Oil and gas industry impact on Arctic wetlands, mitigation, recovery and restoration options

FOR INTERNAL USE ONLY

Final report of the project :
«***Shell Wetland International Partnership Study of Oil and Gas industry impact mitigation on Arctic Wetlands, wetands recovery and restoration***»
under the collaborative partnership between Shell and Wetlands International
Project No:4600005499; Signed by Shell: 11/06/09; Signed by WI: 26/05/09

Wetlands International
Ede 2011

2.3. Arctic wetlands and natural processes *(Olivia Bragg, Vladimir Batuyev, Peter Kershaw, Alexander Kondratiev, Olga & Igor Lavrinenko, Tatiana Minayeva, Sergey Novikov, Marieke Oosterwoud, Saake van der Schaaf, Andrey Sirin, Ludmila Usova, Hok Woo, Kathy Young)*

2.3.1. Arctic wetlands: classifying diversity

Wetlands, as defined by the Ramsar Convention[1], are widely represented in the Arctic (Fig. 2.2). The purpose of this review is to explain in the simplest possible way that different Arctic wetland types have different features and function in different ways. As a result, they provide different ecosystem services, they have different levels of sensitivity to disturbance, and different capacities for restoration. They are also subject to different legislation and decision-making mechanisms at national and international levels.

The diversity of natural ecosystems is usually described in terms of a classification of some sort. Whatever classification principles are used, it seems that biodiversity scientists are never able to describe or predict all natural diversity in this way. Therefore, the common practice is to develop different classification schemes for different purposes. In this review, we use a very simple classification of wetlands to underpin the tasks of impact assessment and planning of mitigation and rehabilitation activities.

To deal with legislation, frame political decisions and undertake planning, it is often sufficient to distinguish only four groups of wetlands – marine, coastal, freshwater and terrestrial. This is the grouping used by CAFF (one of the working groups of the Arctic Council). To deal with ecosystem services, we need to be more specific in terms of wetland and landscape types; for example by distinguishing between mires and lakes, and between polygon and palsa mires, different types of lakes, etc.

Finally, when we come to develop succession patterns based on sensitivity data, restoration potential, etc., we need to classify at the level of ecosystems or vegetation cover. The most important principle is that, in order to make the classification available for application by non-specialists, it should be no more detailed than is absolutely essential, reflecting the underlying patterns in the simplest way that fulfils the purpose.

Using these principles, and accommodating traditional differences between the viewpoints of American and European scientists, we have developed a rather traditional classification of wetland types for the purposes of this review. This classification is summarized in Table 2.2.

[1] For the purposes of the Ramsar Convention, wetlands are areas of marsh, fen, peatland or water, whether natural or artificial, permanent or temporary, with water that is static or flowing, fresh, brackish or salt, including areas of marine water the depth of which at low tide does not exceed six metres.

2.3.1.1. Terrestrial Wetlands

The origin of Arctic terrestrial wetlands is not generally linked to persistent open water bodies, although they can form on intermittently flooded ground, e.g.,floodplain or karst lakes. They are characteristically located on watersheds, often with excess ice, where the water surplus is due to high net precipitation or near-surface permafrost.

Table 2.2: Summary of the wetland classification scheme developed for the purposes of this review.

Agreed name	**Synonym**	**Position in landscape**	**Vegetation**
Terrestrial Wetlands			
I. Paludified shallow peatlands	Tundra	Plateaus on watersheds and terraces; drained areas	On loamy soils – dwarf-shrub moss on sandy soils – dwarf-shrub lichen;
II. Polygon mires (with and without thermokarst ponds)			
II.1. Low-centered polygon mires	Flat polygon, concave polygon, polygon bolster mires; after *Usova, Novikov, Batuyev*…2009)	Flat watersheds of any order	Hollow – sedge-cotton grass-moss; Trenches/troughs – *Sphagnum* carpet; shoulders – dwarf birch or Labrador tea.
II.2. High-centered polygon mires	(syn. mounded polygon mires; after *Usova, Novikov, Batuyev*…2009)	Terraces, coastal areas, local watersheds in valleys	Polygon centre - cloudberry, dwarf shrubs and some sparse mosses / lichens with sparse dwarf shrubs.
III. Palsa mires (with and without thermokarst ponds)			
III.1. Peat plateau mires	Small mounded palsa mires, flat palsa mires; after *Usova, Novikov, Batuyev*…2009	Flat watersheds and diluvial terraces, coastal lowlands or lake transgression landscapes underlain by coarse mineral soil	Hummocks – lichens and dwarf shrubs, in south tundra *Sphagnum* mosses and cotton-grass; hollows – *Sphagnum*-sedge mesotrophic
III.2. Palsa mires	Gently sloping convex palsa mires, large mounded palsa mires	Watersheds, alluvial terraces and their sloping flanks underlain by fine mineral soil	
IV. Patterned string fen	Aapa mires after Cajander (1913); 'mixed mire' after Sjors *et al.*, 1965; ribbed fen after Zoltai *et al*. (1988)	Gentle slopes of terraces and watersheds	Mesotrophic *Sphagnum*-sedge and *Hypnum*-sedge mires - in flarks
V. Raised bogs	Hummock-hollow non-frozen peatlands	Watersheds of different orders, mainly as elements within other peatlands; not mire massifs	Typical raised bog vegetation – oligotrophic on ridges and hummocks, mesotrophic in hollows
VI. Thermokarst, kettle hole peatlands	Kettle hole mires and alases	Areas of continuous deep permafrost	Typical mire vegetation depending on the stage of mire formation (floating mats, carpets, small sedge and tall sedge)

(continued overleaf)

Table 2.2 (continued)

Agreed name	Synonym	Position in landscape	Vegetation
Freshwater (lacustrine and riverine) Wetlands			
VII. Rivers/streams	Permanently and intermittently flowing water		Riparian and freshwater vegetation
VIII. Deltas	A combination of streams, valley bottom mires, freshwater marshes, sandy spits and islands		Vegetation depends on the wetland type - riparian, freshwater and fen
IX. Lakes			
IX.1. Closed lakes IX.2. Flowing water lakes		Watersheds and floodplains; peatland slopes	Freshwater floating vegetation, quaking mats with *Sphagnum*
X. Drained depressions	hasyri		
XI. Riparian mires			
XI.1 Sloping floodplain mires	Sloping fens	Sloping terraces, islands	Moss-sedge carpets, dwarf shrubs and graminoids
XI.2 Valley-bottom mires	Valley-bottom fens	Oxbows and low bank depressions, bays	Tall sedge, forbs and graminoids with green mosses, willows
Coastal and Marine Wetlands			
XII. Estuaries		deeply penetrating 'sea bays' at the mouths of rivers; brackish or freshwater	Freshwater floating vegetation, floating mats, freshwater marshes
XIII. Coastal wetlands			
XIII.1. Intertidal flats	Low saline marshes	Periodically covered by tides	Saline species, algae
XIII.2. Saline marshes	High saline marshes	Along the sea shore	Tall sedges, hypnum mosses, emergent grasses and forbs, saline species
XIII.3. Freshwater marshes		Along the shorelines of estuaries, in deltas	Tall sedges, hypnum mosses, forbs
XIII.4. Coastal tundra		On low terraces along the sea shore	Lichens, dwarf shrubs, mosses, sedges
XIV. Ephemeral wetlands		Dunes, sandy spits and islands in open sea, rivers and deltas	Psammophyte forbs, grasses, sedges
XV. Marine wetlands			
XV.1. Coral reefs		Marine waters	Corals and associated species
XV.2. Sea grasses		Marine waters	Submerged vascular plants

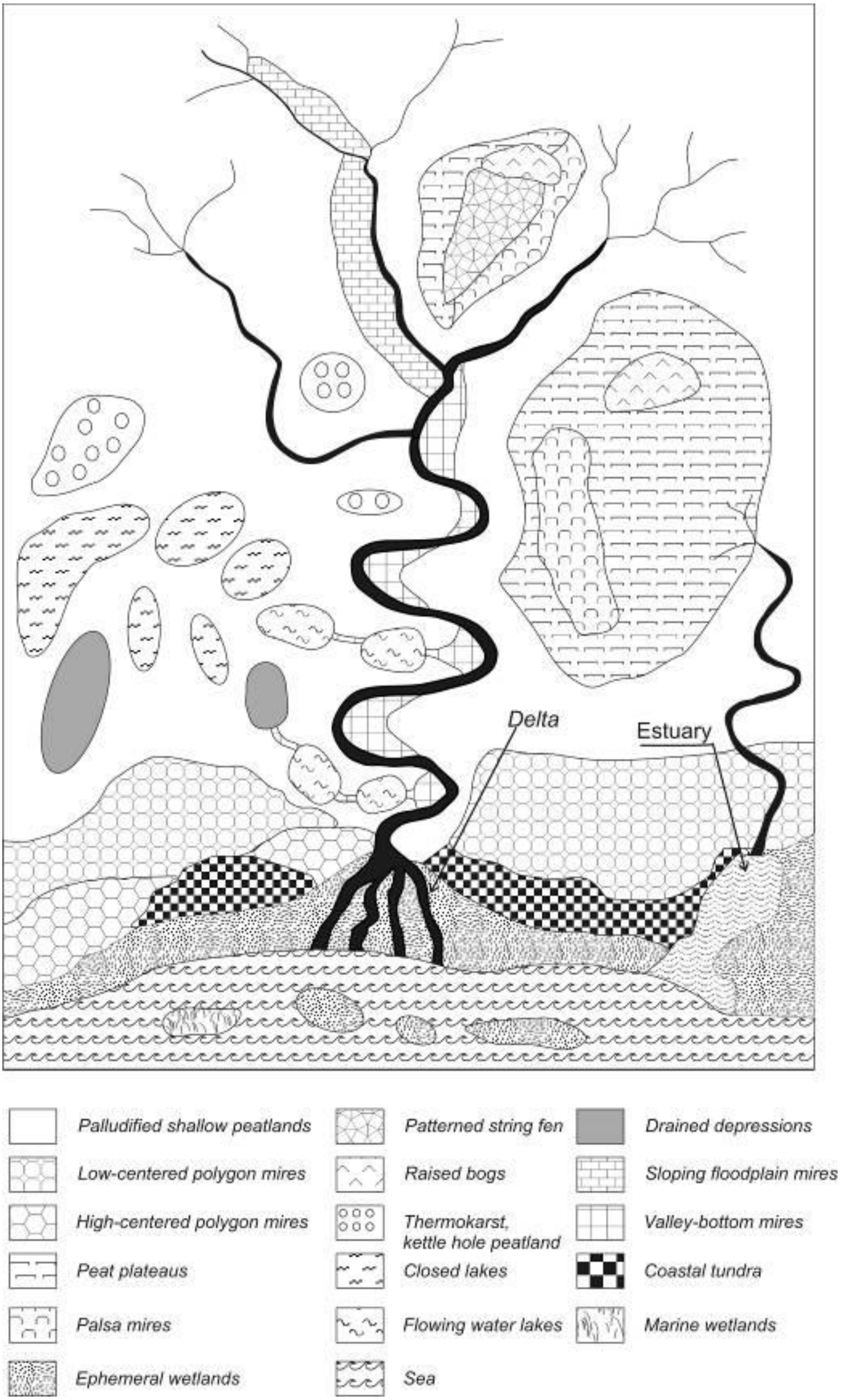


Figure 2.2. Arctic wetland types: relative positions in the landscape.

2.3.1.1.1. Paludified shallow peatland (tundra)

This is the most widespread terrestrial wetland type on watershed areas in the Eurasian Arctic, forming vast areas of shallow peatland overlying sandy or loamy soils (Fig. 2.3). It occurs more sporadically in North America, where it is often replaced by plateau peatland. The peat layer may be partly degraded or decomposed; and the profile can contain alternating layers of peat and mineral material, indicating that this type of peatland is sometimes re-covered by mineral soil.

The lighter sandy soils are associated with alluvial (riverine, lacustrine or oceanic) processes, and are colonized by dwarf shrub-lichen vegetation. Patches with more snow host mainly fruticose lichens belonging to the genus *Cladonia*. Areas with less snow have species of *Cetraria* and *Alectoria.*

The heavier loamy soils are associated with diluvium; they help to retain water in shallow peat layers, leading to increased dominance of both green mosses (in the southern tundra zone) and *Sphagnum* (in northern areas and uplands), cottongrass, sedges and dwarf shrubs.

The shallow peat tundra on coastal or highland plateaus can have features resembling polygonal structures, and here the cracks can host green mosses, dwarf birch and willow. Degraded areas that retain some peat or an organic soil layer are covered by crustose lichens (*Gymnomitrion concinnatum* as well as members of the genera *Ochrolechia* and *Pertusaria*). The main colonizers of degraded tundra with sandy soil are psamophyte species; for example, in Nenetsky Okrug, the lichen *Sphaerophorus globosus*, the mosses *Racomitrium lanuginosum* and *Polytrichum piliferum*, and the vascular plants *Armeria maritima*, *Juncus trifidus, Festuca ovina, Diapensia lapponica* and *Loiseleuria procumbens*. Of all ecosystem types in the Arctic, shallow peat tundra on sandy soils is one of the most vulnerable to erosion.

