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Variability of Snowmelt Runoff and Soil Moisture Recharge

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The spatial and temporal variability of snowmelt runoff and soil moisture recharge within small watersheds must be quantified for use in distributed parameter snowmelt models. Snowmelt runoff, over-winter changes in soil moisture and soil temperatures were monitored over three annual snowmelt periods on two reclaimed watersheds in central Alberta, Canada. Slope aspect had a major influence on fall soil antecedent conditions and soil temperature. The south-facing slopes produced snowmelt the earliest, cleared of snow the soonest, yielded the least amount of runoff and had the greatest gain in over-winter soil moisture. Over-winter change in soil moisture was minimal when fall soil moisture levels were greater than 75% relative saturation. The power relationship between infiltration and snow-water equivalent of Granger *et al.* (1984) was not verified in this study, likely due to mid-winter melts that altered near-surface soil moisture and subsequently enhanced snowmelt runoff.

Introduction

The process of snowpack melting is fairly well understood (Granger and Gray 1990), and is primarily determined by energy exchanges at the air/snow and snow/soil interface, and by the physical characteristics of the snowpack (Kane *et al.* 1991; Dingman 1994).

The snowmelt process does not occur uniformly within a watershed; often there are major differences in the timing and amount of runoff from hillslope plots with similar snow accumulation and snow density characteristics (Lewkowicz and French 1982; Kane *et al.* 1991). The type and extent of soil frost influences the amount of infiltration and hence runoff (Granger *et al.* 1984), as does the type and extent of vegetative cover (Chanasyk and Woytowich 1985). Soil moisture differences in the uppermost 30-40 cm of the soil profile (defined as the active zone) prior to snowmelt are the main reasons that different infiltration rates and amounts, and hence variations in microscale runoff, occur during snowmelt (Granger *et al.* 1984; Buttle 1989; Kane and Chacho 1990; Burn 1991; Johnsson and Lundin 1991).

Unsaturated frozen soils have lower hydraulic conductivities than unfrozen soils at the same moisture content due to ice in the larger pores of the soil (Kane and Chaclo 1990; Johnson and Lundin 1991). Infiltration of snowmelt water into frozen soils can be initially high due to soil macropores or over-winter soil moisture deficits (Johnson and Lundin 1991), but infiltration into the frozen active layer quickly declines to a rate governed by the amount and continuity of unfrozen water present in small soil pores or unfrozen water existing as a film adhering to soil particles (Burn 1991). Although the infiltration rate of frozen soils is lower than that of unfrozen soils, infiltration of up to 70% of total snow-water equivalent has been reported (Burn 1991).

The spatial and temporal variability of snowmelt runoff within a watershed requires better definition for input into distributed parameter, energy-balance snowmelt models (Leavesley 1989; Bloschl *et al.* 1991). Equally, the variability of factors influencing the amount and timing of snowmelt runoff from within a watershed has to be quantified since watershed snowmelt runoff reflects the contributions from the different hillslopes, aspects and land uses within the watershed.

The objectives of this study were to quantify the spatial and temporal variability of hillslope snowmelt runoff from two reclaimed surface mined watersheds. It was hypothesized that differences in runoff would be related to differences in aspect, slope position and pre-winter soil moisture.

Table 1 – Physical characteristics of the reclaimed watersheds.

	Sandy Subsoil Watershed	West Watershed
Area (ha)	3.4	9.84
Slope Length (m)		
North-facing	100	100
South-facing	42	110
Slope Steepness (%)		
North-facing	16	13
South-facing	17	6

Location

The study area consists of two reclaimed watersheds located within the TransAlta Utilities Highvale Mine boundary, approximately 80 km west of Edmonton, Alberta, Canada (114°34' N Lat., 53°29' W Long.) on the south shore of Lake Wabamun. The watersheds are approximately 2 km apart.

The Sandy Subsoil Watershed was constructed in 1989-1990 and the West Watershed was reclaimed in 1991-1992. Both watersheds were revegetated with a perennial forage mix. Typical soil profiles for the Sandy Subsoil Watershed are a 20- to 40-cm topsoil layer of loam to clay loam texture and a fairly homogeneous subsoil layer of sandy loam texture to depth and for the West Watershed, a loam to clay loam topsoil layer of approximately 20 cm depth overlying a 1.5-m subsoil layer of clay loam texture, overlying clay textured minespoil. Other pertinent watershed information is given in Table 1; topographic maps with measurement locations marked are given in Harms and Chanasyk (1998).

Methods and Materials

A Campbell Scientific® CR21X datalogger was used to monitor air temperature, relative humidity, wind speed, wind direction, solar radiation, soil temperatures and snow depth continuously on the Sandy Subsoil Watershed. A Campbell Scientific® CR10 datalogger was used at the West Watershed to continuously monitor the same meteorological parameters as at the Sandy Subsoil watershed except solar radiation.

Hillslope Runoff

Hillslope runoff was measured using 1-m^2 frames pounded approximately 6 cm into the ground. Runoff originating from within the frame border was routed through a hose into below-ground collection buckets. Within the Sandy Subsoil Watershed, the frames were located on two slope aspects (north and south), at two slope positions (upper and lower) and replicated three times for a total of 12 frames (Harms and Chanasyk 1998). Microframes within the West Watershed were located on two slope aspects (north and south), at two slope gradients (13% and 5%), replicated three times for a total of 12 frames (Harms and Chanasyk 1998). The volume of runoff within the collection buckets was measured at least daily during snowmelt.

Snow depth and density measurements were taken manually adjacent to each microframe and along the hillslopes and channels with a snow core sampler throughout the winter and immediately prior to spring snowmelt each year. Hillslope melt within the Sandy Subsoil Watershed in 1995 began before a thorough snow survey could be completed. Snow-water equivalents (SWEs) for that watershed prior to melt were estimated from those measured for the West Watershed since the melt had not begun there. For year-to-year comparisons, monthly snowfall amounts were obtained from the Stony Plain meteorological station, located 35 km east of the study sites. Spring snowmelt was defined as the period of sustained melt when most of the surface runoff occurs.

