

Application of GIS-based distributed hydrological modelling for estimation of water residence times in the small Swiss pre-alpine catchment Rietholzbach

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Abstract A concept of water residence time distributions in the pre-alpine catchment Rietholzbach in northeastern Switzerland has been developed. The catchment covers an area of 3.18 km² and ranges from 680 to 960 m a.s.l. It is part of the Upper Freshwater Molasse overlaid by Quaternary deposits. The study combines runoff modelling with the use of the isotope ¹⁸O and consists of two parts. In the first part, runoff simulation over the period 1983–1997 was carried out using the model PREVAH-ETH. For the spatial data distribution, 100 m grid data were aggregated into hydrotopes by means of a GIS. An approach including the topographical index was integrated into the model, improving the simulation of runoff components. In the second part, the calculated groundwater recharge rates were used for the weighting of $\delta^{18}\text{O}$ input functions. They served to estimate groundwater residence times at selected sites in the catchment over the period 1994–1997. The mean groundwater residence times range up to 2.5 years and depend on the mixing efficiency within the aquifers. The results form a contribution to the understanding of the water turnover processes in hilly pre-alpine basins with porous structures, as investigated using areal distributed hydrological modelling coupled with tracer techniques.

INTRODUCTION

Water balance studies of Swiss pre-alpine catchments within distinct Tertiary and Quaternary aquifers have shown the characteristics of runoff in this region: considerable runoff rates produced by heavy rainfall events, and a considerable storage potential of the local porous aquifers (König *et al.*, 1994). In the Rietholzbach catchment, these processes have been studied by runoff simulations (e.g. Gurtz *et al.*, 1997) as well as isotopic methods using ¹⁸O (e.g. Vitvar & Balderer, 1997). A promising task for further research is therefore the coupling of both the runoff modelling with the estimation of water residence times in aquifers. This is also of particular methodological importance; the calculated groundwater recharge rates may serve as parameters for a refined weighting of the ¹⁸O input function within the lumped-parameter flow approach, so that a better fitting of the ¹⁸O output functions may be reached. So far, this weighting step has been mostly performed using the runoff coefficient (e.g. Maloszewski *et al.*, 1992) or the lysimeter outflow rates (Vitvar, 1997), although these parameter do not express the aquifer recharge properly.

The aim of this contribution is to develop a link between the distributed runoff simulation and the estimation of groundwater residence times for the Rietholzbach catchment. The work is based on the application of the currently developed runoff model PREVAH-ETH (Gurtz *et al.*, 1997, 1999; Bohrer, 1998) and on the lumped-parameter flow model approach using the ^{18}O isotope (Vitvar, 1997).

STUDY AREA

The Rietholzbach basin (Fig. 1) is a small hilly pre-alpine basin in the middle part of the Thur River basin, northeastern Switzerland. It covers an area of 3.18 km² and is primarily used as pasture. The elevation ranges from 680 to 960 m a.s.l. The geology of the catchment is characterized by the Tertiary deposits of the Upper Freshwater Molasse consisting of consolidated clastic sediments such as conglomerates (“Nagelfluh”), sandstones, layers of marls, and banks of limestone. In the lower part of the catchment there are Pleistocene gravel pockets which represent Würm glacier moraines. In particular, the conglomerates and the Quaternary deposits can be regarded as groundwater aquifers with medium to high hydraulic conductivities and relatively large storage capacities. Average annual values of the catchment water balance for the period 1975–1990 are: precipitation 1600 mm, runoff 1040 mm, evapotranspiration 551 mm (König *et al.*, 1994).