2.3.1.1.2. Polygon mires (with and without thermokarst ponds)

Polygon landscapes arise as a consequence of thermokarst processes, i.e. the seasonal alternation of thawing and freezing near the upper limit of permafrost. When they occur in peat – a soft, unstable and very wet substance – the effects are accentuated, forming deep ice-filled cracks which soon become secure water sources for maintenance of the mire, and in some cases for peat formation. The best simple descriptions of morphology for the two main types of polygon mire – low-centered (concave) and high-centered (mounded) – is given by Tarnocai and Zoltai (1988), and we reproduce their drawing in Fig. 2.4. From this it is clear that successful functioning of the mire system depends upon a complex construction of different types of peat, permafrost and mineral soil. Thus, the key message for this mire type is that it is an integrated dynamic system driven by structural and permafrost processes, so that even partial physical disturbance or destruction can unpredictably shift the equilibrium of the whole dynamic system.

A popular review of the distribution and structure of polygon mires, which includes a photograph of an exposed profile, is also available from Minke *et al*. (2007). Polygon mires occur in the high Arctic. In North America they are found on the Arctic coastal plains of Alaska and in the Canadian Mackenzie Delta. In Eurasia, there are relic mounded polygons along the shore of the White Sea, both types occur regularly on the shore terraces along the Barents Sea coastline, and farther east they are found on the terraces of large inland rivers. They are abundant in eastern Yamal and on the Gydansky Peninsula; and cover immense parts of the Yenisey lowlands in Taymyr, the Yana-Indigirka and Kolyma lowlands, and the Lena delta. Relic polygon mires have also been described in Northern Sakhalin and even the Amur River delta (Figs. 2.5–2.7).

Shallow peat tundra on loamy sands near Naryan-Mar. Photo by Tatiana Minayeva.

Shallow peat tundra on loamy sands in the Korovinskaya Bay area. Photo by Tatiana Minayeva.

Shallow peat tundra on sandy soils in Pechora Bay. Photo by Igor Lavrinenko.

Shallow peat tundra with highly decomposed peat overlying sandy soils on Kolguyev Island. Photo by Igor Lavrinenko.

Figure 2.3. Examples of paludified shallow peatland (tundra).

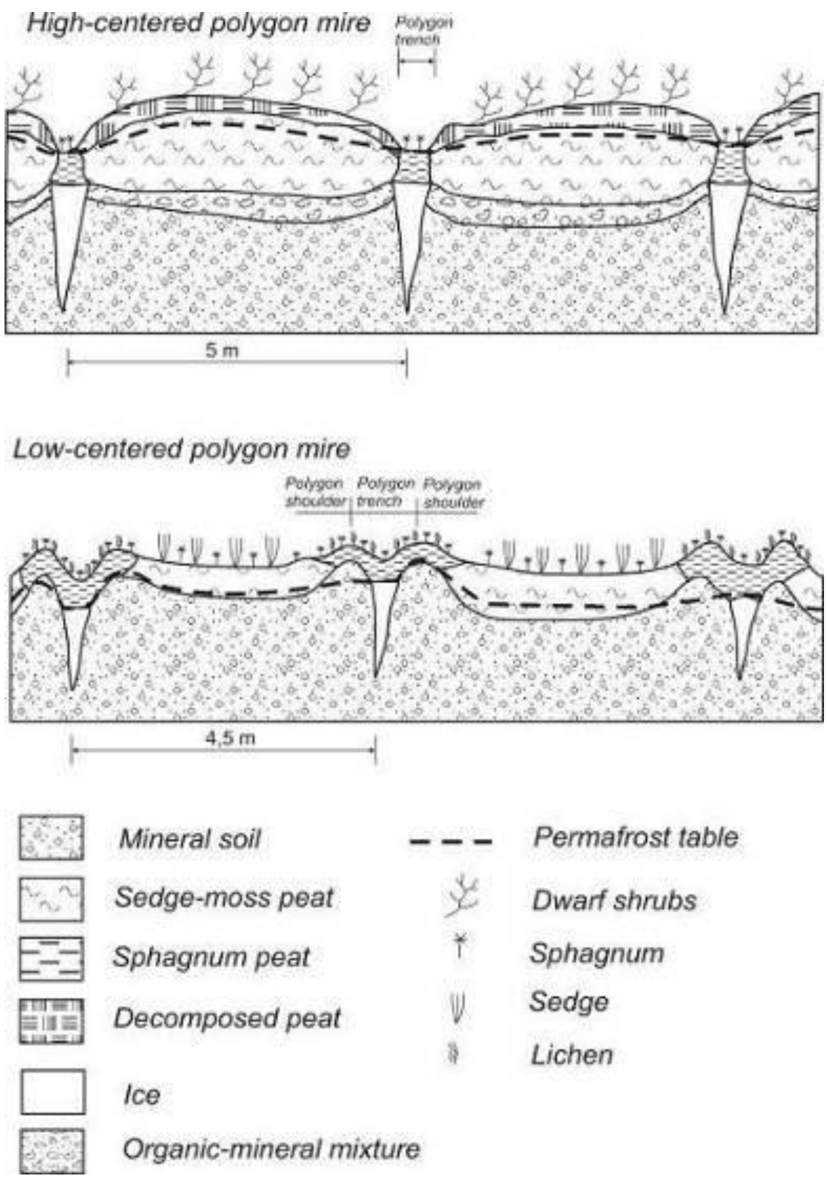
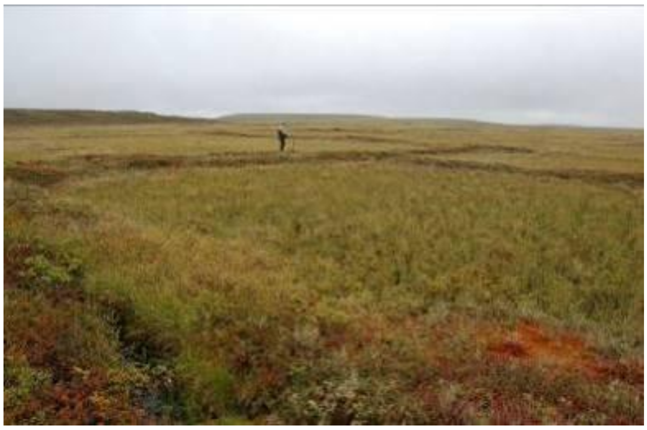


Figure 2.4. Cross-sections of high-centered polygon and low-centered polygon mire, from Tarnocai and Zoltai (1988).

Polygon mires are not rich in biodiversity, and host no more than 30 species of vascular plants, 30 species of mosses and 45 species of lichens; but they represent a unique ecosystem type. Low-centered polygons have sedge-cotton grass-moss vegetation typical of peatland hollows; their shoulders offer better-drained conditions and often support shrubs like dwarf birch and Labrador tea; and the ice in the trenches is covered by *Sphagnum* peat and *Sphagnum* carpets. The tops of high-centered polygons are usually covered by cloudberry, dwarf shrubs, and some mosses which remain sparse because they do not compete successfully with the dwarf shrubs – especially *Empetrum nigrum*. In the high Arctic and on coastal terraces, the caps of high-centered polygons are covered by lichens with sparse dwarf shrubs.

Peat thickness depends on the landscape position. The peat layer is usually 1–2 m and sometimes 3–5 m thick on watersheds, on old terraces and in deep erosion gulleys. In valleys and on small terraces it may be only 0.2–0.5 m thick. The shallow polygon mires on the Yang River and coastal terraces are extremely vulnerable to surface damage and are very often affected by erosion.

(a)



(b)

(c)

(d)

Figure 2.5. Stages in the development of coastal polygon mires from low-centered to high-centered. (a) and (b): Yakutia (Laptevyh Sea); (c): Yugorsky Peninsula (Kara Sea); (d): Nenetsky (Barents Sea). Photos by Andrey Sirin (a–b) and Igor Lavrinenko (c–d).

Figure 2.6. General view on coastal polygon mires. Photo by Andrey Sirin.

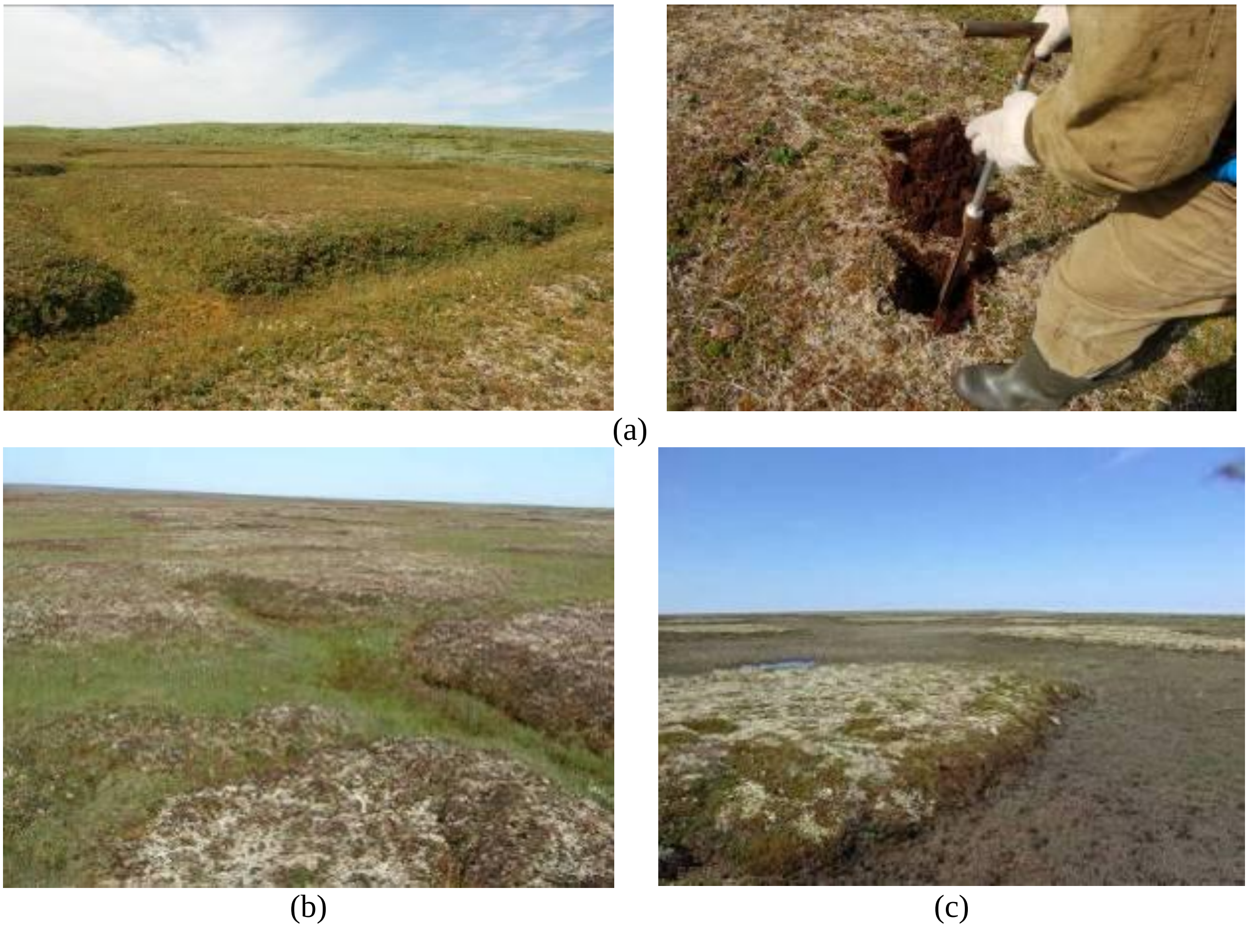


Figure 2.7. Mounded-polygon mires in the Barents Sea region. (a): Pechora Bay; (b): Dolgy Peninsula; (c): Vaygach Peninsula. Photos by Tatiana Minayeva (a) and Igor Lavrinenko (b, c).

2.3.1.1.3. Peat plateaus and palsa mires

The palsa mires make up the second group of peatlands whose genesis and maintenance is related to permafrost. A schematic representation of the interactions between peat, vegetation, permafrost, water and mineral soil is given in Fig. 2.8 (after Tyuremnov 1979, Tarnocai 1988 and Novikov 2010). The key points are: the mounds are not created by peat formation, but by heaving of the underlying mineral ground; the hummocks consist of fen peat (formed from mesotrophic plant communities), but their present vegetation is oligotrophic; the underlying mound of mineral material contains ice lenses; and the upper limit of permafrost is close to the ground surface in palsa mounds and deeper or absent in the intervening depressions. Numerous authors have suggested mechanisms for palsa formation on the basis of their own analyses of this general structure.

Palsa mires differ from polygon mires in that the permafrost-related processes in palsas work from inside rather than from the surface, and peat plays a more active role in creating the palsa structure. In polygon mires, the role of peat becomes pertinent when the basic structure is already in place – peat begins to form on the edges of pre-existing trenches and gradually modifies the hydrological and temperature regimes thereafter. In palsa mires, the peat is originally formed in flooded sedge-moss plains (i.e., on flat areas). When a mire is present, the drier layer of peat at the surface enhances freezing processes in the wetter mineral soil beneath. During the warm part of the year, the mineral soil becomes saturated with water, which subsequently freezes.

