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The effect of frozen soil on snowmelt runoff at Sleepers River, Vermont†

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Abstract:

Soil frost depth has been monitored at the Sleepers River Research Watershed in northeastern Vermont since 1984. Soil frost develops every winter, particularly in open fields, but its depth varies greatly from year to year in inverse relation to snow depth. During the 15 years of record at a benchmark mid-elevation open site, the annual maximum frost depth varied from 70 to 390 mm. We empirically tested the hypothesis that frozen soil prevents infiltration and recharge, thereby causing an increased runoff ratio (streamflow/(rain + snowmelt)) during the snowmelt hydrograph rise and a decreased runoff ratio during snowmelt recession. The hypothesis was not supported at the 111 km^2 W-5 catchment; there was no significant correlation of the runoff ratio with the seasonal maximum frost depth for either the pre-peak or post-peak period. In an analysis of four events, however, the presence of frost promoted a large and somewhat quicker response to rainfall relative to the no-frost condition, although snow cover caused a much greater time-to-peak regardless of frost status. For six years of flow and frost depth measured at the 59 ha agricultural basin W-2, the hypothesis appeared to be supported. The enhancement of runoff due to soil frost is evident on small plots and in extreme events, such as rain on frozen snow-free soil. In the northeastern USA and eastern Canada, the effect is often masked in larger catchments by several confounding factors, including storage of meltwater in the snowpack, variability in snowmelt timing due to elevational and aspect differences, interspersed forested land where frost may be absent, and the timing of soil thawing relative to the runoff peak.

KEY WORDS frozen soil; snowmelt; runoff; Vermont

INTRODUCTION

Seasonal ground frost is widespread in cold regions (Dingman, 1975; Woo and Winter, 1993). Ground frost develops more extensively in open land relative to the forest (Kienholz, 1940; Pierce *et al*., 1958; Dingman, 1975). Open land receives greater radiation, leading to more melting and less insulating snowpack cover, while at the same time it is subject to greater radiational cooling at night. In the northeastern USA and eastern Canada, the occurrence of ground frost has been documented for several decades (Diebold, 1938; Sartz, 1957, Pierce *et al*., 1958; Dunne and Black, 1971; Fahey and Lang, 1975; Stein *et al*., 1994). However, research on hydrologic effects has largely been confined to infiltration measurements and small plot studies.

Surface runoff over frozen ground has been reported in the interior Pacific Northwest rangelands, USA (Johnson and MacArthur, 1973; Zuzel and Pikul, 1987; Seyfried *et al*., 1990; Seyfried and Wilcox, 1995); midwestern USA (Garstka, 1945; Willis *et al*., 1961); Alaska (Kane and Stein, 1983; Sand and Kane, 1986); Sweden (Johnsson and Lundin, 1991; Franzén, 1991) and the former Soviet Union (Shipak, 1969; Alexeev

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et al., 1973). Runoff from frozen ground also has been implicated in Sierra Nevada floods (Haupt, 1967) and in the large New England flood of March 1936 (Diebold, 1938).

Ground frost varies in its infiltration characteristics (Kane and Stein, 1983; Johnsson and Lundin, 1991). Concrete frost is the frost type most commonly found in open land (Sartz, 1957; Pierce *et al.*, 1958; Trimble *et al.*, 1958) and sometimes in forested land as well (Fahey and Lang, 1975). Concrete frost has extremely low permeability (Trimble *et al.*, 1958; Haupt, 1967; Kane and Stein, 1983) which promotes overland flow and greater overall surface runoff relative to the frost-free condition (Dunne and Black, 1971; Seyfried *et al.*, 1990). The development of concrete frost is favored by high soil moisture content (Willis *et al.*, 1961; Shipak, 1969; Kane and Stein, 1983), and is prevalent in fine-textured soils. Dry soils may change little in their infiltrability when frozen (Shipak, 1969). Munter (1986) observed rapid groundwater response during a melt event on a frozen soil in Alaska, suggesting that the frozen soil retained its permeability. Infiltration characteristics in frozen ground tend to change quickly and in complex fashion as the soils thaw, giving rise to several different modeling algorithms (Gray *et al.*, 1985).

In addition to its role in snowmelt runoff flooding, frozen ground may lead to water quality impairments. Frozen ground is vulnerable to surface erosion as it begins to thaw (Garstka, 1945; Franzén, 1991; Seyfried and Flerchinger, 1994). Frozen ground provides an impermeable surface for overland flow of runoff from highways containing road salt and other contaminants. Likewise, it may cause winter applications of fertilizer and manure to run off quickly from agricultural fields directly into streams.

Dunne and Black (1971) observed surface runoff due to ground frost on an experimental hillslope at Sleepers River, Vermont. Earlier experiments on the plot during the summer and fall (Dunne and Black, 1970a,b) had shown that overland flow on saturated areas was the overwhelmingly dominant flow pathway. The much higher runoff ratios during snowmelt, coupled with direct observation of impermeable concrete frost, suggested that ground frost further increased the overland flow component. At a given location, ground remained frozen until about one day after the disappearance of snow. Dunne and Black (1971) viewed the ground frost areas as complementary contributing areas to the surface-saturated areas.

For this study we return to Sleepers River to investigate linkages between frozen ground and streamflow. The famous trench where Dunne and Black (1970a,b; 1971) quantified surficial and subsurface flows is long gone, but instead we have 15 years of ground frost depth and streamflow records. We used these data to assess empirically whether Dunne and Black's (1971) well-documented field observations of runoff over frozen ground at the hillslope scale were important in a mesoscale catchment ($\sim$100 km^2). Specifically, we tested the following hypothesis: *Frozen ground causes an increase in the direct runoff of rain and snowmelt to stream channels and decreases groundwater recharge*. We reasoned that 15 years was a sufficiently long period for the significant interannual variation in ground frost patterns to manifest itself in the hydrologic record, in spite of the confounding factors that affect streamflow.

SITE DESCRIPTION AND METHODS

Sleepers River Research Watershed was founded in 1958 and has a long-term hydrologic and meteorologic data base (Anderson *et al.*, 1977; Shanley *et al.*, 1995). The watershed comprises 111 km^2 in northeastern Vermont (Figure 1). It ranges in elevation from 199 m to 780 m. The watershed is 67% forested, primarily northern hardwoods of sugar maple, ash, beech, and yellow birch. Softwoods make up about 15% of the forest and include red spruce, balsam fir, tamarack, hemlock, and white cedar. The remaining 33% of the basin is open land primarily used for dairy farming, divided between pasture, hayfield, and a small amount of corn. Nearly all of the open land lies below an elevation of 525 m, which is the effective limit for viable agriculture. The watershed is rural and has a population of a few hundred.

