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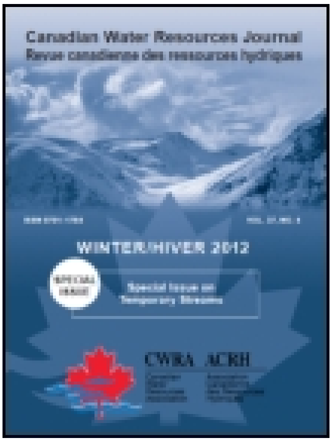

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The Influence of Wetland and Mineral Terrain Types on Snowmelt Runoff in the Subarctic

Jonathan S. Price[1]

Abstract:
The water storage and runoff characteristics of wetland and mineral terrain types were assessed during the snowmelt period to determine their contribution to basin streamflow. Mineral terrain stored most of the meltwater produced because of its dry condition and depth to the water table, while fens were the most important source of runoff due to the impermeable frozen surface layer. Bog generated some runoff, but had considerable storage capacity compared to fens. The streamflow hydrograph during early melt was dominated by surface runoff from the fens, but basin lag increased daily as more of the basin contributed. The recession constant also increased daily as the thawing surface increased resistance to flow. While wetlands provided little ability to attenuate the spring flood, the occurrence of mineral terrains in the basin moderated the basin response.

Résumé:
Une évaluation des caractéristiques de retenue et de ruissellement des terrains de types marécageux et rocheux, réalisée pendant la période de fonte des neiges, a permis d'établir leur apport au débit du bassin. Les terrains rocheux, en raison de leur sécheresse et de la profondeur de la nappe phréatique, emmagasinaient la plus grande partie de l'eau produite par la fonte des neiges tandis que les marais constituaient la plus grande source de ruissellement à cause de la couche imperméable de glace qui recouvrait leur surface. Les marécages produisaient un certain ruissellement mais leur capacité de retenue était plus grande que celle des marais. Au début de la période de fonte, le ruissellement provenant des marais dominait l'hydrogramme de débit mais l'avance du dégel faisait augmenter quotidiennement le décalage entre les différents types de terrains dans le bassin. La constante de décrue augmentait également quotidiennement, car la surface qui fondait résistait davantage à l'écoulement. Alors que les marécages offraient peu de résistance aux crues du printemps, les terrains rocheux présents dans le bassin en modéraient l'avance.

Introduction

Recent research in northern hydrology has provided evidence to suggest that soil type (organic vs. mineral) and terrain type (wetland vs. hillslope) have a strong influence on snowmelt runoff. Plot studies have isolated the effect of local conditions (Landals and Gill, 1972; Lewkowicz and French, 1981), while basin studies have reported on the integrated basin response (Roulet and Woo, 1986; Ryden, 1977; Dingman, 1973). Interbasin comparisons have proven difficult due to the variety of soil and terrain conditions that may exist in a given basin. Therefore, a study of the local hydrologic processes of individual terrain units should be included in basin scale investigations in order to understand how the processes are integrated in the basin response. This is particularly true for wetland drainage systems which occur widely throughout the subarctic. They exhibit a diverse hydrologic response (FitzGibbon, 1982), and are frequently interspersed between and within mineral drainage systems.

In a drainage area with mixed terrain types, wetland portions of the basin interact with the mineral terrains, variously gaining or losing water. In the spring, outflow from the wetland portion of the basin exceeds inflow from the mineral terrain, producing considerable runoff (Bavina, 1972). However, the complexity of the hydrological processes is increased by the variety of ground frost conditions which can be found within a basin with a variety of terrain types. Landals and Gill (1972) compared snowmelt runoff from experimental