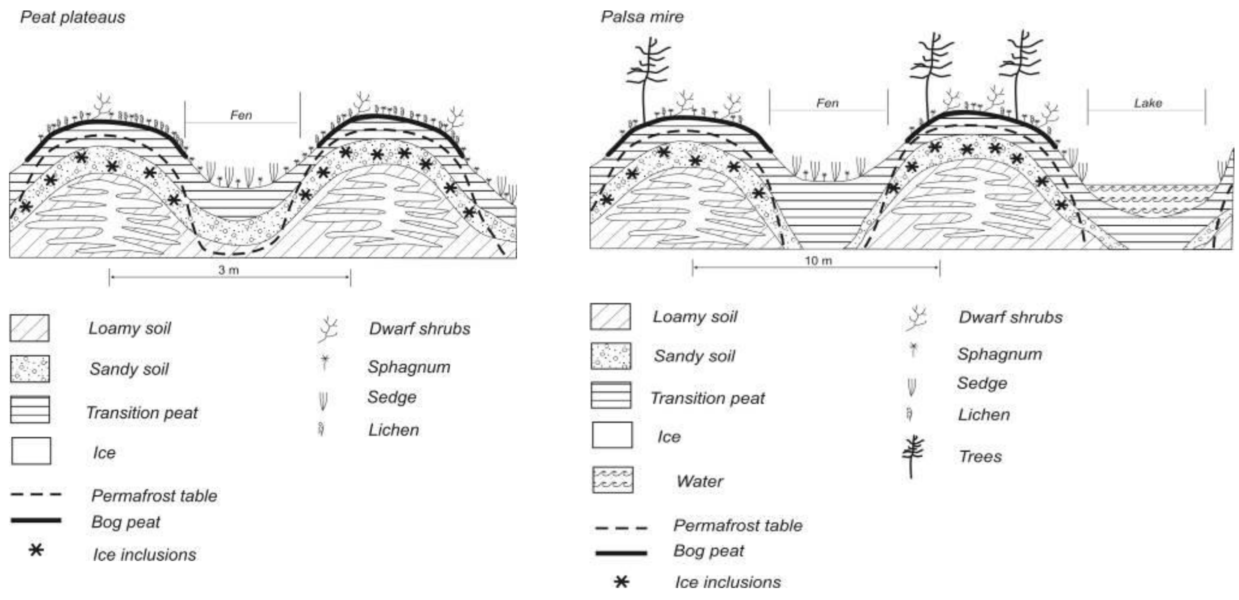


Figure 2.8. Structural characteristics of peat plateaus and palsa mires. Given peat plateau scale is more typical for Russia, and can be quite different in North America. The plateaus can be square km in scale with the fen only a minor part of the landscape.

The peat provides insulation which reduces heat gain in summer. In locations where the surface relief was originally uneven (e.g,. in a hummock), ice lenses accumulate over many years, stacked on top of one another in the mineral core to progressively create the palsa mound. Thus, the mound-hollow relief of palsa mires is created by a frost heaving process. Fine-particled mineral sediments are more susceptible to frost heaving than coarse ones, and the structure of the mineral soil beneath the peat is the main factor in determining how pronounced this relief becomes. True palsa mires with large convex mounds, separated by vast hollows and occasional ponds, are characteristic for regions with fine mineral soils. ‘Peat plateaus’ form where access to water is limited, either by low hydraulic conductivities in the mineral sediments or because continuous permafrost only permits water to migrate to ice lenses around the perimeter of the features. In either case the plateau cannot gain heights over ~2.5 m because insufficient water can be drawn to ice lenses to grow taller features (Figs. 2.9, 2.10).

Whatever their size and shape, the mounds of northern peat plateau and palsa mires are usually dominated by dwarf shrubs and lichens, whereas in the south tundra their vegetation consists of *Sphagnum* and green mosses (mainly *Dicranum elongatum*, *Polytrichum juniperinum* and *Sphagnum fuscum*). Treed palsas have also been described. Where the peat has become degraded it may be covered by scale lichens *(Icmadophila ericetorum, Ochrolechia frigida, Omphalina hudsoniana)* and form an effective springboard for invasions of new species from the south. The hollows have sedge-*Sphagnum* vegetation and often contain thermokarst ponds.

The degradation of palsas is described in numerous publications, and is highly significant in the present context. As a palsa mound grows, the vegetation cover of its top gradually degenerates; this is a natural physical process. Following breakdown of the vegetation cover, the peat layer starts to degrade so that its thermal insulation function is gradually lost and the permafrost begins to melt. In some cases, all of the supporting ice disappears leaving a roundish patch of bare peat in the tundra (Figs. 2.10, 2.11). The full cycle of palsa formation and degradation can be completed within a few decades, and the degradation phase may take just a few years, especially if assisted by surface damage due to reindeer overgrazing or vehicle activity. Therefore, the planning process for oil and gas operations should take into consideration the highly dynamic character of this type of landscape. For instance, a dry hill chosen as the ‘ideal’ site for a construction plot could just disappear within a couple of decades if it turns out to be a large palsa.

Peat plateau mire.
Photo by Igor Lavrinenko

Peat plateau mire with hollows (flat palsa mire).
Photo by Igor Lavrinenko

Peat plateau mire with ponds. Photo by Andrey Sirin

Figure 2.9. Peat plateau mires.

(a) (b)

Figure 2.10. Palsa mires in the forest tundra belt. (a): Malozemelskaya tundra in Nenetsky, photo by Igor Lavrinenko; (b): surroundings of Noyabrsk (West Siberia), photo by Andrey Sirin.

(a) (b)

Figure 2.11. Degradation of palsas. (a): palsa mounds with degraded caps; (b) caps of large palsa mounds with patches of degraded peat. Photos by Igor Lavrinenko.

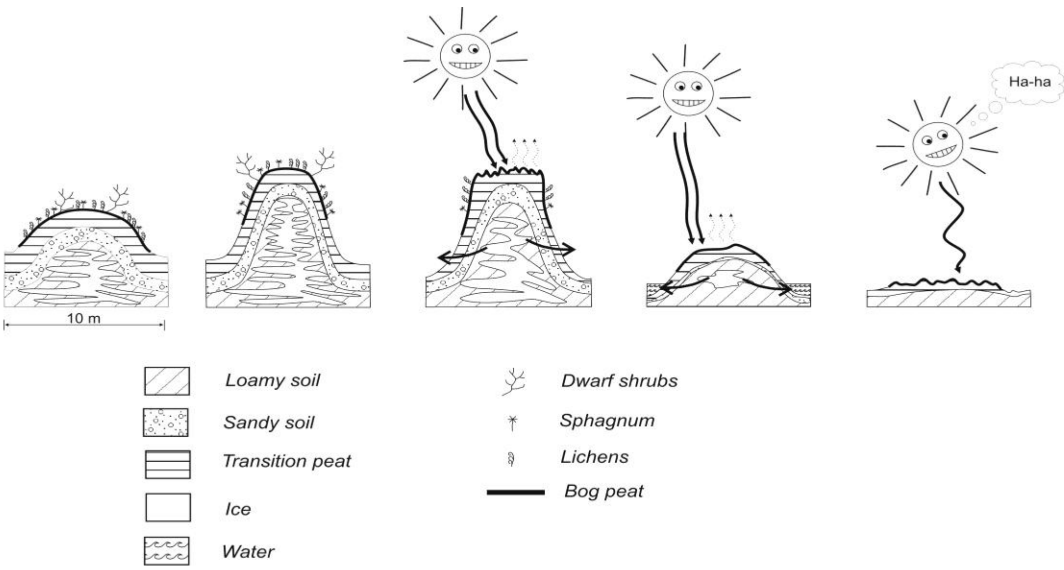


Figure 2.12. Sketch of palsa degradation.

2.3.1.1.4. Patterned string fen (aapa mire) and raised bogs

These two wetland types occur in the Arctic, Subarctic and Boreal zones and are not directly connected with permafrost, although permafrost can play a role in certain stages of their formation. At first glance the patterns of hummock-hollow complexes in raised bogs look similar to those in patterned string fens. However, there are important differences between them in terms of structure and depth of the peat deposit, which lead to differences in hydrology and vegetation patterns. In patterned string fen, the dominant peat type is fen peat, with bog peat being found only on the hummocks (Fig. 2.13). Patterned string fen is generally more sensitive to surface impacts than raised bog, insofar as its microtopographical structure does not regenerate readily.

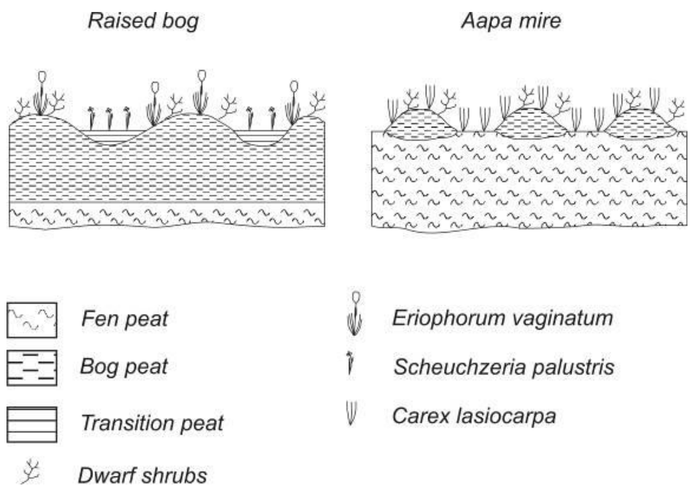


Figure 2.13. Comparison of the structures of raised bog and aapa mire microtopes.

Patterned string fen, or aapa mire, is widespread in the Eurasian Arctic and Subarctic, and it occurs in North America where it is known as ribbed or stringed fen. The main distinguishing feature of an aapa mire massif is its concave or inclined form, which means that it receives both direct rainfall and water with a higher mineral content as inflow from the surrounding land. The peat layer of aapa mire is shallow (0.8–1.5 m), so that deep-rooted plants can also access mineral-enriched water in the soil beneath. The typical landscape position of aapa mire is on gently sloping ground with permanent surface flow, which is a key factor in the formation of hummock-hollow complexes. The hummocks and hollows are usually well defined, and both host mesotrophic species. The patterns they form at the landscape level depend on morphology. Aapa mires are non-frozen peatlands, but seasonal ice in hummocks can persist throughout the summer under certain conditions. The strings or hummocks are largely composed of *Sphagnum* peat. The difference in peat characteristics between hummocks and hollows is more pronounced in northern ribbed fens than in southerly examples (Zoltai *et al*. 1988). Also, the "bog" peat of the hummocks extends farther into fen peat, making the peatland more resistant to mechanical disturbance.

Raised bogs occur mostly in the boreal belt, where they can be recognised as separate mire landscapes. In the Arctic and Subarctic zones, raised bogs occur only as elements within peatlands and wetlands of other types which occupy lake depressions, relic water channels, etc., mostly in areas with melted permafrost. Raised bogs have typical vegetation patterns made up of hummocks with ericaceous and non-ericaceous dwarf shrubs, sedges, cottongrass and *Sphagnum* mosses, and mesotrophic hollows with *Sphagnum* and small sedge carpets. Raised bogs are ecosystems with high resistance to surface damage. The key driver is shallow water flow, which should be properly maintained when linear corridores are constructed.

2.3.1.1.5. Thermokarst kettle hole peatlands

Thermokarst kettle hole peatlands or alases are typical Arctic wetland ecosystems. A kettle hole is a distinctive steep-sided depression formed by the thawing of permafrost, which may contain a thermokarst lake or an ecosystem in lake succession – floating mat, true peatland, etc. The vegetation depends on the stage of development and may consist of sedges, hypnaceous mosses or *Juncus*.

2.3.1.1.6. Biota of peatlands

The bird fauna of tundra peatland is as diverse and variable as the wetland type itself, and depends on the area of peatland, the adjacent landscapes, and habitat patchiness. Extensive grass-and-moss mires with numerous lakes typically have relatively large and species-rich bird populations that include many species of dabbling and diving ducks, White-fronted Goose, waders (Ruff, Broad-billed Sandpiper, Wood Sandpiper), citrine and yellow wagtails, and pipits. In waterlogged swamps, this list is augmented by Red-throated and Black-throated divers, cranes and gulls. Species richness is often relatively high in peat plateau (flat palsa) mires, although the number of individuals belonging to each species is low. The typical species for sedge-and-moss swamps are Ruff, Dunlin and Wood Sandpiper, but these habitats are also used by species that prefer dry peat mounds and use waterlogged sites only during the breeding period (Ringed Plover, Golden Plover, Pacific Golden Plover, Grey Plover, skuas, Rough-legged Buzzard, Peregrine, White-fronted Goose, Bean Goose, Whooper Swan, Wheatear, Citrine Wagtail, Red-throated Pipit).

2.3.1.2. Freshwater wetlands (lacustrine and riverine)

Surface freshwater bodies and the other wetlands associated with them are distinguished from terrestrial wetlands to reflect the overriding influence of open water on their formation and maintenance.

2.3.1.2.1. Rivers and deltas

Most flatland areas in the Arctic zone are characterized by low river channel densities which seldom exceed 0.5 km km^{-2}. Small rivers are relatively few. They typically have snowmelt or glacial sources and protracted ice-covered periods, and they often freeze to the bottom.

