CONTRIBUTIONS TO RUNOFF FROM A MELTING PRAIRIE SNOW PATCH AS TRACED BY OXYGEN-18

592-75

By

H. Steppuhn 1/, H. R. Krouse 2/ and D. E. L. Erickson 1/

Introduction

The melting of winter snow commonly supplies more than half the surface water generated within the northern Great Plains of North America. The onset of spring melt rapidly alters snowcover continuity over northern prairies and forms areal patterns of discontinuous snow patches. The melting of snow patches have been investigated by Boyer (1954), Dunne and Black (1971), DeWalle and Meiman (1971), Lin and Steppuhn (1972), and others.

Natural water consists of a number of stable isotopic forms. The most important forms, $H_2{}^{16}O$, $HD^{16}O$ and $H_2{}^{18}O$, occur with average abundances in the ratios 10000:3:20, respectively. The relative isotopic composition of a water sample can be routinely compared to a standard with a precision of better than 0.01% in any individual isotope laboratory. Therefore, isotopic abundances are expressed on a 'del' scale. For oxygen isotopes this scale is defined as,

$$\delta^{18}O_{\text{sample}} \text{ in } {}^o/oo = 1000 \left(\frac{({}^{18}O/{}^{16}O)_{\text{sample}}}{({}^{18}O/{}^{16}O)_{\text{SMOW}}} - 1 \right)$$

The scale expresses the deviation in parts per thousand (^{o}/oo) of the relative numbers of ^{18}O's to ^{16}O's in a sample to the standard SMOW (Standard Mean Ocean Water), which represents an average value for ocean waters (Craig, 1961). A similar δD scale exists for deuterium.

The determination of relative isotopic compositions in natural waters provides a technique for tracing contributing sources to snowmelt runoff.

Dincer et al (1970) monitored the relative concentrations of oxygen-18 and tritium within a 2.65 km^2 watershed in Czechoslovakia. They concluded that the winter snowcover and subsurface storage contributed about 1/3 and 2/3, respectively, to runoff volumes during the 1966 snowmelt period.

Meiman et al (1973) determined that the δD of snow covering a 31.8 km^2 mountainous watershed in Colorado averaged 34 ^{o}/oo lower than that of the base flow and about 80 ^{o}/oo lower than that of the summer rain. On the basis of their data, these differences did not appear in the runoff. δD values of the streamflow decreased only 4 ^{o}/oo in response to snowmelt despite increased flow rates of 30 to 1 greater than base flow.

Holecek and Krouse (1973) examined the relative abundances of oxygen-18 for waters within a forested basin in central Alberta. $\delta^{18}O$ values of -14.7, -15.3 and -18.5 ^{o}/oo for three streams sampled during Fall 1972 apparently reflected contributions from two subsurface sources, one shallow at -19 ^{o}/oo and one deep at -15 ^{o}/oo. Water obtained from the shallow source in April 1973 maintained a high $\delta^{18}O$ value of -18.5 ^{o}/oo relative to that of the melting snow which averaged -23.0 ^{o}/oo. Apparently, the movement of snow water into the shallow system did not coincide with spring melt.

The study reported herein involves the determination of $^{18}O/^{16}O$ ratios for waters associated with a melting prairie snow patch. Specifically, relative oxygen isotope abundances of three possible sources, snow, soil and springs, were compared to isotopic values for runoff flowing from the patch.

1/ Hydrologist, Division of Hydrology, University of Saskatchewan, Saskatoon, Sask.

2/ Professor, Department of Physics, The University of Calgary, Calgary, Alberta

Study Snow Patch and Methods

The snow patch under study was located within the Bad Lake Representative (I.H.D.) Basin (Lat. 51°23'N., Long. 108°26'W.) 210 km southwest of Saskatoon, Saskatchewan (Figure 1). Figure 2 outlines the approximate topographical position of the patch situated on the southeastern flank of a small, sharp-crested, morainal ridge.