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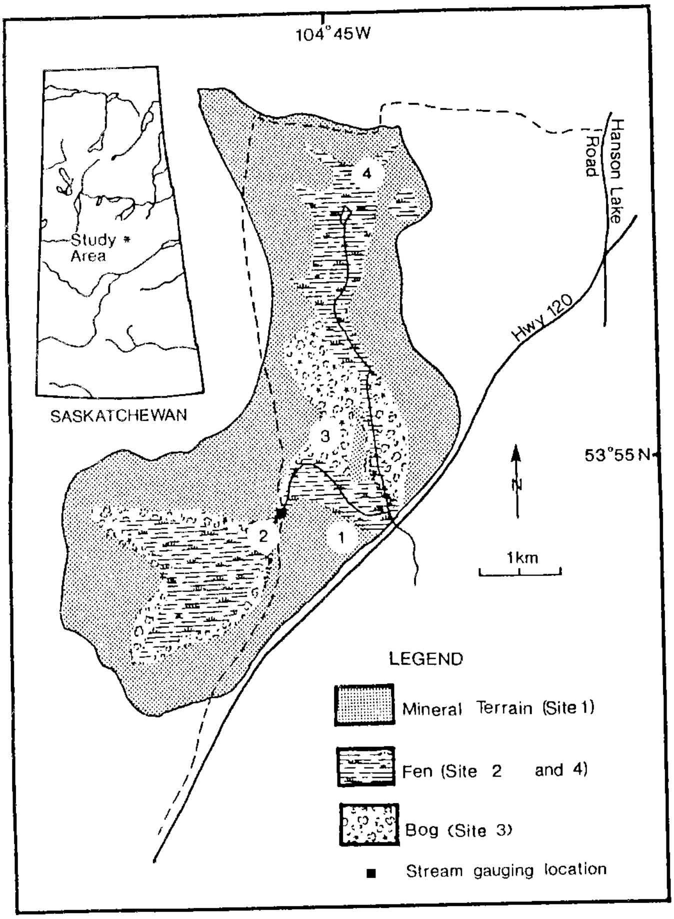
plots of different terrain types and found that a wetland underlain by permafrost produced less flow than mineral terrain. Mineral slopes underlain by permafrost produced a large and rapid runoff response compared to seasonally frozen mineral terrains (Chacho and Bredthauer, 1983; Kane *et al.*, 1983, 1981, 1978; Dingman, 1973) because of inhibited infiltration. Similarly, infiltration in wetlands underlain by permafrost was minimized by refreezing of meltwater percolating to the upper layers of soil (Roulet and Woo, 1986). This, along with saturation produced by pre-freeze weather events (Landals and Gill, 1972), minimizes wetland storage capacity at the time of snowmelt runoff.

There is little information dealing with these processes in seasonally frozen wetlands, where water transfer is not inhibited by permafrost. The purpose of this investigation is to identify the role of each terrain type in producing spring runoff, the interaction between terrain types, and the relationship between these processes and the integrated basin streamflow response.

Study Area

The study was carried out in a 17.4 km² drainage basin in Nipawin Provincial Park, Central Saskatchewan (53° 55′ N, 104° 45′ W) (Figure 1), north of the mean annual 0°C isotherm. At

FIGURE 1: Study Location Map



LaRonge, 125 km northwest of the area the 30 year mean annual precipitation is 485 mm/year, of which 164 mm is snow, and the mean January and July temperatures are -22.6°C and 16.7°C respectively (Environment Canada, 1982). The area is of subarctic mixed wood vegetation, and mineral soils are primarily podzolic (Richards and Fung, 1969). The surficial geology is characterized by gently to moderately rolling till plain with a shallow layer (1.2-2.0 m) of sandy aeolian and fluvio-glacial material overlying a compact relatively impermeable clay till (hydraulic conductivity 2.2 to 8.6 x 10^{-8} m/s).

The four terrain types found in the area are investigated in this study; mineral terrain, and wetland types including peat plateau bog, channel fen and northern ribbed fen (for descriptions see Tarnocai (1979)). All four terrain types are represented in the 6.9 km² sub-catchment in the southwest portion of the study area. However, due to access limitations only Site 1 (mineral terrain) and Site 2 (channel fen) are actually within this smaller drainage area which was gauged for streamflow. Site 3 (peat plateau bog) and Site 4 (northern ribbed fen) are located nearby, but do not drain into the gauged portion of the watershed. Mineral terrain constitutes 61 percent of the sub-catchment, fen comprises about 34 percent and bog 5 percent.

Site 1 is located on mineral terrain (Figure 1), and the sandy overburden is 1.2 m thick, with a vegetation cover of primarily white spruce (*Picea Glauca*) and jack pine (*Pinus banksiana*) with some aspen (*Populus tremuloides*). Mineral terrain occupies the higher, outlying portions of the basin.