It is striking that the mouths of the largest Eurasian and North American rivers are all located within the Arctic region. These include the Pechora, Pyasina, Khatanga, Anabar, Yana, Indigirka, Kolyma, Colville and Mackenzie; as well as the largest Siberian rivers – the Ob (3,650 km long, or 5,410 km with its tributary the Irtysh), the Yenissei (4,090 km) and the Lena (4,400 km). Indeed, more Russian territory lies within the Arctic Ocean basin (which includes most of Siberia and Northern Europe) than in any other ocean basin.

The lower portions of these large Arctic rivers all flow in broad valleys and usually enter the sea through large fjord-like bays (guba). Some of them have sediment-accumulating deltas which have built up extensive networks of channels covering huge areas; for example, the delta of the Lena River covers an area of more than 45,000 km^2 and the Mackenzie River's delta is ~13,500 km^2.

Rivers have a significant effect on permafrost, preventing its formation beneath their bed and often around their banks, with an ameliorating effect on climate in the vicinity. The effect of river water on the hydrology and ice regime of the sea may be noticeable at distances of several hundred kilometers from the mouth. In most large transit rivers, the timing of spring floods varies between different parts of the catchment, leading to ice jams which can cause flooding of vast areas. Many of the large rivers have floodplains tens of kilometers wide.

Many Arctic rivers have deltas and floodplains with complex mosaics of diverse wetland types including various mires and waterlogged habitats together with permanent and seasonal watercourses and lakes. Other rivers have estuaries and guba bays, which are distinctive coastal wetland formations.

2.3.1.2.2. Lakes

Lakes are possibly the most typical Arctic wetlands. Their distribution is non-uniform and depends on topography, geological conditions and sedimentation regime. Lakes that are connected to river and stream networks are termed “flowing” or “open”. Closed lakes exchange surface water and groundwater with their surroundings by seepage only.

All lakes can be classified into two groups, namely peatland lakes and lakes with mineral basins. Most lakes in the permafrost zone (up to 80% of those in West Siberia) are peatland lakes. These are usually located within lake-peatland microlandscapes, but larger lakes surrounded by peatlands are also included. Peatland lakes are shallow – usually less than three meters deep. They characteristically have intricate shorelines because they form by merging of smaller lakes.

Arctic lakes with mineral basins are provisionally divided into three groups on the basis of genesis and morphology. The first group comprises relict lakes, basin of which is of glacial origin. These are relatively rare in Eurasia but common in North America, and are usually large and deep. The second group contains the water erosion lakes that occur mostly on extensive river floodplains and in deltas. Finally, thermokarst lakes are formed by subsidence due to the thawing of thaw-susceptible permafrost. This is the most dynamic group in terms of both water regime and morphology. Thermokarst lakes can form quickly and disappear equally suddenly. When they persist, they may display temporal phases. For example, alas lakes in East Siberia can gradually develop paludified shores and change into mires or even meadows.

The bird fauna of upland tundra lakes, considered as zonal biotope wetlands, is characterized by the greatest uniformity across the whole tundra zone. Major variations are related primarily to latitudinal and longitudinal gradients and secondarily to the diversity of lake size and origin. Small and medium-sized lakes in the typical and southern tundra zones have the highest bird numbers and the richest species composition, and their bird fauna is dominated by carnivorous diving ducks and ichthyofagous divers. The commonest species in offshore habitats are Long-tailed Duck and Black-throated Diver accompanied by Velvet Scoter, Black Scoter and Scaup in the southern tundra; by King Eider in the Arctic tundra; and by King Eider and more numerous Red-throated Diver in coastal habitats.

2.3.1.2.3. Drained depressions (syn. hasyry)

Thermokarst processes very often lead to the drainage and drying-out of lakes and ponds. The resulting “former lakes” have the local name “hasyry” (which means “dry lake”) in Nenents. These ecosystems are unique for the Eurasian Arctic insofar as peatland development and peat formation is relatively recent. Hasyri can be regarded as models for the consequences of climate change. Permafrost is not a factor in their genesis and function, and for this reason they lack patterning (Fig. 2.14). Their vegetation is species-diverse, consisting of tall sedges (*Carex aquatilis, C.rariflora, C.rotundata*) and *Sphagnum* communities (*Sphagnum lindbergii, S. girgensohnii, S. squarrosum, S. fimbriatum, S. angustifolium, S. warnstorfii*) with forbs which may include some extremely rare species; for example the Red Data Book species *Ranunculus pallasii* in the case of Nenetsky. In wetter places, *Sphagnum* mosses are replaced by green mosses like *Warnstorfia exannulata*, *Limprichtia revolvens*, *Calliergon stramineum*, *Sanionia uncinata*, *Mnium spp.*, *Meesia triquetr*, *Paludella squarrosa* and, more typically at mesotrophic sites, vascular plants like *Calamagrostis neglecta*, *Comarum palustre* and *Epilobium palustre*. Occasional hummocks are present, and these host oligotrophic species – ericoid shrubs and *Sphagnum* mosses.

In valleys of the southern tundra and the forest-tundra, hasyry are often colonised by pine or larch trees which grow very rapidly. The hasyry provides an excellent model of natural vegetation succession which might be applied in planning restoration activities.

(a) (b)

Figure 2.14. Hasyry (a) with homogeneous sedge-moss mire (b). Photos by Igor Lavrinenko.

2.3.1.2.4. Riparian mires

Deltas play a significant role in the ecology of the Arctic, as buffers for the impact of changing river flow. Within deltas we find all wetland types; from ephemeral dunes and sandy spits near beaches, to valley-bottom mires with sedges and *Hypnum* moss in oxbows and along low riverbanks with or without gravel embankments (Fig. 2.15). Sloping floodplain fens which are dependent on the fluvial regime are also regarded as riparian mires.

Sloping floodplain fens, and especially valley-bottom fens, have homogeneous vegetation structure and highly organic soils including peat deposits. Their vegetation consists of willows, tall sedges and mosses. These are the most productive of all Arctic ecosystems, and so have very high restoration potential

Of all the intrazonal wetland ecosystems of the tundra, river floodplains possess the highest diversity of wetland bird species such as Anseriformes (ducks, geese and swans) and Charadriiformes (gulls, terns and shorebirds). Moreover, southerly waterbirds like grebes use floodplains to reach the tundra zone. River floodplains are complex habitats which can be highly heterogeneous in terms of area and landscape, and the size and diversity of the bird population within a particular floodplain are determined by its area and the diversity of its biotopes. Thus, the floodplain biotopes of the tundra zone also have high numbers of Passerines (songbirds) associated with shrub and meadow communities (pipits, wagtails, bluethroats, warblers, thrushes, buntings and other species). Southerly Passerine species that travel to the tundra along floodplains include the Short-eared Owl, Hen Harrier, Redwing, Hooded Crow, Blackcap, Sedge Warbler, and Bluethroat; and the Passerine communities associated with both large and small watercourses in the tundra zone can vary considerably depending on the shrub-related species that occur in forest communities to the south. Some species, for example Chiffchaff, are confined to the forest zone in European Russia, but are able to penetrate along floodplains into the tundra zone of Siberia.

Willow meadow communities in the Pechora Delta. Photo by Igor Lavrinenko

A valley-bottom fen in Yakutia. Photo by Tatiana Minayeva.

Figure 2.15. Riparian mires.

2.3.1.2.5. Coastal and marine

Estuaries are rare ecosystems for the Arctic, which span the gradient from saline to fresh water. Here, coastal wetlands are juxtaposed with such ecosystem types as intertidal flats, saline marshes, freshwater marshes and coastal tundra. An example of their distribution along a transect in the Mackenzie Delta is provided by Tarnocai and Zoltai (1988) (Fig. 2.16). Along the estuaries one can usually also find freshwater marshes, for which there is a significant gap in scientific knowledge.

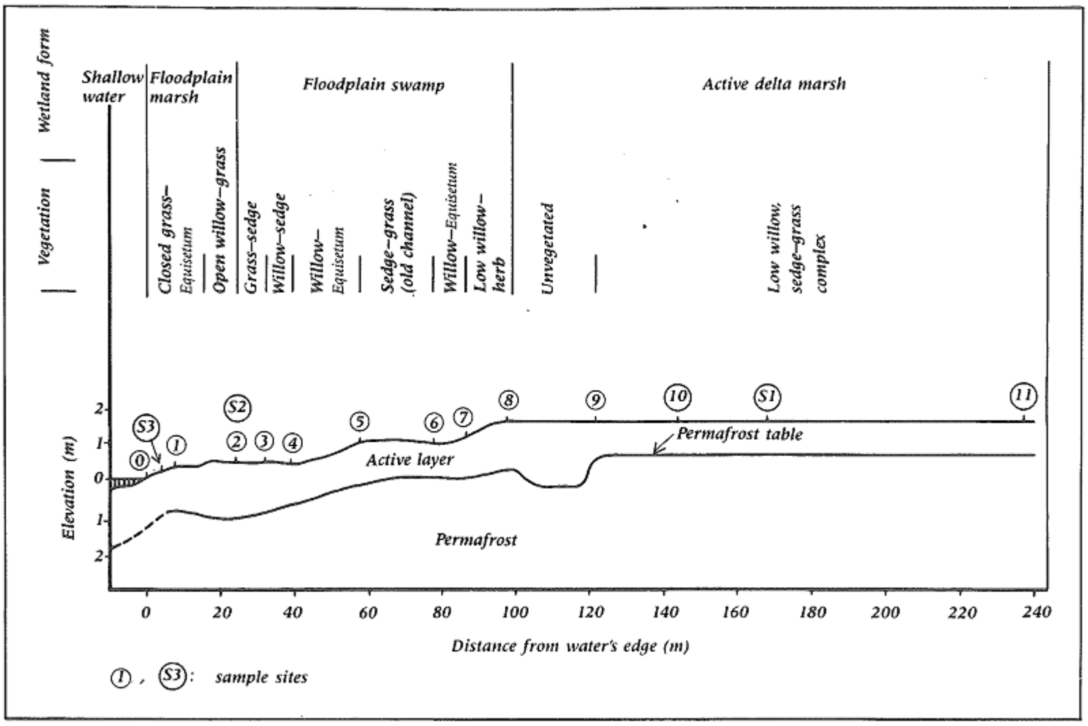


Figure 2.16. A transect located at Lat. 69°22' N, Long. 134°02' W in the Kittigazuit Bay area, Mackenzie Delta, showing various wetlands (Tarnocai and Zoltai, 1988)

In Eurasia, low-level marshes (intertidal flats) host only two halophyte species (*Carex subspathacea* and *Puccinellia phryganodes*), which are early colonizers plants and, at the same time, highly vulnerable to pollution. In view of their location in the intertidal zone, low-level marshes are the most vulnerable of coastal ecosystems to marine oil spills or oil transported into the ocean from rivers contaminated by land-based spills. They will be exposed to the full impact of any contaminants washing ashore, acting as traps for any oil brought in by currents and tides, because they occupy the lowest onshore locations. The main current of the Pechora Sea flows from southwest to northeast towards the Kara Strait, which means that any spilt oil will accumulate in the bays of Vaigach, Dolgiy, Matveyev, and Zelentsy islands, all of which have federal or regional protected status. The North Slope coast of Yukon and Alaska would be similarily vulnerable to spills originating in the Beaufort Sea or Mackenzie Delta.

Salt marshes occupy low-lying flat areas in the intertidal zones of ocean bays and river estuaries. They are formed from fine sediments (silt and clay) brought to the coast by rivers draining interior landscapes dominated by fine-grained sediments and directly from glacial meltwater. The smallest (silt) particles from the river sediment load are carried farthest, reaching brackish sea bays where they are deposited in the intertidal zone. Marsh vegetation traps the fine sediment particles brought by the tide. Due to silt deposition, intertidal marshes can grow upwards as fast as 0.35 to 1.35 cm per year (Safyanov 1987). In addition to the vertical accumulation, marshes tend to spread horizontally due to sedimentation.

Community of *Puccinellia phryganodes* submerged twice daily during high tides (foreground); community of *Puccinellia phryganodes* and *Carex subspathacea* (middle distance); and community of *Carex subspathacea* waterlogged twice daily during high tides but submerged only during the highest (spring) tides (background).

Community of *Puccinellia phryganodes* (background); community of *Carex subspathacea* (middle distance); and community of *Calamagrostis deschampsioides* with *Carex glareosa* (foreground).

The zonation of vegetation on microforms reflecting the succession: community of *Carex subspathacea* with forbs (*Potentilla egedii*, *Plantago schrenkii*, *Arctanthemum hultenii*) on hummock slopes; and community dominated by *Salix reptans* and *Festuca richardsonii* with *Parnassia palustris* on hummock tops. Photo by Igor Lavrinenko.

Figure 2.17. Succession of vegetation types accompanying the rise in surface of a saltmarsh relative to sea level:

Sedimentation of silt and accumulation of organic matter (vegetation remains) lead to a gradual rise of the marsh surface above sea level and, consequently, to changes in the periodicity and duration of seawater effects. This results in changes of salinity – the main ecological factor determining the composition and structure of the vegetation. Vegetation succession taking place after the surface rises above sea level and through time the sequence of plant communities that can be seen along the spatial gradient from low, inundated marshes to the higher stable coastal marshes that border the littoral zone (Fig. 2.17). As the surface rises, pioneering associations of *Puccinellia phryganodes* and *Carex subspathacea* on unstable sand and silt give way to medium-level marsh communities of *Carex subspathacea* with dicotyledonous grasses (*Potentilla egedii*, *Plantago schrenkii*, *Arctanthemum hultenii*) and associations dominated by *Calamagrostis deschampsioides* and *Carex glareosa*. In the final stage of succession, higher features – where seawater effects are limited to wave splash and occasional inundation by surges – are colonised by stable upper marsh communities dominated by *Festuca richardsonii* and *Salix reptans*, with *Rhodiola rosea*, *Parnassia palustris* and other halophyte and salt-tolerant tundra species including mosses. When the moss cover develops, the marsh surface begins to rise again due to peat accumulation.

