Deuterium as a tracer in snow hydrology

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ABSTRACT: Average deuterium content of 24 widely distributed samples of April 1 snowpack in the Colorado Front Range averaged \(-172^{\circ}/_{oo}\) relative to SMOW. The range extended from \(-180\) to \(-165^{\circ}/_{oo}\). Deuterium content of snow was significantly different from base streamflow and rain and can be used to label snow input to the hydrologic system on small watersheds. Snowmelt on a small forested catchment underwent considerable mixing with water in subsurface storage before appearing as runoff.

INTRODUCTION

The stable isotopes deuterium and oxygen-18 are useful as tracers in hydrologic systems. They are naturally present as part of the water molecules and their concentration is influenced by physical processes operating within the hydrologic cycle. Water containing the heavier isotopes has a lower vapour pressure than \(H_2O\).

The objective of this study was to investigate the feasibility of using deuterium in snow hydrology studies. Specifically, this involved studying: (1) the areal variability of snowpack deuterium content, and (2) the relationship between deuterium content of the snowpack and that of runoff from small watersheds.

Previous studies \cite{1} indicated a wide variability in individual snowfall deuterium content at a single location but considerable homogenization during metamorphic changes in the snowpack. These studies suggested that the snowpack becomes somewhat heavier (higher) in deuterium content as the snow season progresses.

Dincer, et al. \cite{2} used oxygen-18 and tritium to study snowmelt runoff from a mountain watershed in northern Czechoslovakia. Their results indicated that about two-thirds of the meltwater infiltrated the soil and displaced water recharged during previous years toward the stream channel.

Deuterium was used as a tracer by Simpson, et al. \cite{3} to study seasonal recharge to groundwater in southern Arizona. Friedman, et
al. [4] report on the variation of deuterium content of precipitation and runoff over a wide geographic area. Friedman and Smith [5] found that the deuterium content on the west slope of the Sierra Nevada snowpack in April, 1969, increased approximately 40°/oo per km increase in elevation and showed a strong west-east gradient related to topography.

STUDY AREA AND METHODS

Samples for comparison of snowpack deuterium content in the northern part of the Colorado Front Range (Fig. 1) were obtained from the April 1, 1971, snow survey by U.S. Soil Conservation Service personnel. Cores obtained with the snow sampler were placed in plastic bags, sealed, and allowed to melt. The meltwater was thoroughly mixed and a sample poured into a small bottle which was then tightly capped until processing.

Two small watersheds (Clear Creek (lat 39°41'N., long 105°54'W.) and Little Beaver (lat 40°38'N., long 105°38'W.) (Figs. 1-3)) were selected within the Front Range area for more intensive snow and stream sampling. The watershed area of Clear Creek is 8.5 km² with a mean elevation of -3,500 m, and that of Little Beaver is 31.8 km² with a mean elevation of ~2,800 m.

Snow samples were obtained at numerous positions in these watersheds on April 6, 1971, at Clear Creek, and on March 18, 1971 at Little Beaver. Stream samples were obtained during 1971 from both watersheds before, during, and after the "snowmelt runoff season". This snowmelt runoff season for watersheds such as those studied extends from April through August and includes 80 per cent or more of the total annual flow.

Aerial photographs of the Little Beaver watershed were used in estimating snow cover disappearance during the snowmelt runoff season (Table 1).

Table 1

<table>
<thead>
<tr>
<th>Date</th>
<th>% watershed</th>
</tr>
</thead>
<tbody>
<tr>
<td>March 29</td>
<td>93</td>
</tr>
<tr>
<td>May 28</td>
<td>59</td>
</tr>
<tr>
<td>June 11</td>
<td>28</td>
</tr>
<tr>
<td>June 28</td>
<td>4</td>
</tr>
</tbody>
</table>

All samples were converted in the laboratory to hydrogen gas and analyzed by mass spectrometer [6, 7]. Deuterium content is reported as parts per thousand deviation relative to SMOW (Standard Mean Ocean Water). Measurement is precise to ±1°/oo.

