Modelling snowmelt runoff using environmental isotope and conventional methods

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ABSTRACT In the small hydrological research basin of Lange Bramke (Harz Mountains, Federal Republic of Germany) snowmelt periods are analysed with respect to runoff mechanisms using the stable isotope $^{18}O$ as a tracer. For this purpose, isotope hydrological characterizations of open area and forest test plot snow covers (snowpack and snow layers) are performed as well as determination of isotopic input functions from recording and automatically sampling snow lysimeters. Isotopic separation of direct snowmelt runoff components shows that groundwater is the dominant contribution to flood formation by more than 90%. This is confirmed by application of a simple but physically-based conventional Snowmelt-Runoff Model (SRM).

La modélisation du ruissellement des eaux de fonte avec utilisation des méthodes environnementales classiques et par isotopes

RESUME Dans le petit bassin de recherche hydrologique de Lange Bramke (Montagnes du Harz, République Fédérale d'Allemagne), les périodes de fonte nivale sont analysées concernant le mécanisme de ruissellement, en utilisant l'isotope stable $^{18}O$ comme traceur. Dans ce but, on a exécuté des caractérisations hydrologiques par isotopes des couvertures de neige sur des terrains d'essai (en zone découverte ainsi qu'en forêt). On a aussi déterminé les fonctions isotopiques d'entrée au moyen de lysimètres de neige enregistreurs et échantillonneurs automatiques. La séparation isotopique des éléments du ruissellement direct des eaux de fonte conduit à des contributions dominantes des eaux souterraines à la formation des crues (plus de 90%), cet ordre de grandeur étant confirmé par l'application du modèle classique "fonte nivale-ruissellement" qui est simple mais à base physique.
Studies of snowmelt runoff components using environmental isotope measurements (Herrmann et al., 1979; Sklash & Farvolden, 1979; Rodhe, 1984) demonstrate the dominant role of groundwater in peak discharge formation during melt periods. This finding seems also to be valid for rainfall induced mixed floods (Herrmann & Rau, 1984), and conforms with the results found for storm hydrographs (Stichler & Herrmann, 1985). The hydraulic mechanism involved might be attributed to local rise of groundwater levels with compression of the capillary fringe when the infiltration process starts (Sklash & Farvolden, 1979; Stauffer & Job, 1982). As a consequence of such analytical solutions, the traditional concepts that runoff is mainly generated by surface flow must be revised. As far as snowmelt runoff is concerned, synthetic hydrograph treatment, such as that proposed by Viessman (1970) for example, is not very useful because it ignores basic hydraulic facts. The WMO (1986) intercomparison of snowmelt runoff models and our own experience (Herrman et al., 1979; Herrman & Rau, 1984) suggest that predominantly physically-based models, such as the Snowmelt-Runoff Model (SRM; Martinec et al., 1983), where recession flow and actual input are combined, can satisfactorily simulate discharge during melt periods because in these models realistic description of the runoff mechanism is included.

In this study, basin input-output relationships during snowmelt are discussed using the stable environmental isotope $^{18}O$ as a tracer. The results are compared to those obtained by applying the SRM. Up to now, hydrological knowledge about tracers stratified snow cover stores and their outflows has been restricted to at most a daily time basis and to the Alpine area as demonstrated by Herrmann et al. (1979) or Stichler et al. (1981). Therefore, considerable experimental effort was made in order to obtain a deeper insight into the turnover of water during snowmelt periods. The case study of the Lange Bramke highland basin of Palaeozoic rock situated in the Harz Mountains, Lower Saxonia, FR Germany described here coincides with the demand for further non-alpine applications of the isotope technique (Stichler & Herrmann, 1982). However, the limits of the technique become obvious in this area mainly because there is a considerable damping of the isotopic input function compared to the Alps and a less significant basin response to the tracer input signal.