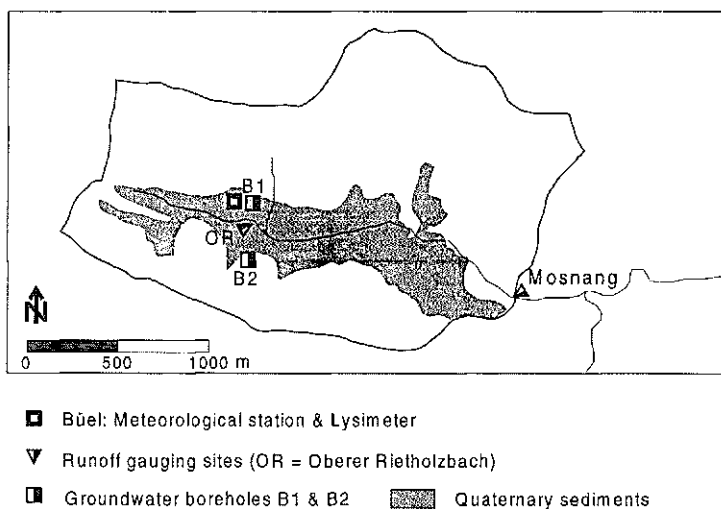


Fig. 1 Map of the Rietholzbach catchment in Switzerland with the location of selected sampling sites as well as the Quaternary glacial deposits.

DATA COLLECTION

The meteorological and hydrological parameters of the Rietholzbach basin, including percolation water at a 2.20 m deep lysimeter, have been measured since 1975 with high temporal resolution. The GIS information at 100 m grid resolution is based on the

digital elevation model of Switzerland "RIMINI", the digital soil map of Switzerland (Anonymous, 1980), and the Swiss "Arealstatistik" land-use characteristics (BFS, 1995). The sampling programme for the ^{18}O records is summarized in Table 1 (see also Fig. 1). The $\delta^{18}\text{O}$ values are expressed with reference to Standard Mean Ocean Water (SMOW) in units of parts per thousands (per mille).

Table 1 Outline of the locations, periods and intervals of the regular probe sampling for ^{18}O measurements.

Water	Location	Sampling period	Sampling interval:	
			1994–1995	1996–1997
Precipitation	Büel	1994–1997	month	month
Stream water	Mosnang	1994–1997	week/day	2 weeks
	Oberer Rietholzbach	1994–1997	week	2 weeks
Groundwater	B1, B2	1995–1997	week	2 weeks

METHODS

Runoff modelling

The PREVAH-ETH (Precipitation-Runoff-Evapotranspiration-Hydrotope related model) model uses parameters based as far as possible on physical relationships (Gurtz *et al.*, 1997). It relies on several subsystems of higher complexity, such as a snow model, an interception model, a model of soil water storage and depletion by evapotranspiration, the runoff generation model, and the discharge concentration and flood routing model.

Specific rules were adopted for evaluation of evapotranspiration and runoff generation, as well as for the extraction of hydrologically similar response units (HRUs). Potential evapotranspiration was calculated following the Penman equation and real evapotranspiration was based on the Penman–Monteith equation. The amount of net radiation available for evapotranspiration is a function of exposure, slope, and the albedo of the vegetation, land surface characteristics, or snow cover. The important link between the loss of water by evapotranspiration and runoff is given by the plant-available water storage of the unsaturated zone of the soil. The storage capacity is determined by the soil depth available for the roots and the field capacity of the soil. Specific rules were also adopted for surfaces with rocks or wet areas, for surfaces without vegetation and for urban areas. The submodels for runoff formation originate in an ETH-version of the HBV-model (Bergström, 1976) which was strongly modified and adapted to the HRU-based spatially distributed modelling of runoff formation. The calculation of the flood-routing is based on the combination of linear storages and translation components. The distribution of fast and slow flow components is governed by the topographical index. The extraction of the HRUs is performed from digitalized data; in this case the 100 m grid resolution from data about elevation, slope, exposition, soil type, land use, topographical index, and geology have been used (Bohrer, 1998). The meteorological input data were interpolated for each grid cell (Gurtz *et al.*, 1997). The determination of the parameter values involves relatively large uncertainties. Therefore, the model application in various catchments is the object of the current studies (Gurtz *et al.*, 1999).