Site 2, a channel fen herein referred to as lower basin fen, is a narrow constriction located at the lowest end of the basin which transmits flow from the entire sub-catchment. Mean peat thickness here is 1.7 m, and is dominated by *Carex* sedges, with *Salix* (willow) and *Alnus* (alder) shrubs at the edges.

Site 3, is peat plateau bog, which has an irregular hummocky surface about 1 m above surrounding fen (Tarnocai, 1979). It is located between the fen and the sloping mineral terrain, and has a locally perched water table. Subsurface drainage from the mineral terrain apparently passes beneath the bog, depriving it of nutrient rich water. The mean peat thickness is 1.4 m and the 60-80 percent hummocky ground cover comprises primarily *Sphagnum* mosses, with Labrador tea (*Ledum Groenlandicum*) on the hummocks and a 20-50 percent crown cover of stunted black spruce (*Picea mariana*).

Site 4, referred to as the upper basin fen, is northern ribbed fen, and horizontal fen. It is the most widely occurring organic terrain type in the area. This site is representative of the upper fen location in the gauged watershed. Peat thickness is approximately 1.8 m, and consists of alternating rib and trough (flark) microtopography oriented perpendicular to the direction of flow. *Carex* is the dominant surface cover, with alder on the ribs, and tamarack (*Larix laricina*) at the edges of the fen.

Methods

Maximum, minimum, and continuously recorded air temperature measurements were made on the mineral terrain and bog sites. Supplemental data was obtained from the LaRonge, Saskatchewan weather station. Temperature at LaRonge was strongly correlated with site data ($r = 0.98$). Snow courses consisting of 10 graduated stakes were established in each of the terrain types to provide a spatially representative sample of the snow depth. To determine the basin snowpack water equivalent a snow survey was performed on 30 March 1982. A Mount Rose snow sampler and spring balance was used to collect and measure 25 samples per terrain type. Ten samples were weighed independently in the laboratory to ensure accuracy of the spring scale which read in units of mm water equivalent.

In order to obtain depths of frost penetration a transect of 10 frost tubes was established at each site beside snow stakes. These were constructed according to the specifications of Rickard and Brown (1972). The clear plastic inner tube was inserted into an immobilized PVC outer tube placed vertically in the ground. The inner tube contained sand saturated with a fluorescein solution (0.01 percent) which changed from green to clear when frozen. The length of the clear section was measured manually.

At each site a 0.1 m diameter perforated ABS pipe extended 1.5 m below the ground surface. The above ground portion was unperforated, and covered by an unheated but insulated housing. A methyl-alcohol/ethylene-glycol solution was maintained in the tube to prevent freezing, and a light oil was added to prevent evaporation of the alcohol. A Leupold Stevens type F recorded stage continuously at each well.

Specific yield was determined by gravimetric analysis on samples corded in the frozen state on 15 February 1982. The saturated samples of known weight and volume were allowed to drain for 24 hours and the weight differential was measured to calculate the specific yield.

Stream velocity was measured with a Price type pygmy current meter at the outlet of the lower basin fen (Site 2) where it crosses mineral terrain. No ice cover formed at this location, therefore a stage—discharge rating curve was used to estimate continuous discharge. Stage was recorded in a 0.3 m diameter PVC stilling well with a Belfort stage recorder.

Results

Ground Frost Condition

The average frost depth on mineral and bog terrains on 30 March 1982 was 58 and 27 mm respectively. Both sites froze in an unsaturated condition, hence the frost was granular and permeable. The upper and lower basin fens had 36 and 43 mm of impermeable concrete frost respectively, formed by freezing of saturated peat. More detailed frost data is given by Price (1983).

Basin Water Storage

The snow survey data of 30 March indicates the water equivalent of the snowpack for the mineral, bog, upper and lower fen sites was 94, 107, 97 and 89 mm respectively, and the areally weighted basin average was 93 mm. The available water storage capacity in the soil matrix was calculated by multiplying the specific yield times the depth of unsaturated soil (Table 1). The total available water storage capacity in mineral soil averaged 265 mm. With 94 mm of snow accumulated at the surface, 171 mm of excess storage capacity was unused. Bog (Site 3) however, had 112 mm of storage capacity available, and 115 mm of snow, producing a 3 mm water surplus. The fen peats were saturated, thus had no available water storage capacity.