Coastal tundra (high-level marsh) resembles regular tundra, but is influenced by salt water. It is initially dominated by halophytes but eventually common tundra species like *Carex subspathacea, Calamagrostis deschampsioides*, *Carex glareosa*, *Festuca richardsonii, Salix reptans*, *Empetrum hermaphroditum*, *Rhodiola rosea*, *Parnassia palustris*, *Comarum palustre* and mosses belonging to the genera *Bryum* and *Drepanocladus* predominate (Fig. 2.18).

Coastal marshes are important feeding and nesting grounds for waterfowl including barnacle (*Branta leucopsis*) and snow geese (*Chen caerulescens*), whose basic food source is the two halophyte species *Carex subspathacea* and *Puccinellia phryganodes*. Grazing by herbivores can improve the productivity of ecosystems (van der Graaf *et al*., 2004) but overgrazing can lead to habitat distruction (Jefferies et al., 2003) (Fig. 2.19).

Figure 2.18. Coastal tundra dominated by *Salix reptans* and *Rhodiola rosea*. Photo by Igor Lavrinenko.

Figure 2.19. Overgrazed *Carex subspathacea* community by geese in the marshes on Kolguyev Island.
Photo by Igor Lavrinenko

Ephemeral wetlands are regarded as marine wetlands. They are represented by dunes, sandy spits, etc. as on the mainland; they also occur on islands (Fig. 2.20).


Sandy bars east of Kolguev.

Active drilling in intertidal marshes.

Figure 2.20. Examples of coastal wetlands. Photos by Igor Lavrinenko.

The first species to colonise sand dunes is *Honckenya oblongifolia*, followed by *Leymus arenarius* and *Deschampsia obensi* (Fig. 2.21).

Accumulation of wind-blown sand on the leeward side of a *Honckenya oblongifolia* plant.

The long-rhizomed plant *Leymus arenarius* stimulates dune formation. Photo by Igor Lavrinenko.

Figure 2.21. Sand dunes.

Coastal wetlands in the tundra zone range from brackish lagoons with waterlogged marshes on their shores to narrow sand and gravel beaches, and their avifauna is correspondingly heterogeneous. These bird communities may be species-poor or species-rich, depending on latitude and the particular combination of habitat patchiness and regional peculiarities at the location in question. The commonest birds of sand and gravel beaches are generally waders; Ringed Plover is the most widespread species, but oystercatchers and turnstones become subdominant or even dominant in some areas. In many Arctic regions, a narrow coastal strip of tundra provides the main habitat of Grey Plover. Outside the breeding season, Calidrids (sandpipers) and turnstones are common, as well as some Passerines such as the Pied Wagtail. Migrating waders including Calidrids, plovers, oystercatchers, curlews, godwits and gulls concentrate within the littoral zone. Coastal salt marshes (marsh flats) with numerous brackish pools probably host more birds and bird species than any other intrazonal tundra ecosystem, because the number of breeding birds is often exceeded manifold by visitors during seasonal migrations or moulting. This is where the largest aggregations of breeding and moulting Barnacle Goose and Bewick's Swan are to be found; where waders such as Ruff and Dunlin congregate *en masse* during migrations; and where large flocks of moulting dabbling ducks have also been observed. Thus, maximum population densities are recorded here for many tundra bird species, even though none of them can be regarded as exclusive inhabitants of coastal salt marshes. Coastal marshes—and indeed the whole of the coastal zone—attract raptors such as the White-tailed Eagle, which travels into the tundra from the south along the seashore. Peregrines and many large gulls and skuas also commonly hunt in these habitats. Marine terraces that are no longer directly affected by the sea but still have many saline wetlands (pools, lakes, and mires) are connected to and often directly fringed by older upper terraces with a wide variety of freshwater wetlands which provide the most important habitats for Bewick's Swan, divers, White-fronted Goose, many species of diving and dabbling ducks, and a large number of wetland-related waders.

2.3.1.2.6. Marine wetlands (coral reefs, sea grasses)

It was previously understood that these wetland types were not represented in the Arctic. The most recent publications suggest that both are, in fact, found within the official Arctic boundary; but that they are still essentially associated with the temperate zone. Although our review is concerned primarily with the impact, mitigation and restoration of terrestrial infrastructure, we mention this wetland type with the development of onshore infrastructure serving marine installations in mind.

2.3.2. Permafrost processes and classification

Permafrost is strictly a temperature phenomenon with <0°C for at least two consecutive years (van Everdingen, 2005). Given this definition, it is possible to have dry permafrost when there is no ice in sediments or bedrock through to areas with up to 100 % ice by volume. When the amount of ice exceeds the capacity of the host sediments to absorb the water released upon melt, the permafrost is termed thaw-susceptible because it has excess ice.

The International Permafrost Association recognises four categories of permafrost (van Everdingen, 2005), namely continuous, discontinuous, sporadic and isolated. The categories are based on the areal extent of permafrost and its temperature (Brown *et al*., 1997). In the continuous permafrost zone more than 90 % of the surface, including the smaller rivers and lakes, is underlain by permafrost with temperatures ranging from -5 °C to -15 °C (Brown, 1970). In the discontinuous permafrost zone, permafrost underlies 50–90 % of the landscape and its temperature ranges from 0 C to -5 C. In the sporadic permafrost zone, 10–50% of the landscape is underlain by permafrost; and in the zone of isolated patches, less than 10 % of the landscape has permafrost. Permafrost temperatures in the sporadic and isolated patches zones are close to 0 °C. In these zones permafrost is present only where highly localized conditions permit its formation and/or maintenance.

Permafrost forms where the mean annual heat budget is negative, i.e., where more heat is lost in winter than can be stored in summer (Williams and Smith, 1989). Factors that affect heat loss in winter are the insulation provided by the litter from herbaceous plants and the snowpack. The snowpack is the more significant of these factors in that it forms a continuous barrier to heat flux from the soil to the atmosphere above the snow surface (Smith and Riseborough, 2002).

Conversely, in summer, the vegetation and surface soil layer impede heat gain. Dense plant cover shades the ground, blocking direct solar radiation and reducing the flux of heat into the soil. The nature of the near-surface soil is also critical. The drier the surface soil and the lower its thermal conductivity, the lower the soil temperature will remain. In some circumstances a wet surface can dissipate heat as latent heat of evaporation, but in general wet soils conduct heat more rapidly than dry soil and thus facilitate heat gain. In spring, seasonal ground frost thaws from the active layer, which can be very deep (e.g., 8 m) in bedrock where there is negligible water content and very shallow (e.g., 0.5 m) where there is a foliose lichen cover over dry peat at locations within close proximity of one another (Brown and Péwé, 1973; Brown, 1978a, 1978b).

2.3.3. Processes relating to organic matter

Wetlands in Arctic locations are mostly peatlands (Tarnocai and Zoltai, 1988). Peatlands are areas where the long-term rate of organic matter production exceeds the rate at which it decomposes (Crum, 1992). Production is not high compared with more temperate locations but decomposition is much slower. As a consequence, plant remains can accumulate for millennia, and once locked into the permafrost they remain essentially undecomposed and often recognizable to species level. In unglaciated parts of the Arctic the organics can be more than 40,000 years old (Schirrmeister *et al*., 2002), whereas in other areas such as coastlines that are still emerging due to isostatic rebound after the last glaciation, they are very recent (Dredge and Mott, 2003).

Decomposition can be limited by a number of factors. In a thawed state, peat that is saturated with water can be decomposed only by anaerobic organisms (Schuur *et al*., 2008). The water in wetlands is often cold, especially when in contact with permafrost, and this will limit any chemical processes/reactions. Where Arctic winters are long, the part of the year during which the wetland is thawed can be very short and decomposer activity is thus limited to a portion of the thawing season. Seasonal freezing and thawing are slow processes in wetlands due to the latent heat released on freezing of water and the amount of heat required to change its state from frozen to thawed. Finally, peatland water can be acidic, and this will limit decomposition to the few taxa that can tolerate low pH.

Any or all of the factors mentioned in the last paragraph can limit decomposition, enabling the accumulation of organic matter to form peat (Keddy, 2002). As a result, Arctic wetlands have globally-significant stores of organic carbon estimated at 16.7 Gt (Tarnocai *et al*., 2009). Some of these peatlands contain organic carbon that is tens of thousands of years old and are thus significant long-term carbon sinks. Almost 90 % of the carbon is frozen into permafrost and so cannot decompose (Tarnocai *et al*., 2009). However, it has been hypothesized that Arctic wetlands will become significant sources of atmospheric greenhouse gasses ($C0_2$ and CH_4) as climate change proceeds (Anisimov, 2007; Dolman *et al*., 2010).

2.3.4. Hydrological processes

2.3.4.1. Hydrological classification

Wetlands are defined as ‘lands saturated for most parts of the growing season to allow the development of hydric soils, or support of hydrophytes, or prolonged flooding up to a depth of 2 m’ (National Wetlands Working Group, 1988). For hydrological purposes, wetlands can be subdivided into bogs, fens and inundated lands which include marshes, swamps and ponds. Bogs obtain water mainly from the atmosphere (rain, snow, fog) and shed water to their surroundings, whereas fens usually receive lateral drainage from surface and subsurface sources. Marshes and swamps (the latter have an abundance of trees) are located along shorelines, and are periodically inundated by river, lake or sea water. Ponds are arbitrarily distinguished from lakes on the basis of a 2 m depth threshold; it has also been suggested that ponds are water bodies that freeze to their bottoms in winter whereas lakes retain free water (Sheath, 1986). Arctic wetlands occur as isolated patches with areas of 1–10 km^2, or they cover extensive parts of the landscape (Woo and Young, 2006). Patchy wetlands are particularly common in the High Arctic, while extensive wetlands are commonly encountered on coastal and interior plains.

2.3.4.2. Natural hydrology of Arctic wetlands

2.3.4.2.1. Water balance and wetness

To survive over time, a peatland needs a high degree of water saturation during most of the thawing season. This is ensured by a water table that does not fall to a substantial distance below the ground surface, so that water losses by evapotranspiration ET and any form of outflow Q_{out} are, to a large extent, compensated for by water gains from snowfall Sn, rainfall R (where total precipitation $P = Sn + R$) and the total of surface and subsurface inflows Q_{in}.

In equation form:

$$\underbrace{\Delta S}_{\text{Storage change}} = \underbrace{P + Q_{in}}_{\text{Inputs}} - \underbrace{ET - Q_{out}}_{\text{Losses}} \qquad (1)$$

ΔS may be temporarily negative in the summer season, but its absolute value should be sufficiently small, in combination with the storage properties of the soil, to maintain the water table at a sufficiently high level to meet the demands of the vegetation. Depending on whether ΔS is positive or negative, areas of open water and adjacent wet areas expand or shrink over a summer season. Table 2.3 presents values of water balance components for selected wetlands across the Arctic. The period of study ranges from one to several years (Young and Woo, 2004).

Table 2.3. Water balance components for selected wetlands in the Subarctic, Low Arctic and High Arctic zones of Canada and Alaska (all values in mm).

