Using tracers techniques to investigate hydrosystems and to improve rainfall-runoff modelling

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Monitoring of water quantity and chemistry and additional tracer experiments were carried out in the meso-scale (40 km^2) mountainous Brugga basin, south-western Germany, since 1994. A thorough insight was gained into the runoff generation processes. The main source areas of runoff components, flow pathways and mean residence times of the runoff components were determined by using different tracer methods. In addition, the contributions of different runoff components were quantified during single events and for a seasonal time scale. On this basis a process-oriented rainfall runoff model (TAC, tracer aided catchment model) was developed. The model was applied successfully to the Brugga basin, several sub-basins and a neighbouring basin as the total discharge was modelled well. A model validation using additional tracer data was carried out (multiple response validation).

This paper gives a summary of an invited presentation by the author held during the NHV Scientific Meeting on "Natural isotopes for water systems analysis and modelling", 8.11.2000, Alterra, Wageningen, The Netherlands. This paper summarises findings which were published before, detailed descriptions of the results are given by Uhlenbrook (1999), Uhlenbrook and Leibundgut (1999), Uhlenbrook et al. (2000) and Uhlenbrook and Leibundgut (2001).

Introduction

Runoff generation processes are poorly understood at the scale of a catchment, unless experimental investigations are carried out. Recently, soil physical (e.g. McDonnell, 1990), hydrochemical and tracer methods (as summarised by e.g. Bonell, 1998) were used to identify these processes. Experiments using artificial tracers allow insight into the runoff generation processes at the hillslope scale (e.g. Hornberger et al., 1991). The use of natural tracers such as isotopes or hydrochemical tracers provides valuable information about runoff components and their formation and dynamics at the catchment scale (e.g. Buttle, 1994).

In addition, rainfall runoff models have improved in the recent years. Increased computer capacities have made it possible to develop distributed physically-based models (e.g. WASIM-ETH; Schulla, 1997). However, enormous data requirements prevent the extensive use of these models. Conceptual models (e.g. HBV model; Bergström, 1992) are less complex, relatively easy to use and the required input data are available for most applications.

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In the present study, since 1994, different tracer experiments using artificial and natural tracers were carried out in basins at different scales in the Southern Black Forest Mountains in south-west Germany. Detailed insight into the runoff generation processes, for instance the main source areas and residence times of the runoff, were gained. In addition, several hydrological models (conceptual and physically based) were applied and a new runoff generation module was developed. The objective of this paper is to demonstrate the approach and to give a concise overview of the main experimental and modelling results.

Study area

The study was performed in the meso-scale Brugga basin (40 km^2) and smaller subbasins (15.4, 6.1 and 1.4 km^2, see Figure 1), and in the neighbouring Zastler basin (18.4 km^2), located in the Southern Black Forest in southwest Germany. These are mountainous catchments with elevations ranging from 438 to 1493 m a.m.s.l. and a nival runoff regime. The mean annual precipitation amounts to approximately 1750 mm, generating a mean annual discharge of approximately 1220 mm (values for the Brugga basin, there are only slight deviations for the others). The bedrock consists of gneiss, covered by soils and drift of varying depths (0–10 m). The hydraulic conductivity of the soils is generally high. Saturated areas amount to 6.2% and 7.1% in the Brugga and Zastler basin, respectively, and are not considerably variable in their spatial extent (Güntner et al., 1999a; 1999b). They are mostly connected to the river system directly. The basins are mostly forested (75%) and the remaining area is pasture; urban land use is less than 3% of the area.