Sleepers River receives about 1100 mm of precipitation annually, distributed fairly evenly throughout the year (Anderson *et al.*, 1977). From 20–30% falls as snow. Snow cover persists on average from early December to early April. There is considerable variability to the start of snow cover, especially at lower

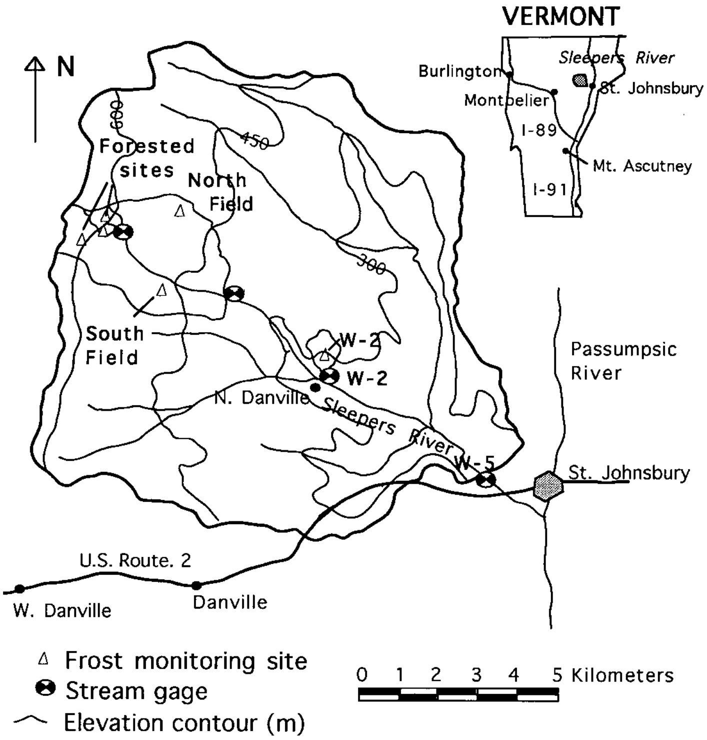

Figure 1. Map of frost monitoring sites and stream gages at Sleepers River Research Watershed, Vermont

elevations, and some occurrence of mid-winter snowpack loss, particularly during January thaws. The average January temperature is −8 C (Anderson *et al.*, 1977).

Streamflow was measured at broad-crested weirs at the W-5 (111 km^2) and W-2 (59 ha) gages (Figure 1). The W-5 gage is the outlet of the Sleepers River catchment. The W-2 gage drains an agricultural tributary catchment to Sleepers River. The W-2 catchment has tile drains which causes some groundwater to bypass the weir, but flow through the weir is sustained year-round. Bypass flow is a relatively small percentage of total flow during the spring when flow is dominated by snowmelt.

At a network of ten sites within W-5, precipitation quantity was recorded continuously by weighing bucket rain gages and snow water equivalent (SWE) was measured weekly by an Adirondack type snow tube. Ground frost was measured from 1983 to present in three different forest types and in two pastures at about 500 m elevation. In 1994, the W-2 catchment at 285 m was added as a sixth site. Each site or land type had from five to nine frost tubes, consisting of a fixed 25 mm PVC casing within which was suspended a clear flexible polyethylene tube filled with a dilute methylene blue solution (Ricard *et al.*, 1976). On freezing, the methylene blue remains in the liquid phase, yielding clear ice that marks the depth of ground frost. Ground frost was measured approximately weekly during the season.

GROUND FROST DYNAMICS

Spatial patterns

Throughout the 15 years of frost monitoring at Sleepers River, frost depth varied consistently by land cover type in the order deciduous < mixed canopy < coniferous < South Field < North Field (Figure 2). Ground frost develops more extensively in open land relative to the forest due to lower snow cover. Within the forest, coniferous stands tend to develop more ground frost relative to hardwoods because they lose more

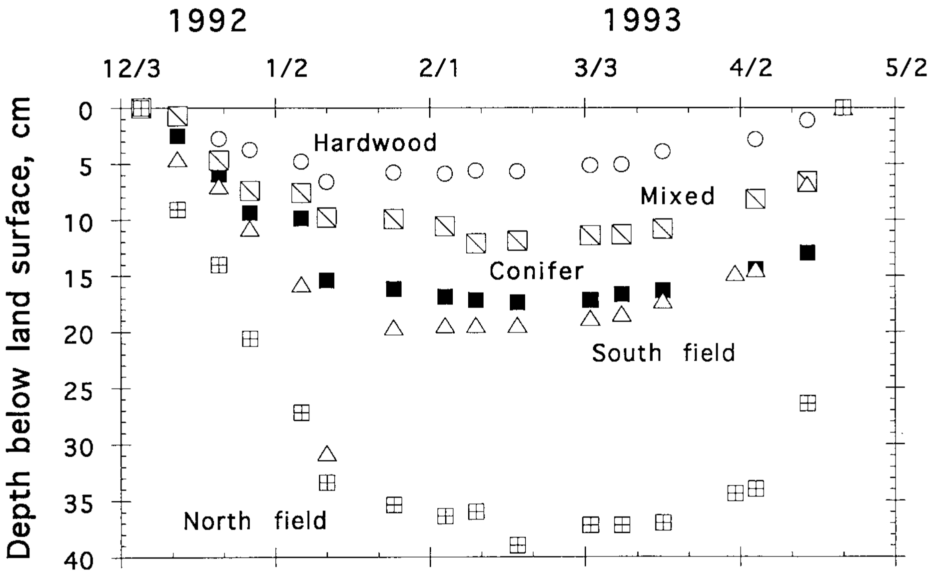

Figure 2. Temporal variation in average frost depth for different land cover types during the winter of 1992–1993. Each point represents an average of between five and nine individual measurements

snow to interception. In this paper the North Field is used as the indicator site for comparing interannual variations in frozen ground in the basin. The median relative standard deviation of frost depth for the five individual measurements at North Field was 60%. The site of deepest frost was used as the indicator site because Pierce *et al.* (1958) found that when frozen ground was discontinuous in an area, frost depth at a single site was a good index of the percentage of frozen ground area.