Soil Moisture and Temperature

A CPN 503 neutron probe lowered down aluminum access tubes installed adjacent to each microframe was used to measure soil moisture at 10-cm depth intervals to a depth of approximately 95 cm starting at 15 cm. Over-winter soil moisture gain or loss was defined as the difference between spring soil moisture after snowmelt and the preceding fall soil moisture (positive difference indicates a gain in soil moisture over winter). The fall soil moisture readings were taken on November 16, 1992 and October 13, 1993. Spring soil moisture readings were taken on April 15, 1993 and May 4, 1994. The snow-cover period of 1994-1995 was excluded for over-winter soil moisture change analysis because the final soil moisture readings for 1994 were taken in the middle of September, perhaps too early to be truly representative of fall soil moisture conditions.

Hillslope soil temperatures during the melt period were measured with nests of thermistors (5-, 10-, 20- and 40-cm depths) installed adjacent to each hillslope frame on the Sandy Subsoil Watershed, and from a single nest between the three frames on a given slope steepness and aspect within the West Watershed. Soil temperature readings were taken between 1300 and 1500 h throughout the melt period in 1993 and less frequently during the 1994 melt.

Soil bulk density was measured in each soil moisture access tube using a depth moisture/density gauge twice annually. Average bulk density at a given depth was used in conjunction with volumetric moisture content to 40 cm to determine relative saturation. Evaporation during snowmelt was calculated using a mass balance approach as the difference between the snow-water equivalent and the sum of runoff and change in soil moisture. Such calculations were conducted only for those frames for which there was no evidence of deep percolation from soil moisture measurements.

Significant differences in soil temperature and runoff among position and aspect were determined using the Least-Significance Difference ($p \leq 0.05$) procedure for a non-randomized block design outlined in the SAS User's Guide (SAS Institute 1988). Frequency distributions (0-180% in increments of 20%) for the runoff coefficients of variation (CVs) were determined for the two watersheds to assess possible patterns in spatial runoff variability.

Table 2 – Total snowfall and average temperature from November 1 to March 31 inclusive for the Stony Plain Meteorological Station.

	1992-1993	1993-1994	1994-1995	LTN
Snowfall (mm)	79.9	114.0	45.0	111.5
Temperature (°C)	-7.3	-7.6	-7.0	-7.7

Results

Meteorology

Snow accumulation during winter 1992-1993 was 72% of the long-term normal (LTN) for November through to March (Table 2). January and February snowfall amounts were extremely low and well below the LTN (monthly data not shown). Snow accumulation for November 1993 through March 1994 was slightly above the LTN, largely due to near record snowfall in January 1994 comprising nearly one-

Table 3a – Pre-melt snow water equivalents for the Sandy Subsoil Watershed (mm).

Frame	25-Feb-93	13-Mar-93	2-Mar-94	1-Feb-95	8-Mar-95
South-facing slopes					
L1[+]	50	0	97	3% ice	-
L2	55	0	111	2% ice	-
L3	55	0	113	8% ice	-
U1[++]	48	0	115	2% ice	-
U2	55	0	108	2% ice	-
U3	43	0	105	5% ice	-
Mean (SD)	51 (5)		108 (7)		
North-facing slopes					
L1	50	22	83	9	-
L2	50	22	97	18	-
L3	48	22	103	16	-
U1	48	19	92	12	-
U2	50	19	81	12	-
U3	55	22	113	20	-
Mean (SD)	50 (3)	21 (2)	95 (12)	15 (4)	-
Watershed Mean	51 (4)	11 (11)	102 (12)	-	9

* Snow depth and density were not obtained for individual frames; the watershed average was used.

[+] L = lower slope position; [++] U = upper slope position; 1, 2 and 3 = replicate number.

SD = standard deviation.

Table 3b – Pre-melt snow water equivalents for the West Watershed (mm).

	25-Feb-93*	13-Mar-93	2-Mar-94	1-Feb-95	8-Mar-95
North-facing slopes					
S1[++]	-	26	123	22	-
S2	-	26	123	24	-
S3	-	26	113	22	-
F1[+]	-	19	107	19	-
F2	-	19	117	30	-
F3	-	19	125	26	-
Mean (SD)		23 (4)	118 (7)	24 (4)	
South-facing slopes					
S1	-	16	112	30	-
S2	-	16	109	8	-
S3	-	16	112	12	-
F1	-	16	117	14	-
F2	-	16	117	16	-
F3	-	16	115	18	-
Mean (SD)		16 (0)	114 (3)	16 (8)	-
Watershed Mean	59	19 (4)	116 (6)	20 (7)	15

* Snow depth and density were not obtained for individual frames; the watershed average was used.

[++] S = steep; [+] F = flat; 1, 2 and 3 = replicate number.

SD = standard deviation.

half of the total winter accumulation. Snow accumulation during the winter 1994-1995 was only 40% of the LTN. Average air temperatures for the over-winter periods were slightly above normal all three years (Table 2).

Trends in snow-water equivalents paralleled those of snow accumulation (Table 3a and b). Standard deviations of the snow-water equivalents were generally low, indicating a generally uniform snow cover within the two watersheds. Snow-water equivalents were generally similar for the two watersheds, likely due to the proximity of the watersheds and to their lying on an east-west axis.

Timing and Volume of Snowmelt

In contrast to snow accumulation, hillslope snowmelt runoff did not occur uniformly throughout the two reclaimed watersheds. South-facing aspects of both watersheds cleared of snow the soonest and generally had significantly less daily and total runoff (except notably 1993-94 for the West Watershed; Tables 4 and 5).

