Church (1974)

Fig. 3.9 Wetland regime

Summary

For much of the year in the North, water is stored in snowbanks; lake, river, and sea ice; and glaciers. Snow and ice play a major role in the hydrologic cycle of northern environments. Thawing of snow and ice involves the fluxes of solar radiation and latent heat; hence, the radiation, energy, and water balances are strongly linked in northern environments. Water balance is a tool that is employed to examine the flux of water between the atmosphere and the Earth's surface. Precipitation is delivered from the atmosphere to the Earth's surface in the form of rain and snow. A portion of this precipitation is returned to the atmosphere through the processes of evapotranspiration. Another portion of the precipitation flows across the ground surface as surface runoff and contributes to stream flow. Lastly, another portion of the precipitation enters the ground surface under the force of gravity to become groundwater.

Total annual precipitation varies from less than 100 mm to more than 400 mm in northern Canada. The partitioning of total annual precipitation into rain and snow varies from region to region. In the Subarctic zone, the bulk of the precipitation falls as rain, especially in the summer season. In the Low Arctic and High Arctic zones, the bulk of the precipitation falls as snow, particularly in the fall season.

Evapotranspiration and groundwater storage are directly influenced by the presence of permafrost. Hydrologic activities are largely restricted to the active layer or isolated taliks within permafrost. Evapotranspiration is low; the flux of water vapour declines northward from the Subarctic boreal forest through the Arctic tundra. Evapotranspiration and the discharge of groundwater are generally greatest in the summer, when insolation is at its maximum and water can infiltrate thawed soil and rock.

Stream flow is supported by water derived from surface runoff, groundwater flow, and direct precipitation as rain. Hydrologists recognize several different hydrologic flow regimes: nival, proglacial, and wetland. In the nival flow regime, the melting of snow is the principal source of water that supports stream flow. Peak stream discharges (nival freshet) are generated by rapid snowmelt in late spring and early summer. The melting of glaciers is the principal source of water that supports stream flow in the proglacial regime.

The nival freshet occurs 4 to 6 weeks later in the proglacial regime relative to the nival regime. The delay in peak discharges is related to the development of a network of internal drainage channels within glaciers that serve as conduits for the discharge of meltwater. The wetland regime is associated with poorly drained lowlands characterized by abundant vegetation that creates resistance to the flow of water.

Supplementary Readings

Pielou, E. C. 1994. Terrain. In *A Naturalist's Guide to the Arctic*, 57–61. Chicago: The University of Chicago Press.

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Study Questions

A. Multiple Choice Questions

1. With respect to the timing of the nival freshet, indicate which of these statements is true:
   a. It occurs earlier in the Subarctic region than in the Arctic region.
   b. It occurs later in the Subarctic region than in the Arctic region.
   c. It is associated with a decrease in net all-wave radiation.
   d. It is associated with an increase in net all-wave radiation.
   e. both a and d
   f. both b and c

2. This form of energy is responsible for the melting of snow and ice:
   a. short-wave radiation
   b. long-wave radiation
   c. latent heat
   d. sensible heat
   e. geothermal heat

3. Melting of snow and ice is promoted by ______________________.
   a. an increase in insolation
   b. an increase in surface albedo
   c. a decrease in surface albedo
   d. a decrease in insolation
   e. both a and c
   f. both b and d

Answers to Multiple Choice Questions

1. e
2. c
3. e

B. Essay Question

Sketch representative hydrographs for rivers that exhibit Subarctic nival and proglacial flow regimes. Use this information to state the similarities and differences of the influence of snow and permafrost on the hydrologic processes operating in these two environments.

Glossary of Terms

active layer	the upper zone of soil in higher latitude locations that experiences daily and seasonal freeze-thaw cycles.
aquiclude	rock formations that are impermeable to groundwater.
hydrology	the science of the properties of the Earth's water, esp. of its movement in relation to land.

talik	an unfrozen section of ground found above, below, or within a layer of discontinuous permafrost. These layers can also be found beneath water bodies in a layer of continuous permafrost. A number of different types of talik have been distinguished: closed talik, open talik, and through talik.

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