The tracer hydrology research programme being carried out in the Lange Bramke basin (0.76 km$^2$, 543-700 m a.m.s.l., 90% forested) since 1980, including the experimental network design, is described by Herrmann et al. (1984). Technical information about the two recording 2 m$^2$ snow lysimeters, which are equipped with tipping buckets and automatic sampling devices and situated in the centre of the basin at 580 m a.m.s.l. in an open area and an adjacent 35 years old spruce stand, is given in Herrmann & Rau (1985). Discharge is also automatically sampled. Other parts of the snow hydrological research programme consist of basin snow cover surveys by snow tube measurements at weekly intervals at least, and of snow profile assessments according to the techniques given by UNESCO/IAHS/WMO (1970).
Oxygen-18 is a constituent of the water molecule and, therefore, an ideal tracer for the water cycle (for further information see Moser & Rauert, 1980; Gat & Gonfiantini, 1981). Oxygen-18 contents are defined as a relative deviation, $\delta\%$, from an international standard water (V-SMOW). The measuring accuracy is $\pm 0.15 \delta\%$.

HYDROLOGICAL AND ISOTOPICAL CHARACTERISTICS OF THE BASIN

The mean annual precipitation over the period 1949-1984 in the Lange Bramke basin is 1315 mm and the mean annual runoff is 700 mm. The Penman evaporation amounts to about 500 mm per year. Since 1979, the average maximum areal snow cover depth has been 55 cm in open areas and 40 cm in the spruce stands. The respective water equivalents are 125 mm and 100 mm. Whereas precipitation is uniformly distributed all over the year, runoff dominates by 2/3 during the winter half-year. As shown in Fig. 1, high discharge periods are
closely connected with snowmelt, frequently coinciding with rainfall.

Figure 1 shows the annual isotopic input-output relationships for the Lange Bramke basin, where the $^{18}O$ curves describe typical sinusoidal basic waves with superimposed single peaks. In general, higher summer temperatures lead to isotope enrichment, whereas the lower winter temperature moves the peaks towards minor isotope concentrations. However, annual input variation ranges are distinctly less than in the Alps for instance.

Monthly values are damped by 1/3 compared to high and low alpine altitudes (Stichler & Herrmann, 1982). The damping or storage effect of the basin can be evaluated from comparison of the isotopic input and output functions in Fig.1. Modelling studies based on mathematical combination of these functions give less significant results than direct field experiments. Consequently refined versions of the common field experiments, with data collected automatically rather than manually, are required for the Lange Bramke basin.

The following considerations refer to the experimental results from March and April 1984. This interval is characterized by two distinct melt periods with a contribution of isotopically light meltwater to runoff as can be seen from Fig. 1.

**ISOTOPE HYDROLOGY OF SNOW COVER**

**Stratigraphy**

Accumulation and conservation of snow layers causes the typical isotope structures (profiles) of snow covers as demonstrated for high-alpine environments by Stichler et al. (1981). Such labelling of individual layers allows isotopic exchange processes and internal turnover of water to be evaluated provided that individual layers can be continuously identified and separated from each other. However, great difficulties could be expected in identifying such distinct layers in highland snow covers which are almost permanently near the melting point. In fact, the stratigraphic development of highland snow covers is characterized by frequent homogeneization phases with macroscopic merging of single layers as a main consequence (Herrmann & Rau, 1984) as shown in Fig. 2. Repeated melting and meltwater percolation prevent original isotope structures from being preserved over weeks or even months. The conditions resulting from such structural and isotopical merging are rather unfavourable for assessment of water fluxes within the snow cover and even for isotopic analysis of basin hydrology. This is because a significant deviation of the isotope level of the actual input from the background level of subsurface reservoirs is needed, as discussed below. Clear tracer input signals from snow cover outflows originating from isotopically very light snow layers are the exception in highland regions. This is, of course, mainly due to the smaller temporal variation in $^{18}O$ content of the winter precipitation and spatial variation within the snow. The differences between single layers, amounting to only 5-6% (Fig. 2), are largely minor as compared to cold high-alpine snowpacks with up to 10-15% (Stichler et al., 1981) spatial variation corresponding to the original variation range $^{18}O$ content in individual precipitation events.
Structural homogenization and isotopic merging effects are even more evident under a forest canopy where the surplus of net longwave radiation energy is used for melting. But forest snow layers are isotopically heavier than those in the open site. This finding is also valid for new snow layers.

Snowpack

The $^{18}$O contents of the two experimental snowpacks shown in Fig.3 describe typical curves. The general trend towards isotopic
depletion until the end of January is mainly caused by the accumu-
lation of lighter precipitation from progressively colder precipi-
tating air masses. This is followed by a period of stabilization
until the last 10 days of March. Superimposed peaks generally
reflect the isotopic effects of newly deposited snow, minor rain-
water storage and mass losses from specific layers through meltwater
outflow. Distinct melt periods occur during the first 10 days of
February, and the last 10 days of both March and April. These
intervals correspond to a more or less pronounced $^{18}$O concentration
increase due to heavy rainwater storage and loss of isotopically
lighter fractions. Abrupt decreases such as after the March melt
event are caused by light new snow deposition.