Results of the experimental investigations

Different tracer investigations were carried out in the study area:

i Hydrograph separation using the natural tracers oxygen-18, chloride and dissolved silica. This made it possible to estimate the contribution of different runoff components during events, i.e. the contribution of surface and sub-surface runoff or the contribution of event water and pre-event water. For the latter, event water is defined as that part of the total runoff that entered the hydrological system during the rainfall event, whereas pre-event water is defined as that part of the total runoff stored in the catchment prior to the event (Sklash and Farvolden, 1979).

ii Major anions (cloride, sulfate and nitrate) and cations (calcium, magnesium, potassium and sodium) were analyzed during events in the stream water and at different springs to interpret flow paths and source areas of the runoff.

iii Tracer experiments with artificial tracers (using different dyes and sodium-bromide) at hillslopes and the river channel system were carried out to investigate flow pathways at the plot scale.

iv Mean residence times of the water in different flow systems were estimated using oxygen-18, tritium (^3H) and CFC concentrations. Therefore the tracer concentrations of the investigated runoff components and the falling precipitation were measured for a few years.

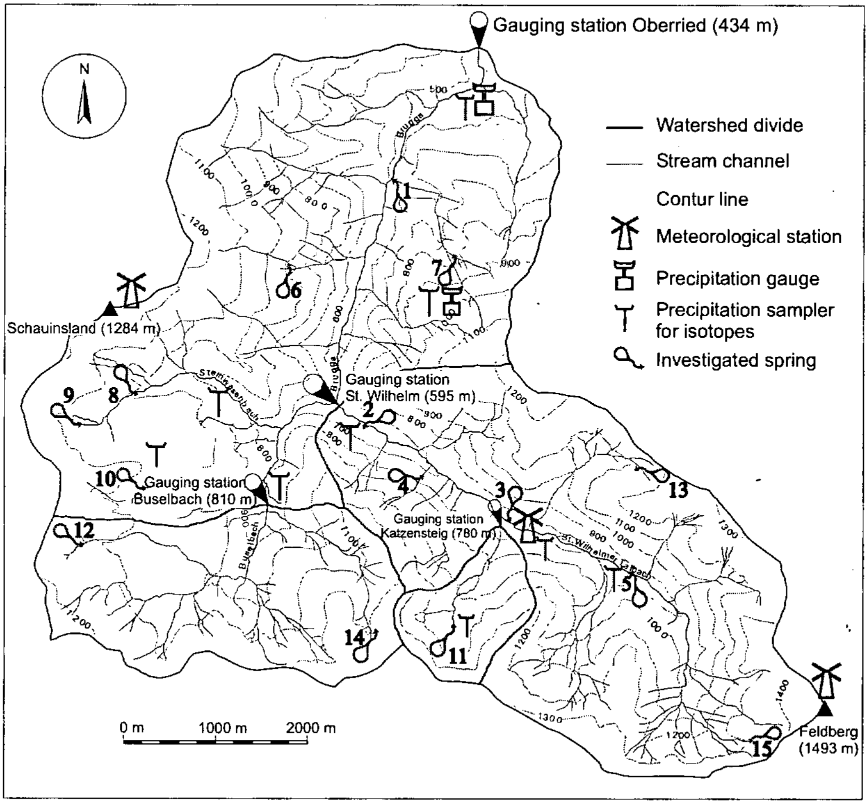

Figure 1: Schematic sketch of the Brugga basin with instrumentation and investigated springs (adapted from Uhlenbrook and Leibundgut, 2001).

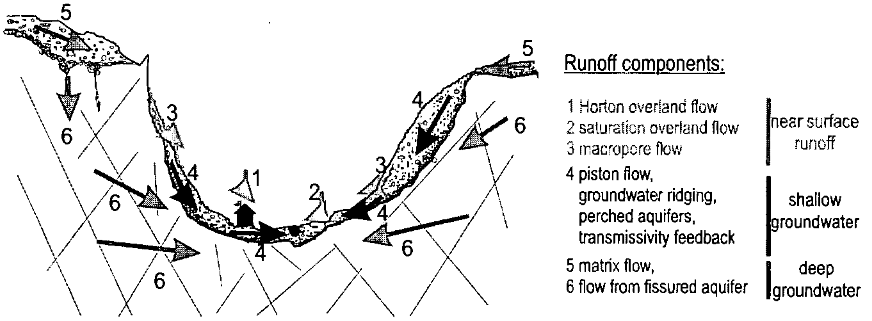

Figure 2: Schematic depiction of the runoff generation at the test site (adapted from Uhlenbrook and Leibundgut, 2000).