Temporal patterns

Although depth of frost varied with land cover, the temporal pattern of frost depth in any given year was quite similar among cover types (Figure 2). Ground frost was present every year, but there was considerable interannual variation (Figure 3). At the North Field site the annual maximum frost depth ranged from 70 to 390 mm. In an earlier study (Peaco, 1981) before the start of routine frost measurements, frost depth reached 600 mm at a nearby site during the relatively snow-free winter of 1980. Ground frost develops quickly on cold nights when snow cover is thin or absent, for example when the snowpack is late to develop at the start of the winter, or when the snowpack is removed by a January thaw.

After frost develops, its status is controlled by the balance of thermal flux from the unfrozen soil below and the escape of heat to the colder air above. Under insulating snow cover, soil frost gradually thaws from the bottom. This process is slow enough that if deep frost develops early in the winter it often persists well into the snowmelt season. At that time it may dissipate rapidly (Figures 2 and 3), but sometimes not until after most of the snow has melted (Dunne and Black, 1971). Rapid dissipation of frost suggests release of latent heat by the freezing of infiltrating meltwater or rain. Only the lower frost boundary was recorded (W. Roberts, *pers. comm.*, 1998), meaning that gradual top-down thawing may be construed from the record as a rapid loss of frost when the soil thaws completely. The band of frozen soil thawing from above probably remained an effective barrier to infiltration (Alexeev *et al.*, 1973; Seyfried and Flerchinger, 1994), though flow could occur in the thawed layer (Peaco, 1981).

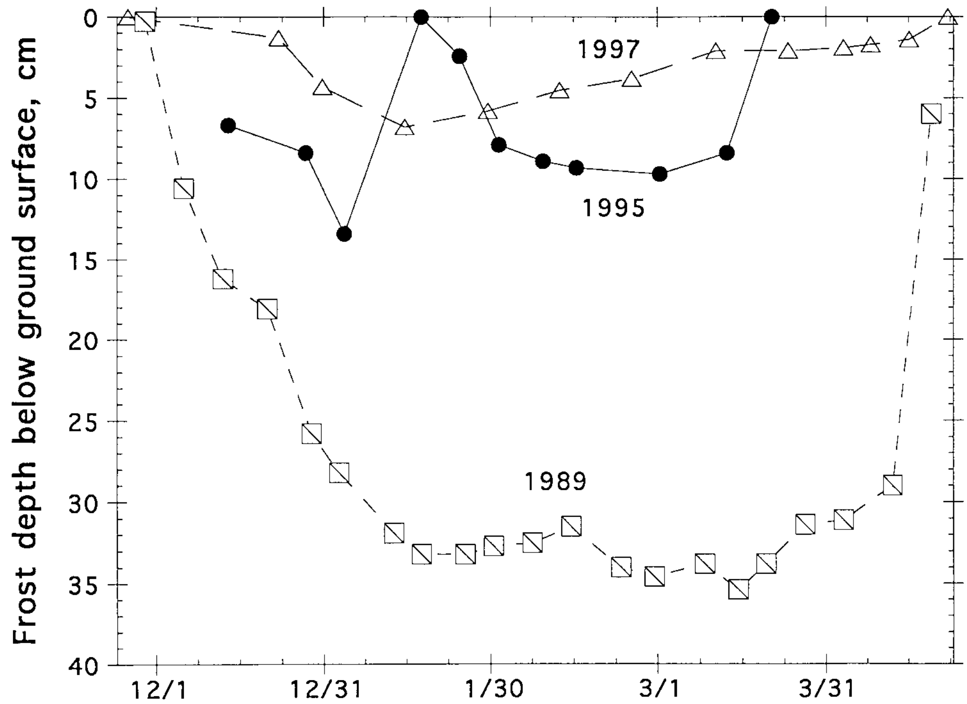

Figure 3. Temporal variation in average frost depth at North Field for three winters representing the broad range of patterns possible

FROZEN GROUND AND STREAMFLOW

Large catchment (W-5), 1984–1998

For each of the 15 snowmelt seasons, the W-5 hydrograph was divided into a pre-peak period, from the initiation of snowmelt through the day of peak snowmelt, and a post-peak period, from the day following peak melt until the return of low-flow conditions several weeks later, always by mid-May. For each year we determined the pre-peak and post-peak inputs and outputs (Table I). The input was the sum of snowmelt (determined by difference from SWE surveys) and precipitation during each period. The output was the cumulative streamflow for each period. Because the output is strongly controlled by the input, we used the output/input *ratio* (streamflow/(rain + melt)) to empirically test for a ground frost effect on runoff.

The output/input ratio for the pre-peak period was positively but not significantly correlated to either seasonal maximum frost depth (Figure 4a) or frost depth at start of melt (not shown). There was also no significant correlation of the post-peak output/input ratio to frost depth (Figure 4b). In most years ground frost had nearly disappeared by the time of peak melt (Table I). For the post-peak period we expected a negative correlation due to the limited recharge under frozen soil conditions; the lack of recharge should promote a quicker return to low-flow conditions, and correspondingly low runoff ratios. For this large basin, however, the empirical relation of runoff ratios to ground frost depth failed to support our hypothesis.

Small catchment (W-2), 1993–1998

The temporal patterns of frost depth and duration at W-2 were quite similar to those at North Field (Figure 5). Despite the lower elevation of W-2 compared to the other frost sites, two years had less frost and three years had more frost than the North Field site. The five years of data from W-2 were too few to test statistically, but the relation of runoff ratio and frost depth (Figure 6) suggested agreement with our

Table I. Summary of: ground frost conditions; snowmelt hydrograph start, peak, and end dates; peak flow; pre-peak and post-peak inputs and runoff ratio. Data for W-5 and W-2 sites. Pre-peak period is snowmelt start date until peak flow date; Post-peak period is peak flow until snowmelt end date. Ppt. is precipitation; Melt is snow meltwater input (calculated by difference from snow surveys); Total input is sum of ppt. and melt. Flow is cumulative runoff depth; RO/P is ratio of output/(ppt. + melt)