Ecologically, the site forms part of a semi-arid, shortgrass prairie under moderate summer grazing. The climate is cool and continental, with mean annual precipitation and potential-evapotranspiration-deficit averaging 320 and 410 mm, respectively. The subsurface mantle ranges from 4 to 8 meters in thickness and consists of a brown silty-loam soil near the surface which grades with depth into a silty clay containing some boulders.

The study patch consisted of snow accumulated from November 1972 through March 1973 and measured approximately 100, 25 and 0.4 meters in mean length, width and depth, respectively. Influenced by warm, sunny days and cool, clear nights, the patch was in a state of diurnal melt and freeze during observation and sampling on the 21st and 22nd of March 1973. The upper 10 centimeters of the snow patch were sampled daily at 10 or more locations before the beginning of each day's melt. Snow samples were also taken at 10 centimeter intervals within vertical profiles at two locations.

Surface runoff emerging from the study patch formed a single channel, topographically separate from runoff from adjacent patches of snow. The runoff was periodically sampled at the snowpatch portal, ⓐ, and at two locations 250 meters, ⓑ, and 450 meters, ⓒ, downstream (Figure 2).

Water samples were also obtained from potential subsurface sources. These included three springs and one flowing well all located within three kilometers horizontally and 70 meters vertically of the study patch. Soil water represented another potential contributor to runoff. A large fraction of this soil water originated as rain which fell during the previous Autumn (1972). Consequently, analysis included samples from three rains occurring in Autumn 1972 and three in Autumn 1973. The 1972 rain samples were obtained from a weather station situated 210 km northeast of the study site, while comparative 1973 rain samples were collected within 4 km of the site.

All samples were transported in sealed, glass jars to the stable isotope laboratory at The University of Calgary. Abundance ratios of $^{18}O/^{16}O$ were determined by mass spectrometric analysis of CO_2 which had been equilibrated isotopically with standard waters at 25°C (Epstein and Mayeda, 1953).

Results

Figure 3 outlines $\delta^{18}O$-values determined for the surface (0 - 10cm) snow sampled by location and date. These values show a definite trend of relatively light to heavy water from south to north. Analyses of samples from the vertical snow profiles (Figure 4) indicated that this directional trend also occurred at all depths. The $\delta^{18}O$ fluctuations within individual profiles were less than the observed areal variability. Such a pattern could have resulted by topographically-induced depositions of snow from different storms containing varying concentrations of oxygen-18, as presented schematically in Figure 5.

Runoff samples at locations ⓐ, ⓑ and ⓒ (Figure 2) were collected intermittently throughout duration of flow. Figure 6 relates $\delta^{18}O$ to time and runoff flow. Consistent relationships between flow magnitudes and $\delta^{18}O$ values are not evident. Trends due to runoff sample location were also absent. An analysis of variance for $\delta^{18}O$-data grouped by location exhibited no significant difference with an α-probability of 0.6. Least square correlations for daily $\delta^{18}O$-values of ⓐ with ⓑ and a with ⓒ yielded correlation coefficients no greater than 0.28 in 5 out of 6 comparisons.

Mean $\delta^{18}O$-values are summarized in Table 1 and indicate a slight enrichment from surface snow to runoff. Mean enrichments of 0.98 °/oo and 0.62 °/oo for the 21st and 22nd of March exceed the estimated laboratory precision of ± 0.1 °/oo and appear valid. However, inspection of the associated sampling confidences and ranges in Table 1 reveals consistent overlap for $\delta^{18}O$ between surface snow and associated runoff.

