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Isotope Input into Runoff Systems from Melting Snow Covers

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Stable environmental isotope techniques contribute to reasonable separations of the direct runoff component in snowmelt hydrographs. For the separation procedure, the actual isotope input from snow cover outflows is required. In order to study the effects of isotope fractionation and exchange processes in the snow cover on the isotopic outflow concentrations several cold room experiments have been carried out with isotopically homogeneous and stratified snow columns. To simulate natural conditions the columns were treated with different heat supply and rainwater at the surface, and the outflows analysed for ^{2}H and ^{18}O contents. Some fundamental results are discussed with respect to the more complex natural situation. Finally, the hydrological application of such experience is demonstrated for a natural environment.

Outline of the Problem

The stable environmental isotopes deuterium (^{2}H) and oxygen-18 (^{18}O) are ideal tracers in the hydrologic cycle, thus supplying effective insight into basin runoff mechanisms and storage dynamics. Isotope techniques have been systematically applied to a catchment of 18.7 km^2, 670-1,801 m a.s.l. during 1975-78 (Herrmann and Stichler 1980). The Lainbach valley is situated in the Bavarian Alps about 60 km south of Munich. 80% of the area is covered by timber, with spruce dominating. The annual precipitation rate amounts to 2,000 mm, 1/3 of it being snow.

To achieve the mentioned research aims, stable isotope balances have been established for different time ranges: single runoff events, main seasons, and

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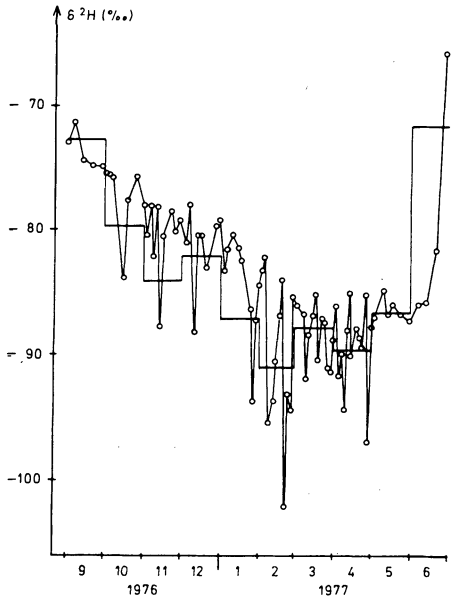

Fig. 1. Deuterium contents of the Lainbach Creek with weighted monthly means during the snow cover season 1976-77.

years. Accordingly, different requirements had to be set towards the resolution of the isotope input in time. The annual stable isotope input is delineated by a sinusoidal curve with an amplitude of about 50‰ for δ^2H. Differences of the ^2H inputs in the order of 50-100‰ are quite common between subsequent precipitation events. Even during single events variations of up to 15-20 are not unusual.

During summer the isotope contents of the rainwater directly affect the isotopic output function of the basin (Herrmann and Stichler 1980), whereas, during winter temporary water and isotope storage in a snow cover is intercalated. This causes specific isotopic output curves. In Fig. 1, the ^2H contents of the Lainbach creek are plotted together with the weighted monthly means using the snow cover season 1976-77 as an example. As a consequence of the isotopically light water of the winter precipitation, output peaks also indicate low isotope contents. But maximum variations are now restricted to 20‰. Furthermore, the output curve implies distinct phase shifts in comparison to the original isotope input up to several weeks.

The hydrological applications of environmental isotope techniques (see below) require the real or actual isotope input values from the snow cover outflows. Their isotope contents are mainly controlled by: 1) the inverse melting of the original accumulation sequence in snow layers, and 2) isotope fractionation and exchange processes during snowmelt in the snow cover (Stichler et al. 1981). Additional effects result from the variations of melt intensities, isotopic inhomogeneity of the snow cover, and from the influence of rainwater. The following results of laboratory experiments contribute to better insights into the complex superposition of these effects in nature.