Water residence times

Lumped-parameter flow models describe the transformation of a given tracer input (concentration in precipitation or air C_{in}) into the tracer output (concentration at an outflow site C_{out}) within a continuous flow system (Maloszewski & Zuber, 1982; Amin & Campana, 1996). For environmental isotopes as tracers, this expression takes the form of a convolution integral with a system response function:

$$C_{out}(t) = \int_0^{\infty} C_{in}(t-T)g(T)dT$$

The function $g(T)$ characterizes the type of water mixing, or, the model concept itself; t and T are chronological and residence time, respectively. Mixing can range from the piston-flow concept (no mixing) to complete mixing as in the exponential concept. Therefore, for simulating the most probable partial mixing type occurring in natural systems, a two-parameter exponential/piston-flow combination of the above-described limiting cases or the dispersion model concept are used. The main model parameter is always the mean water residence time.

The modelling in the Rietholzbach catchment has been made in monthly steps for the period 1994–1997. The ^{18}O output functions of the baseflow consist only of values measured during low flow periods as the purpose is to determine the residence time of water stored within the aquifer.

Two original parameterization steps for the ^{18}O input functions have been carried out. Firstly, the local ^{18}O monthly record in precipitation was completed for the period 1983–1993 by use of monthly values from two close IAEA/WMO stations Bern and Konstanz. Secondly, the complete input function was weighted by monthly values of (a) measured outflow rates from the lysimeter installed within the Rietholzbach catchment (Vitvar, 1997), and (b) groundwater recharge rates derived from the PREVAH-ETH model runoff simulation. As a consequence, the weighted input function eliminates that part of the precipitation which does not contribute to baseflow.

RESULTS AND DISCUSSION

Figure 2 shows the simulation of daily runoff at the gauging station Mosnang for the year 1997 as a part of the simulation for the whole modelling period 1983–1997. The modelled groundwater recharge data were used for the weighting of the ^{18}O input. Figure 3 compares the simulated ^{18}O output functions with measured values for selected output sites. The exponential type of residence time distribution for the stream baseflow at the runoff gauging site Oberer Rietholzbach (mean residence time 24.5 months) indicates efficient mixing within the glacial deposits. A larger amplitude of the output function representing the baseflow at the mean runoff gauging site Mosnang indicates lower mean water residence time; the best fit was obtained for 12.5 months. This demonstrates that the eastern catchment part where some parts are formed by steep slopes includes a small volume fraction of the piston-flow water transport. Such a mixing type may be typical for storage reservoirs within the molasse conglomerates particularly on slopes oriented to the south. A faster flow exists in the form of hillslope fluxes through small conglomerate formations overlaying the banks of marls and

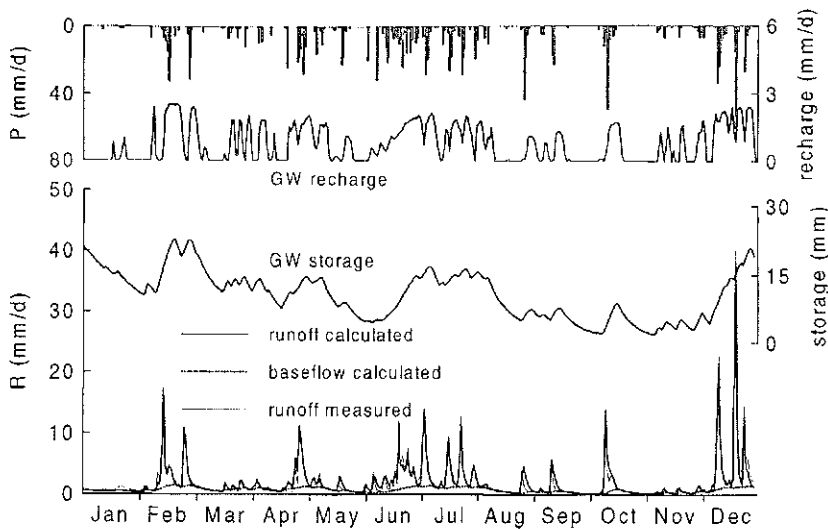


Fig. 2 Simulation of daily runoff at the Mosnang gauging station for the year 1997 using the model PREVAH-ETH. This year was used for the model calibration with $r^2 = 0.95$. *Top*: Daily precipitation amounts. *Middle*: Groundwater storage levels and daily groundwater recharge rates. *Bottom*: Measured and simulated daily runoff rates including the baseflow component.