Figure 1. Map of Western North America Locating the Bad Lake Hydrologic Basin

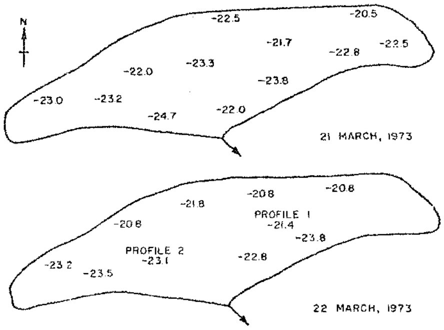

Figure 3. Approximate Sample Locations and $\delta^{18}O$-Values for Snow Patch

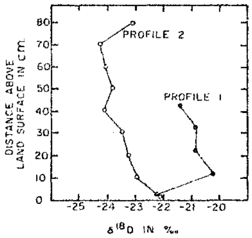

Figure 4. $\delta^{18}O$-Values for samples from Two Vertical Profiles of the Study Snow Patch

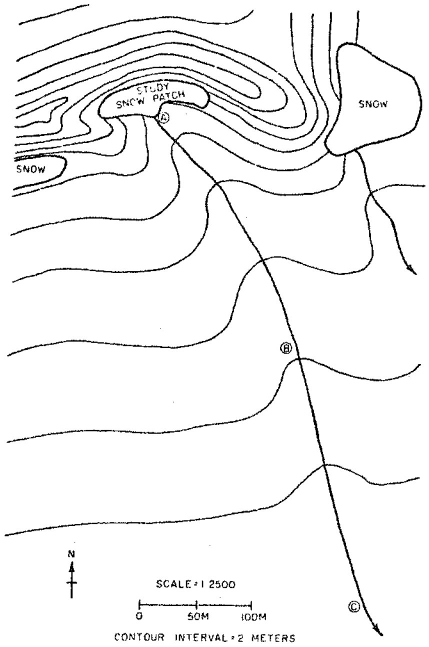

Figure 2. Topographic Plan of Study Site, Featuring Snow Patch and Runoff Channel with Sampling Points ⓐ, ⓑ, and ⓒ

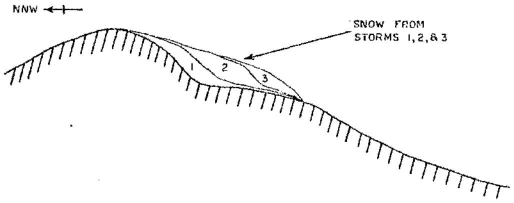

Figure 5. Schematic Profile of the Study Snow Patch Along a NNW - SSE Axis

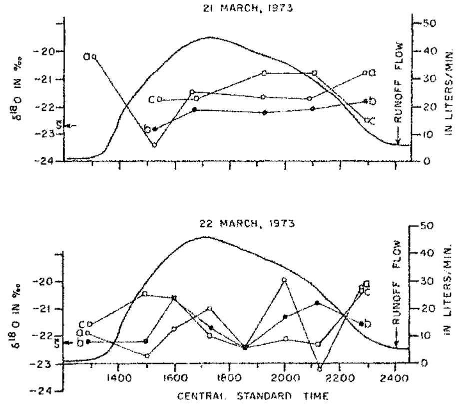

Figure 6. Time-Dependent $\delta^{18}O$-Values for Runoff Samples Taken at Locations ⓐ, ⓑ and ⓒ Presented with Measured Runoff Flows from a Comparable Snow Patch; S Indicates Mean $\delta^{18}O$ for Surface Snow