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Laboratory Experiments

In cold room experiments at the GSF Institut für Radiohydrometrie, the effects of melting and rain on a snowpack were simulated with snow columns of 65 cm^2 in area, and of 35 cm or 100 cm in length. In the course of the experiments, snow of different structure in isotopically homogeneous and stratified columns was treated with different intensities of melt and rain. Temperature and air humidity in the cold room were kept constant at a few tenths below 0°C and at 60%, respectively.

The Experimental Arrangement (Fig. 2)

A plexiglass tube filled with snow stands on a sieve, which covers the top opening of a funnel. From there, the outflowing water drops into a bottle on an electronic balance. The cumulative outflow is continuously weighed. After a chosen time interval that can be preselected with an electronic timer the weight is printed.

In order to simulate atmospheric heat input, a flat heating spiral lies permanently on the top of the snow column. The electrical heating power is controlled by means of a transformer. To simulate rain on snow, liquid water is poured with a burette.

a) *Homogeneous snow cover*

Description of the experiment:

Length of snow column	: 100 cm
Snow density	: 470 kg/m^3
Deuterium content of snow	: –103.0‰
Deuterium content of outflow	: –101.5‰
Isotopic enrichment	: 1.5‰
Average melt rate	: 50 mm/d
Duration of experiment	: 6 d

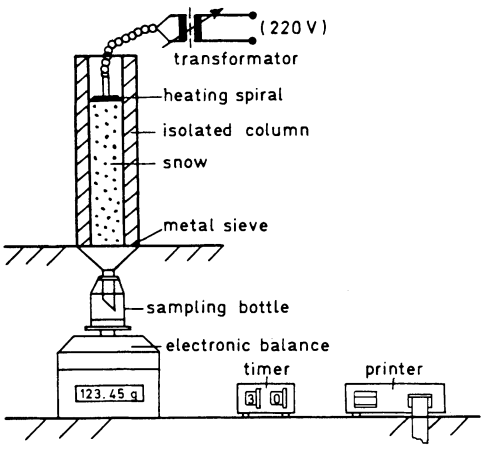

Fig. 2. Instrumentation for snow column experiments.

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With this basic experiment continuous melt at a constant rate of an isotopically and structurally homogeneous snowpack is simulated. The average melt rate corresponds to maximum amounts in nature.

Results (Fig. 3)

The ^2H contents of the meltwater outflow and the remaining snow describe characteristic curves of different slope. The first meltwater sample has a ^2H content of about 15‰ less than that of the initial snow due to fractionation effects. With progression of the melt process the isotope contents of the outflow and the snow approach each other. A final difference originates in the sum effects of evaporation and condensation. An isotopical enrichment of 1.5‰ during the experiment is calculated from the isotope balance, which results from minor evaporation loses in the order of 7%. This is confirmed by the water balance.

These results are compatible with the experiments carried out by Arnason (1969a, 1969b), and with the theoretical consideration by Buason (1972). In literature different fractionation factors are found for the isotopic fractionation between ice and water due to a lack of equilibrium conditions during the experiments. The "effective fractionation factor" (Arnason 1969a) is for the mentioned experiment 1.017 which is very close to the theoretical value of 1.0192. Consequently, the experiment was well arranged.

Under homogeneous conditions the δ^2H-$\delta^{18}O$-relations for snowpack outflows can be approximated by a straight line with a slope of about 6.3 (Fig. 4). The diagram also demonstrates the non-equilibrium conditions during the permanent

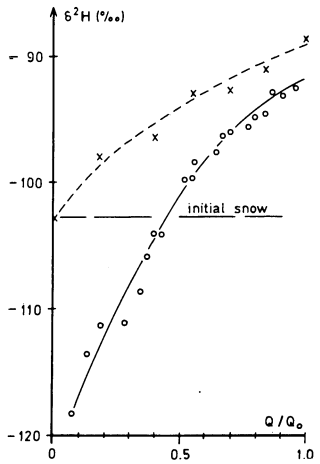

Fig. 3. Development of the ^2H contents of a steadily melting and isotopically homogeneous snow column, and of the outflowing water.