Basin	Site description	Year	*Sn*	*R*	*P=Sn+R*	Q_{out}	*ET*	ΔS	Q_{out}/P
SUBARCTIC Pelletier Wetland - patterned fen, 54°48'N, 66°49'W (Quinton and Roulet, 1998)	Pool-ridge moss-peat complex; Open-closed lichen woodland (0.242 km^2)	**?**	268	211	479	196	181	NA	0.38
SUBARCTIC Peat Plateau, 61°18' 48.9'N, 121°18''22.7"W (Wright et al., 2008)	Raised bog, treed plateau (black spruce, moss, lichen) 22 km^2	2004 (29 Mar-4 Jun) 2005 (29 Apr - 8 Jun)	222 206, plus ground icemelt of 162	53 63	275 269	238 213	56 67	143 152 (as soil moistu-re chan-ge)	0.86 0.79
LOW ARCTIC Lone Gull, Keewatin, 64°27'N, 97°47'W (Roulet and Woo, 1986b)	Sedge meadow fen site (0.15 km^2) in a 1.17 km^2 catchment	1983 15 May-5 Aug	146, plus ground icemelt of 210	34	180, plus inflow of 430	332	223	265 minus 210, as ground ice change)	
LOW ARCTIC Putuligayuk Watershed, Coastal Plain, Alaska, 70°N, 148°45'W (Bowling et al., 2003)	Tundra sedge/shrub (471 km^2)	1999 2000 2001	81 117 93	172 146 NA	253 263 NA	49 87 56	188 161 NA	-2 -25 NA	0.19 0.33 NA
LOW ARCTIC Coastal Plain, Prudhoe Bay, Alaska	Tundra sedge/shrub (0.224 km^2)	1992 1993	NA NA	NA NA	50.2 70.5	NA NA	165 201	-111 -114	NA NA

Basin	Site description	Year	*Sn*	*R*	*P=Sn+R*	Q_{out}	*ET*	Δ*S*	Q_{out}/P
70°26'n, 148°53'W (Rovansek et al., 1996b)									
HIGH ARCTIC Muskox Fen, Ellesmere Is., 79°58', 84°28'W (Glenn and Woo, 1997)	Sedge meadow (3700 m^2)	1993 (13 May to 8 Aug)	47	34	81	15	118	33	0.18 (0.28 for the melt period)
HIGH ARCTIC Vendom Fiord, 78°03'N, 82°12'W, (Marsh and Woo, 1977)	Tundra pond (800 m^2) in a 0.5 km^2 catchment	1975 6 Jul-17 Aug	NA	30	NA	NA	27	3	NA
HIGH ARCTIC Intensive Watershed, Devon Island, 75°33'N, 84°40'W, (Rydén, 1977)	Coastal wetland (0.12 km^2) with 63% vegetated and bare soil, 12% water, 25% bedrock	1972 1973 1974 *Mean* *SD*	132 111 169 *137* *29*	36 73 35 *48* *22*	168 184 204 *184* *18*	66 83 101 *83* *18*	69 110 65 *81* *24*	1 -50 4 *-15* *30*	0.39 0.45 0.50
HIGH ARCTIC Eastwind Lake, 80°08'N, 85°35'W, (Woo and Guan, 2006)	Tundra ponds P1 (1080 m^2) P2 (2056 m^2) P3 (1494 m^2) P4 (1211 m^2) P5(2104 m^2)	2005 12 Jun-11 Aug (post-melt)	NA	28	NA	NA	 155 163 157 159 156	 -106(-21) -70(-65) -130(+1) -140(+10) -70(-58)	NA
HIGH ARCTIC Creswell Bay, 72°43'N, 94°15'W, (Abnizova and Young, 2010)	Ponds (areas in m^2): moraine (149) plateau (1074) coastal (1386) bedrock (646) moraine (149) plateau (1074) coastal (1386) bedrock (646)	Post-snowmelt 2005 12 Jun-25 Aug 2006 12 Jun-11 Aug	 NA NA	 41 68	 NA NA	 NA NA	 15 73 123 56 10 64 95 38	 -17(-8) -301(-254) -286(-202) -129(-88) -1 (-2) -183(-151) -319(-276) -107(-87)	 NA NA

P = precipitation; *Sn* = snowfall in snow water equivalent; *R* = rainfall; Q_{out} = runoff; *ET*=evapotranspiration; ΔS = change in storage

Note that for storage change of Eastwind Lake and Creswell Bay, the first number is measured Δ*S* and the second (in brackets) is the difference between calculated and measured Δ*S*.

2.3.4.2.2. Water sources

The water supply to wetlands is derived from direct precipitation, melting of snow and ground ice within the wetland itself, spillage from lakes and rivers, coastal inundation, and inflows of meltwater and surface water from nearby hillslopes or from upstream catchments. Snow is particularly important for Arctic wetlands, the major hydrological factor being the total winter accumulation of snow rather than any individual snowfall event. Snowmelt replenishes storage deficits in spring, so that the wetlands start each new hydrological year with saturated conditions for plant growth and an adequate storage buffer against summer drought. Snow accumulation is highest – typically >200 mm – in subarctic wetland catchments (Table 2.3) (Quinton and Roulet, 1998; Payette *et al*., 2004; Wright *et al*., 2008), decreasing northwards to around 100 mm on the Alaskan Coastal Plain (Bowling *et al*., 2003) and the Arctic Archipelagos, reflecting the drier and colder environments of the High Arctic. There are local variations. For instance, in a warm and dry polar oasis, snowpacks of <100 mm are the norm, but wetlands in cold and dry polar deserts often capture 100–200 mm, and occasionally >200 mm on ponds situated in incised hollows (Abnizova and Young, 2010).

The bulk of accumulated Arctic snow does not melt until sustained above-freezing air temperatures arise in spring. The timing and duration of snowmelt is crucial to wetland systems because they define when and how much water becomes available for surface storage, infiltration and runoff. Evapotranspiration also commences when snow disappears from the wetland surface. Melting begins earlier in the Subarctic than in the Low Arctic and the High Arctic. Quinton and Roulet (1998) noted melt starting at the end of April for a ridge-pool fen in subarctic Quebec, while snowmelt typically commences in mid-May on wetlands in the Low Arctic (Rovansek et al., 1996b) and in many polar oases of the High Arctic. Despite their being located at similarly high latitudes, snowmelt commences several weeks earlier in polar oases with warmer springs and higher solar radiation than in polar deserts (Woo and Young, 1997). There is, however, much variability in the amount, timing and duration of snowmelt from year to year, from site to site, and even over short distances, owing to local wind-topography interactions in the High Arctic, or wind-vegetation interactions in the Low Arctic and the Subarctic.

Table 2.4. Mean annual rainfall at selected stations in western and central Subarctic and Arctic of Canada (between 90° and 135°W)

Station	Latitude and Latitude	Rainfall (mm)
Mould Bay	76°14'N, 119°20'W	27
Sachs Harbour	72°00'N, 125°16'W	52
Cape Parry	70°10'N, 124°43'W	67
Tuktoyatuk	69°27'N, 133°00'W	75
Igloolik	69°23'N, 81°48'W	102
Cambridge Bay	69°06'N, 105°08'W	70
Inuvik	68°18'N, 133°28'W	117
Norman Wells	65°16'N, 126°48'W	166
Lupin	65°45'N, 111°15'W	161
Baker Lake	64°17'N, 96°04'W	157
Rankin Inlet	62°49'N, 92°07'W	182
Fort Reliance	62°43'N, 109°10'W	172
Yellowknife	62°27'N, 114°26'W	164
Fort Simpson	61°45'N, 121°14'W	224
Hay River	60°50'N, 115°46'W	203

Source: Environment Canada

The frequency and duration of rainfall are important in the summer water budget, especially for the ponds and wet meadows that do not receive reliable lateral inflows. Late-summer rain can recharge ponds to snowmelt-season levels (Woo and Guan, 2006; Abnizova and Young, 2010). There is much variability in rainfall across the Arctic landscape. Table 4.4 summarizes the annual rainfall along a north-south transect of weather stations in central and western Canada where vast tracts of Arctic wetland are located. Rainfall decreases northwards, from over 200 mm in the Subarctic to 50 mm or less in the High Arctic. At meso-scale (more detailed scale), wetlands in polar oases receive less rain than polar desert sites (Woo and Young, 1997); greater exposure to open water and the frequent passage of low pressure systems generally deposits more rainfall; and high elevation zones have more precipitation (Young *et al*., 2006).

Both the existence of most patchy wetlands and the maintenance of a high degree of saturation in extensive wetlands depend upon surface and subsurface inflows, including water from lateral flooding of riparian and littoral zones (Woo and Young, 2003), spillage from lakes (Roulet and Woo, 1986c), slope drainage (Rovansek et al., 1996b), glacier runoff and meltwater from late-lying snowbeds (Young and Lewkowicz, 1988). Woo and Guan (2006) found that inflow from upslope was the main water source responsible for filling High Arctic ponds in spring; similar findings are reported by Bowling *et al*. (2003) and Rovansek *et al*. (1996) for the Alaskan Arctic coastal plain and Wright *et al*. (2008) for subarctic wetlands. The discharge of groundwater from deep-seated (e.g., sub-permafrost) sources provides steady water supply to some wetlands in the discontinuous permafrost areas, particularly in terrain dominated by carbonate lithologies (e.g., limestones and dolomites).

Riparian wetlands are usually flooded at high flows associated with the annual breakup of river ice. However, complete inundation of all wetlands in a large delta does not necessarily occur during the spring flood. For example, only 60 % of the Colville delta is flooded in any given year (Walker and Hudson, 2003). The presence of ice jams on rivers amplifies the spring flood, and this is crucial for wetlands which are perched above the regular stage level, such as the Peace-Athabasca Delta (Prowse and Conly, 1998) and for wetlands which are separated from the river channels by levees, such as the Mackenzie Delta (Marsh and Hey, 1989). In addition, episodic storm surges can produce backwater effects that raise the river stage to inundate deltaic wetlands, as happened in the Mackenzie Delta (Marsh and Schmidt, 1993).

The importance of the ground ice contribution varies with the ice content of the frozen soil and the depth of seasonal thaw. Woo and Guan (2006) found that ground-ice melt was not an important source of water for their cluster of tundra ponds despite the presence of massive ground ice in the vicinity. Elsewhere in the High Arctic, it has been reported that ground-ice melt can be important for patchy wetlands (Young and Woo, 2000), while Abnizova and Young (2010) found that ground-ice melt elevated the pond water level during a dry, warm year. Roulet and Woo (1986b) and Wright *et al*. (2008) also found ice melt to be significant in a low-Arctic fen and at a subarctic peat bog, but much of the moisture in the wetland soil froze back as ground ice in the winter.

2.3.4.2.3 Water storage in wetlands

There is a misconception that wetlands are generally effective modulators of streamflow due to their storage capacity, and this fallacy applies particularly to Arctic wetlands. Saturated wetlands, especially those with much open water, react to precipitation like any other open water surface, i.e. extremely rapidly. Subsurface storage capacity is limited to the active layer, a seasonally frozen and thawed zone overlying the permafrost. On top of this zone is a peat layer which ubiquitously covers most wetlands. The top part of the peat layer, known as the acrotelm, has large pores and hence has high hydraulic conductivity, in contrast to the lower more compacted layer, known as the catotelm, which has higher density, small pores and restricted hydraulic conductivity. As a result, the hydraulic conductivity, a measure of how easily water can be transmitted through the medium, decreases exponentially downward from the ground surface (Fig. 2.22) (Ivanov, 1957; cited by (Romanov, 1968; Ivanov, 1981; Ingram and Bragg, 1984; Van der Schaaf, 1999; Quinton et al., 2008). This vertical distribution of the hydraulic conductivity explains the quick reaction of discharge to precipitation from a saturated wetland and the slower reaction of a less saturated one (Van der Schaaf, 2005). The large pores in the acrotelm allow effective uptake and release of water to and from storage. Consequently, most of the subsurface water storage and movement occurs in the acrotelm and through the living plant mat of the wetlands, and a high proportion of any incident rainfall is rapidly transferred to watercourses. The reputed streamflow modulation function of wetlands is largely restricted to floodplain systems in the lower reaches of rivers, where much of the storage capacity available to absorb floods is located above the ground surface.

Water storage in Arctic wetlands undergoes large changes during the course of the year. The seasonal freeze-thaw depth in wetlands is shallower than in the adjacent uplands due to the effective insulation property of thawed (and especially dry) peat (Carey and Woo, 1998). Freezing of the active layer converts most of its water into ground ice for winter storage. Where a groundwater supply is sustained through the winter, as in subarctic fens, descent of the freezing front forces some water to break through the frozen cap and spread and freeze as above-ground ice (Fig. 2.23) (Price and FitzGibbon, 1987). In addition to icing, surface storage in winter includes ice in the many pools and ponds, and snow that falls and stays on the wetlands.

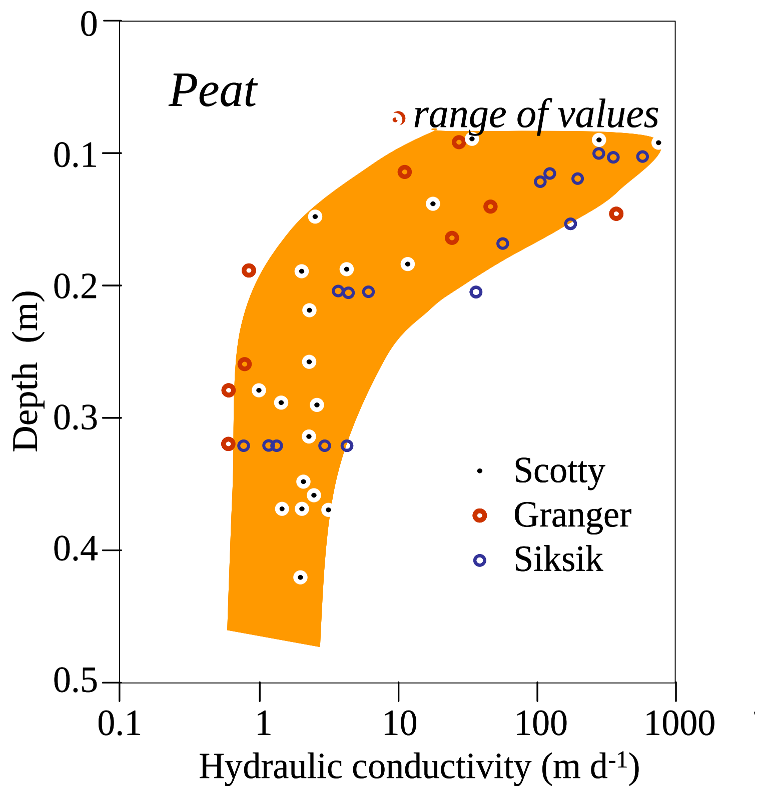


Figure 2.22. Vertical change in hydraulic conductivity in peat as exemplified by samples from three permafrost sites (after Quinton *et al*., 2008).

