Natural tracers for investigating residence times, runoff components and validation of a rainfall–runoff model

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Abstract The objective of this study was the separation and modelling of the runoff components in the mountainous Brugga catchment (Black Forest, Germany). Discharge data and the tracer concentrations of $^{18}$O, $^3$H and dissolved silica observed during several single events and over a period of three years were used. Three different runoff components, one direct and two indirect, were found. The direct runoff component was important only during floods (up to 50% during the peak discharge), but of minor importance for longer periods (11% on average). The two indirect components originated from shallow and deep groundwater outflows. The importance of the debris and drift cover of the slopes (shallow groundwater) for the runoff generation was demonstrated (69%). The deep groundwater flowing through the fissured aquifer contributed about 20%. Based on the experimental investigations the conceptual rainfall–runoff model TAC was developed. The model was applied and calibrated to the discharge data measured for a period of 3.2 years. Additionally, the model was validated using a tracer-data-based and a classical model validation procedure.

INTRODUCTION

Runoff generation processes are very complex and normally poorly understood without experimental investigation. Different interacting processes occur which are spatially distributed within the catchment (e.g. Bonell, 1998). These processes are defined by physiographic characteristics and they depend on the initial states of the various hydrological reservoirs and on the characteristics of the hydrological input. The knowledge of processes and flow pathways is crucial for evaluating the vulnerability of surface and groundwater systems (e.g. Leibundgut et al., 1998). For instance, the determination of the relative amounts of shallow and deep groundwater and the preferred flow pathways taken by infiltrating waters (i.e. direct flow components) is essential for the evaluation of the acidification potential of a catchment.

Tracer methods provide suitable tools for investigating runoff generation processes. Artificial tracer experiments are widely used to examine processes on the micro-scale. Naturally occurring tracers (environmental isotopes or geochemical tracers) are commonly used to examine runoff formation processes on the catchment scale (e.g. Sklash & Farvolden, 1979). Using isotopes it is possible to determine source
areas of runoff, flow pathways, residence times, reservoir volumes and the hydraulic characteristics of flow systems (e.g. Maloszewski et al., 1983). Based on this data a physically realistic hydrological model can be developed.

**MATERIALS AND METHODS**

**Study site**

The study was performed in the Brugga basin (39.9 km²), located in the Southern Black Forest in southwestern Germany. It is a mountainous catchment with elevation ranging from 450 to 1500 m a.m.s.l. and a nival runoff regime. The mean annual precipitation amounts to 1750 mm generating a mean annual discharge of approximately 1220 mm. The bedrock consists of gneiss and anatexis, covered by soils and drift of varying depths (0.5–10 m). The permeability of the soils is generally high. Saturated areas amount to 6.2% and are almost constant in their spatial extent (Güntner et al., 1999). The basin is widely forested (75%) and the remaining area is pasture; urban land use is below 2%.

**Calculation of residence times**

In the literature, several mathematical models are presented which have been applied for interpretation of environmental isotope data (e.g. Yurtsever, 1995; Maloszewski & Zuber, 1996). In the present paper, lumped parameter models were used (see e.g. Maloszewski & Zuber, 1996).

**The TAC model**

The Tracer Aided Catchment (TAC) model (for detailed description see Uhlenbrook, 1999; Uhlenbrook & Leibundgut, 1999), is a conceptual rainfall–runoff model with a modular model structure. The runoff generation module was developed for the Brugga basin based on results of tracer investigations, whereas further modules (snow and soil modules) were adapted from other conceptual models. The spatial discretization was based on a delineation of zones, each with characteristic dominating runoff generation processes, and elevation zones. The model operates on a daily time step with simulated discharge and concentrations of dissolved silica using precipitation, temperature and potential evapotranspiration as input data.

**RESULTS OF TRACER INVESTIGATIONS**

**Examination of the direct runoff component**

To quantify the contribution of the direct runoff component, different single events were investigated. The results of hydrograph separation using $^{18}$O, silica and chloride
as tracers (for the method see Sklash & Farvolden, 1979) showed the general dominance of the indirect components. The direct runoff component contributed up to 50% during peak discharge, but several hours after the event this component was negligible (Frey, 1999; Uhlenbrook, 1999).

Examination of indirect runoff components

Five springs were investigated for a longer period of time. Due to the different runoff behaviour, temperature variations, electrical conductivities and silica contents of the springs, it was concluded that the groundwater (Fig. 1(a)) has two different origins (Lindenlaub, 1998; Uhlenbrook, 1999). One part originates from the debris and drift cover of the slopes and is characterized by a lower silica content and distinct yearly temperature variations ("shallow groundwater"). The other part originates from the deeper parts of the drift cover and the crystalline hard rock aquifer ("deep groundwater"). This water contains higher silica concentrations and shows no seasonal temperature variations. The conceptual model of water flow in the catchment is shown in Fig. 1.

