the ephemerally connected peatland; at certain times of year, usually during spring snowmelt, a peatland can receive water either as surface or subsurface flow from adjacent hydrological components of a drainage basin. Once the exchange ceases, discharge from the peatland recedes. The spring recession in flow extended over a month in a small southern Ontario cedar swamp seasonally connected to a perched aquifer (Taylor and Pierson 1985), but lasted less than two weeks in a low arctic fen which received water from the overflow of adjacent lakes and streams (Roulet and Woo 1988). An isolated peatland depends on direct precipitation for its water input, and discharge occurs in response to snowmelt and rainfall. A peatland that is effective in sustaining flow is usually connected to a larger hydrologic system. In some peatlands, discharge can be very large. For example, the mean annual daily runoff from a southern Ontario headwater swamp was 46 mm $d^{-1}$, but the peatland itself had little effect on the magnitude of the flux, which was controlled, rather, by groundwater discharge through the peatland (Roulet 1988).

The magnitude and timing of storm runoff from a peatland is a function of the size of the storm input, the antecedent storage capacity of the peatland, and the ability of the peatland to shed water. If a peatland has little available storage capacity, the storm response will be large, whether or not the peatland is hydrologically isolated or connected. An understanding of controls on antecedent storage capacity is important in explaining response to storms. Isolated peatlands have a high degree of variability in response because the antecedent storage capacity depends on the frequency and magnitude of rainfall, which is itself highly variable. Peak stormflow from a Minnesota peatland was three times larger when the water table was near the peat surface than when it was 15 cm below (Bay 1969). In ephemerally isolated peatlands, response to storms is large when the peatland is still connected to additional sources of water (Taylor and Pierson 1985), but is similar to that of the isolated peatland once the connection is broken. Storm run-off was produced for all rain events in a headwater cedar swamp because continuous groundwater input between storms maintained areas of saturation (Roulet 1988). Groundwater input varied little, and the proportion of rain discharged as storm flow was reasonably constant (e.g., approximately 31 per cent of direct precipitation onto the wetland) (author's unpublished data).

Current runoff theory explains the characteristics of stormflow hydrographs by relating the magnitude and rate of change in storage to the mode of transport of water through a hydrological system. The production of runoff from peatlands should be treated in the same way (e.g., Verry, Brooks, and Barten 1988) to improve the understanding of the hydrological role of peat-covered wetlands.

## COASTAL SALT MARSHES: HYDROLOGY AND SALINITY

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Coastal wetlands are among the world's most productive ecosystems. They are juxtaposed with large bodies of water whose fluctuations help maintain a flow of water and nutrients. Two categories of coastal wetland are proposed for North America, based on the regional trend of sea-level change.

Emerging coastlines produced by isostasy are found in northern North America, especially in Labrador, James and Hudson Bays, and the Arctic (Andrews 1970), where 'nascent' wetlands are formed by the lateral accretion of sediments over marine deposits with a low gradient and permeability. Progradation rapidly elevates these sediments above the zone of regular tidal inundation where infrequent flooding is not conducive to peat development. Further inland, however, raised beach ridges impede drainage from the interior, resulting in paludification and hence peat formation. These processes have formed, in the James and Hudson Bay regions, one of the world's largest wetland complexes.

The second category of coastal marsh is produced on submergent coastlines like the Pacific and especially the Atlantic coasts of North America; these coastal wetlands are 'senescent,' and survive only where vertical sediment accretion equals or exceeds the local sea-level rise. This occurs most frequently in estuaries where fluvial sediment input is high and where drowned river valleys provide protected embayments which limit wave erosion. The marsh surface is aggraded by sediment deposition during flooding, and so is in equilibrium with the vertical range of the tides. Water distributed by the numerous tidal channels, therefore, regularly seeps into and floods over the banks, producing a predominantly saturated condition which promotes peat development (Hemond et al. 1984).