Table 1. Statistical Summary of $\delta^{18}O$ - Data

Sample	No. of Samples	$\delta^{18}O$ in ^{o}/oo (SMOW)		
		Mean	Confidence at $\alpha = 0.05$	Range
21 March 1973				
Surface Snow	12	- 22.72	± 0.71	- 24.7 to - 20.5
Runoff at ⓐ	6	- 21.55	± 1.11	- 23.4 to - 20.2
Runoff at ⓑ	5	- 22.20	± 0.43	- 22.8 to - 21.8
Runoff at ⓒ	5	- 21.50	± 0.84	- 22.5 to - 20.8
Combined ⓐ ⓑ ⓒ	16	- 21.74	± 0.43	- 23.4 to - 20.2
22 March 1973				
Surface Snow	10	- 22.20	± 0.85	- 23.8 to - 20.8
Runoff at ⓐ	8	- 21.65	± 0.93	- 23.2 to - 20.0
Runoff at ⓑ	8	- 21.60	± 0.54	- 22.4 to - 20.6
Runoff at ⓒ	8	- 21.49	± 0.70	- 22.4 to - 20.4
Combined ⓐ ⓑ ⓒ	24	- 21.58	± 0.37	- 23.2 to - 20.0
Vertical				
Profile #1	5	- 21.08	± 0.88	- 22.2 to - 20.2
Profile #2	9	- 23.43	± 0.53	- 24.2 to - 22.1
21 & 22 March 1973 Combined				
Surface Snow	22	- 22.48	± 0.50	- 24.7 to - 20.2
Runoff at ⓐ	14	- 21.61	± 0.62	- 23.4 to - 20.0
Runoff at ⓑ	13	- 21.83	± 0.38	- 22.8 to - 20.6
Runoff at ⓒ	13	- 21.49	± 0.47	- 22.5 to - 20.4
Combined ⓐ ⓑ ⓒ	40	- 21.64	± 0.27	- 23.4 to - 20.0

Unpaired t-tests for various combinations of $\delta^{18}O$-data from snow and runoff also suggest that the observed enrichments could have resulted solely by chance. Results shown in Table 2 include t-test probabilities, α_t, and least significant differences, lsd, for the six combinations of ^{18}O-samples obtained over the two days and at runoff locations ⓐ, ⓑ and ⓒ. Probabilities, α_t, that the oxygen-18 enrichments occurred by chance ranged from 0.045 to 0.32. Differences between mean $\delta^{18}O$ for surface snow and runoff are less than the statistical lsd in all tests at $\alpha = 0.01$ and in four of six tests at $\alpha = 0.05$ (α is the probability of a greater lsd). Combining ^{18}O-data for the two test days gave similar t-test results.

Unpaired t-tests were applied to other data combinations as listed in Table 2. Mean $\delta^{18}O$ values for snow sampled in vertical profiles #1 and #2 proved statistically different at an α-probability of < 0.001. Significance in $\delta^{18}O$-differences were not evident for combinations between daily runoff at ⓐ and ⓒ, between surface snows of the 21st and the 22nd, nor between runoff of the 21st and 22nd at ⓐ, ⓑ, or ⓒ.

Components forming snow patch runoff included two possible subsurface sources, (1) spring water and (2) autumn rain via the soil. However, the probability of contributions from springs were minimal. Local piezometric surfaces calculated from topographic and water well data were estimated to lie at least 25 meters below location ⓐ. Also, daily recessional flows for runoff were small and almost ceased during the night.

Table 2. Summary of Unpaired t-Tests for Various Combinations of $\delta^{18}O$ - Data

Test Combinations	t-Test Probability[1] α_t	Difference Between $\delta^{18}O$-Means	Least Significant Difference[2] $\alpha = 0.05$	$\alpha = 0.01$
		°/oo	°/oo	°/oo
21 March 1973				
Surface Snow : ⓐ	.06	1.17	1.14*	1.56
Surface Snow : ⓑ	.32	0.52	1.06	1.46
Surface Snow : ⓒ	.045	1.22	1.12*	1.55
ⓐ : ⓒ	> .50	0.05	1.28	1.83
22 March 1973				
Surface Snow : ⓐ	.32	0.55	1.18	1.62
Surface Snow : ⓑ	.22	0.60	1.01	1.38
Surface Snow : ⓒ	.18	0.79	1.07	1.47
ⓐ : ⓒ	> .50	0.16	1.08	1.49
Vertical Snow Profiles #1 : #2	< .001	2.35	0.86*	1.20*
21 March : 22 March				
Snow : Snow	.30	0.52	1.02	1.38
ⓐ : ⓐ	> .50	0.10	1.30	1.82
ⓑ : ⓑ	.08	0.60	0.72	1.01
ⓒ : ⓒ	> .50	0.01	1.01	1.42
21 & 22 March Combined				
Surface Snow : ⓐ	.035	0.88	0.77*	1.04
Surface Snow : ⓑ	.090	0.65	0.70	0.94
Surface Snow : ⓒ	.011	0.99	0.73*	1.00

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[1] α_t is the probability of error in inferring that the mean $\delta^{18}O$-values of the combination are actually different.