Within the Sandy Subsoil Watershed for all years (Table 4), runoff during the first day of major melt (February 27, 1993; March 11, 1994; and February 9, 1995) was

Table 4 – Snowmelt microframe runoff (mm) for three seasons, 1992 to 1995 for the Sandy Subsoil Watershed.

		Mean				Coefficient of Variation			
		North-facing		South-facing		North-facing		South-facing	
Year		Lower Slope	Upper Slope	Lower Slope	Upper Slope	Lower Slope	Upper Slope	Lower Slope	Upper Slope
1992-93	13-Dec	7.6a	16.4a	0.0b	0.0b	126	72	-	-
	27-Feb	0.0a	7.7a	7.0a	8.5a	-	121	95	129
	1-Mar	20.8a	10.5a	10.4a	7.2a	34	90	34	17
	2-Mar	1.7a	0.4a	0.1a	0.0a	103	150	141	-
	20-Mar	15.2a	12.7a	0.0b	0.0b	62	88	-	-
	22-Mar	0.5a	0.5a	0.0a	0.0a	173	39	-	-
	Total	45.8	48.2	17.5	15.7				
1993-94	26-Dec	8.9a	15.8a	2.6a	2.3a	148	39	41	76
	11-Mar	5.9a	4.5a	12.8b	14.5b	-	13	11	22
	12-Mar	3.8a	3.3a	8.7a	10.4a	9	32	82	139
	13-Mar	19.7a	29.8a	11.4a	0.0a	12	29	141	
	14-Mar	13.5a	23.8a	18.1a	14.0a	19	26	139	134
	15-Mar	16.0a	15.0a	17.6a	14.1a	104	-	87	111
	16-Mar	14.4a	11.2a	0.0b	1.1b	90	36	-	150
	18-Mar	2.7a	2.0a	0.0b	0.0b	-	50	-	-
	25-Mar	3.0a	0.6a	0.0a	0.0a	116	173	-	-
	Total	87.9	106.0	71.2	56.4				
1994-95	1-Feb	0.6a	2.7a	16.6a	8.0a	91	61	94	100
	9-Feb	2.0a	2.1a	10.4b	5.0ab	43	43	53	141
	21-Feb	12.2a	8.0a	14.1a	4.0a	68	25	69	141
	22-Feb	11.3a	8.6a	4.1a	8.9a	101	59	76	122
	24-Feb	2.7a	0.8b	0.0b	0.0b	40	38	-	-
	11-Mar	4.1a	5.0a	11.7b	9.6b	74	79	52	141
	12-Mar	9.1a	9.0a	0.6b	0.2b	45	36	91	141
	13-Mar	5.4a	1.4b	0.0b	0.0b	71	111	-	-
	14-Mar	9.2a	1.6b	0.0b	0.0b	130	147	-	-
	15-Mar	15.7a	2.4a	0.0a	0.0a	68	152	-	-
	16-Mar	7.9a	0.8b	0.0b	0.0b	49	173	-	-
	Total	80.2	42.4	57.5	35.7				

* Missing coefficients of variation indicate zero runoff from slope position or data obtained from only one frame.

Means within a row with same letter are not significantly different at $p < 0.05$.

$n = 3$ for each slope aspect and position.

Table 5 – Snowmelt microframe runoff (mm) for the West Watershed.

		Mean				Coefficient of Variation			
Aspect		North-facing		South-facing		North-facing		South-facing	
Slope Gradient		13%	5%	13%	5%	13%	5%	13%	5%
Year									
1992-93	13-Dec	0.4a	0.0a	0.0a	0.0^{+}	159	-	-	-
	27-Feb	0.0a	1.3a	0.0a	1.1	-	-	141	-
	28-Feb	1.7a	5.1a	3.3a	7.0	170	92	1	-
	1-Mar	12.4b	12.8b	24.0a	20.1	11	16	3	-
	2-Mar	15.9a	0.7a	8.8a	10.3	59	76	141	-
	3-Mar	6.0a	0.0a	4.6a	0.0	69	27	-	-
	4-Mar	2.4a	0.0a	4.1a	0.0	36	76	-	-
	5-Mar	5.1a	0.0a	1.1a	0.0	62	173	-	-
	6-Mar	12.1a	0.0b	1.3b	0.0	30	173	-	-
	7-Mar	4.3a	0.0b	0.0b	0.0	24	-	-	-
	20-Mar	1.4a	3.9a	6.7a	4.4	25	108	1	-
	21-Mar	15.7a	0.0b	3.0b	0.0	37	173		-
	22-Mar	12.8a	0.1a	0.1a	0.0	80	173	1	-
	23-Mar	0.2a	0.0a	0.0a	0.0	100	-	-	-
	Total	90.4	23.9	57.0	42.9				
1993-94	26-Dec	3.9a	1.0a	3.3a	1.7a	95	122	140	173
	13-Mar	6.3a	9.3a	6.5a	13.6a	34	87	141	45
	14-Mar	4.3a	0.0b	1.9a	0.0b	6	173	-	-
	15-Mar	3.3a	0.0a	3.3a	3.9a	18	87	-	173
	16-Mar	2.0a	0.1b	1.1ab	0.0b	11	88	141	-
	18-Mar	3.0a	3.9a	1.0a	2.2a	8	140	173	141
	25-Mar	28.3a	0.0a	13.1a	11.1a	61	84	-	136
	26-Mar	39.3a	0.0b	3.6b	5.4b	23	38	-	151
	27-Mar	16.3a	0.0b	29.4a	0.0b	91	40	-	-
	28-Mar	10.1a	0.0a	6.4a	0.0a	126	-	-	-
	30-Mar	6.2a	0.0a	8.7a	0.0a	154	153	-	-
	Total	123.0	14.3	78.3	37.9				
1994-95	9-Feb	0.0a	18.0b	0.0a	14.7b	-	83	-	88
	21-Feb	0.0a	26.6b	0.0a	0.0a	-	50	-	
	22-Feb	0.0a	7.5a	0.0a	4.2a	-	135	-	108
	11-Mar	0.0a	0.6a	21.0a	23.0a	-	88	63	91
	12-Mar	4.4a	7.4a	20.2a	16.2a	34	10	108	90
	13-Mar	4.4a	0.9ab	0.3b	0.0b	80	173	173	-
	14-Mar	3.9a	0.2ab	0.0b	0.0b	120	173	-	-
	15-Mar	9.5a	1.9b	0.0b	0.8b	82	173	-	113
	16-Mar	3.2a	0.0a	0.0a	0.0a	141	-	-	-
	Total	25.4	63.1	41.2	58.9				