Year	Frost at North Field					Snowmelt hydrograph				Pre-peak					Post-peak				
							Dates			Input					Input				
	Frost depth max (mm)	Depth at start of melt (mm)	Depth at peak flow (mm)	Date of max frost	Date of last frost	Start	Peak	End	Peak flow (mm/hr)	Ppt. (mm)	Melt (mm)	Total (mm)	Output flow (mm)	RO/P	Ppt. (mm)	Melt (mm)	Total (mm)	Output Flow (mm)	RO/P
W-5																			
1984	70	70	0	22 Mar	6 Apr	14 Mar	6 Apr	3 May	1·27	93	99	192	79	0·41	46	75	121	124	1·02
1985	180	10	10	24 Jan	8 Apr	27 Mar	16 Apr	4 May	0·63	36	65	101	71	0·70	49	74	122	77	0·63
1986	80	0	0	24 Dec	3 Mar	25 Mar	31 Mar	25 Apr	0·87	9	128	137	51	0·37	29	46	75	122	1·62
1987	140	70	20	16 Dec	6 Apr	23 Mar	1 Apr	14 Apr	1·34	40	131	171	70	0·41	11	19	30	46	1·54
1988	70	0	0	3 Feb	4 Apr	21 Mar	5 Apr	22 Apr	0·70	37	100	137	72	0·53	27	62	90	69	0·78
1989	350	320	310	17 Mar	20 Apr	14 Mar	7 Apr	25 Apr	1·06	99	50	149	84	0·57	19	87	106	73	0·69
1990	130	0	0	27 Dec	3 Apr	5 Mar	17 Mar	9 Apr	1·46	17	79	96	45	0·47	80	64	143	99	0·69
1991	250	240	150	28 Feb	16 Apr	26 Mar	9 Apr	21 Apr	0·77	30	79	109	65	0·60	42	4	46	47	1·03
1992	250	220	0	22 Mar	20 Apr	24 Mar	25 Apr	10 May	0·95	96	105	201	137	0·68	7	15	22	56	2·51
1993	390	370	200	18 Feb	21 Apr	23 Mar	17 Apr	2 May	1·14	56	177	233	138	0·59	30	19	49	63	1·29
1994	180	150	60	8 Mar	18 Apr	29 Mar	16 Apr	11 May	1·37	88	132	220	103	0·47	52	71	123	133	1·08
1995	130	90	0	3 Jan	22 Mar	8 Mar	22 Mar	1 Apr	0·41	46	60	106	40	0·38	8	20	28	23	0·80
1996	200	170	160	23 Feb	26 Apr	10 Apr	21 Apr	9 May	1·32	78	8	86	71	0·82	75	57	132	119	0·90
1997	70	20	20	15 Jan	23 Apr	26 Mar	7 Apr	14 May	0·77	18	79	97	52	0·53	83	120	203	163	0·80
1998	70	20	0	22 Dec	29 Mar	26 Mar	1 Apr	19 Apr	1·66	21	127	148	96	0·65	17	36	53	81	1·53
W-2	Frost at W-2																		
1993	390*						Same dates as above used for calculation purposes		1·69	51	162	213	136	0·64	27	0	27	23	0·86
1994	130	80	10	12 Jan	19 Apr				1·69	80	132	212	73	0·34	47	5	52	78	1·49
1995	130	120	10	28 Feb	22 Mar				0·25	42	65	107	22	0·21	7	0	7	14	1·89
1996	330	300	290	18 Mar	25 Apr				0·62	71	7	78	32	0·41	68	0	68	70	1·02
1997	210	160	20	29 Jan	22 Apr				0·58	16	125	141	35	0·24	75	18	93	106	1·13
1998	180	140	90	23 Dec	9 Apr				1·18	19	98	117	36	0·31	17	0	17	86	4·98

* Used North Field frost value (see text).

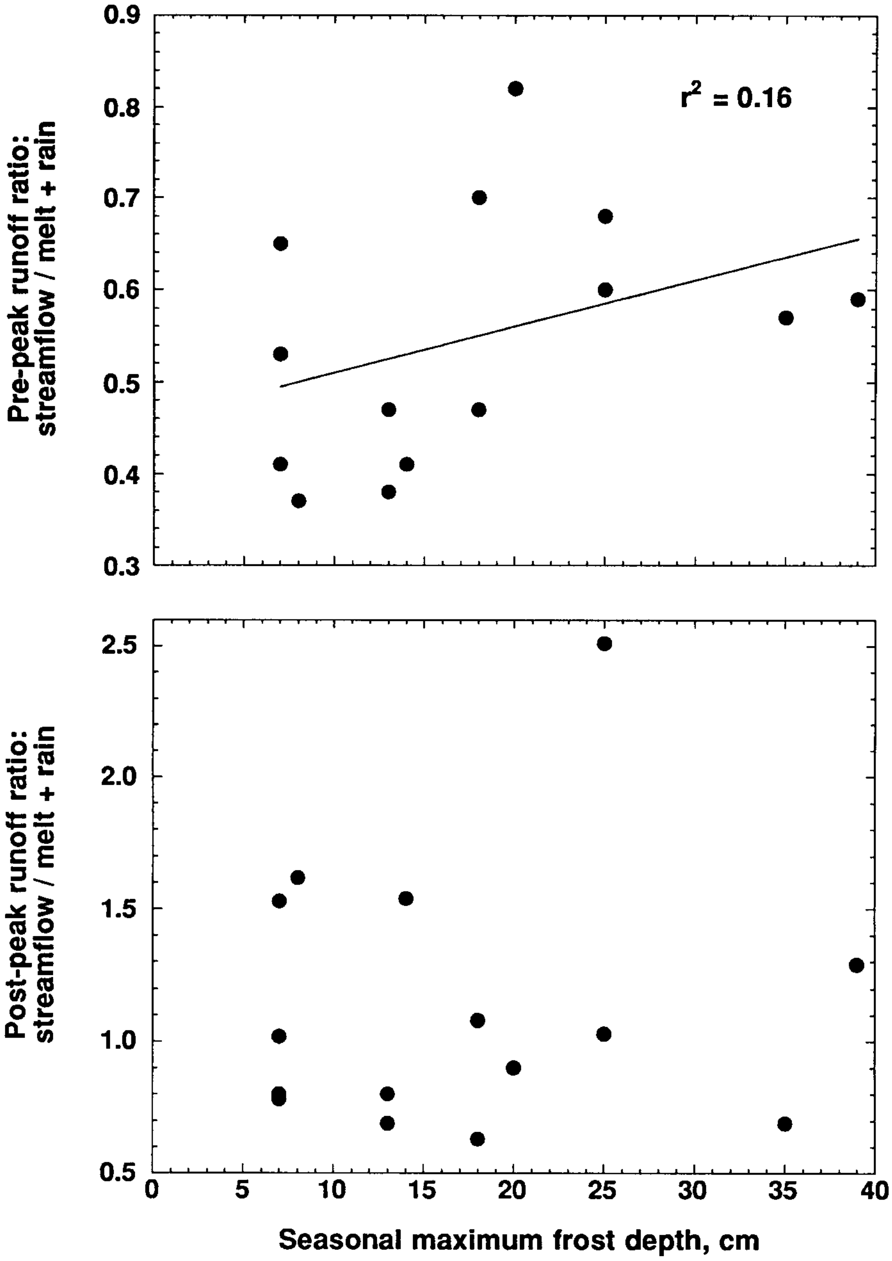

Figure 4. Pre-peak and post-peak runoff ratios for the W-5 catchment as a function of maximum seasonal frost depth at North Field during the snowmelt period, 1984–1998

hypothesis. If for the extreme frost year of 1993, the year before frost measurements were begun at W-2, we substitute the frost depth at North Field in Figure 6 (square symbol), the correlations are improved.