Precipitation measurements (Table 2) at the Quigley weather station near the mouth of the Little Beaver watershed at 2,470 m and the Bennett Creek snow course just adjacent to the watershed at an elevation of 2,835 m indicate seasonal distribution of precipitation. Past studies on snow distribution in the Little Beaver watershed indicate a large topographic variability, but a general increase in maximum snowpack accumulation of ~42 mm (water equiv.) per 100 m.
Table 2
Precipitation and snowpack indices for Little Beaver watershed, 1971

Quigley weather station (elev. 2,470 m)

<table>
<thead>
<tr>
<th>Month</th>
<th>Precipitation (mm), (water equiv.)</th>
<th>Month</th>
<th>Precipitation (mm), (water equiv.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>January</td>
<td>18</td>
<td>July</td>
<td>28</td>
</tr>
<tr>
<td>February</td>
<td>21</td>
<td>August</td>
<td>33</td>
</tr>
<tr>
<td>March</td>
<td>19</td>
<td>September</td>
<td>69</td>
</tr>
<tr>
<td>April</td>
<td>104</td>
<td>October</td>
<td>12</td>
</tr>
<tr>
<td>May</td>
<td>42</td>
<td>November</td>
<td>9</td>
</tr>
<tr>
<td>June</td>
<td>29</td>
<td>December</td>
<td>9</td>
</tr>
</tbody>
</table>

Bennett Creek snow course (elev. 2,835 m)

<table>
<thead>
<tr>
<th>Date</th>
<th>Snow water equivalent (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>February</td>
<td>165</td>
</tr>
<tr>
<td>March</td>
<td>211</td>
</tr>
<tr>
<td>April</td>
<td>226</td>
</tr>
<tr>
<td>May</td>
<td>231</td>
</tr>
</tbody>
</table>

RESULTS AND DISCUSSION

The results from the snow samples are presented in Figures 1-3. Deuterium values from the April 1 snow survey in the Front Range north of Denver fall within the range -180 to -165°/oo. The two study watersheds, though in different parts of the region and at different elevations, show similar snowpack deuterium values and are representative of the whole region.

Streamflow measurements were not taken at Clear Creek, but a continuous record of runoff is available for Little Beaver. Precipitation, snow cover, streamflow, and deuterium content of the stream are shown in Figure 4. The strong influence of snowmelt on runoff without any significant effect on deuterium content is apparent.

Deuterium determinations are summarized in Table 3. The deuterium values and associated snowpack water equivalents for the two small watersheds are presented in Table 4. The deuterium content of runoff is markedly higher (less negative) than that of the snowpack for both watersheds. The runoff from Clear Creek shows a decrease in deuterium content during the peak snowmelt runoff season. Little Beaver exhibits no such clear response in deuterium content during the snowmelt runoff. These results suggest that snow supplies a greater percentage of the actual water running off during the snowmelt season on Clear Creek in contrast to Little Beaver. Little Beaver apparently has a much greater mixing of the lighter-deuterium-content snowmelt with heavier-deuterium-content subsurface water.

Two periods of summer rainfall during 1971 were sampled for deuterium concentration on the Little Beaver watershed. During the period July 19 to July 29, 25.2 mm of rain had a deuterium value of -78°/oo. An additional 6.4 mm of rain fell in the period July 29 to August 4 and had a deuterium value of -102°/oo. These samples were accumulated in a standard U.S. rain gauge (8-in orifice with funnel)
Table 3
Summary of 1971 deuterium determinations, \(^{0}/_{oo}\)D relative to SMOW (Standard Mean Ocean Water)

<table>
<thead>
<tr>
<th>Regional Samples - April 1</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Average of 24 samples</strong></td>
</tr>
<tr>
<td><strong>Range</strong></td>
</tr>
</tbody>
</table>