limestone, particularly on the slopes oriented to the north (as represented by the borehole B2). In contrast, the aquifer represented by the groundwater in the borehole B1 best demonstrates the buffering effect of the glacial sediments. Detailed notes on the dating as well as the parameters are given in Vitvar & Balderer (1997) and Vitvar (1997). Although the calibration in these studies was performed for the relatively short period January 1994–June 1996 and by use of the lysimeter-weighted ^{18}O input function only, the identical parameters also show a very good applicability for the whole period 1994–1997. Figure 4 shows the sensitivity of the input weighting parameter for the stream baseflow samples at the station Mosnang. The input function that has been weighted by use of the calculated groundwater recharge gives the best fit during the whole period. The reason is that this weighting factor really reflects that part of the precipitation input that recharges the aquifer. In contrast, the weighting by use of lysimeter outflow rates also incorporates the vertical infiltration of fast components that do not recharge the aquifer outside the lysimeter column.

CONCLUSIONS

In the present study, a methodological link between the distributed runoff simulation model PREVAH-ETH and the approach for dating shallow groundwaters by use of ^{18}O has been developed and applied. Within the small pre-alpine catchment Rietholzbach, there are relatively fast hillslope fluxes through molasse aquifers. Efficient mixing processes occur in the part where Quaternary glacial deposits are located. The simulation results obtained using ^{18}O show a very good applicability of the lumped-parameter flow approach in aquifers characterized by short mean residence times. The weighting of the ^{18}O input function by use of the groundwater recharge rates derived

