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Snowmelt and groundwater storage in an Alpine basin

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ABSTRACT In contrast to usual runoff concepts emphasizing the role of surface flow, tracer studies using environmental isotopes reveal a big groundwater recharge from snowmelt and a similarly large amount of groundwater in the discharge from the Alpine basin Dischma. Concentrations of tritium indicate an average residence time of groundwater of four to five years. Thus the groundwater storage capacity appears to exceed significantly the conventional estimates for mountain basins. A quick effect of meltwater infiltration on the outflow from groundwater reserves, caused by rapid pressure transmission, has to be assumed. Such an effect was actually demonstrated by Stauffer *et al.* (1981) in a laboratory model. This runoff mechanism seems to be confirmed in various other basins by other authors.

INTRODUCTION

The seasonal snow cover offers a good opportunity to study the runoff process. During the snowmelt period, the quantity and time distribution of input into a basin is predictable relatively well. This facilitates the use of environmental isotopes as tracers. In particular, snow has usually a contrasting tritium concentration in comparison with groundwater.

In the Alpine basin Dischma (43.3 km^2, 1668-3146 m a.m.s.l., 2.6% glacierized), tritium concentrations in the snow cover, in groundwater and in the discharge at the outlet have been measured since 1969. This study leads to a reassessment of the role of groundwater in the runoff. The proportion of groundwater in the discharge and its residence time lead to a new runoff concept.

RUNOFF REGIME OF MOUNTAINOUS BASINS

In high mountains the proportion of snow in precipitation exceeds 50% and the snowmelt becomes a dominant factor in the runoff regime. From the good agreement between the amount of snow accumulated and the resulting runoff volume, as qualitatively illustrated in Fig.1 for two years with snow covers of different depths, it might be concluded that meltwater leaves the basin in several weeks or months

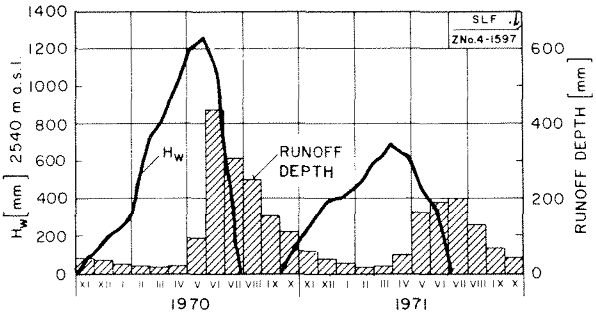

FIG.1 Comparison of the snow accumulation with the subsequent runoff in the Dischma basin. H_W is the water equivalent of the snow cover.

as the melting of the snow cover progresses.

This would be possible only by overland flow or quick-return subsurface flow since the flow velocity of groundwater is small.

Over the past 15 years, the runoff concept emphasizing the surface component has repeatedly been contradicted by tracer studies using environmental isotopes (Dincer *et al.*, 1970; Martinec *et al.*, 1974; Sklash & Farvolden, 1979; Fritz *et al.*, 1976). In the Dischma basin, we have been able to separate the rapid snowmelt runoff from the groundwater component by means of tritium measurements, using the fact that tritium concentrations in snow cover (winter precipitation) are distinctly lower than in groundwater which represents a mixture of winter and summer precipitation. Even during strong snowmelt periods, the tritium concentration of the discharge never reached the values of the winter snow, but was intermediate between those of snow cover and winter baseflow (=groundwater). The fraction of groundwater in the total discharge, determined from the tritium concentrations, is on an average over the whole snowmelt season approximately 60% (Martinec *et al.*, 1974; Martinec *et al.*, 1982). Thus, while snowmelt is clearly responsible for a drastic increase of the volumetric discharge in spring, less than half of all meltwater runs off rapidly, the major fraction infiltrates and forces older groundwater to discharge. We estimate that the groundwater component also makes up about 60% of the total annual discharge which is influenced by rain as well as by snowmelt. An equivalent amount of snowmelt and rainwater must infiltrate into the groundwater.