[2] the smallest difference which is statistically detectable according to the sample variance within α-probabilities of 0.05 and 0.01.

*indicates those least significant differences exceeded by the differences between means of the test combinations.

For comparison, $^{18}O/^{16}O$ ratios were determined for springs and soil water. $\delta^{18}O$-determinations from springs (including one flowing well) were -14.7, -17.4, -18.5 and -19.2 °/oo. Values for three Autumn 1972 rains were -11.2, -14.1 and -16.9 °/oo. Three rains during Autumn 1973 contained corresponding amounts of the ^{18}O-species, -11.1, -15.0 and -18.1 °/oo. Bailey *et al* (1973) reported $\delta^{18}O$-values of -16.4 to -14.1 °/oo for subsurface waters in southeastern Saskatchewan, which they considered meteoric.

Table 3 contains the maximum probable percents of total runoff passing locations ⓐ, ⓑ and ⓒ, which could have originated from soil water or spring sources. These percents were computed for each possible subsurface source, R_{sub}, by

$$R_{sub} = 100 \frac{(\delta^{18}O_{runoff} - \delta^{18}O_{snow})}{(\delta^{18}O_{sub} - \delta^{18}O_{snow})} .$$

Another argument favouring a very small contribution from subsurface sources is presented by the observed temporal variation in δ^{18}O for runoff. These compare closely to the areal variation of δ^{18}O for the melting snow. Differential melt rates over the patch caused by varying sun angle and cloud cover alone could easily account for this variability in O-18 runoff. Subsurface sources seldom display such fluctuations over such a short time interval.

Table 3. Maximum Probable Runoff Contributions from Two Subsurface Sources in Percent of Total, if the Observed δ^{18}O Differences Were Significant

		Subsurface Sources	
	(Mean δ^{18}O)[3]→ ↓	Soil Water (- 14.07)	Springs (-17.45)
		Max. Percent	Max. Percent
21 March 1973			
Surface Snow	(- 22.72)		
Runoff at ⓐ	(- 21.55)	13.5	22.2
Runoff at ⓑ	(- 22.20)	6.0	9.9
Runoff at ⓒ	(- 21.50)	14.1	23.2
22 March 1973			
Surface Snow	(- 22.20)		
Runoff at ⓐ	(- 21.65)	6.8	11.6
Runoff at ⓑ	(- 21.60)	7.4	12.6
Runoff at ⓒ	(- 21.49)	8.7	14.9

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[1] Based on three autumn 1972 rain samples computed as the sole subsurface source

[2] Includes samples from three springs and one flowing well computed as the sole subsurface source

[3] Mean δ^{18}O in ^{o}/oo listed in parenthesis for each group

Conclusions

Melting snow from the study patch contributed at least 85%, if not 100%, of the water flowing as surface runoff. Two days of monitoring δ^{18}O of the snow and the runoff resulted in an observed mean difference of 0.8 ^{o}/oo which was well within the average least significant difference of 1.5 ^{o}/oo. Oxygen-18 determinations associated with the soil water, the most likely subsurface source, differed sufficiently from those of the snow to suggest a maximum probable contribution between 5 and 15%.

These estimated maxima ignore any probability that a slight enrichment in oxygen-18 from snow to runoff, if significant, could have resulted from isotopic fractionation during evaporation.

According to a review by Krouse (1974), a number of investigators have reported slight oxygen-18 enrichments in association with the melting of snow or ice. If evaporation was significant, our data show that close to 100 percent of any day's runoff from the prairie snow patch was derived directly from the melting snow of that day.

ACKNOWLEDGMENTS

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