The upper and lower basin fens experienced a large water storage surplus. At these loca-

TABLE 1: Storage Characteristics of the Various Terrain Types. All Values in mm. Except Specific Yield (Dimensionless)

Location	Min.	Lower Fen	Bog	Upper Fen
Site #	1	2	3	4
Snow (P)	94	97	115	89
White Ice (I)	-	179	-	128
Total Inputs ($T_i=P+I$)	94	276	115	217
Specific yield (s_y)	0.28	0.15	0.28	0.15
Unsaturated depth (h)	946	0	400	0
Storage available ($S_a=h \cdot S_y$)	265	0	112	0
Storage residual ($S_r=T_i-S_a$)	-171	+272	+3	+217

tions, high groundwater pressure early in the winter (Price and FitzGibbon, in press) forced the water table to rise above the surface, causing groundwater to seep through the frozen layer and saturate the snow lying on the surface. This eventually refroze producing 150 and 211 mm of white ice above the upper and lower basin fen surfaces. White ice, having a median density of 850 kg/m^3 (Adams, 1976), therefore represented 128 and 179 mm of water stored above their respective surfaces. When the snow water equivalent of 89 and 97 mm respectively are included, the total storage values become 276 and 217 mm. In the lower basin fen, the water table pressure was maintained above the peat surface throughout the winter and snowmelt period. At the upper basin fen the water table pressure declined to 180 mm below the peat surface during the winter. However, the water table did not drop below the lower limit of the saturated frozen layer, and no desaturation of the underlying peat occurred. The volume of water thus represented by the decline in the water table pressure was very small, and here considered negligible (see Price and FitzGibbon, in press).

Groundwater Response

Maximum and then mean daily temperatures became positive on 7 April and 12 April respectively. The snowpack had ripened by 17 April, and the release of meltwater caused a water table rise in both mineral and bog sites (Figure 2). The water table on these sites peaked on 20 and 22 of April respectively.

Mineral terrain was the only terrain type which had sufficient available storage capacity to contain local snowmelt (see Table 1). Infiltration occurred readily as evidenced by the early water table response, and the lack of overland flow observed there. Thus meltwater on mineral terrain provided groundwater recharge, behaving in manner similar to non-permafrost terrains observed by Kane *et al.* (1978) and Kane and Stein (1981), and did not make a significant contribution to streamflow during the melt period.

Bog (Site 3) behaved similarly to mineral terrain in that the unsaturated frozen layer was quite permeable to meltwater. Following the daily melt wave input, drainage occurred rapidly, as indicated by the sharp nightly water table decline, because the water table was within the permeable upper layers of the moss. This rapid drainage prevented the water table from reaching the surface despite the small calculated surplus of available water. After 23 April, the diurnal melt wave input was no longer occurring on the bog, and the water table experienced a gentle decline. The slow recession was probably due to the high water table in the underlying mineral material through which the bog must drain. Thus although some snowmelt was made available for streamflow, most meltwater was retained to satisfy the storage deficit. This was possible because of the low water table in this bog prior to snowmelt.

Both fen locations had a considerable accumulation of white ice overlaying 0.4-0.5 m of frozen saturated peat. Therefore little or no infiltration of meltwater could occur, and there was no subsurface water storage capacity available for meltwater. In the lower basin fen, white ice formation over the winter created a blockage to local and basin drainage until 18 April, when the water table at the lower basin fen peaked. On this date flowing water carved a channel in the white ice and caused the frozen layer to thaw rapidly (Figure 3). As ponded melt water was released, the hydrograph exhibited an extreme response (Figure 2), and the water table at the lower fen subsequently decreased. Similar features have been observed in snow jammed channels in the subarctic (FitzGibbon and Dunne, 1981) and in the arctic (Woo and Sauriol, 1980), in which ponded meltwater is released catastrophically following erosion of the blockage by flowing water. Thus in addition to being responsible for the sudden pulse of water in the stream hydrograph, the lower basin fen site had a relatively large volume of water to contribute by virtue of its large storage surplus.