generally highest from the frames located on the south-facing aspect but just a few days later, the frames located on the north-facing aspect were contributing the most (March 1, 1993; March 13, 1994; and February 22, 1995; Table 4). In the West Watershed the trend is less clear but the frames located on the 13% south-facing slope generally had the most runoff during the first one-three days of melt (February 27-March 1, 1993; March 13, 1994; and March 11-12, 1995; Table 5). The timing and volume of hillslope runoff between aspects during the main snowmelt were similar for watersheds for all three study years.

There was more runoff from north-facing than south-facing aspects of both watersheds during December melts in both 1992-93 and 1993-94. There was no runoff from the south-facing frames in the Sandy Subsoil Watershed during a late melt on March 20 to 23, 1993 (Table 4) even though snowfall accumulations of 12 cm occurred from March 9 to 19, 1993.

Average total snowmelt runoff volumes were higher for the north-facing slope of the Sandy Subsoil Watershed than the south-facing slope (Table 4; except for the upper slope position in 1994-95) by factors of 2.8, 1.5 and 1.5 for the three consecutive melt periods. There was no clear trend in total runoff in upper *versus* lower slope positions for this watershed, regardless of aspect.

Total snowmelt runoff volumes for the West Watershed were also higher for the north-facing than south-facing slope, but by smaller factors than those for the Sandy Subsoil watershed: 1.1, 1.2 and 0.9 for the three study years. The effect of slope gradient was notable for the 1992-93 and 1993-94 snowmelt periods for the West Watershed with the 13% slope having 2.2 and 1.3 times the total runoff volume that of the 5% slope. The trend for rather low total volumes of runoff from the 5% north-facing slope in the first two years was completely reversed in the last year.

Snowmelt runoff volumes from replicated frames at a given aspect and slope position often differed by an order of magnitude (data not shown), resulting in high coefficients of variation (Tables 4 and 5). Snowmelt runoff was minimal from several frames throughout the study. For the Sandy Subsoil Watershed, the distributions for the runoff CVs for the lower-slope position were generally uniform across all classes, while that for the north-facing upper slope position was skewed to the low end; with an upper-end skew for the south-facing upper slope position. No clear trend in CV distribution was evident for the West Watershed either, nor was there any trend in CV variation across years for either watershed.

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* Missing coefficients of variation indicate zero runoff from slope position or data obtained from only one frame; n = 3 for each slope aspect and gradient.

Means within a row with the same letter are not significantly different at $p < 0.05$.

$^+$ Only one frame was operational.

Table 6 – Average soil temperature (°C) for slope positions within the Sandy Subsoil Watershed during snowcover periods 1993 and 1994.

		1992			1993									1994		
	Depth (cm)	11-Nov	20-Nov	13-Dec	6-Feb	27-Feb	2-Mar	3-Mar*	4-Mar	5-Mar	6-Mar	9-Mar	13-Mar	15-Apr@	12-Mar	13-Mar	26-Mar
SL	05	5.8a	-1.3a	-6.6a	-3.5a	-3.1a	-1.3a	-1.6a	-2.1a	-1.2ab	-1.1ab	-0.9a	-2.8a	4.5ab	-1.0a	-1.0a	-1.0b
SU	05	6.3a	-1.5ab	-6.8a	-3.3a	-2.9a	-1.1a	-1.6a	-1.8a	-0.8a	-0.7a	-1.0a	-2.8a	4.8a	-1.0a	-1.0a	1.3a
NL	05	4.1b	-1.6ab	-5.4b	-4.0b	-5.0b	-1.9b	-2.5b	-4.2b	-2.0bc	-1.5b	-1.3a	-3.9b	1.5c	-1.2a	-1.2a	-1.4b
NU	05	5.6a	-1.7b	-5.6b	-3.3a	-4.5b	-1.4a	-2.0a	-3.6b	-1.6c	-1.3ab	-1.6a	-3.9b	3.2b	-1.2a	-1.1a	-1.3b
SL	10	4.9a	-1.1a	-6.2a	-4.3a	-3.7a	-1.6a	-1.8a	-1.8a	-1.4a	-1.3a	-0.9a	-2.6a	3.9a	-1.0a	-1.0a	-1.1a
SU	10	5.0a	-1.2a	-6.3a	-4.2a	-3.5a	-1.5a	-1.7a	-1.6a	-1.0a	-1.3a	-0.9a	-2.7a	3.9a	-1.1a	-1.2ab	-0.5a
NL	10	3.6c	-1.4a	-5.1b	-4.4a	-5.1b	-2.1b	-2.7b	-2.7b	-2.1b	-1.6b	-1.7ab	-3.7b	1.2b	-1.3a	-1.2ab	-1.4a
NU	10	4.1b	-1.3a	-5.2b	-4.4a	-5.0b	-2.0b	-2.7b	-3.2b	-2.0b	-1.8b	-2.0b	-4.0b	1.5b	-1.2a	-1.3b	-1.5a
SL	20	4.6a	-0.3a	-5.4a	-4.9a	-4.2a	-2.0a	-2.1a	-2.0a	-1.4a	-1.6a	-1.4a	-2.1a	3.7a	-1.2a	-1.1a	-1.0a
SU	20	4.4a	-0.4ab	-5.2ab	-4.7a	-4.1a	-2.1a	-2.0a	-1.9a	-1.5a	-1.5a	-1.1a	-1.9a	3.8a	-0.9a	-1.4b	-1.1a
NL	20	3.5b	-0.8b	-4.5b	-4.9a	-5.5b	-2.7b	-3.3b	-3.7c	-2.6b	-2.2b	-1.3a	-3.3b	0.1b	-1.6a	-1.6b	-1.6b
NU	20	3.5b	-0.7b	-4.5b	-5.1a	-5.2b	-2.6b	-3.1b	-3.3b	-2.5b	-2.1b	-2.0a	-3.4b	0.9b	-1.8a	-1.5b	-1.6b
SL	40	5.2	1.5	-3.1	-3.5	-4.1	-2.4	-2.2	-2.1	-2.2	-1.8	-0.6	-1.3	3.5	-1.5	-1.4	-0.8
SU	40	5.3	1.4	-2.6	-3.2	-4.1	-2.6	-2.3	-2.1	-2.2	-1.8	-1.4	-1.3	2.6	-1.5	-1.4	-1.0
NL	40	3.6	0.4	-2.8	-4.1	-5.0	-3.0	-3.2	-3.1	-2.9	-2.4	-1.3	-2.3	-0.3	-1.8	-1.4	-1.5
NU	40	3.6	-0.2	-3.5	-4.5	-5.5	-3.2	-3.1	-3.9	-3.0	-2.7	-3.5	-2.3	1.0	-1.8	-1.6	-1.6