The 1993 point in Figure 6 may be hypothetical, but in fact we observed broad areas of overland flow during the 1993 melt at W-2 which appeared to be caused by frozen ground. This overland flow was isotopically similar to meltwater and much different from groundwater. The isotopic results suggest that meltwater was flowing at the surface due to frozen ground rather than saturated ground. Overland flow from

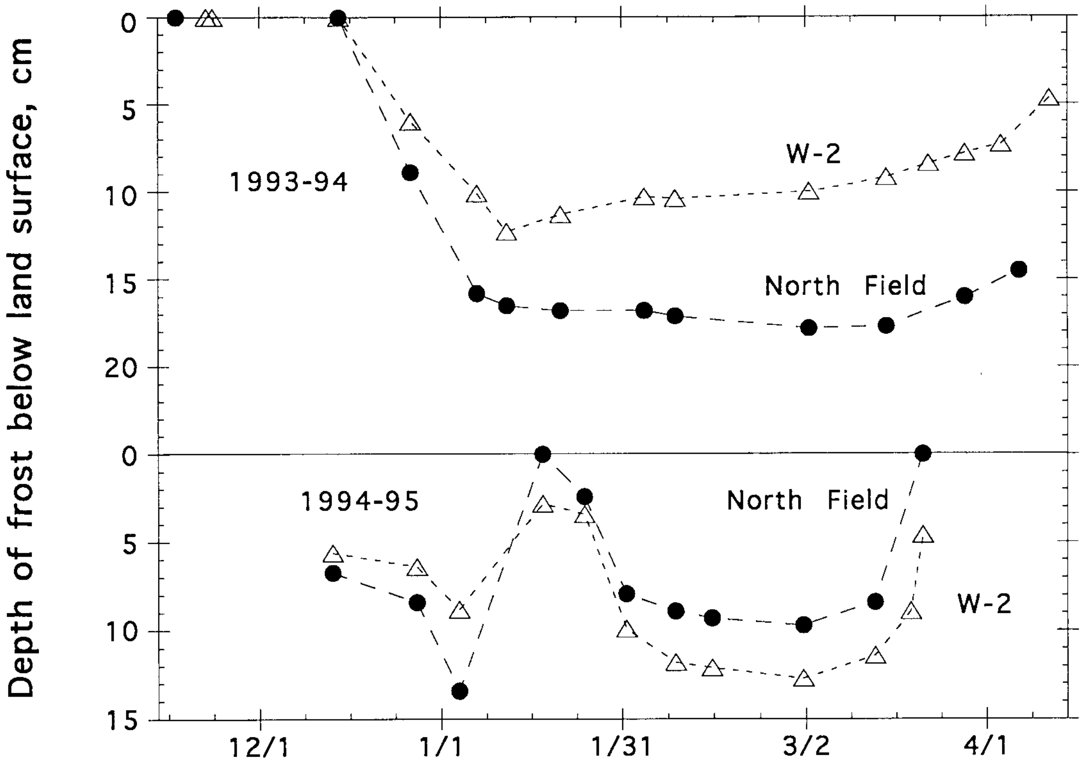

Figure 5. Comparison of temporal variation in frost depth at North Field (elevation 490 m) and W-2 (elevation 285 m) during two winters

saturation excess would have strong isotopic influence from exfiltrating groundwater, as found at Sleepers River by Titus *et al.* (1995). Isotopic results for the entire snowmelt period indicate that W-2 streamwater was dominated by meltwater in 1993, when frost was widespread, and by groundwater in 1994, when frost was minor (Shanley *et al.*, 1996).

The effect of the deep ground frost in 1993 is illustrated by a comparison of the 1993 and 1994 hydrographs at W-2 (Figure 7). The initial 1993 melt period at the end of March produced a major peak and sustained high flow from 20 mm rain and 76 mm snowmelt. This major event, however, caused little recharge. Flow rapidly receded to a low level that was matched in the 1994 melt by the daily minima of the first few small diurnal melt cycles. These periods are readily compared (Figure 7) as they happen to coincide for the two years on 3–5 April. Note that the trough of the daily hydrograph may include detained surface runoff in addition to baseflow groundwater discharge.

In the succeeding sequence of diurnal melt cycles in both years, the daily peaks were much higher in 1993, but flow returned to nearly the same minimum level at the end of each daily cycle. Greater groundwater recharge occurred in 1994 as indicated by the smaller peaks and successively rising daily hydrograph troughs (Figure 7). By the time of peak flow in 1994, the daily minimum flows were two times those of the 1993 melt, despite very similar inputs of rain and snowmelt (Table I). The gradual flow recession in 1994 after snowmelt peak on 16 April, indicative of the gradual discharge of groundwater stored from the recent snowmelt, contrasts sharply with the rapid return to stable base flow in 1993 (compare 16–21 April both years). The hydrograph pattern, supported by isotopic evidence, suggests that ground frost in 1993 promoted direct runoff of meltwater while preventing groundwater recharge. In 1994, under low-frost conditions, most meltwater infiltrated to recharge groundwater which in turn sustained a very gradual flow recession after the main melt period.