GROUNDWATER AGE AND VOLUME

By the thermonuclear weapon tests, relatively large amounts of tritium were produced. As a consequence, high tritium concentrations were observed in precipitation, mainly in the early 1960's (Fig.2). By measuring tritium in groundwater and comparing with the time-dependent concentration in precipitation, one can estimate the mean age of the water. Since groundwater is a mixture of components of different ages, it is, however, necessary to assume a model residence-time distribution, h(T), which indicates the

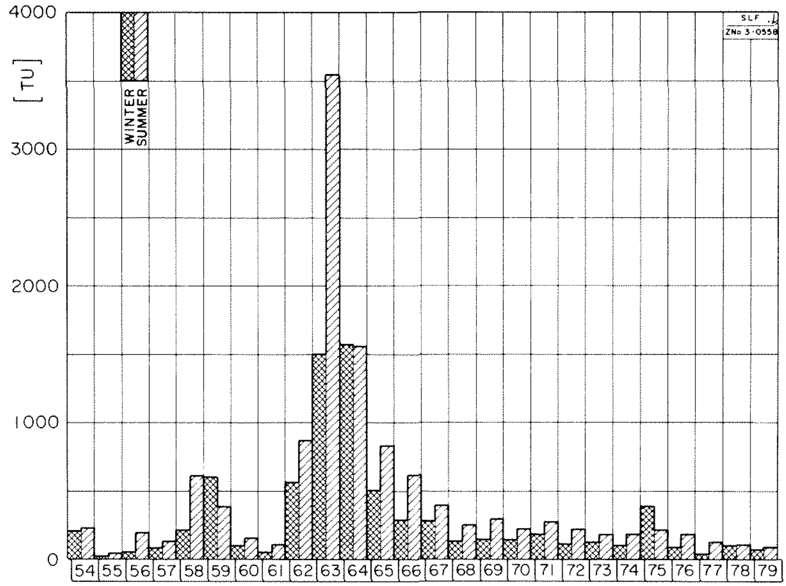

FIG.2 Tritium concentrations in precipitation in Central Europe, half-year averages.

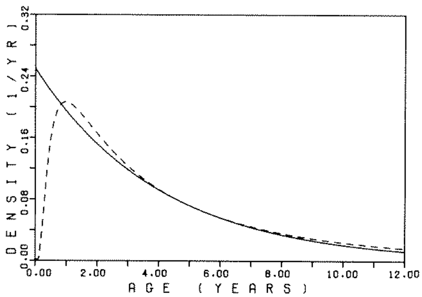

FIG.3 Model age distributions (densities) used for computing the curves in Fig.4. Solid line: exponential, mean age 4 years; dashed line: dispersive, mean age 5.25 years.

relative fraction of water of residence time T. Two different residence-time distributions (Fig.3) are applied: an exponential distribution, according to which the youngest water is most frequent, and a dispersive model in which the very young water is not so strongly represented. The exponential model implies one parameter, the mean age, the dispersive model two parameters characterizing the mean velocity and the dispersion coefficient. The procedure is to compute output time series of tritium, C_{out}, using mean concentrations in precipitation, C_{in}, (Fig.2) as input. The varying groundwater recharge is taken into account by weighting with the discharge Q(T). The output concentration is given by:

$$C_{out}(t) = \int_{0}^{\infty} C_{in}(t - T)\ Q(t - T)/Q_{o}\ h(T)\ dT \qquad (1)$$

where Q_o is the long-term mean discharge.

The exponential distribution is given by

$$h(T) = \frac{1}{T_R} \exp(-T/T_R)$$

where T_R is the mean age. The dispersive distribution is more complicated (Siegenthaler, 1971):

$$h(T) = \frac{2}{\sqrt{\pi}\, dT} \exp\left\{-\frac{(T - T_o)^2}{dT}\right\} - \frac{2}{d}\, e^{4T_o/d} \operatorname{erfc}\left\{\frac{T - T_o}{\sqrt{dT}}\right\}$$

where $d = 4D/v^2$ and $T_o = x/v$; x is the distance of flow, v the velocity and D the dispersion coefficient. For our purposes, T_o and d are considered as adjustable parameters.

For the actual computations, mean annual input data are used and the integral in equation (1) is replaced by a discrete sum. The annual mean input concentration is computed by assuming that because of evaporation losses, summer precipitation contributes relatively less than winter precipitation (weights: 1 for winter, 0.7 for summer). The model parameters - T_R or T_o and d - are varied until an optimum (least-square) fit with the observed groundwater concentrations is obtained.

In Dischma basin, winter baseflow of the brook is not influenced by meltwater and represents only groundwater discharge. Measured tritium concentrations of winter baseflow and the best-fit model curves for either distribution are shown in Fig.4. The corresponding times T_R are 4.0 years for the exponential and 5.25 years for the dispersive distribution (T_o = 2.75 years, d = 10 years).