* – Hillslopes were clear of snow and runoff is finished. Snow commenced again after March 10, 1993.

@ – Runoff finished March 22,1993.

Means for a given depth with the same letter for the same date are not significantly different at ($p \leq 0.05$).

n =3 for each slope aspect and gradient.

SL = south-facing lower slope.	SU = south-facing upper slope.
NL = north-facing lower slope.	NU = north-facing upper slope.

Soil Temperature

Within the Sandy Subsoil Watershed, soil temperatures were < 0°C at all depths for all dates during the snowmelt period in 1993 (Table 6). They were generally significantly higher for the south- compared to the north-facing slopes at the 10 and 20-cm depths throughout most of the 1992-1993 snow-cover period (February 6 to March 13, 1993). There was no upper or lower slope position effect on soil temperature at any depth. Soil temperatures were similar for all depth intervals and both aspects prior to the commencement of the principal melt on March 12, 1994. The deep snow-cover insulated the soil.

The influence of aspect on soil temperatures within the West Watershed was similar to that within the Sandy Subsoil Watershed (data not shown). Soil temperatures were higher at all depths for the south- than for the north-facing aspect during the early part of the principal melt. Soil temperatures were similar at all depths during the second melt period in late March 1993.

Soil temperatures at a 5-cm depth did not rise above 0°C for either the south- or north-facing aspects of either watershed during the entire main melt periods of 1993 and 1994, indicating the ground was frozen during this important runoff period.

Fall Soil Moisture and Over-winter Change in Soil Moisture

Fall soil moisture in the Sandy Subsoil Watershed to a depth of 45 cm was higher for the north-facing than for the south-facing aspect in both study years, significantly in fall 1993 (Table 7a). There were no significant differences in fall soil moisture between slope position either year. Also, there were no significant differences in over-winter soil moisture gain or loss between either position or aspect.

Soil moisture gain/loss was generally similar for the frames located on the north-facing aspect at the upper slope position within the Sandy Subsoil Watershed both years (Table 7a), even though runoff amount was quite different for the three frames (data not shown). Fall soil moisture levels were also similar (Table 7a), so differences in runoff among frames could be due to differences in evaporation.

Soil moisture for frame locations on the south-facing aspect of the Sandy Subsoil Watershed (Table 7) was slightly lower in 1993 (average 90 mm) than in 1992 (average 115 mm), and similar between years for the frames on the north-facing aspect (125 and 118 mm, respectively in 1992 and 1993). Soil moisture in the upper 45 cm of the profile was substantially higher for frame south-facing U1 than for the other two frames at this slope position (data not shown); a soil moisture loss occurred over-winter 1992-93 with a small gain in 1993-94. In contrast north-facing L3 had a lower soil moisture than did the other two frames at the same slope position, but had a high over-winter soil moisture gain only in 1993-94.

Soil moisture increases were recorded to at least 85 cm at four of the 12 microframe locations within the Sandy Subsoil Watershed in 1992-93 (data not shown) and to at least the depth of monitoring (95 cm) at eight locations over-winter 1993-94. However, the greatest gain of soil moisture for all frames occurred in the upper-

Table 7a – Fall soil moisture levels and over-winter soil moisture changes: Sandy Subsoil Watershed.

		1992-93		1993-94	
	Frame	TSM45[1] (mm)	ΔSM[2] (mm)	TSM45[1] (mm)	ΔSM[2] (mm)
South-facing Slope	U1	166	-16	140	18
	U2	82	14	63	18
	U3	97	45	66	28
	L1	94	12	104	13
	L2	100	7	84	30
	L3	93	5	73	47
Mean (SD)	Upper	115a (45)	14a (31)	90a (44)	21a (6)
	Lower	96a (4)	8a (4)	87a (16)	30a (17)
North-facing Slope	U1	124	4	127	9
	U2	123	1	115	10
	U3	127	1	111	19
	L1	148	10	149	2
	L2	158	-4	154	1
	L3	116	36	116	12
Mean (SD)	Upper	125a (2)	2a (2)	118a (8)	13a (6)
	Lower	141a (22)	14a (20)	140a (20)	5a (6)
Watershed Position Mean	Upper	120a (29)	8a (21)	104a (32)	17a (7)
	Lower	118a (28)	11a (13)	113a (33)	18a (18)
Watershed Aspect Mean	South-facing	105a (30)	11a (20)	88b (29)	26a (12)
	North-facing	133a (17)	8a (15)	129a (19)	9b (7)

1 TSM45 = total soil moisture to a depth of 45 cm, measured in the fall.

2 ΔSM = over-winter soil moisture gain or loss (-).