Systematic isotopic enrichment of forest in comparison to open
area snowpacks, of the order of 1-2% $^{18}$O, has been reported for
the first time by Stichler & Herrmann (1978b). The same phenomenon
is now being observed in the Harz Mountains, and is again valid for
both snowpacks and newly deposited snow. Isotopic enrichment of new
snow is probably caused by isotope exchange between snowflakes and
water vapour in forest stands. This effect could be amplified by
the low sinking velocities of snow flakes compared to rain drops,
for such differences in isotope content have not yet been ascertained
for rainwater samples. This hypothesis will be checked using cooling
trap experiments for sampling both water vapour and fog. The
isotopic enrichment of forest snow covers means that the tracer
signal from melting snow in heavily forested Lange Bramke basin is
distinctly attenuated and makes its later use for hydrograph
separation more difficult.

Snow cover outflows

Snow lysimeter outflows are sampled and recorded by 0.05 mm steps
i.e. with high resolution in time. Samples are usually mixed for
mass-spectrometric analysis on a 1 mm and daily basis. The $^{18}$O
content of the lysimeter outflows (Fig.4) can be considered as
realistic approximations of the mean areal isotope input concentra-
tion to the Lange Bramke system.

The $^{18}$O concentration curves of lysimeter outflows in Fig.4 agree
surprisingly well with the isotope contents of the snowpacks shown
in Fig.3. The rising limbs are mainly controlled by meltwater being
preferentially produced in the isotopically heavy top layers thus
producing continuously enriched outflows. Superimposed on this
development are the effects of isotope fractionation from melting,
i.e. in the initial state of meltwater production the isotopically
light fractions are leaving the snowpack followed by the heavier
fractions. Continuous isotopic enrichment of snow cover outflow
and the remaining snowpack under uninterrupted melting conditions
[which has been predicted from theoretical considerations by Buason
(1972) and verified by laboratory tests (Herrmann et al., 1981) and
field experiments in the Alps (Herrmann et al., 1979; Stichler et
al., 1981)] is achieved perfectly in mid-April at both experimental
sites despite much more difficult natural conditions. Unfortunately,
it is hardly possible to separate the stratigraphic and fractiona-
tion effects on the isotope content of the snowpack outflows. But
it seems that both effects are responsible for the distinct isotopic
enrichment of snow covers and outflows by 4% $\delta^{18}O$ at the open site and by 5.5% in the forest stand. These values agree well with the values of 3% and 7.5% which have previously been reported from medium and high-alpine altitudes (Herrmann et al., 1979, 1981; Stichler et al., 1981).

The absolute difference in the isotopic enrichment of outflows from both experimental snowpacks might be attributed to different initial isotope structures and combined isotope exchange processes during meltwater percolation through the snowpack. In any case a realistic quantification of all effects cannot be performed without considering the free water content temporarily stored within single layers and repeatedly mobilized by increased meltwater supply from the snow-cover surface. Taking into account the fact that forest snow covers are thinner and equipped with a simple hydraulic system of well draining pipes (Wankiewicz, 1979) and a low structural storage capacity, the time lags between the $^{18}O$ concentration curves in Fig.4 are clearly a result of the shorter percolation distances and residence times of meltwater in forest as compared to open area snowpacks, assuming that outflow rates are the same.
According to Fig. 5 there are hardly any significant diurnal variations of the isotopic content of snowpack outflow have been produced for instance in laboratory experiments by Herrmann et al. (1981). In these experiments an isotopically homogeneous snow column underwent diurnal melt energy and free water content changes including complete refreezing and, therefore, different fractionation effects. As a result, increased meltwater production was first succeeded by isotope depletion, and meltwater decrease by isotope enrichment. For the first time, a corresponding curve for natural field conditions can be presented. This is associated with the initial phase of the melt period on 14 April (Fig. 5). Once meltwater production and percolation are under way the isotope content of outflows from isotopically stratified natural snow covers are of rather complex origin.