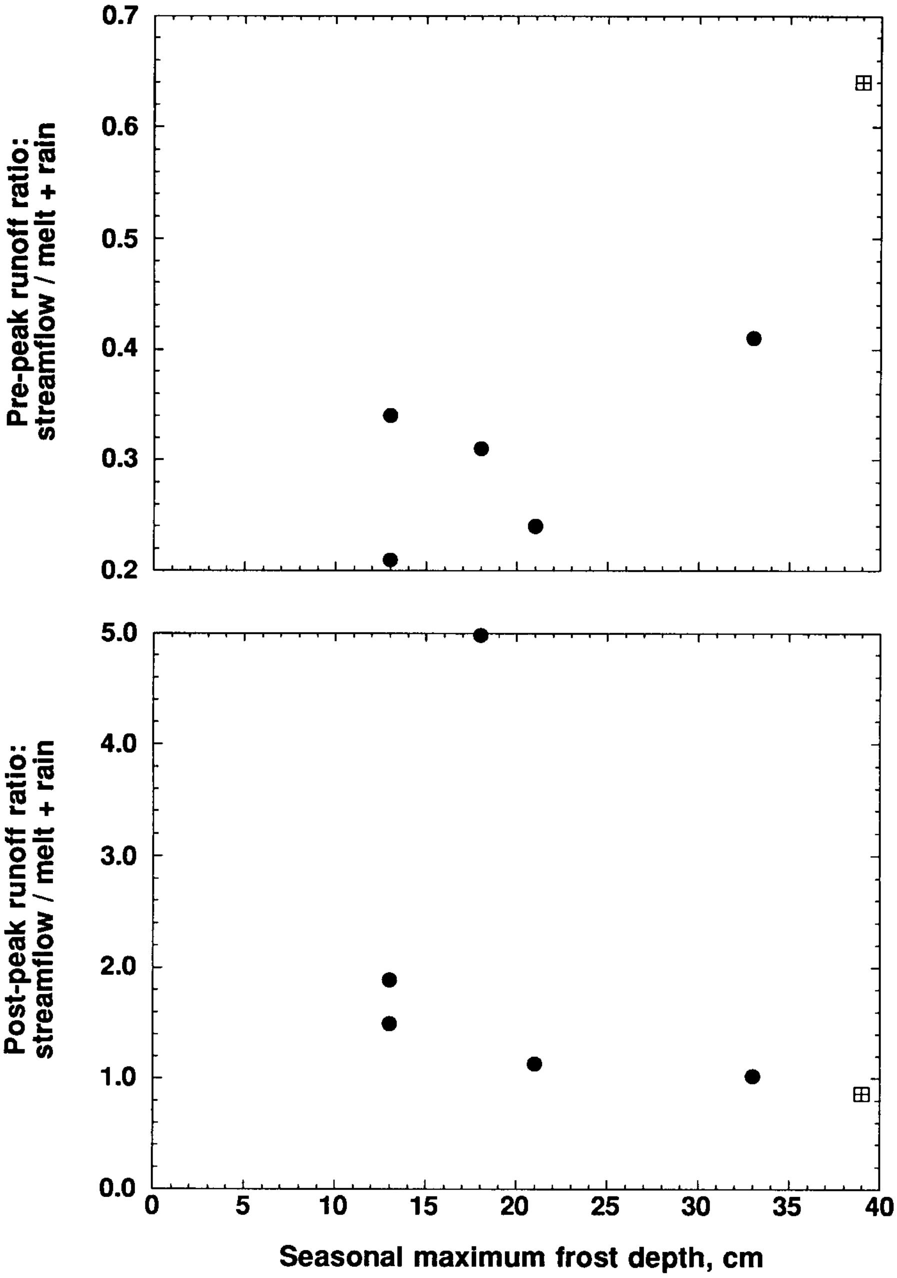

Figure 6. Pre-peak and post-peak runoff ratios for the W-2 catchment as a function of maximum seasonal frost depth at W-2 during the snowmelt period, 1993–1998. Frost depth from North Field used for 1993 and denoted by square symbol (see text)

Runoff events with and without ground frost

A comparison of four events representing each of the possible combinations of presence or absence of frost and snow illustrates some effects of ground frost as well as some difficulties in isolating those effects. We selected spring events triggered by 'pulse' rainfall inputs, with highly contrasting snow and frost conditions (Table II). For each event we determined a start point (initial rise) and an end point (first hydrograph trough with flow not significantly greater than 0·1 mm/hr). Total runoff in mm was computed for the event duration,

Table II. Characteristics of W-5 events used in analysis (Figure 9), including: storm date; presence or absence of snow or ground frost; snow depth and water equivalent (SWE), mean of ten sites; standard deviation of SWE; mean snow density; event duration in days and hours; rain and meltwater inputs, with total; output as cumulative runoff depth during the event; and output/input ratio. Melt input calculated by difference from snow surveys

Event	Year	Storm date	Snow	Frost	Snow depth (mm)	SWE mean (mm)	SWE std dev (mm)	Snow density (kg/m3)	Frost depth (mm)	Duration	Inputs			Output runoff (mm)	Output/ input
											Rain (mm)	Melt (mm)	Total (mm)		
A	1980	9–12 Apr		x	*	*	*	*	600**	3 d 12 h	27·9		27·9	24·1	0·86
B	1988	28 Apr–2 May			*	*	*	*	0	4 d 10 h	32·3		32·3	16·6	0·52
C	1992	7–14 March	x	x	397	129	34	325	250	6 d 20 h	32·8	36·4	69·2	33·7	0·49
D	1986	13–17 March	x		760	190	19	250	0	3 d 18 h	50·0	−0·8	49·2	16·9	0·34

* 0 or 1 site of 10-site network reporting snow; ** Frost depth at site near North Field, from Peaco (1981).