Means for position or aspect comparisons followed by the same letter are not significantly different at $p \leq 0.05$.

SD = standard deviation.

most 40 cm. Granger *et al.* (1984) found that the greatest gain at their study site occurred to a depth of 30 cm.

In the West Watershed, aspect had a significant effect on fall soil moisture both years, with the south-facing aspect having significantly higher fall soil moisture both years (Table 7b). Slope gradient had a significant effect on fall soil moisture for the north-facing slope both years, but not for the south-facing slope. However, over-winter soil moisture gain/loss was similar for all slope and aspect considerations. Over-winter soil moisture losses occurred in numerous instances.

The influence of fall soil moisture on over-winter soil moisture changes is quite

Table 7b – Fall soil moisture levels and over-winter soil moisture changes: West watershed.

		1992-93		1993-94	
	Frame	TSM45^1 (mm)	ΔSM^2 (mm)	TSM45^1 (mm)	ΔSM^2 (mm)
South-facing	F1	229	-21	206	-8
	F2	173	12	181	5
	F3	208	5	205	6
	S1	198	-1	180	0
	S2	189	22	191	6
	S3	-	-	184	9
Mean (SD)	F (5%)	203a (28)	-1 (17)	197a (14)	1 (8)
	S (13%)	194a (6)	11 (16)	185a (6)	5 (5)
North-facing	F1	185	-5	168	7
	F2	183	14	164	19
	F3	182	-3	195	-6
	S1	149	-2	159	-3
	S2	149	16	148	10
	S3	137	1	153	-6
Mean (SD)	F (5%)	183a (2)	2 (10)	176a (17)	7 (13)
	S (13%)	145b (7)	5 (10)	153b (6)	0 (9)
Watershed Gradient Mean	F (5%)	193a (21)	0a (13)	187a (14)	4a (10)
	S (13%)	164a (27)	7a (11)	169a (17)	2a (7)
Watershed Aspect Mean	South-facing	199a (22)	3a (16)	191a (12)	2a (6)
	North-facing	164b (22)	4a (9)	165b (17)	4a (10)

1 TSM45 = total soil moisture to a depth of 45 cm, measured in the fall.

2 DSM = over-winter soil moisture gain or loss (-).

Means for gradient or aspect comparisons followed by the same letter are not significantly different at $p \leq 0.05$.

SD = standard deviation.

clear for the frames located on the north-facing F (5%) slope position within the West Watershed (Table 7b). The frame with the lowest fall soil moisture (south-facing F2) had the highest soil moisture gain during snowmelt, while net soil moisture losses over-winter occurred in the frame with the highest fall soil moisture (south-facing F1). Fall soil moisture was similar for the frames at the other slope positions within the West Watershed, therefore, differences in over-winter soil moisture changes would be a function of different soil surface or snowpack conditions during snowmelt. For example, the greatest volume of snowmelt runoff from the frames located on the north-facing S (13%) slope position was from frame S2, yet a high over-winter soil moisture gain during snowmelt also occurred at this location.

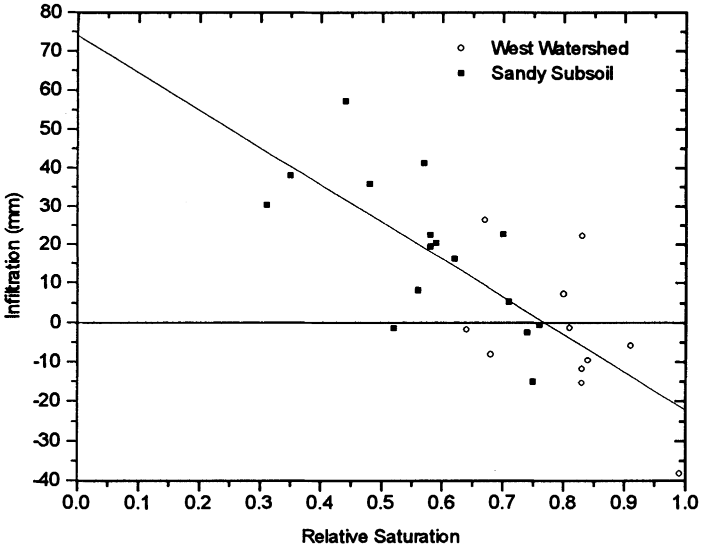

Fig. 1. Relationship between 1993 snowmelt infiltration and relative saturation in the fall 1992 for both watersheds.

Fall soil moisture was generally similar among the three replicates at a given watershed position, as evidenced by generally low standard deviations (Tables 7a and b). Note especially the three north-facing U locations of the Sandy Subsoil Watershed in fall 1992 (124, 123 and 127 mm; Table 7a) and the three north-facing F (185, 183 and 182 mm) and three S locations (149, 149 and 137 mm) of the West Watershed also in fall 1992 (Table 7b). Location south-facing U1 of the Sandy Subsoil Watershed, which had approximately twice the amount of soil moisture that its two replicates had, was a notable exception to this observation. In contrast, over-winter soil moisture changes showed great spatial variability, with SDs commonly exceeding their means.