Fig. 6 summarizes the main features of typical isotopic input functions from the snow cover stores of the Lange Bramke system. These functions have been slightly smoothed and weighted with the associated area as shown in Fig. 8, in order to make them suitable for the hydrological application discussed below. At both experimental sites, clear signals come from heavy rain (14 mm) on 16 April with $\delta^{18}O = -9.53\%o$. According to these results and laboratory experiments with ripe snow columns by Herrmann et al. (1981), the rainwater input should have totally passed through the snowpacks within a few hours.
Isotope balance

Some reliable combined isotopic and hydrological balances of experimental snow covers have been reported by Stichler et al. (1981) (from the Weissfluhjoch test plot near Davos/Switzerland at 2540 m a.m.s.l.) and by Stichler & Herrmann (1978a) (from the Eibelsfleck test plot situated in the Lainbachtal basin, Bavarian Alps, at 1030 m a.m.s.l.). At these sites the water balances could be verified using the associated energy balances. The main problems in such studies are that the initial water equivalent of the lysimeter snowpack has to be observed and an empirical isotope fractionation factor ($\alpha$) has to be used to estimate evaporation loss by comparing the $\delta$-values of the lysimeter outflow ($\delta_{\text{out}}$) and the initial snow column ($\delta_{\text{snow}}$) plus precipitation ($\delta_{\text{prec}}$). Maximum evaporation losses can be calculated by using the Rayleigh equation for distillation at equilibrium:

$$
(\delta_{\text{out}} + 1.000) = (\delta_{\text{snow+prec}} + 1.000) f^{1/\alpha-1}
$$

(1)

where $f$ is the fraction of (snow + prec) remaining after evaporation. A value of $\alpha$ ($^{18}O$) = 1.01423 may be derived from Kuhn & Thürkauf (1958) and O'Neil (1968). Better assessments of evaporation losses can be expected from the approach of Craig & Gordon (1965) if $\delta$-values of air moisture are available. For the results in Table 1 a value of $\alpha$ = 1.01 was used.

In reality, the maximum evaporation losses computed from isotope balances represent the sum of the effects of isotope fractionation by evaporation and condensation processes. Thus, according to Table 1, isotopic enrichment of the forest snow cover means that evaporation dominates condensation, whereas the final mass gain at the open site corresponds to isotopic depletion. But the order of magnitude of these differences is negligibly low compared to alpine environments, where mass losses of up to 10% of the total have been calculated and confirmed by the respective water balances. The $\delta_{\text{out}}$-values in Table 1 can be used to estimate average actual
TABLE 1  Mean $^{18}$O concentrations ($\delta$) and hydrological data (in mm) of major components as used for isotope balances of lysimeter snow covers, 12-23 April 1984

<table>
<thead>
<tr>
<th></th>
<th>Open area</th>
<th>Forest</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\delta_{\text{prec}}$</td>
<td>-12.27</td>
<td>-11.74</td>
</tr>
<tr>
<td>$\delta_{\text{(snow+prec)}}$</td>
<td>-12.46</td>
<td>-11.53</td>
</tr>
<tr>
<td>$\delta_{\text{out}}$</td>
<td>-12.46</td>
<td>-11.53</td>
</tr>
<tr>
<td>Precipitation</td>
<td>149</td>
<td>136</td>
</tr>
<tr>
<td>Outflow</td>
<td></td>
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<thead>
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<th>Isotope balance</th>
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<tr>
<td>Open area</td>
<td>+2%</td>
</tr>
<tr>
<td>Forest</td>
<td>-2%</td>
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meltwater contributions to basin runoff using equation (2) after areal weighting.

BASIN RUNOFF

Isotope contents

By substituting $\delta_1 = -9.38\%$ [which is the average $^{18}$O content of the subsurface runoff component of Lange Bramke Creek in 1981-1984 (Herrmann et al., 1985) the influence of isotopically light winter precipitation and meltwater supply on basin runoff can be roughly evaluated from Fig.1. In Fig.7, attention is focussed on the spring melt period 1984.

In Fig.7, a significant reaction to an isotopically light melt-

![FIG.7](image_url)  
**FIG.7** Multiple overlapping means of weighted daily $^{18}$O contents of total runoff with discharge ($Q$) of Lange Bramke Creek, 15 March-15 May 1984.
water input can be observed in the basin runoff. The initial subsurface background value of $\delta^{18}O = -9.42$ is close to the mean value for the whole subsurface reservoir previously mentioned. This initial value is regained at the end of April when basin snow cover storage is almost zero. The onset of this final melt period of the season is analysed further in the following section where the runoff mechanisms are considered.