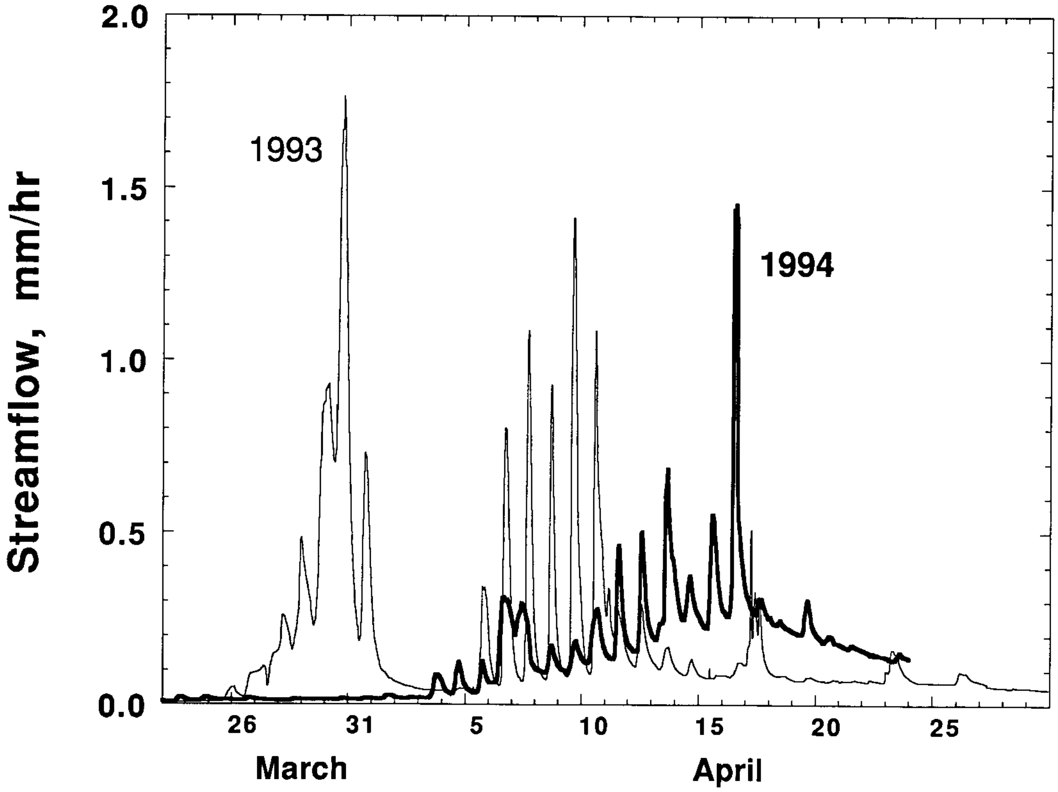

Figure 7. Comparison of snowmelt period discharge at W-2 for 1993 and 1994

which ranged from 3·5 to 6·8 days. We determined total input in rain and snowmelt, the latter by difference in SWE from surveys.

A rainstorm of 28 mm fell on frozen snow-free ground on 9–10 April 1980 (Figure 8a). Widespread ground frost was present for this event, which pre-dated the routine frost measurements (Peaco, 1981). The 1980 storm had the highest runoff ratio (86%) and highest peak flow of all four events despite having the lowest input. The effect of frozen ground is illustrated by comparison of this 1980 event to an event in 1988 in unfrozen snow-free conditions. The 1988 storm had a very similar rainfall pattern (Figure 8b), with nearly the same maximum intensity and 15% greater overall rainfall amount. Despite this similar input, peak flow was only 50% and runoff volume 65% of the 1980 event. The impervious surface provided by the frozen ground was most likely responsible for the greater runoff response in the 1980 event. Differences in antecedent wetness can be discounted as an explanation of the contrasting hydrograph responses by noting that preevent flows and time-to-peak were closely similar in the two events.

Presence/absence of snow appeared to be a more important factor in runoff response than presence/absence of frost (Figure 8). The snow-free events had sharper hydrograph peaks and greater runoff ratios (Table II). Regardless of frost status, the response time of the catchment from peak rain intensity to peak runoff was two to three hours for the snow-free condition and six to eight hours with snow present. However, for each snow condition (present or absent), the event with frost present had a considerably higher runoff percentage than the event with no frost present. The 1986 storm (Figure 8d) had the lowest runoff ratio because rain and snow inputs were incorporated in the unripe snowpack. (Pre-storm snowpack density averaged 250 km/m^3 in the 1986 storm (Figure 8d) compared to 325 kg/m^3 in the 1992 event (Figure 8c)). This limited comparison in part supports our hypothesis that ground frost increases surface runoff, but demonstrates the strong masking effect of the snowpack.