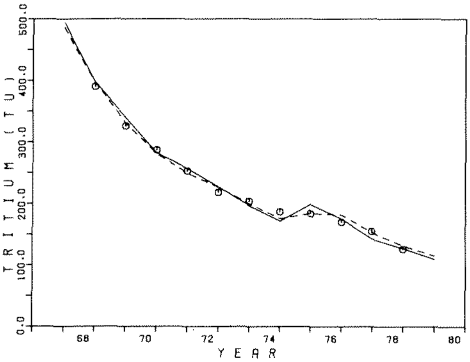

FIG.4 Tritium concentrations in winter baseflow, Dischma basin. Circles: observed values (seasonal means); solid line: calculated by means of the exponential model; dashed line: calculated by means of the dispersive model.

The volume of the groundwater reserves, V, is related to the mean residence time by

$$V = Q_e T_R$$

where Q_e is the rate of exchange by input and output. From the component separation (see above) we estimate that Q_e is 60% of the total annual discharge, corresponding to 750 mm year^{-1}. With T_R = 4 year, which is probably a lower limit, the groundwater storage corresponds to about 3000 mm on the average over the whole basin area, or a volume of 130 x 10^6 m^3.

ASSESSMENT OF GROUNDWATER STORAGE BY DRILLING

The surprisingly large volume of groundwater storage could so far be supported by only two boreholes drilled at 1702 m a.m.s.l. (piezometer 1, Fig.5) and at 1973 m a.m.s.l. (piezometer 2). In the first case the active groundwater profile was 20 m deep and in the second case about 40 m. Assuming an effective porosity of 20%, an average groundwater storage capacity of 6 m is obtained for the valley bottom. This value probably decreases on the side slopes but an overall average of 3 m for the whole basin is at least not excluded. The intention is to evaluate the spatial distribution of groundwater reserves in more detail, taking also into account the storage in fissures in the solid rock of the valley slope.

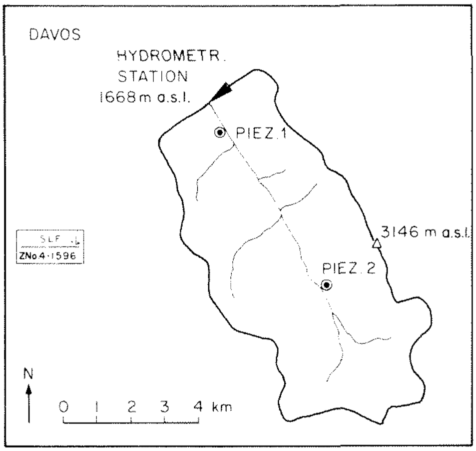

FIG.5 Map of the drainage basin Dischma.

An example of fluctuations in groundwater level in the borehole at 1702 m a.m.s.l. is shown in Fig.6. At that stage the snowmelt in the area was in full swing. The groundwater level was within only 10 or 20 cm below the surface and reflected the daily fluctuations of snowmelt rates. On 24 May at 1400 h the groundwater level reached its daily minimum but was still about 10 cm higher than the water level in the brook in its nearest cross-section (25 m distance). This would indicate that groundwater was contributing to the channel flow by exfiltration. Consequently, it remains to be clarified whether the daily groundwater fluctuations resulted from an effect of meltwater infiltration which propagated quickly or whether they were caused by stage fluctuations of the water in the brook.

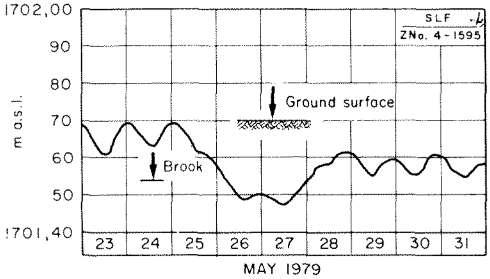

FIG.6 Groundwater level fluctuations in piezometer 1 during snowmelt.

CONCLUSIONS

The strong proportion of groundwater in the snowmelt runoff indicates a much larger underground storage capacity in the mountain basin Dischma than is given by conventional estimates. Limited verifications by two drillings do not contradict this result.

Even if the large groundwater volume exists, it remains to be explained how the infiltrated meltwater causes a corresponding amount of groundwater from an unconfined aquifer to appear at the outlet of the basin so quickly that the output agrees quantitatively with the input and is not delayed by years.

Groundwater waves caused by periodic changes of the pressure head have been shown to travel quicker than the subsurface water while the infiltrated water particles are not being transported (Vischer, 1970). A recent study on a physical model (Stauffer *et al.*, 1981) reveals that following drainage of groundwater from the soil, even a small quantity of infiltrated water causes an increase of the pressure head which propagates quickly. The increase of the flow gradient propagates without carrying the particles of infiltrated meltwater along and causes an additional significant exfiltration of groundwater into surface channels. This would be in agreement with the absence of a major constituent of meltwater in the outflow from the basin.

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