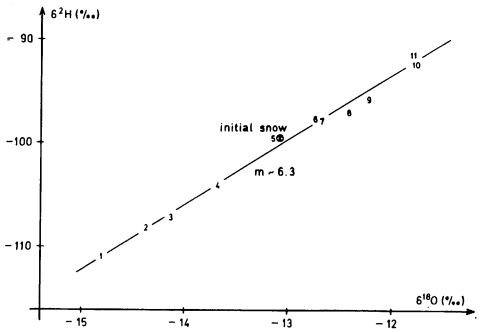

Fig. 4. $\delta^2H - \delta^{18}O$ – relations for the outflowing water from a steadily melting and isotopically homogeneous snow column.

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isotopic enrichment of the outflowing water. In this case, a structurally and isotopically homogeneous snow column of 35 cm in length was melted at an average rate of 70 mm/d.

b) *Alternating melting/non-melting*
Description of the experiment:

Length of snow column	: 35 cm
Snow density	: 370 kg/m^3
Deuterium content of snow	: –111.4‰
Deuterium content of outflow	: –110.7‰
Isotopic enrichment	: 0.7‰
Average melt rate	: 41.5 mm/d
Duration of experiment	: 2.5 d

Using an isotopically and structurally homogeneous snowpack, the experiment simulates the daily energy alternations at the snow cover surface – with energy gain during the day, and energy loss during the night. For this purpose, the heating was turned on and off in a rhythm of 12 hours.

Results (Fig. 5)
The meltwater which is produced during the first melt period does not leave the column before the repeated meltwater production on the 2nd day leads to the outflow of the isotopically lightest fractions. Starting from a minimum isotope content of 12.5‰ below that of the initial snow column, an important isotopic enrichment of up to 8.3‰ above the isotope content of the initial column is observed afterwards. As a consequence of repeated melting, this continuous enrichment is interrupted on the 3rd day by the pushing out of isotopically heavy meltwater dating from the day before, and followed again by a significant but less distinct isotopic enrichment because of the reduced length of the column. From the heat flux increase by 1/3 after 2/3 of the outflow have been accomplished result nearly constant isotope contents of the outflow. This is mainly due to the quick passage of the meltwater through the remaining snow column.

To sum up, alternations of the melt intensities can cause marked variations of the isotope contents of snowpack outflows. Increased meltwater production is first succeeded by heavy-isotope depletions, and meltwater decrease by enrichments. As a result of reduced isotopic exchange processes rapid passage of the meltwater through the snowpack effects nearly equal isotope concentrations in snowpack outflows.

c) *Stratified snow cover*
Description of the experiment:

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Length of snow column	: 35 cm			
		surface layer	bottom layer	
Snow density	:	386	409	kg/m^3
Deuterium content of snow	:	−141.4	−124.8	‰
Weighted deuterium content of snow column	: −132.9‰			
Deuterium content of outflow	: −130.1‰			
Isotopic enrichment	: 2.8‰			
Average melt rate	: 48.7 mm/d			
Duration of the experiment	: 3 d			

By this experiment the melting of a structurally and isotopically stratified snowpack under constant heat supply was simulated.

Results (Fig. 6)

Under homogeneous conditions differences of the ^2H contents between the initial snow and the outflows in the order of 15‰ are common (cf. a). In this experiment, the difference of 2‰ between the surface layer, where the initial meltwater is produced, and the outflows is very small. The reason is their isotopic enrichment while percolating through the isotopically heavy bottom layer. The melting procedure enriches the bottom layer with heavy isotopes due to the isotope fractionation processes in the surface layer. By this mechanism the difference between the

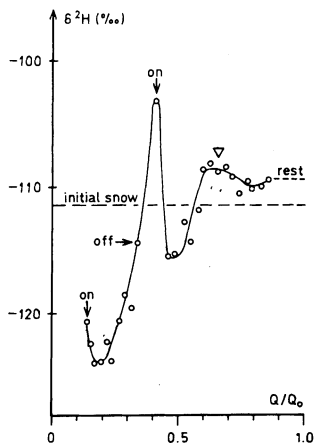

Fig. 5. Developments of the ^2H contents of the outflowing water from an isotopically homogeneous snow column, to which heat supply is alternatively turned on and off, and increased (∇).