There is little subsurface lateral water movement in both these wetland types, except near tidal streams (Nuttle 1988; Price and Woo 1988a), although upward groundwater flow is sometimes important (Hemond and Fifield 1982). Evaporation and the infiltration of rainwater, the primary water flux processes, therefore control

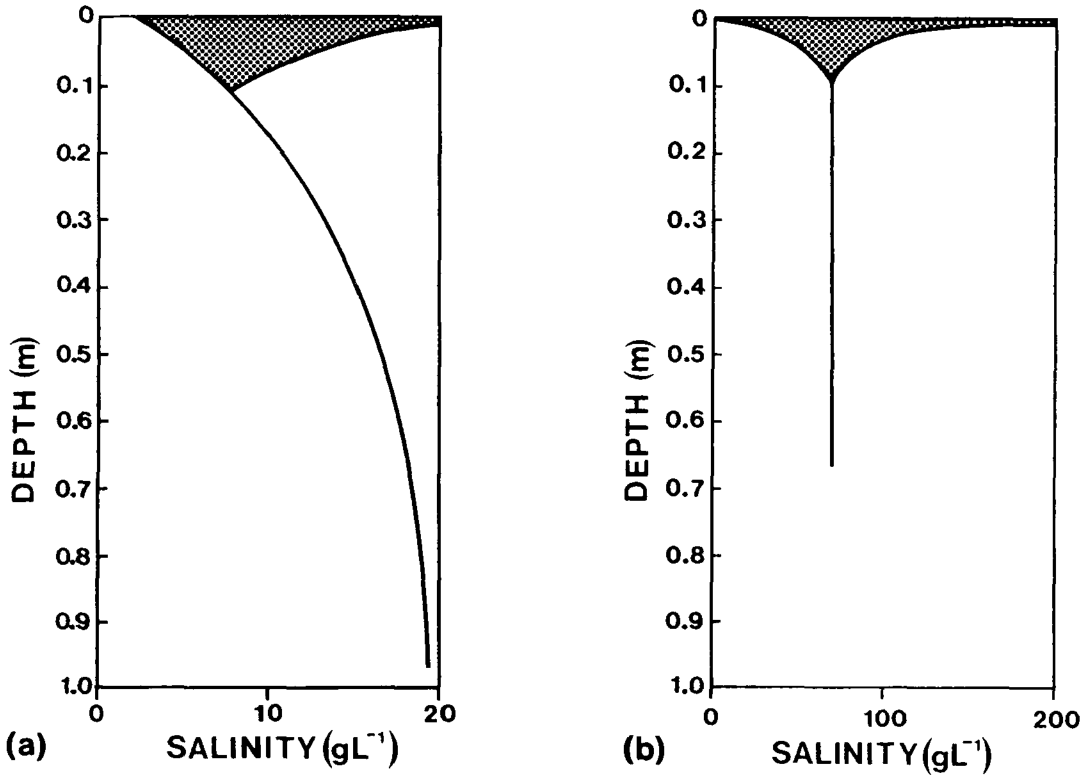

**Figure 3**

Generalized salinity profiles of salt marshes of (a) southern James Bay and (b) Atlantic coast, U.S.A. (adapted from Casey and Lasaga 1987). Note the difference in salinity scales.

the surface salinity. The zone below mean high water (MHW) is inundated by semi-diurnal tides, so the surface salinity reflects the ambient salinity of tidal water. Above MHW, the water table is lower relative to the local surface because evaporative loss is not replenished regularly by tidal floods. The surface salinity rises above that of the tidal water (Figure 3) because (1) moisture (and salt) flow towards the surface in response to evaporation and (2) solute concentration increases as water is lost from the aqueous solution due to evaporation. Salt is leached downward where infiltration is sufficient, but the marsh sediments often have low infiltration rates (Hemond et al. 1984), so salt is lost in surface runoff. During one tidal cycle in a James Bay wetland, Price (unpublished data) found that water offshore had a total salinity of 18 g $L^{-1}$, but increased to 40 g $L^{-1}$ when it flooded onto the marsh. Thus, salt at the surface was readily taken into solution by the tidal water, and carried away as the tide receded. This mechanism is important in salt marshes without significant subsurface drainage – otherwise, the salinity would continue to rise in response to further inputs of salt water, and the marsh would soon become inhospitable for vegetation.

Many similar processes operate on both nascent and senescent wetland types, but certain morphological characteristics produce distinct patterns of hydrology and salinity. On nascent wetlands, coastal emergence results in a smooth regular coastline, on which tidal sources of salt, water, and sediment occur in bands parallel to the shore. The nascent wetlands develop over uplifted marine deposits, where salinity may be higher in the tidal water (Price and Woo 1988b). The salinity profile in the saturated zone is therefore characterized by an increase in salinity with depth (Figure 3a), resulting in salt transport toward the surface by molecular diffusion. This process can maintain a limited supply of salt to the wetland even after it has prograded well beyond the present-day tidal limit (Price and Woo 1988c).