**Direct runoff separation**

The isotopic technique for direct runoff separation has recently been summarized by Stichler & Herrmann (1985). The formula for calculating the proportion, $d$, of direct to total runoff for stable isotopes and the simple two-component case is:

$$d = \frac{R_d}{R_t} = \frac{(\delta_t - \delta_i)}{(\delta_d - \delta_i)}$$

(2)

where $R$ is runoff, $\delta$ isotope concentration, and $t$, $d$ and $i$ are the proportions of the total, direct and indirect components of flow with $t = d + i = 1$. By the equation

$$\delta_d = \delta_{in}$$

(3)

the direct runoff component $R_d$ is defined as having the isotope concentration $\delta_{in}$ of the actual input which is here assumed to be equal to the weighted $\delta_{out}$ from snowpacks (cf. Table 1).

The results of the isotopic snowmelt hydrograph separation are given in Fig.8 together with those from the application of the simplified SRM (Martinec et al., 1983) with elevation intervals neglected:

$$R_n = c_n M_n (1 - k) + R_{n-1} k_n$$

(4)

where $R$ is the mean daily discharge, $M$ the daily meltwater input, $c$ the runoff coefficient, $k$ the recession coefficient, $n$ the sequence of days. In this model, $k$ is analogous to the indirect component $i$ in the mixing formula:

$$\delta_t = \delta_d (1 - i) + \delta_i i$$

(5)

SRM works on a daily basis and was mainly developed for runoff simulation and forecasting. Other conventional separation approaches have been excluded from this study because they can hardly contribute to realistic solutions of the problems.

**Results**

According to the results of isotopic direct runoff separation shown in Fig.8 the groundwater reservoirs (porous and fractured rock) play a dominant role in snowmelt hydrograph generation (in this basin). The mean direct runoff proportion of 10% for the time interval under consideration exceeds the average of the whole period 1980-1984
(Herrmann et al., 1985) by 1.5%, but is at most only half of that in alpine catchments (Stichler & Herrmann, 1982, 1985). If the minor contributions of antecedent light infiltration water transiently stored in the unsaturated soil zone were considered the direct runoff would be even less. As a matter of fact, considerable quantities of meltwater infiltrate the soil thus maintaining the quantitative balance between basin input and output.

These findings provide another experimental demonstration of the hydraulic turnover mechanism during single runoff events mentioned in the introduction. It should be remembered however that the accuracy of the isotopic separation results are much lower than in the alpine applications because of the analytical error for $^{18}O$. As far as conventional approaches to the problem are concerned even the SRM model, which seems to work well in alpine areas (Herrmann et al., 1979), largely over-estimates direct runoff proportions (cf. Fig. 8) as do the usual graphical hydrograph separation methods. Some slight improvement can be expected from more realistic time-dependent runoff coefficients.

![Graph showing areal $^{18}O$ input ($\delta_{in}$) and output ($\delta_r$) functions of Lange Bramke basin, snowmelt hydrograph (Q) with indirect flow as derived from isotopes ($i_{iso}$) and SRM ($i_{SRM}$), and respective direct runoff proportions d, 12-23 April 1984.](image)

**FIG. 8** Areal $^{18}O$ input ($\delta_{in}$) and output ($\delta_r$) functions of Lange Bramke basin, snowmelt hydrograph (Q) with indirect flow as derived from isotopes ($i_{iso}$) and SRM ($i_{SRM}$), and respective direct runoff proportions d, 12-23 April 1984.
CONCLUSION

The application of environmental isotope techniques to basin hydrology allows some additional insight into storage and turnover mechanisms during snow cover seasons even under difficult natural conditions provided that reliable hydrological and isotopic data are available. However, extraordinary expense was necessary in order to achieve the field study described in this paper. The justification of such effort is multi-layered, including regional and basic scientific interest for technical/experimental and theoretical/modelling improvements, which represent priority tasks in this field. More attention should now be given to the benefits of both conventional and modern analytical approaches to determining basin response to an input. Snowmelt seasons seem especially favourable for elaboration of the respective strategies because of the high standard of snow hydrological observation and modelling techniques, in combination with rather clear input signals from melting snow cover stores.

REFERENCES