Over-winter soil moisture change averaged for each watershed across years was very small: 13 mm for the Sandy Subsoil Watershed and 3 mm for the West Watershed. Most of the over-winter soil moisture gains to a depth of 450 mm were less than 20 mm. Of the 24 values for over-winter soil moisture change for the Sandy Subsoil Watershed for the two study years, two were soil moisture losses; for the West Watershed the number of losses was nine. Over-winter soil moisture changes on the hillslopes were negligible when fall relative saturation was greater than 0.75 (Fig. 1). Higher water-holding capacity of the clay to clay-loam subsurface material in the West Watershed (37% @ 33 kPa) than the sandy-loam subsurface material (17% @ 33 kPa) of the Sandy Subsoil Watershed would translate into generally higher fall relative saturation in the West Watershed than in the Sandy Subsoil Watershed.

Mid-winter melts during all three years of monitoring (December 13, 1992; December 26, 1993; February 1, 9; 1995; Tables 4 and 5) would have increased near-surface soil moisture prior to the main melt period each year, likely diminishing the influence of fall soil moisture on snowmelt runoff, especially if the fall soil moisture levels were low.

Evaporation

Evaporation and/or sublimation from the snowpack for the overwinter periods 1993 and 1994 varied between 0.05 and 0.74 of the snow-water equivalent (Table 8). Higher evaporation proportions were calculated for the south-facing aspect (0.47) than for the north-facing aspect (0.38) within the Sandy Subsoil Watershed and for the south-facing aspect (0.43) than for the north-facing aspect (0.28) within the West Watershed. Although the number of microframes considered was small, the SDs for the % snow-water evaporated were generally < 50% of their means.

Table 8 – Percentage of snow-water that evaporated during the 1993 and 1994 snowmelts.

	Number of Microframes	Mean (%)	Standard Deviation (%)
Sandy Subsoil Watershed			
North-facing	6	38	22
South-facing	6	47	19
West Watershed			
North-facing	4	28	14
South-facing	3	43	9

Discussion

Influence of Aspect

Incoming solar radiation is the dominant parameter in the energy balance equation for more northerly areas (Braun and Slaymaker 1981; Hinzman *et al.* 1991), governing the timing of melt and the snowmelt rate (Granger and Gray 1990). South-facing slopes were more directly exposed to daily incoming solar radiation than were the north-facing slopes. More energy available for snowmelt from incoming solar radiation and advection of sensible heat from nearby snow-free areas once the melt has progressed would translate to an earlier appearance of meltwater and a shorter melt period for the hillslopes with the south-facing aspect. Distributed parameter models for predicting the timing and amount of snowmelt runoff should therefore account for the differential melt rates due to differences in aspect even within fairly small watersheds.

The parameters that influence the differences in volume of snowmelt runoff between aspects can be combinations of differences in snow-water equivalents, infiltration and evaporative losses. Snow-water equivalents prior to the principal melt in both 1993 and 1994 were slightly higher for the south-facing than the north-facing aspect of the Sandy Subsoil Watershed. Therefore, the lower snowmelt runoff volume from the south-facing aspect must be related to differences in infiltration and/or evaporation and not differences in snow depths, with greater infiltration and evaporation on the south-facing slopes.

At soil temperatures slightly below 0°C, a considerable portion of the soil moisture can exist in the unfrozen state (Burn 1991) facilitating melt-water infiltration. This may have been true for both watersheds, given the medium to fine texture of their surface soils. Soil temperatures on south-facing aspects were higher than those on north-facing aspects during the snowmelt period and greater gain in soil moisture was generally observed on the south-facing slopes.

Since average fall soil moisture of the Sandy Subsoil Watershed was consistently lower for the south-facing than for the north-facing aspect, there would be more opportunity for the first meltwater to fill the unsaturated pore space once snowmelt water appeared at the bottom of the snowpack, translating to less water available for runoff. This could in part explain why the south-facing aspects did not produce any runoff during some mid-winter melt periods. However, given that the soil was frozen during these periods the infiltrating water likely did not move far in the soil before freezing, thereby likely reducing subsequent infiltration and enhancing runoff.

Relating snowmelt runoff to fall soil moisture is complicated when mid-winter snowmelt events occur. Changes to soil moisture, unsaturated pore space and soil surface permeability during these events can render measured fall moisture levels unrepresentative of pre-melt levels in such instances. Soil moisture should be monitored continuously over-winter to determine the influence of mid-winter melts on its status and to quantify the extent of internal soil moisture redistribution within the soil profile.

Bengtsson (1980) proposed that evaporation from a snowpack is a minor component of the mass balance equation during snowmelt, usually averaging less than 1 mm per day or 10 to 20 mm for the snow ablation period. Near saturated conditions of the air immediately above the snow surface minimizes the vapor pressure gradient necessary for evaporation to proceed. However, total evaporation during snowmelt from an Arctic watershed varied between 20 to 34% of the snow-water equivalent (Kane *et al.* 1991). Calculated average evaporative losses within the two reclaimed watersheds were within the range or higher than those reported by Kane *et al.* (1991). Evaporation in this study was higher for the south-facing than for the north-facing aspects for both watersheds during the snowmelt periods and comprised a significant portion of snowpack ablation.

Infiltration and Redistribution of Melt-water

Infiltration is reduced when soil moisture is high prior to the melt period (Kane *et al.* 1991) or there is a restriction to infiltration (Granger *et al.* 1984). Consequently more of the snow-water becomes runoff and infiltration is reduced. The power relationship between infiltration and snow-water equivalent ($INF = a(SWE)^n$ where a, n are derived coefficients) shown for central Saskatchewan by Granger *et al.* (1984) is not evident from the snowmelt data on the reclaimed watersheds. Such a relationship was difficult to derive for this study because distinct snow accumulation and snow ablation periods were rare during the three years of the study. During the 1992-93 snow period, there were five separate snow accumulation-ablation periods, in 1993-94 there were two, and in 1994-95 there were four. A major mid-winter melt can dramatically change surface soil moisture conditions, the nature of the soil frost and snowpack conditions for subsequent snowmelt periods (Price and Hendrie 1985).