(a)

Runoff components:
- direct runoff
- shallow groundwater
- deep groundwater

(b)

Precipitation, snow melt

Fig. 1 (a) Schematic sketch of the runoff generation in the Brugga basin; (b) conceptual model of the hydrological system of the test site.

Residence times in different flow systems

For the residence time calculations the environmental isotopes $^{18}$O (monthly base) and $^3$H (yearly base) were used. The $^{18}$O content in the precipitation was measured weekly or bi-weekly at different altitudes for the period July 1995 to July 1998. This input
The yearly $^3\text{H}$ input was obtained from Ottawa, Canada, (up to 1961), and from Hohenpeissenberg, Germany (1962–1998). The monthly varying infiltration coefficients for both isotope input functions were computed with a rainfall-runoff model (Uhlenbrook et al., 1999).

The mean residence times ($t_0$) were found to be between 28 and 36 months based on $^{18}\text{O}$ data (Fig. 2) for shallow groundwater, and between 6.2 and 8.6 years based on $^3\text{H}$ data (Fig. 3) for deep groundwater. Mathematically, residence times of about 40 years for the deep groundwater would be also possible because of the $^3\text{H}$ data. The isotope measurements during high discharges were not taken into account. The additional measurement of freon concentrations (F-11, F-12 and F-113) in the deep groundwater has shown that the mean residence time is less than 10 years (Frey, 1999; Uhlenbrook, 1999). This excluded the possible residence time of 40 years for that aquifer system.

**Fig. 2** Results of the residence time calculations for two springs of the shallow groundwater system using $^{18}\text{O}$ as tracer; the analytical error is ±0.2‰.

### Portions of flow components

Taking into account the investigation of single events and the fact that the direct runoff can only be generated on saturated areas and boulder trains (estimated to extend over 7% of the catchment area) the mean direct flow component $\alpha_1$ was calculated as 11.1% for a period of three years (Uhlenbrook, 1999). The portions of the two indirect flow components were found by applying the conceptual hydrological model (Fig. 1(b)) to the $^{18}\text{O}$ data. The $^{18}\text{O}$ concentrations of three components were calculated using lumped parameter models with the following parameters: direct runoff ($t_0 = 0$), shallow groundwater system ($t_0 = 32$ months, mean value of the two springs) and deep groundwater system ($t_0 = 7.1$ years, mean values of the three springs). The seasonal variation of the $^{18}\text{O}$ content in the three components is given in Fig. 4. The mean values of $\alpha_2$ and $\alpha_3$ estimated on a monthly base were 69.4% and 19.5%, respectively.

To check the plausibility of the results, simple geometric calculations (e.g. Maloszewski et al., 1983) were used to estimate the extent of the aquifers. The mean volumes of the stored water were $8.8 \times 10^7$ m$^3$ and $6.6 \times 10^7$ m$^3$ for the shallow and deep groundwater systems, respectively. Assuming a porosity of 30% and that the recharge
surface of the shallow groundwater system equal to 86% of whole catchment surface, the mean thickness of the shallow aquifer was calculated to be 8.5 m. The total porosity of the crystalline hard rock aquifer (deep groundwater system) was found to be 2% based on the estimated volume of the rock. Both values of the aquifer parameters correspond well with data found in the literature.
VALIDATION OF A RAINFALL–RUNOFF MODEL USING TRACER DATA

The rainfall–runoff model TAC was developed in parallel with the investigations of runoff generation. It was applied for the period 15 July 1995 to 7 October 1998 with reasonable success (Uhlenbrook & Leibundgut, 1999; Uhlenbrook, 1999). The simulated runoff components of the model were grouped into the three main flow systems (Fig. 1). The TAC simulated contributions from the direct runoff component, and the shallow and deep groundwater system components were 9.9%, 66.6% and 23.5%, respectively. These values are in a very good agreement with those found based on the tracer measurements for the same period. In addition, the simulated and measured silica concentrations were compared showing very good agreement for short observation periods (Fig. 5). These results confirmed the reliability of the TAC simulations.

Fig. 5 Results of the application of the TAC model: precipitation, discharge simulation, runoff components and silica concentrations for the period 3 March 1998–7 October 1998 (part of the validation period).
CONCLUSIONS

The results have shown the importance of the shallow groundwater system, and consequently the role of the debris and drift cover of the slopes, for runoff generation. Direct runoff components play a major role during floods, but for long time periods they are of minor importance. The combined use of environmental tracers made it possible to estimate: (a) the residence times of water, (b) the origin of runoff components, (c) the properties of aquifer systems, and (d) to quantify the amounts of runoff components during single events and during a longer period. In addition, it was demonstrated how tracer data can be used to validate a rainfall–runoff model (multiple response validation).

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REFERENCES