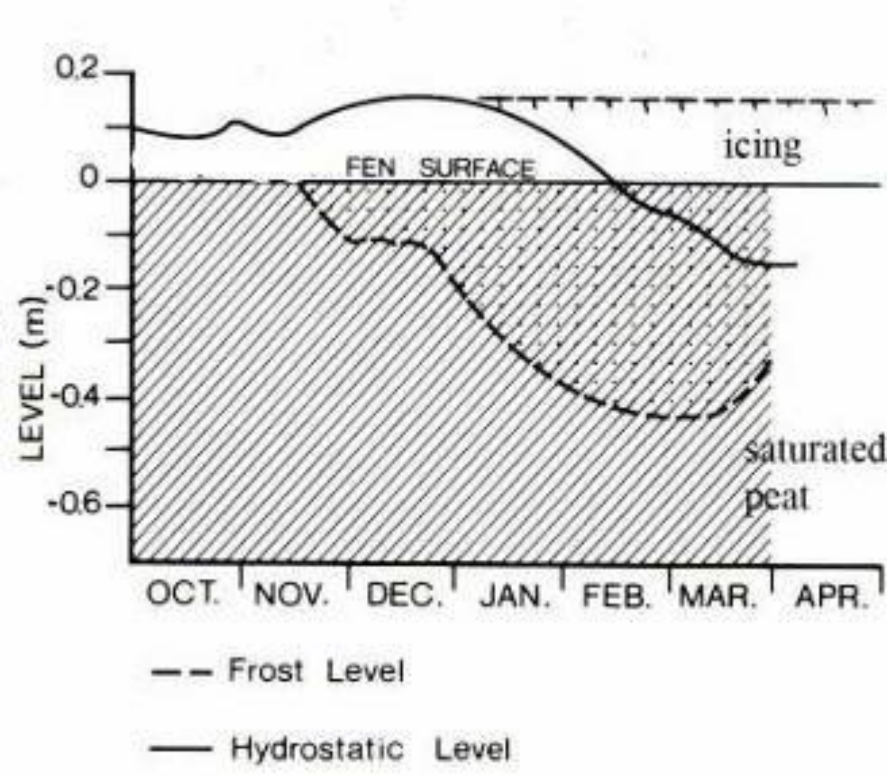


Figure 2.23. Formation of icing upon freezing of groundwater extruded under artesian pressure at a fen site in central Saskatchewan (modified after Price and FitzGibbon, 1987).

The arrival of spring replenishes wetland storage with ample snow meltwater. Surface storage in the thawing season is afforded by numerous depressions of different sizes on the wetland surface. They range from inconspicuous undulations and small rills, the troughs between earth hummocks and tussocks, cracks along the rims of ice-wedge polygons, pools of patterned bogs and fens, to the tundra ponds and shallow depressions on floodplains, deltas and coastal zones. Subsurface storage switches from frozen soil with extremely low liquid storage capacity to a thawed state that can accommodate water inputs. However, it is often the surface rather than the subsurface component of storage that holds most water. In summer, storage is drawn down mainly by evapotranspiration. It is chiefly in the dry season, with a deepened thawed layer and a low water table, that Arctic wetlands possess capacity to absorb and retain water from rain and lateral inflow. The stored water is then released gradually to outflow.

2.3.4.2.4. Evapotranspiration

The intensity of evapotranspiration depends on the availability of water and energy, the vapour pressure gradient from the evaporating surface, and the intensity of turbulent motion. Surface cover (percentages of open water and bare or vegetated land) and surface roughness, mostly determined by the vegetation structure (shrubs, herbs) and vegetation type (vascular or non-vascular plants), further modify evapotranspiration rates. Between the end of the main snowmelt season and the end of summer, much of the water in wetlands is lost to evapotranspiration. When snow disappears from a wetland, the freshly exposed surface has a high moisture content. Ample available moisture and the large input of energy in May and June enable high evapotranspiration in the immediate post-thaw period, as evidenced by the daily evapotranspiration rates of a High Arctic wetland (Fig. 2.24). Plant growth adds transpiration loss but lichens and mosses, being non-transpiring, can hinder evaporation by covering the wet substrate with a dry cladding (Kershaw and Rouse, 1971). Evapotranspiration declines when wetlands become drier and solar radiation becomes lower in the later parts of summer. Deviations from this seasonal trend are due to changes in the weather and in wetland storage status (Young and Woo, 2003).

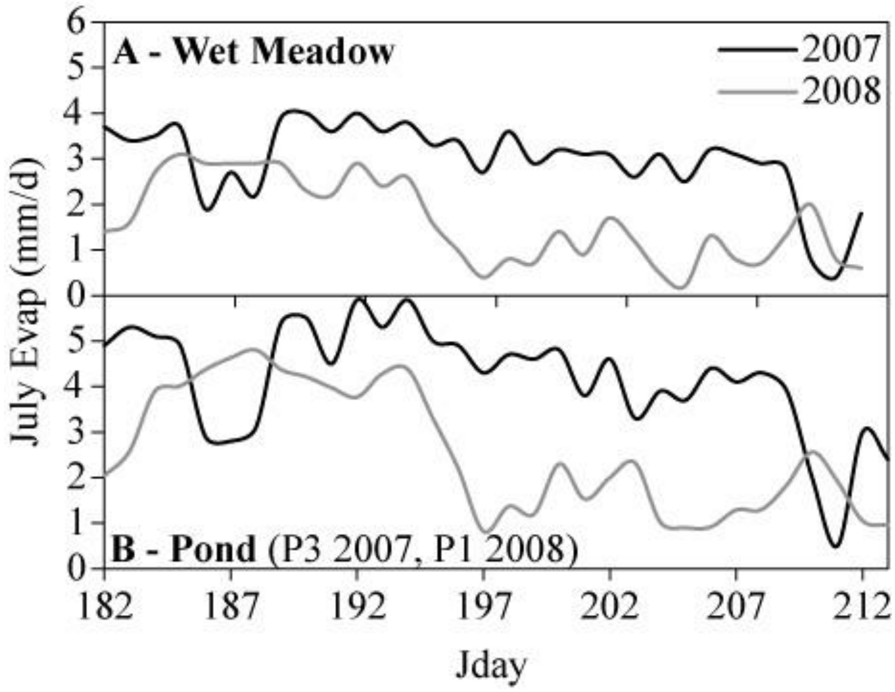


Figure 2.24. Daily evaporation from tundra ponds at Polar Bear Pass, Bathurst Island (Young and Labine, 2010)

As suggested by reported evapotranspiration (ET) values from the Arctic (Table 2.5), bogs tend to have lower rates than fens and ponds have the highest rates. The advection of heat to the wet surface augments evaporation (Marsh and Bigras, 1988), as do summers with warmer and drier conditions than normal. The length of the evapotranspiration season is a major consideration, being longer in the Subarctic than in the Arctic. Taking these factors into account, evapotranspiration rate for the same wetland can vary greatly between years (Fig. 2.24).

Table 2.5. Rates of daily evapotranspiration (mm d^{-1}) from selected locations in permafrost regions.

Location	Wetland type	Period	Evapotranspiration	Reference
High Arctic				
Hot Weather Ck., Ellesmere Island	Sedge-moss fen	7 Jun – 8 Aug, 1993	0.5–3.8	Glenn and Woo, 1997
Eastwind Lake, Ellesmere Island	Pond Wet meadow	10 Jun – 10 Aug, 1993	1.0–4.6 1.0–4.0	Woo and Guan, 2006
Vendom Fiord, Ellesmere Island	Pond	6 Jul – 17 Aug, 1975	0.6[a]	Marsh and Woo, 1977
Resolute, Cornwallis Island	Patchy wetland	29 Jun – 8 Aug, 1997 (cool and wet) 14 Jun – 8 Aug, 1998 (warm and dry)	1.7 [a] 2.6 [a]	Young and Woo, 2003
Creswell Bay, Somerset Island	Sedge-moss fen Pond Sedge-moss fen Pond	July 2005 July 2006	1.4 [a] 1.8 [a] 1.5 [a] 2.2 [a]	Abnizova and Young, 2010
Polar Bear Pass, Bathurst Island	Sedge-moss fen Pond Sedge-moss fen Pond	July 2007 July 2008	0.4-4.0 (3.0 [a]) 0.5-5.9 (4.2 [a]) 0.2-3.1 (1.6 [a]) 0.8-4.8 (2.6 [a])	Young and Labine, 2010

Location	Wetland type	Period	Evapotranspiration	Reference
Low Arctic				
Lone Gull or Kiggavik, Keewatin	Sedge meadow	22 Jun – 1 Aug, 1983	2.2–7.3 (4.5[a])	(Roulet and Woo, 1986a)
Prudhoe Bay, Alaska	Pond	9 Jun – 14 Sep, 1992 29 May – 11 Sep, 1993	2.0 [a] 2.1 [a]	(Rovansek et al., 1996a)
Putuligayuk River, Alaska	Pond	10 Jun – 15 Sep, 1999 17 Jun – 13 Sep, 2000	1.9 [a] 1.8 [a]	Bowling et al., 2003
Mackenzie River Delta, NWT	Pond (NRC Lake)	7 Jun – 31 Aug, 1984 9 Jun – 1 Sep, 1985 16 Jun – 2 Sep, 1986	2.9 [a] 2.8 [a] 2.5 [a]	Marsh and Bigras, 1988
	Pond (Dishwater Lake) subject to heat advection	15 Jun – 11 Sep, 1982 15 Jun – 1 Sep, 1983 7 Jun – 29 Aug 1984 9 Jun – 27 Aug, 1985	3.9 [a] 4.1 [a] 4.6 [a] 3.9 [a]	
Subarctic				
Hudson Bay Lowland, Manitoba	Wet fen Dry fen	Summer	3.1 [a] 2.6 [a]	(Lafleur, 1990)
Schefferville, Quebec	String fen	24 May – 18 Jul, 1997	4.5 [a]	Quinton and Roulet, 1998
Scotty Creek, NWT	Peat plateau	29 Mar – 4 Jun, 2004 19 Apr – 8 Jun, 2005	0.8 [a] 1.3 [a]	Wright et al., 2008
Washkugaw Ck., Ontario	Marsh/swamp	28 May – 16 Aug, 1985	1–7 (3.0 [a])	(Woo and diCenzo, 1989)

[a] indicates daily mean, otherwise the numbers indicate the range of daily evapotranspiration during the study period

2.3.4.2.5. Lateral flow

The delivery of water within and from an Arctic wetland is strongly seasonal. A freshet is common in the spring due to rapid melting of snow accumulated over the long Arctic winter. The modes of surface runoff include overland flow on wetland surfaces, spillage from ponds and lakes as they become full, and channelled flow in rills, gullies and streams that cut through the wetland. These modes of flow often alternate or merge with each other within a wetland. Overland outflow and spillage take place when storage is filled to capacity (Woo and Young, 2006) and water spills over vegetated borders and pond rims. Flooding of Arctic wetlands recurs every spring when substantial snowmelt cannot be absorbed into storage by the frozen ground.

Channeled flow is facilitated by frost cracks in the permafrost landscape, as noted by Abnizova and Young (2008) in the High Arctic. Fluvial and thermo-erosion along frost cracks enlarge the channels (Fortier *et al*., 2007; Boike *et al*., 2008), thus enhancing wetland drainage. In extreme cases, thermokarst and erosion by running water carve new channels in ice-rich permafrost and catastrophically drain the ponds impounded by the permafrost rim (Marsh *et al*., 2009). Other landscape alterations leading to drainage include meander encroachment on lake or pond shorelines (Eisner *et al*., 2009) and fluvial and aeolian erosion of pond rims (Boike *et al*., 2008).

Subsurface drainage of wetlands includes vertical seepage and lateral flow. Infiltration is facilitated by the highly permeable nature of the acrotelm. Deep percolation depends on the properties of the substrate, being retarded by the catotelm, limited by high ice content and restricted by fine-grained mineral soils or bedrock underlying the peat. Much water can seep into coarse soils and flow out of the wetland where the hydraulic gradient is steep (e.g. Abnizova and Young, 2010). Subsurface lateral flow increases after snowmelt as the ground begins to thaw. When the water table resides in the acrotelm, much of the flow moves through the soil matrix because of its relatively large hydraulic conductivity. Soil pipes are also common in the peat. They effectively convey water from wetlands to creeks (Woo and diCenzo, 1988) and their presence can lead to widespread thermokarst on some river terraces (Seppälä, 1997). For a subarctic wetland, Wright *et al*. (2009) found that subsurface flow is almost as important as snowmelt runoff from a raised bog to a fen.

Connectivity of flow pathways is important in the generation of wetland outflows. Spring freshet is the prime time for storage recharge, and once accomplished, surplus water can be shed from the wetland. Although the overall snow cover pattern is similar between years, slight changes in snow distribution alter the runoff pathways and linkages within a wetland (pond to pond, pond to wet meadow etc.). The prevalence of frozen ground in all wetlands during snowmelt encourages flooding and overland flow, providing strong connectivity within the wetland and with non-wetland zones in the catchment, thereby allowing easy transfer of water and nutrients (Thompson and Woo, 2009).

Within a large wetland complex, some areas generate runoff while others receive it or convey it out of the basin. Quinton *et al*. (2003) identified several hydrological functions in a subarctic continental wetland: permafrost plateaus that generate runoff, flat bogs that store water, and channel fens that carry water out of the wetland. Flow connections among the peat plateaus, the bogs and the fens change during the course of the thaw. Outflow from the wetland is high when these various components are linked to tap the runoff generated in large parts of the wetland, as often occurs in the snowmelt season.