At the upper fen (Site 4), the water table was 180 mm below the peat surface throughout much of the melt period, but began to rise as the local ground frost decayed. The water table response was unusual (Figure 2), and may have been caused by a collapse of the frozen layer, which was initially formed when the water table was 310 mm higher than its post-winter low, thus causing an apparent gradual, then sudden rise in the water table. The unstable frozen layer masked the nature of the processes occurring there. Movement of the surface of a string bog was also noticed during snowmelt by Heron and Woo (1986), who attributed it to swelling due to water input, rather than the collapse of the unsupported frozen layer. In spite of the confusing response registered here, it was clear that there was a large water surplus due to the accumulation of white ice and snow over the saturated peat. On 18 April, when the stream hydrograph was peaking, most of the snow from the upper fen had melted. There did not appear to be much water on the fen, except

FIGURE 2: Air Temperature, Water Table Elevation and Stream Discharge

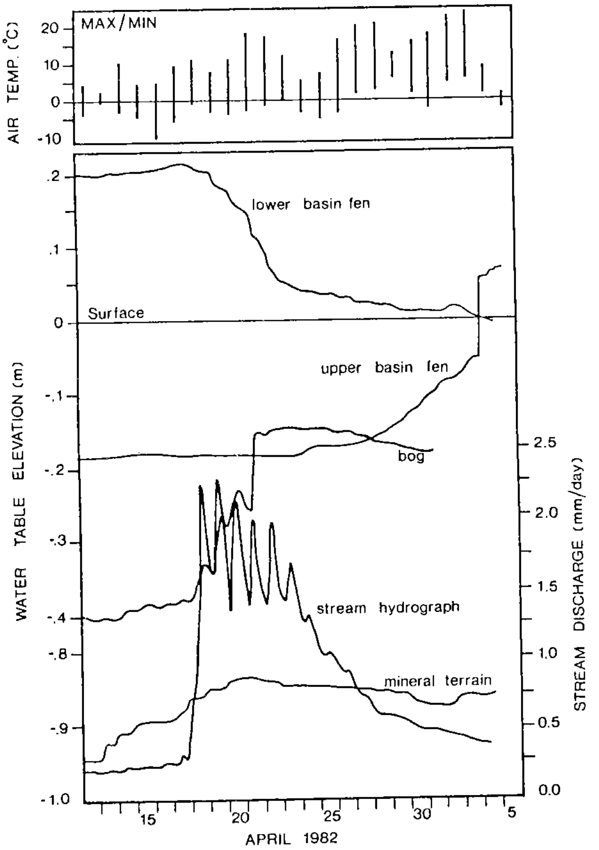
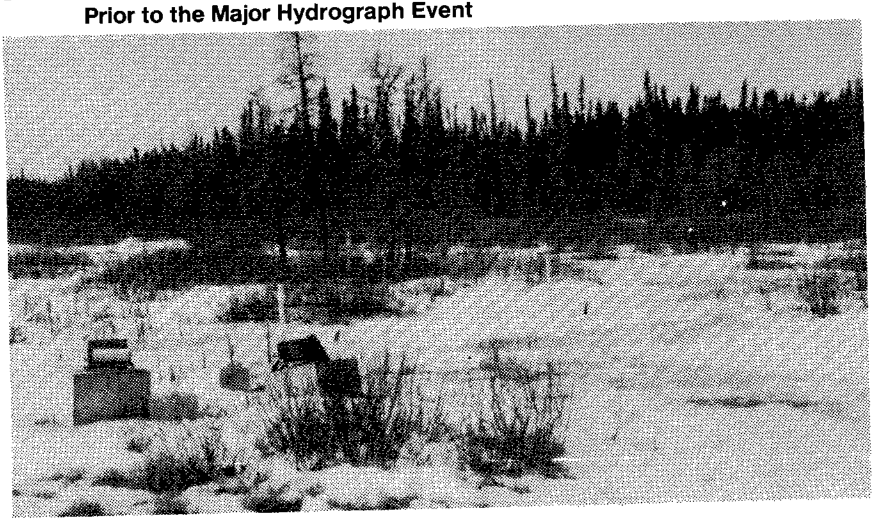


FIGURE 3: Lower Basin Fen on 18 April, Showing Snowmelt Flowing Over White Ice Prior to the Major Hydrograph Event



along the borders where it was in contact with mineral terrain, suggesting that some water was being lost from the fen to mineral terrain.