During snowcover periods 1992-93 and 1993-94 there was considerable micro-scale variability in change in over-winter soil moisture and thus depth of infiltration throughout the watersheds. Differences in over-winter soil moisture gains of greater than 40 mm occurred for replicated frames at similar slope positions and aspects within the West Watershed during the snow-cover period 1993-94.

Soil moisture redistribution or loss at depths greater than 400 mm during the over-winter period likely occurred. Net soil moisture decreases at depths below 300-400 mm for eight of the twelve frames within both watersheds during the 1992-93 snowmelt indicate that either upward or downward soil moisture loss or lateral soil moisture redistribution occurs during the snowcover period. Burn (1991) reported over-winter soil moisture losses to the atmosphere of up to 4 mm from the surface layers of a soil, but this loss was replenished from soil water at greater depths.

Conclusions

Aspect, even for these relatively small watersheds, had a major influence on the timing and amount of runoff available for discharge from the watershed. Differences in the timing and volume of snowmelt between aspects was attributed to differences in pre-winter soil moisture, energy inputs and soil temperatures. Fall soil moisture was lower, soil temperatures were higher during melt and energy inputs were assumed to be higher for the south- than the north-facing aspect within the Sandy Subsoil Watershed. Soil moisture differences were not evident for different aspects within the West Watershed but soil temperature was generally higher for the south-facing aspect.

Even though fall soil moisture and snow-water equivalents were fairly uniform for a given slope position, over-winter soil moisture changes were highly variable and generally very low. The losses at times exceeded the total infiltrated meltwater such that the soil profile had reduced soil moisture post-melt than it did the preceding fall. The spatial variability in the timing and amount of hillslope snowmelt runoff between replicated frames at similar slope positions and between slope positions along the same aspect is surprisingly high. Subtle differences in slope section angle to incoming radiation generally resulted in a difference in the timing and amount of runoff among frames at similar aspect and slope position. Similarly, soil moisture and surface ice characteristics at certain hillslope locations also likely affected melt. Snowmelt evaporation appears to be a significant process on these watersheds.

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References

Bengtsson, L. (1980) Evaporation from a snowcover: Review and discussion of measurements, *Nordic Hydrol., Vol. 11,* pp. 221-234.

Blöschl, G. (1991) The influence of uncertainty in air temperature and albedo on snowmelt, *Nordic Hydrol., Vol. 22,* pp. 95-108.

Braun, L. N., and Slaymaker, H. O. (1981) Effect of scale on the complexity of snowmelt systems, *Nordic Hydrol., Vol. 12,* pp. 225-234.

Burn, C. R. (1991) Snowmelt infiltration into frozen soil at sites in the discontinuous permafrost zone near Mayo, Yukon Territory. In: Northern Hydrology: Selective Perspectives, T. D. Prowse and C. S. L. Ommanney (Editors), NHRI Symposium No.6, National Hydrology Research Institute, Environment Canada, Saskatoon, Saskatchewan, pp. 445-459.

Buttle, J. M. (1989) Soil moisture and groundwater response to snowmelt on a drumlin sideslope, *J. Hydrol., Vol. 105,* pp 335-355.

Chanasyk, D. S., and Woytowich, C. P. (1985) Snowmelt runoff from agricultural land in the Peace River region, *Can. Agric. Eng., Vol. 28* (1), pp. 7-13.

Dingman, S. L. (1994) *Physical hydrology*, Prentice Hall, Englewood Cliffs, New Jersey, 575 pp.

Granger, R. J., and Gray, D. M. (1990) A net radiation model for calculating daily snowmelt in open environments, *Nordic Hydrol., Vol. 21,* pp. 217-234.

Granger, R. J., Gray, D. M., and Dyck, G. E. (1984) Snowmelt infiltration to frozen prairie soils, *Can. J. Earth Sci., Vol. 21,* pp. 669-677.

Harms, T. E., and Chanasyk, D. S. (1998) Runoff response from two reclaimed watersheds, *J. Amer. Water Resour. Assoc., Vol. 34* (2), pp. 289-299.

Hinzman, L. D., Kane, D. L., and Gieck, R. E. (1991) Regional snow ablation in the Alaskan arctic. In: Northern Hydrology: Selective Perspectives, T. D. Prowse and C. S. L. Ommanney (Editors). NHRI Symposium No. 6, National Hydrology Research Institute, Environment Canada, Saskatoon, Saskatchewan. pp. 121-139.

Johnsson, H., and Lundin, L. C. (1991) Surface runoff and soil water percolation as affected by snow and soil frost, *J. Hydrol., Vol. 122,* pp. 141-159.

Kane, D. L., and Chaco Jr., E. F. (1990) Frozen ground effects on infiltration and runoff. In: Cold Regions Hydrology/Hydraulics, W. L. Ryan and R.D. Crissman (Editors). American Society of Civil Engineering Publication pp. 259-300.

Kane, D. L., Hinzman, L. D., Benson, C. S., and Liston, G. E. (1991) Snow hydrology of a headwater arctic basin, 1. Physical measurements and process studies, *Water Resour. Res., Vol. 27*(6), pp. 1099-1109.

Leavesley, G. H. (1989) Problems of snowmelt modelling for a variety of physiographic and climatic conditions, *Hydrol. Sci. J., Vol.34* (6), pp. 617-634.

Lewkowicz, A. G., and French, H. M. (1982) The hydrology of small runoff plots in an area of continuous permafrost, Banks Island. In Proceedings of the Fourth Canadian Permafrost Conference, Calgary Alberta. H. M. French (Editor). National Research Council of Canada, Ottawa, Ontario. pp.153-162.

Price, A. G., and Hendrie, L. K. (1983) Water motion in a deciduous forest during snowmelt, *J. Hydrol., Vol. 64,* pp. 339-356.

SAS Institute (1988) *SAS/STAT User's Guide*, 6.03 Edition, SAS Institute, Cary, NC. USA. 1028 pp.

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