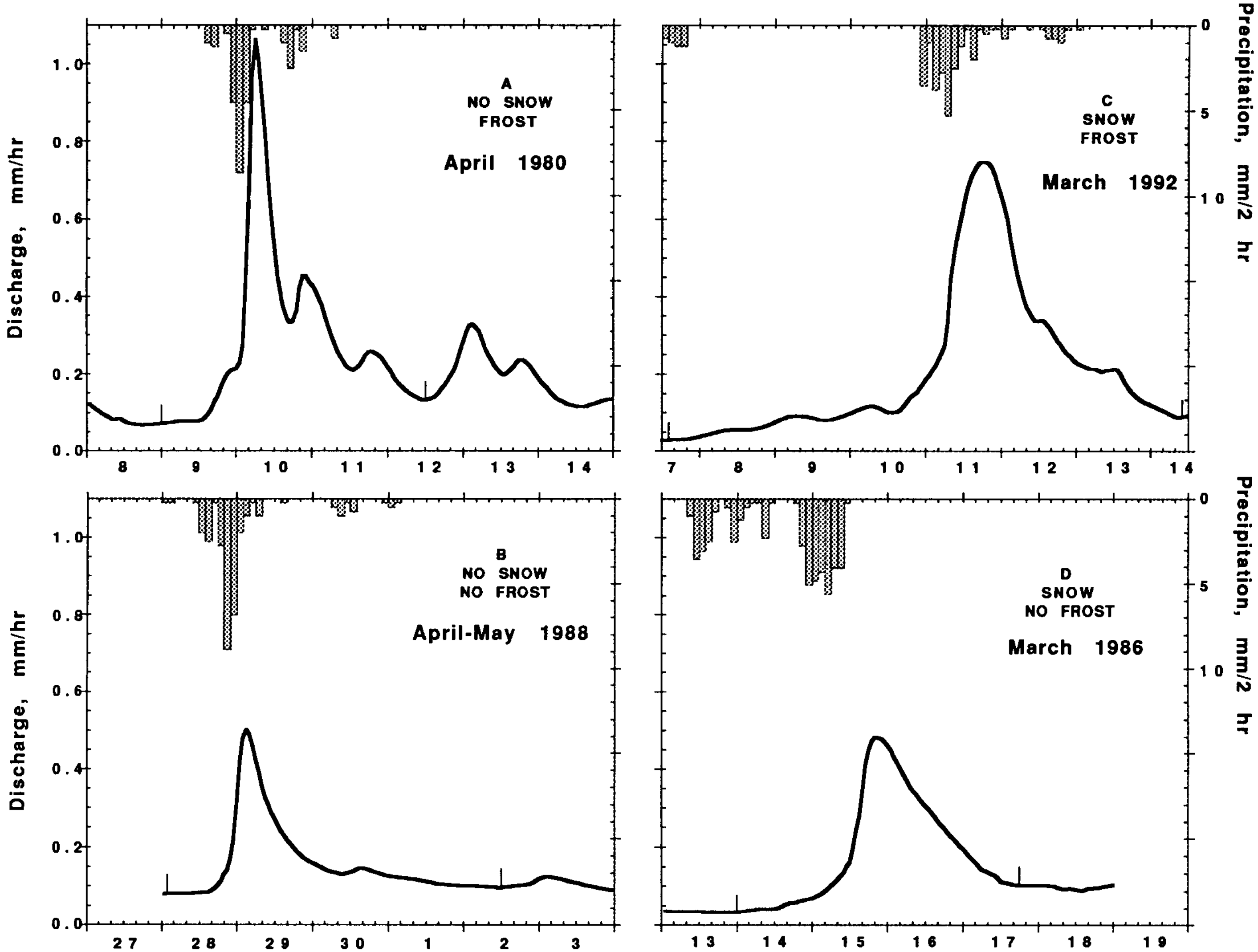

Figure 8. Discharge and rain inputs for four events at W-5 representing the four possible combinations of presence or absence of frost and snow. Snowmelt inputs are not included. The vertical tick marks denote the beginning and end times for the storms used in the calculations (Table II)

DISCUSSION

Working from the detailed field observations of Dunne and Black (1971) of direct overland flow of snowmelt and/or rainfall on concrete ground frost, we set out to determine empirically whether this process had a significant effect on stream runoff at the mesoscale (111 ha catchment). Our results were mixed. We found a strong suggestion of a runoff increase from frozen ground based on a qualitative assessment of an extreme case of rain on bare frozen ground (Figure 8a). We also found strong evidence for a ground frost effect by comparing two snowmelt seasons with very different frost conditions at a small agricultural catchment (Figure 7). However, the empirical analysis of runoff and frost depth for a 15-year period showed only a very slight tendency for increased runoff due to frozen ground (Figure 4a). In a similar empirical study, Shipak (1969) found a reasonably strong dependence of the runoff ratio on both ground frost depth and percentage of land covered by frost.

The lack of an unequivocal result may be due to the difficulty in isolating the effects of frozen ground from the many other confounding factors that control runoff (Dingman, 1975). In Vermont, as in much of the northeastern USA and eastern Canada, the peak flow during the snowmelt period is usually caused by a rain-on-snow event. Peak flow magnitude and flow volumes are governed by depth and ripeness of the snowpack, percentage of snow-covered ground, rainfall amount and intensity, net solar radiation, air temperature, presence of fog (which adds heat of condensation), morphology of the snowpack (presence of basal ice, etc.), and antecedent moisture conditions in the basin. Ground frost effects would be superimposed upon all of these other conditions that control the generation of meltwater and its travel to a stream, and the net effect of these other factors frequently dominates the catchment response.

An alternative approach to assess frozen ground effects is to apply a snowmelt runoff model that captures the main physical processes responsible for runoff but does not simulate reduced infiltration from frozen ground. If frozen ground has a strong influence on the runoff process it should be manifest in the model residuals. Sand and Kane (1986) applied a model that did not account for impermeable ground frost. When ground frost was present, the model underpredicted runoff in the initial part of snowmelt and overpredicted runoff in the later part of snowmelt. Using a similar approach, G. Lindström (Uppsala University, written communication, 1998) found little evidence for a ground frost effect, possibly because frost had thawed before the onset of melt. In general, ground frost receives limited consideration in hydrologic modeling and interpretation, in part because of the complexity of modeling the soil freezing process (Peaco, 1981; Gray *et al.*, 1985; Koren' *et al.*, 1986; Zhao *et al.*, 1997).

One might argue that our lack of a convincing empirical relation between ground frost and runoff results because the frozen ground retains its permeability, as found in some soils by Shipak (1969). However, conditions at Sleepers River are highly suited to the development of concrete frost. High ice content in the soil is the main determinant of concrete frost (Seyfried and Flerchinger, 1994), and Sleepers River is dominated by fine-grained silty loams with high water holding capacity. Summer moisture deficits are replenished by ample autumn rains and occasional mid-winter melt or rain inputs. The tendency for concrete frost is especially high when a mid-winter thaw, which may generate a large input of moisture to the surficial soil, is followed by a period of very cold air temperature, as in January 1995 (Figure 5). Documented incidences in the literature of direct runoff over frozen soils are generally either from small plots (Willis *et al.*, 1961; Dunne and Black, 1971) or from the extreme condition of rainfall on contiguous bare frozen ground (Johnson and McArthur, 1973; Seyfried *et al.*, 1990; Franzén, 1991). Similarly, the strongest evidence in the present study is from the more extreme conditions (1980 rainstorm and 1993 snowmelt). The effects in larger basins may usually be more subtle as a result of the confounding factors discussed above. Another potential factor is that large-scale impervious ground frost surfaces may be rare because in most settings there is enough interspersed forested land where frost is more permeable or frost depth less than in adjacent open lands. Moreover, Dunne and Black (1971) observed that frost thawed within about a day of snow ablation from any given point, suggesting that the area of exposed ground frost — and high runoff potential — may be minimal at any given time at the catchment scale.

SUMMARY AND CONCLUSIONS

Seasonal ground frost occurred in each of 15 years of measurements at Sleepers River Research Watershed in Vermont. Seasonal maximum frost depth ranged from 70 to 390 mm at an open field site, and was considerably less at forested sites. The high moisture content and fine-grained texture of Sleepers River soils ensured the development of concrete frost, which forms a surface nearly impermeable to runoff. Surface runoff over frozen ground was visually observed on hillslopes, and increased runoff due to frozen ground was documented in a small agricultural catchment (59 ha) during a snowmelt season. In a mesoscale catchment (111 km^2), increased runoff from frozen ground occurred during specific rain events, but there was no significant correlation between seasonal runoff ratios and ground frost depth for the 15 years of record. Several factors that influence runoff processes may combine to mask the frost effect, including extent of snow cover, depth and ripeness of the snowpack, variability in soil frost thawing, variability in rainfall amount and snowmelt intensity, and antecedent moisture conditions. Breaks in continuity of the frozen ground, such as interspersed forested patches, may also limit direct runoff. These confounding factors may act to counter adverse effects of frozen ground runoff in the northeastern USA and eastern Canada. Nevertheless, under the right conditions, runoff over frozen soil in this region poses a flooding threat, as well as the potential for soil erosion and rapid transport of surface contaminants to channels.

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