Streamflow

Streamflow experienced small diurnal fluctuations beginning 12 April, but the major rise did not occur until 18 April (Figure 2). Strong diurnal peaks occurred for about 10 days, then diminished. The daily basin lag was calculated as the period between time of maximum daily global radiation (1200 h) and time of peak flow. Basin lag increased from 3.5 h on 14 April to about 22 h on 26 April (Figure 4). Streamflow recession was determined as:

$$Q = Q_p \exp(-t/t^*) \qquad (1)$$

where Q is the flow rate t hours after Qp, the peak flow, and the recession constant t* (hours) is the decay constant for the curve. The steepness of the recession curve from the daily peaks decreased (Figure 5) and is reflected by the recession constant (t*), which increased from 32 to 87 h between 18–27 April.

FIGURE 4: Basin Lag (Hours), Calculated as the Time Between Peak Solar Radiation and the Resulting Hydrograph Peak

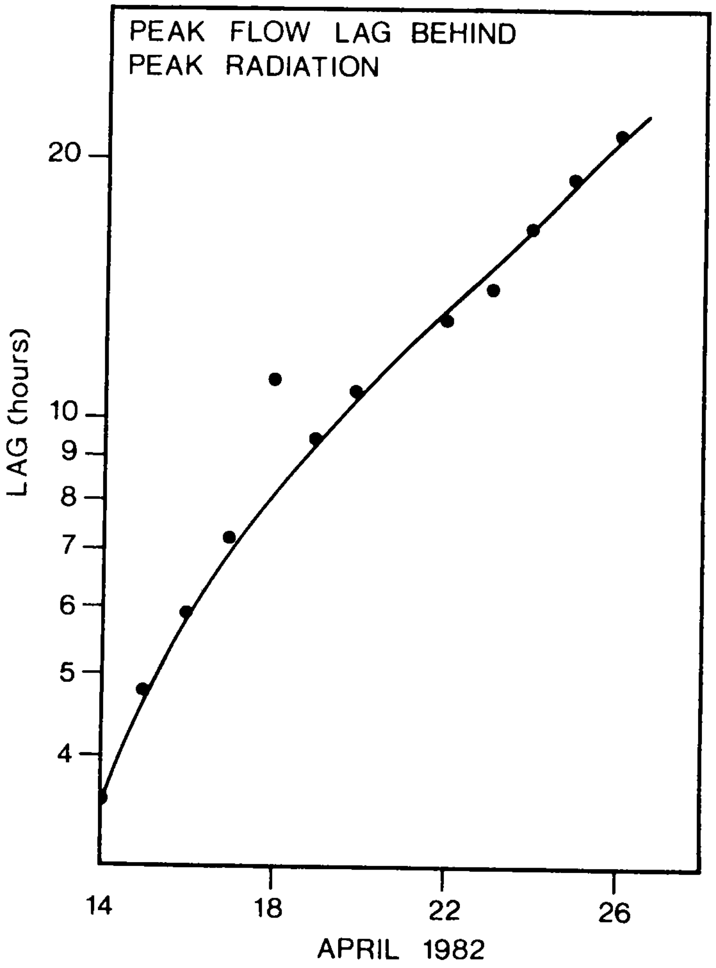
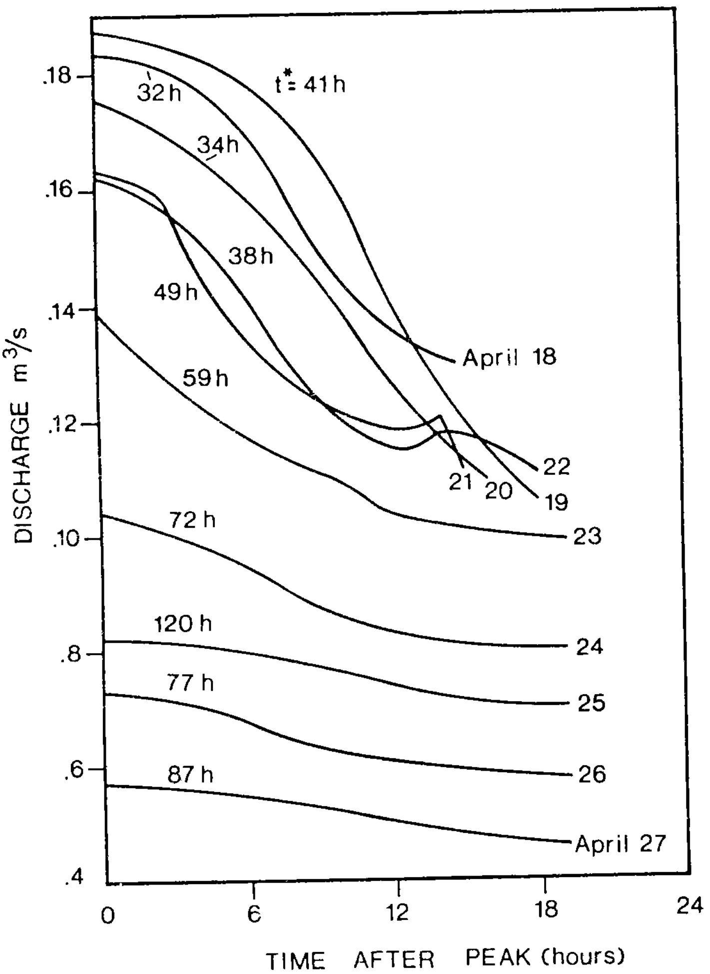