As summer advances, continued evapotranspiration and drainage gradually dry the wetlands. The water table subsides, surface ponds shrink and surface flow connectivity diminishes, causing substantial reduction in wetland outflow. Flow connections across parts of the wetland are occasionally revived when heavy rainfall fills the storage and expands the remaining waterlogged hollows. Such seasonal enlargement and contraction of wet areas is common in Arctic wetlands (Bowling *et al*., 2003). The expansion and contraction of surface ponding and flow connectivity is appropriately described as the “fill-and-spill” mechanism. Ponds also expand as they are filled, and spillage of individual ponds occurs when their levels reach the elevations of their outlet lips. Overflow provides runoff that establishes linkages among ponds and integrates the wetland drainage network.

The fill-and-spill principle also applies to subsurface flow as the ground thaws. Differential thaw rates within a wetland give rise to an uneven frost table with many troughs and depressions that temporarily withhold supra-permafrost groundwater from drainage. Wright *et al*. (2009) found that spatial and temporal variations in active layer thaw create subsurface sills that prevent subsurface flow in a subarctic wetland. When sufficient water has accumulated, subsurface flow occurs as water spills over the sill.

In relatively flat areas, small-scale differences in surface level can cause differences in the length of periods of partial saturation in the summer over relatively short distances. This also implies differences in other physical conditions, for example soil temperature. Such patterns can cause similarly shaped vegetation patterns. In a peat-forming vegetation, these patterns can be self-enhancing, but can also originate from processes related to differences in wetness in the peatland itself (Swanson and Grigal, 1988; Witte *et al*., 2004; Couwenberg and Joosten, 2005). In such cases they are part of a feedback loop because they are affected by, but also affect, flow patterns. Changes in flow pattern, for example induced by unequal subsidence related to thawing of the permafrost, vehicle tracks etc., either natural or man-induced, can have an ecological impact as habitat conditions change rapidly over shorter or longer spatial distances.

2.3.4.2.6. Streamflow from wetlands

The wetland streamflow regime is the average seasonal rhythm of discharge of rivers draining Arctic wetlands (Woo, 1988). The magnitude and timing of seasonal discharge reflect the processes of water inputs and losses, retention and release, and winter freeze and spring thaw.
Wetland rivers emerge from their winter dormancy of no flow or low flow when the snowmelt season arrives. The initiation of streamflow in Subarctic and Low Arctic wetland catchments lags behind snowmelt by one to two weeks (Quinton and Roulet, 1998; Bowling *et al*., 2003), with the delay being more extended for large rivers and in cold and cloudy springs (Young and Woo, 2000). The delay is attributed to the time needed for the meltwater (1) to percolate through the snowpack and reach the ground, including the possibility of refreezing in the cold snow to form ice lenses, (2) to satisfy wetland storage requirements, such as filling topographic depressions, (3) to travel across the wetland as overland flow and through the shallow thawed part of the acrotelm, (4) to clear the channels within the wetland which are usually infilled with snow and ice that block the flow (Woo and Heron, 1987; Young, 2008). Spring peak discharges are attained when the wetland drainage network connects for flow delivery, and peaks are magnified by snow and ice breakup events in the channels. For some large wetland rivers, peak discharge might not occur until more than a week after the end of the main snowmelt season.

Subsequently, discharge recedes as evapotranspiration intensifies and storage declines. Streamflow can rise again in periods of intense or protracted summer rain. However, with a reduced storage status, the wetland becomes more effective in attenuating stormflow than it was during the spring freshet. Depending on preceding moisture conditions and the amount of rainfall, Arctic wetlands might or might not show discharge responses in the rainy period. By early winter, streamflow ceases, or if the river is fed by groundwater, baseflow continues under an ice cover.

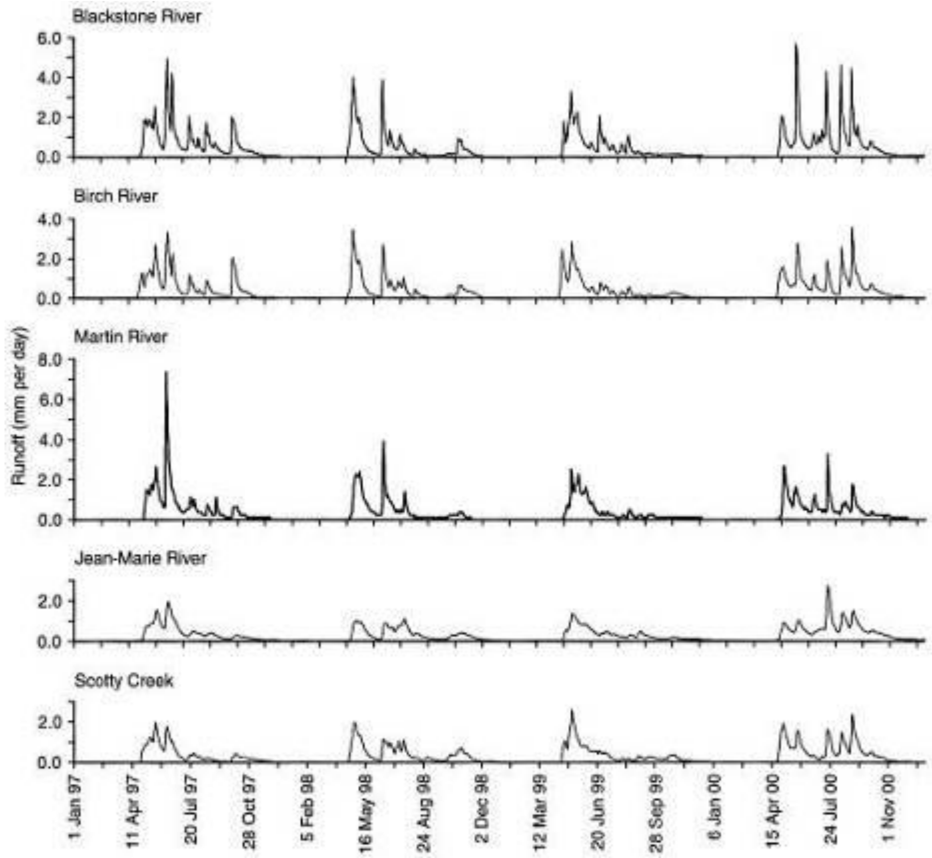


Figure 2.25. Wetland streamflow regime exhibited by five subarctic rivers (after Quinton *et al*., 2003).

The hydrographs of five wetland rivers on the Interior Plain of Canada (Quinton *et al*., 2003) exemplify the wetland streamflow regime (Fig. 2.25). They show little or no winter flow, a pronounced snowmelt freshet followed by a flow recession in summer, but occasionally spiked by rain-induced peaks that are likely to have been attenuated by wetland storage. Departures of individual hydrographs from the average flow pattern are expected due to variability of weather and wetland storage conditions.

2.3.5. Wetland types as habitats: birds

Birds are one of the most mobile taxa of tundra communities. The majority of tundra birds migrate here in large numbers to breed, taking advantage of the rich food resources, limited number of people and low predation levels. Therefore, they are completely dependent on tundra ecosystems during the northern summer. During the rest of the year (northern winter) they disperse to all continents and oceans of the world, some travelling as far south as Tierra Del Fuego in South America, South Africa and New Zealand; and others to the small island states of the Antarctic, Atlantic, Indian and Pacific oceans. Some even change from the terrestrial habits they adopt in the tundra to coastal or marine lifestyles. Thus, their management in the Arctic is closely linked to bird management efforts at global scale.

Even in summer, the ecosystem requirements of tundra birds may change substantially between different stages of their lifecycles and vary with weather conditions, food availability and their physiological readiness for reproduction. The latter may, in turn, be affected by the ecological situations encountered in their winter habitats and/or along their migration routes. Moreover, the great mobility of many birds, especially large species, allows them to use a broad range of tundra habitats (from dry gravelly upland plateaus to waterlogged polygonal or palsa mires and tundra lakes) simultaneously or consecutively during the course of a single breeding season. Thus, although the availability of sufficient areas of nesting habitat is important for most species of tundra birds, they also require a certain level of habitat diversity at landscape level.

While the species diversity of the tundra avifauna is lower than in other ecotypes, for example in the tropics, Arctic wetlands and their surrounding habitats support extremely large numbers of birds during the short northern summer. In general, the Arctic avifauna is dominated by three orders, namely: Anseriformes (ducks, geese and swans), Charadriiformes (gulls, terns and shorebirds) and Passerines (songbirds), which contribute about 80% of the bird diversity of tundra ecosystems. Within these orders, the greatest species diversity is found amongst Charadriiforms belonging to the subfamily Calidriinae (sandpipers), and both the species diversity and avifaunal proportion of this group reach their global maxima in the communities of the Arctic tundra subzone. This same subzone also boasts the maximal singularity and endemism of local and regional avifaunae (Stishov *et al*. 1989).

The intrazonal communities of the Arctic tundra subzone and the zonal communities of typical and southern tundra share a number of widespread intrazonal species, and this increases the inter-regional similarity of wetland fauna across the tundra zone. By and large, the species diversity and numbers of birds occurring in zonal and intrazonal ecosystems vary considerably between different geographical regions of the tundra zone. Species richness in one community may be double that in adjacent zonal communities; while bird numbers and biomass may be several orders of magnitude greater, reflecting known differences in the primary production of zonal and intrazonal communities (Stishov *et al*. 1989). Thus, all representatives of the orders Anseriformes and Gaviiformes (divers), a large proportion of Charadriiformes (the majority of gulls and many waders), and Passerines are associated with intrazonal wetland communities of the tundra zone. Some insectivorous birds (pipits, warblers, small thrushes) can be observed in wetland habitats of the tundra zone, but the actual zonal species (Snow Bunting, Lapland Bunting and Shore Lark) are mixed feeders.

Birds generally occupy the upper trophic levels in the food chains of Arctic ecosystems. They include specialized ichtyofages (divers, Arctic Tern and the widespread Red-breasted Merganser), and rather specialized raptors such as Snowy Owl, Rough-legged Buzzard, Peregrine and Gyrfalcon. Non-specialized predators—such as larger gulls and skuas—are also relatively important in tundra communities. Gulls and skuas are similar to diurnal raptors and owls in that they are large birds occupying the tops of food pyramids; moreover, they have large home ranges and so use a broad spectrum of tundra biotopes, with wetlands usually supplying a considerable proportion of their food.

There are few strictly phytofagic bird species in the tundra, but most of the birds that characteristically graze on land plants (geese and grouse) are present in great numbers and biomass, with geese also having high species diversity. On the other hand, the proportion of waterbirds feeding on the seeds of aquatic plants (dabbling ducks) is small. The most widespread dabbling duck is the Northern Pintail, but this species is abundant only in floodplain and delta communities. Nearly all of the bird species inhabiting lakes in the zonal tundra are strictly or predominantly carnivorous.

The populations of many tundra birds are affected by natural ecosystem processes which are highly variable and sometimes give rise to such extreme variations in species diversity, numbers and breeding success that assessments of anthropogenic impacts become impossible unless sufficient reference sites with zero anthropogenic impacts are available for each wetland type, season, region, and habitat structure.

Two major natural factors that govern the fluctuations of species composition, numbers and breeding success in tundra ecosystems are the climatic profile of the season (snow cover and depth, spring onset dates, air temperatures in May and June, dates and intensity of spring flood in floodplain habitats, cold spells late in the nesting period, etc.) and predation pressure, which is in turn dependent on the abundance of lemmings and voles.

The impacts of mass predators (Arctic fox, Rough-legged Buzzard, Snowy Owl, Pomarine Skua) on populations of wetland birds in tundra ecosystems may differ dramatically between the various phases of lemming cycles.

Weather conditions during the breeding season can result in very different impacts on different bird species, as well as on geographically distinct populations of a single species. For example, for birds that have weak territorial connections with particular breeding areas (e.g. the Little Stint), cold years with late spring onset favor breeding in the southern tundra, and these species do not even appear in the northern tundra (Arctic tundra subzone) in such years (Soloviev 2007). On the other hand, breeding success in cold years is reduced everywhere for species with less flexible territorial connections (e.g. Dunlin).

The irregular periodicity of these two factors (weather conditions and predation pressure) and their poor synchronicity across extensive areas combine to hamper our understanding of natural processes in the tundra such that it is still far from sufficient to support precise quantitative prognoses for bird populations.

The bird populations of tundra ecosystems are also affected by longer-term and directional processes such as: long-term climate change; expansion and contraction of populations and distribution ranges associated with transformations of wintering habitats and stopover sites outside the Arctic; and reciprocal fluctuations of bird species with similar ecological requirements driven by selective hunting. The considerable changes in the numbers and distribution patterns of many

European tundra species that were registered during the 20th century may be associated with such causes. Specifically, the numbers of Lesser White-fronted Goose decreased throughout the region and the numbers of waders such as Turnstone, Grey Plover and Dunlin decreased considerably in many areas; whereas Brent Goose declined in the southern parts of its breeding range and disappeared completely from its traditional breeding ground on Kolguyev Island. Also, in the eastern part of the Eurasian Arctic, the numbers of Bean Goose and White-fronted Goose decreased during the same period. On the other hand, Barnacle Goose numbers increased; and the ranges of Greylag Goose, Mute Swan and Red-breasted Goose expanded.