**Little Beaver Drainage Area**

<table>
<thead>
<tr>
<th>Date</th>
<th>Average</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average of March 18 Snow Survey</td>
<td>-171</td>
<td>-169 to -175</td>
</tr>
<tr>
<td>Snow course at 3,170 m on April 1</td>
<td>-160</td>
<td></td>
</tr>
<tr>
<td>Stream samples - Range</td>
<td></td>
<td>-135 to -141</td>
</tr>
<tr>
<td>February 11</td>
<td>-139</td>
<td></td>
</tr>
<tr>
<td>March 3</td>
<td>-139</td>
<td></td>
</tr>
<tr>
<td>March 30</td>
<td>-138</td>
<td></td>
</tr>
<tr>
<td>May 4</td>
<td>-135</td>
<td></td>
</tr>
<tr>
<td>May 11</td>
<td>-137</td>
<td></td>
</tr>
<tr>
<td>June 2</td>
<td>-138</td>
<td></td>
</tr>
<tr>
<td>July 29</td>
<td>-139</td>
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<tr>
<td>August 20</td>
<td>-138</td>
<td></td>
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<tr>
<td>August 26</td>
<td>-138</td>
<td></td>
</tr>
<tr>
<td>September 2</td>
<td>-135</td>
<td></td>
</tr>
<tr>
<td>September 13</td>
<td>-137</td>
<td></td>
</tr>
<tr>
<td>October 2</td>
<td>-135</td>
<td></td>
</tr>
<tr>
<td>October 15</td>
<td>-137</td>
<td></td>
</tr>
<tr>
<td>October 23</td>
<td>-141</td>
<td></td>
</tr>
</tbody>
</table>

**Clear Creek Drainage Area**

<table>
<thead>
<tr>
<th>Date</th>
<th>Average</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average of April 6 Snow Survey</td>
<td>-175</td>
<td>-168 to -181</td>
</tr>
<tr>
<td>Stream samples - Range</td>
<td></td>
<td>-140 to -152</td>
</tr>
<tr>
<td>April 7</td>
<td>-144</td>
<td></td>
</tr>
<tr>
<td>April 23</td>
<td>-148</td>
<td></td>
</tr>
<tr>
<td>May 30</td>
<td>-150</td>
<td></td>
</tr>
<tr>
<td>July 1</td>
<td>-150</td>
<td></td>
</tr>
<tr>
<td>August 5</td>
<td>-152</td>
<td></td>
</tr>
<tr>
<td>September 7</td>
<td>-141</td>
<td></td>
</tr>
<tr>
<td>October 1</td>
<td>-140</td>
<td></td>
</tr>
<tr>
<td>December 7</td>
<td>-141</td>
<td></td>
</tr>
</tbody>
</table>

Charged with hexadecanol to prevent evaporation. If deuterium values of \(-170^{0}/_{oo}\) for snow and \(-90^{0}/_{oo}\) for rain are assumed, then the Little Beaver runoff would be approximately 60 per cent from snow and 40 per cent from rain. These values appear to be realistic for the watershed considering temperature and precipitation distribution.

Care must be taken in interpreting the results because not all precipitation was sampled throughout the year. Late snows in April and May would be expected to have somewhat higher deuterium content; new snow sampled in late May at an elevation of 3,170 m had a deuterium value of \(-152^{0}/_{oo}\).
Table 4
Snowpack water equivalent and deuterium content of individual cores from snow course

<table>
<thead>
<tr>
<th>Little Beaver, March 18, 1971</th>
<th>Clear Creek, April 6, 1971</th>
</tr>
</thead>
<tbody>
<tr>
<td>mm H₂O</td>
<td>°/oo D</td>
</tr>
<tr>
<td>76</td>
<td>-169</td>
</tr>
<tr>
<td>76</td>
<td>-171</td>
</tr>
<tr>
<td>190</td>
<td>-171</td>
</tr>
<tr>
<td>250</td>
<td>-172</td>
</tr>
<tr>
<td>267</td>
<td>-169</td>
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<tr>
<td>381</td>
<td>-175</td>
</tr>
<tr>
<td>Average</td>
<td>-171</td>
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<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>Average</td>
<td></td>
</tr>
</tbody>
</table>

SUMMARY AND CONCLUSIONS

The average deuterium content of twenty-four widely distributed samples of April 1 snowpack in the Colorado Front Range averages -172°/oo relative to SMOW. The range was from -180 to -165°/oo. More intensive sampling on two small watersheds indicated snowpack values within this range and very close to each other, irrespective of elevation, slope, and aspect. These results are encouraging with respect to potential use of the deuterium content as a label on the snow input to the hydrologic cycle, inasmuch as (1) snow has a relatively uniform deuterium content within a small watershed, and (2) the deuterium content of snow is significantly different from that of base streamflow and of rain [4].

The results of deuterium studies of snow and runoff on the two small watersheds illustrate the potential application of using deuterium as a natural tracer in snow hydrology studies. Clear Creek (a high-elevation, deep-snowpack, small watershed with limited storage capacity as compared to Little Beaver) had a 7 per cent decrease in deuterium content during the peak snowmelt runoff period. Little Beaver, though exhibiting a strong influence of snowmelt in the spring runoff hydrograph, did not show a corresponding decrease in deuterium content in the streamflow. Snowmelt in Little Beaver appeared to undergo considerable mixing with rainwater in subsurface storage before appearing as runoff.