FIGURE 5: Recession Limbs for the Daily Snowmelt Peaks, and the Associated Recession Constants (t*, hours)



The snowmelt hydrograph lag times of 0.5–3.1 h/km^2 compare with the one to two hour lag time noted for rain on a 1.3 km^2 permafrost dominated Alaskan basin (Dingman, 1973). Lag times in this study increased throughout the melt period, as more of the basin contributed to flow. The short initial lag times represent local melt near the gauge site, whereas after 18 April, increasingly more of the basin was contributing, particularly the fens.

The increasing recession constant (t*) indicates that the rate of storage depletion diminished as melt progressed. As ground thaw in the fens developed and the water table dropped, more flow occurred within the peat, increasing flow resistance hence retention storage and thus flattening the peaks and diurnal recession limbs of the hydrograph (Figure 5).

The volume of water discharged over the snowmelt period (17–30 April) averaged over the total basin area was 12.3 mm, which represents 13.2 percent of the pre-melt snow cover. This is small in comparison to that found for a muskeg plot (55.7 percent) by Landals and Gill (1972). The difference can be attributed mostly to the effect of water storage on mineral terrain which covers 61 percent of this basin.

Discussion and Conclusions

Snowmelt runoff in subarctic drainage basins is a major annual event. In addition to climatic factors, basin runoff depends on the volume of water held in the snowpack, the available water storage capacity of each terrain type, and accessibility to the available storage. Storage availability depends to a certain extent on antecedent weather conditions, but is also governed by location within a basin. In steeper and peripheral zones of a basin where mineral terrain and bogs are more common, better drainage lowers the water table which increases available storage capacity. The lower water table also allows granular frost to form in the winter, which is permeable to infiltrating meltwater (i.e. unused storage capacity is accessible). Fens, which are located in the valley bottoms, have a perpetually high water table. This results in the formation of impermeable frost in winter which restricts accessibility to storage, and produces a small available water storage capacity.

The stream hydrograph integrated the hydrologic processes of the basin during the snowmelt period. The timing of the diurnal peaks, and rate and shape of the recession limb were related to the processes occurring on each terrain type. Most of the runoff during the melt period originated from the fens, and to a lesser extent, the bogs, as is indicated by their relative water storage condition (Table 1). On mineral terrain the large storage deficit ensured that most meltwater was retained or delayed. The strong recharge and the slow decline of the water table in mineral terrain confirms this. The rapidly discharging waters from the lower fen during the time of maximum streamflow suggests that this was the most important source of runoff.

The findings indicate that northern wetlands with frozen surfaces have poor flood attenuation properties, but permeable mineral terrains surrounding the wetlands dampen the integrated basin response by providing a large available water storage capacity.

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