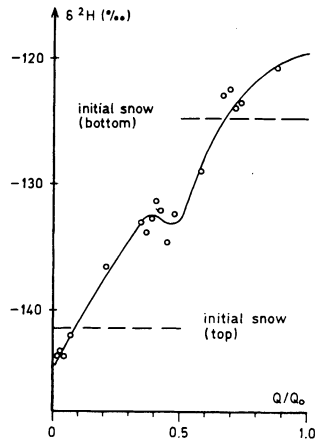

Fig. 6. Development of the ^2H contents of the outflowing water from an isotopically stratified snow column under steady melt (surface layer isotopically light, bottom layer heavy).

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isotope contents of the initial bottom layer and the meltwater produced there is also rather small.

A change in the slope of the δ^2H-$\delta^{18}O$-relationship indicates the inclusion of meltwater from the bottom layer. At this time interval about 1/2 of the outflow is accomplished, and the weighted mean ^2H content of the initial snow column identified.

d) *Rain on a snowpack*
Description of the experiment:

		Column I		Column II	
Length of snow column	:		35		cm
Snow density	:	550		521	kg/m^3
Rainfall depth	:		30.75		mm
Rainfall intensity	:		1.8		mm/min
Deuterium content of snow	:	–117.5		117.5	‰
Deuterium content of rain	:	+ 3.1		–193.9	‰
Deuterium content of outflow					
measured	:	– 99.6		–126.0	‰
calculated	:	–100.9		–128.5	‰
difference	:	1.3		2.5	‰
Average melt rate	:		96		mm/d

With this experiment the influence of rain on the isotope content of the outflow from a melting, structurally and isotopically homogeneous and well draining snowpack was simulated. The rainwater temperature was 0°C. The rain-on-snow experiments with isotopically heavy (Column I) and light rainwater (Column II) started after the first meltwater samples had been taken.

Results

Column I (Fig. 7)
The rainwater portion is 16% of the water equivalent of the snow column. Due to the extraordinary difference between the isotope contents of the rainwater and the initial meltwater of 120‰ the rainwater causes a marked graph of the outflow concentrations. Taking the isotopic output from the homogeneous and purely melting snow column a) as a reference, then the rainwater contributes about 5 hours to the total outflow. For this interval, the rainwater proportion in total outflow is 35% as calculated from the hydrological balance, and 44% from the isotope balance. Consequently, the isotope exchange of the rainwater with the snow column is in the order of 10%.

Column II (Fig. 8)
The experiment with isotopically light rainwater produces a similar but less

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marked graph of the outflow concentrations due to the smaller difference between the isotope contents of the rainwater and the initial meltwater. Rainwater proportions of 49% and 43% in total outflow during a 4.5 hour interval are calculated from the hydrological and isotope balances. The minor isotope exchange of the rainwater with the snow of Column II shows that the rainwater passage was more

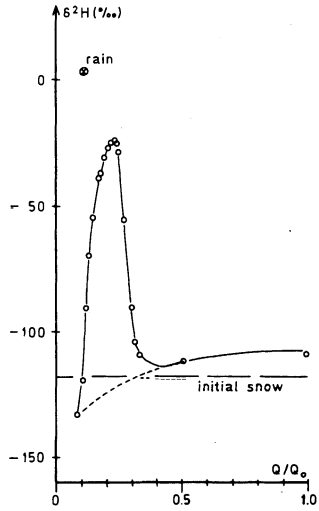

Fig. 7. Development of the ^2H contents of the outflowing water from an isotopically homogeneous snow column under steady melt, and isotopically heavy rainwater on it.

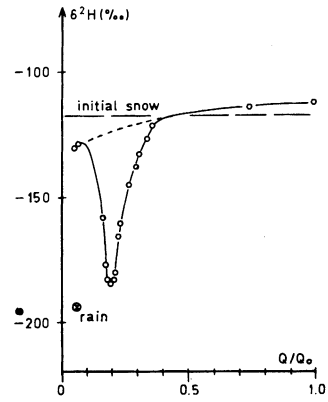

Fig. 8. Development of the ^2H contents of the outflowing water from an isotopically homogeneous snow column under steady melt, and isotopically light rainwater on it.