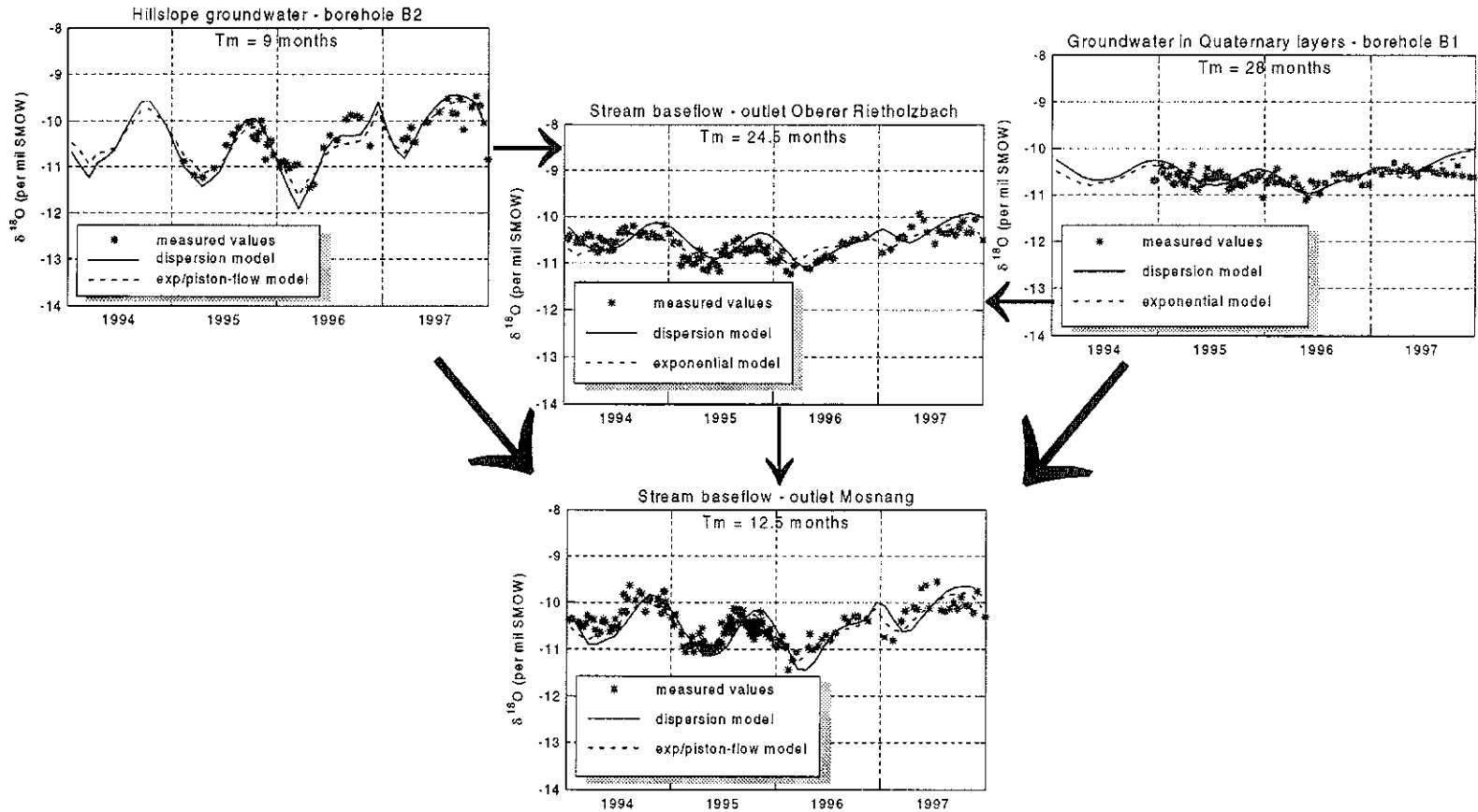


Fig. 3 Simulation of the ^{18}O monthly output functions during the period 1994–1997 at selected sites using two different types of residence time distributions. The parameters are identical with those for the calibration period January 1994–June 1996 used in Vitvar (1997). The input function has been parameterized using the groundwater recharge data derived from the model PREVAH-ETH.

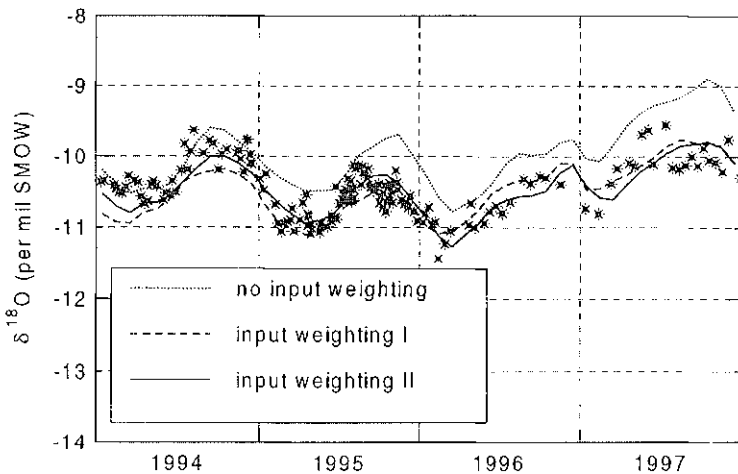


Fig. 4 Simulation of the ^{18}O monthly output function for the stream baseflow at the Mosnang runoff gauging station during the period 1994–1997, as calculated using two methods of the ^{18}O input weighting: lysimeter outflow rates (I), and groundwater recharge rates (II).

from the runoff model substantially improves the modelling of the ^{18}O input–output transfer in comparison to the weighting by use of the lysimeter outflow rates. This contribution to the coupling of hydrological modelling with tracer investigations has to be tested by applications in similar catchments.

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