ACKNOWLEDGMENTS

Special appreciation is extended to personnel of the U.S. Soil Conservation Service Snow Survey who obtained the April 1 samples used in this study and also to the management of the Loveland Ski Area for their cooperation. This study is a cooperative endeavour of Colorado State University and the U.S. Geological Survey and is funded in part under the McIntyre-Stennis Cooperative Forest Research Project No. 15-1482-351.
REFERENCES


Fig. 1. Map of north-central Colorado showing deuterium (°/oo relative to SMOW) in Front Range snowpack on about April 1, 1971. Study watersheds are indicated by large open circles. Elevations on map are given in feet. North is at top of page.
Fig. 2. Deuterium (°/oo relative to SMOW) in snowpack on April 6, 1971, on Clear Creek watershed. Elevations on map are given in feet. North is at top of map.
Fig. 3. Deuterium (°/oo, relation to SMOW) in snowpack on March 18, 1971, on upper part of Little Beaver watershed. Elevations on map are given in feet. North is at top of page.
Fig. 4. Precipitation, snow cover, runoff, and stream deuterium content on Little Beaver watershed, January-September, 1971. Precipitation samples collected adjacent to stream-sampling locality, shown on Figure 3.
DISCUSSION

J. Martinec (Switzerland) - As you pointed out, there is a distinct difference between the deuterium content in rain, snowpack water and streamflow, respectively. I wonder whether a quantitative interpretation would be possible. It would seem that a major part of streamflow originates from or is fed by subsurface water even during intensive snowmelt.

My second question is whether parallel sampling using tritium as a backup technique would assist in confirming the results, as deuterium results might be affected by evaporation at the snow surface and by the snowmelt process.

J.H. Meiman (U.S.A.) - Parallel sampling using other tracers, such as tritium, is an excellent idea. Unfortunately, one must always consider the cost associated with this practice.

The possibility of quantifying streamflow into source components by deuterium tracing is hindered by the difficulty of obtaining representative deuterium contents for rain. Individual summer rains sampled on the Little Beaver Watershed showed very high variability of their respective deuterium contents. The areal variation in rainfall amounts for any one storm also presents difficulty.

Although we applied estimated deuterium concentrations for rain and snow in our paper and obtained realistic rain and snow contributions, we suspect that the large variability and complexity, as Dr. Krouse discussed earlier, would make the problem quite difficult.

K.S. Davar (Canada) - The information conveyed in Figure 4 of your paper provides very important information for modelling watershed response to snowmelt input. It reinforces the growing expectation that meltwater is not moving directly into the channel system; rather, the meltwater enters the watershed storage system which functions in a manner analogous to a reservoir and displaces water in storage which appears subsequently in the channel system.

Further research by such tracing techniques should clarify how surface runoff, subsurface transmission, and the groundwater reservoir system function in the generation of streamflow resulting from snowmelt. Such insights would be of great value in correctly modelling the routing process in predicting overall watershed response.

J.R. Meiman (U.S.A.) - As Dr. Davar states, the routing of water through the system is indeed a major problem in snowmelt models. Stable isotopes used as a tracing tool are not currently sophisticated enough to yield answers to extremely definitive questions.

H. Moser (Federal Republic of Germany) - I would like to underline the comments of Dr. Martinec on the use of tritium measurements for snow investigations. A combination of the results of both isotope measurements (tritium and deuterium) would provide, in certain cases, information about the components of direct runoff and snowmelt routed through the subsurface. Travel times can also be obtained by such measurements.

Using these techniques, researchers have been able to separate glacial runoff quantitatively into contributing components from old glacier ice, snow and subglacial springs, seeping through the glacier. (Published last year in Zeitschift fur Gletscherkunde und Glazialgeologie.)
J.R. Meiman (U.S.A.) - I agree that the application of different kinds of tracers results in more information.

Glacial runoff is usually a more direct response to rain and meltwater input than runoff from watersheds such as the Little Beaver in Colorado. Perhaps this explains the success of tracer techniques used on glaciers and the difficulty in their use on other watersheds.