Senescent wetlands exhibit a less predictable spatial pattern of hydrology and salinity. The lower marsh surface and numerous dissecting channels ensure a more widespread, but irregular, distribution or water and salt. There may be lateral salinity gradients between the channels and the inland marsh. The vertical salinity profiles tend to change seasonally from more saline at the surface in summer, to less saline at the surface in the wet seasons (spring and fall). Below the range of water table fluctuation in the marsh sediments, the salinity profile tends to be relatively constant, reflecting the long-term average surface salinity (Figure 3b).

A knowledge of the relationship between morphology, hydrology, and salinity is basic to understanding vegetation patterns on coastal marshes and will contribute to sound management strategies.

## THE BIOGEOCHEMISTRY OF SMALL HEADWATER WETLANDS

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Freshwater wetlands are increasingly viewed as important components of the landscape because of their role in the regulation of water chemistry (Howard-Williams 1985). Nevertheless, little information is available on the biogeochemistry of small headwater wetlands. Small palustrine (upland) wetlands with outlet streams are typical of many drainage basins in glaciated areas of eastern Canada and adjacent regions of the United States. The location of these wetlands within headwater drainage basins makes them potentially important in modifying the chemistry of water fluxes between upland areas and streams.

Consideration of hydrology provides an essential framework for understanding wetland biogeochemistry (Hemond 1980). This section will examine the influence of wetland/groundwater linkages and hydrological pathways within wetlands on water chemistry. These aspects of hydrology may help to explain major differences in the role of headwater wetlands as sources, sinks, and transformers of mineral elements.

The relationship between headwater wetlands and groundwater constitutes an important control on wetland hydrology and biogeochemistry. Headwater wetlands that are sustained by a perched water table (ephemerally connected wetlands) often exhibit variable discharge, whereas discharge from wetlands connected to regional groundwater systems is more evenly distributed throughout the year (Roulet, this issue).

The timing of water movement through headwater wetlands is critical to their role in the regulation of nutrient fluxes to downstream ecosystems. Wetlands with intermittent streams have little influence on downstream chemistry, except during periods of runoff. In late winter and spring, snowmelt on the wetland area combined with runoff from surrounding slopes frequently produces large fluxes of water, which often represent 50 to 75 per cent of annual runoff (Whitely and Irwin 1986). The magnitude of this flux, combined with short water-residence times and low temperatures, may limit the capacity of these wetlands to retain or transform mineral elements. Input-output budgets for several small wetlands with ephemeral streams on the Precambrian Shield in central Ontario revealed low annual retention of total phosphorus and nitrogen, mainly as a result of large exports of N and P during the late winter and spring (Devito et al. 1989). Groundwater-connected wetlands can influence downstream chemistry throughout the year. A large proportion of annual groundwater inputs flow through these wetlands during the summer and fall months. Warm-season plant uptake and rapid microbial assimilation may increase the capacity of these wetlands to retain or transform nutrients.

Pathways of water movement within wetlands are also important in influencing nutrient flux and transformation. Water can be transported through headwater wetlands by a variety of routes. In groundwater-connected wetlands, water may flow by subsurface paths or emerge as springs producing zones of overland flow. In wetlands sustained by a perched water table, most runoff occurs as saturated overland flow during rainfall or snowmelt events.

Hydrochemistry is affected by differences in the residence times and in the environments encountered by water moving along different flow paths. Linkages between groundwater flow paths and nutrient transformations have been examined recently in a groundwater-connected hemlock-cedar swamp on the Oak Ridges Moraine near Toronto (Hill and Warwick 1987; Warwick and Hill 1988). Three major groundwater flow paths were identified. Shallow groundwater emerges as springs at the upland perimeter of the wetland, producing numerous surface flow lines, which cross the swamp. A second pathway involves deeper subsurface groundwater, which flows upward through the organic soils and enters the surface flow lines within the wetland. These two pathways contribute about 60 per cent of the groundwater input to the outlet stream (Roulet 1988). The third pathway, representing about 40 per cent of the groundwater input, reaches the stream directly as bed and bank seepage.

Groundwater entering the stream as bed and bank