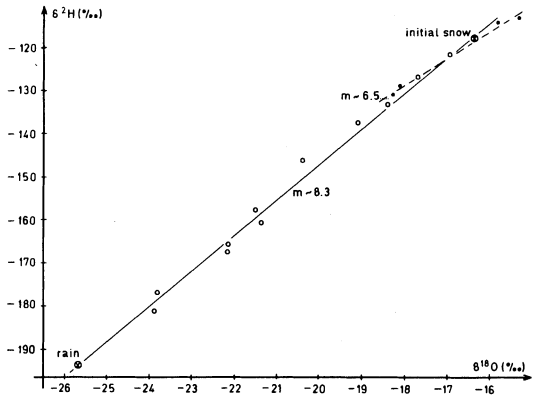

Fig. 9. $\delta^2H - \delta^{18}O$ – relations for precipitation water in Central Europe (slope m ≅ 8), and for the outflowing water from steadily melting, isotopically homogeneous snow columns with (m ~ 6.5) and with rain influence (m ~ 8.5).

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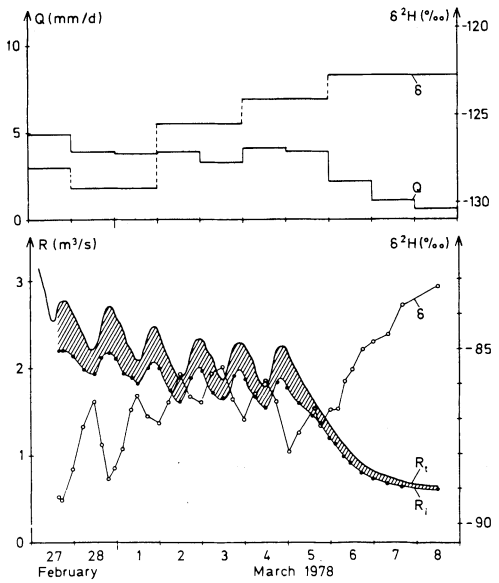

Fig. 10. Variations of the deuterium contents and amounts of the lysimeter outflows (top), and of the deuterium contents and discharge of the Lainbach Creek with isotopically separated direct runoff component (bottom) during an ablation period in the early spring 1978.

rapid than in Column I.

The δ^2H-$\delta^{18}O$-relations in Fig. 9 additionally prove the rainwater influence on the isotopic composition of snowpack outflow. Whereas the initial snow and pure meltwater are arranged around a straight line with a slope of 6.5, the rainwater and the mixture of rain- and meltwater yield a mixing line with a slope of 8.3. This is mainly due to the isotope exchanges of the rainwater with the snowpack. Their effects superimpose those from isotope fractionation as a result of heat input.

Hydrological Application

The main field of application of such experiments is the continuous isotopical separation of snowmelt hydrographs (Herrmann et al. 1978). After the simple two-component separation model the direct runoff is defined to have the isotope content of the actual input, i.e. of the snow cover outflow. Whereas, the remaining variance of the isotope content of the meltwater runoff is caused by the indirect component. For the procedure an exact knowledge of the actual isotope input is a major supposition.

In Fig. 10, the recession limb of a snowmelt hydrograph of the Lainbach creek is drawn at the bottom, together with the ^2H contents of the total runoff. The

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latter describes typical diurnal oscillations. The runoff mechanism derived from the isotopical direct runoff separation is characterized by regular pulsations of the water supplies from surface (snow cover) and subsurface reservoirs (groundwater).

Two recording snow lysimeters (Herrmann 1978) were located in an open area and in a forest stand at the mean area altitude. They were used to ascertain the actual mean areal isotope inputs. The ^2H contents and outflow rates measured at the open area lysimeter are presented at the top of Fig. 10. In general, clearly but less distinctly than in the laboratory experiments also under natural conditions higher snow cover outflow rates correspond to smaller differences between the isotope contents of the outflow and the remaining snow cover. Thus, according to Herrmann and Stichler (1978) specific ablation mechanisms can be concluded from such natural isotope content differences.

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