- v At the seasonal time scale the mean contribution of event water, shallow groundwater and deep groundwater was calculated for a three year period using the oxygen-18 and tritium composition of each of these three runoff components.

Together with further field observations, the experimental results led to the development of the following conceptual model of runoff generation with three main flow systems (Figure 2):

1 Fast runoff components (*event water*) are generated on sealed or saturated areas; both are surface runoff components. In addition, fast runoff components are generated on steep, highly permeable, slopes covered by boulder trains as subsurface storm flow. The mean residence time of the near surface runoff components is in the order of hours to a few days, what was shown by artificial tracer tests (Mehlhorn et al., 1998) and hydrograph separations during events (Uhlenbrook, 1999, Hoeg et al., 2000).

2 An intermediate flow system contributes mainly from the glacial and periglacial deposits on the slopes (*shallow groundwater*). Here soil water displacement takes place or perched water tables can spread above less conductive layers, e.g. condensed soil horizons or the bedrock surface. In addition, macropore flow occurs locally (for process description see, e.g., Bonell, 1998). This results mainly in a delayed runoff component, which can also contribute to flood formation depending on the antecedent moisture content. The mean residence time of the water is 2–3 years, determined by oxygen-18 measurements (Uhlenbrook, 1999; Uhlenbrook et al., 2000). But these relatively long residence times should not mask the importance of this source area for flood formation by soil water displacement effects. High runoff dynamics with a lot of pre-event water were shown for springs located at the toe of hillslopes dominated by this source area.

3 Slow base flow components (*deep groundwater*) originate from the fractured hard rock aquifer and the deeper parts of the weathering zone. The mean residence time of the water amounts to 6–9 years, determined by tritium and CFC measurements (Uhlenbrook, 1999; Uhlenbrook et al., 2000). No evidence was found that these components are significant for flood formation.

The contribution to basin runoff of event water runoff, shallow groundwater and deep groundwater for a period of three years in the Brugga was calculated to 11.1%, 69.4% and 19.5%, respectively (Uhlenbrook et al., 2000). Even if a relatively large uncertainty has to be assumed for these numbers, this demonstrates clearly the dominance of the shallow groundwater system and consequently the importance of the hillslopes covered with a glacial and peri-glacial drift cover for the runoff generation in the test site. For short periods during events event water runoff components may amount up to more than 50%. This was shown by hydrograph separations for different events using hourly time steps in the Brugga and Zastler basin (Uhlenbrook, 1999; Hoeg et al., 2000).

Results of rainfall-runoff modelling

The model TAC

Based on the experimental investigations and using different spatial information (i.e. geology, drift cover properties, saturated areas, topography) unit types with the same dominating runoff generation processes were delineated for the Brugga and neighbouring Zastler basin (Rutenberg et al., 1999). This spatial delineation of the basin was used for the process-oriented catchment model TAC (tracer aided catchment model; for a more detailed model description see Uhlenbrook (1999) or Uhlenbrook and Leibundgut (2001)). It is a semi-distributed model, that uses a hydrotop concept (spatial discretization in zones with the same dominating runoff processes) to incorporate the spatial distribution of the runoff generation mechanism. The TAC model has a modular model structure with a snow, soil and runoff generation module; and uses daily precipitation, temperature and potential evapotranspiration as input data for each hydrotop. The snow routine is based on the degree-day method, having the degree day factor and a temperature threshold (distinguishes between liquid and solid precipitation) as model parameters. The soil routine was adopted from the conceptual HBV model (Bergström, 1992). It contains as model parameters the field capacity of the soil, a parameter that characterises the runoff response of a soil to certain rainfall and a parameter that defines the actual evapotranspiration as part of the potential evapotranspiration. The runoff generation routine was newly developed, based on the experimental findings described above. Here specific routines were developed for each unit type with the same dominating runoff generation processes. The runoff generation processes are conceptualised by specific linear and non-linear storage routines. Concentrations of natural tracers (e.g. dissolved silica) can be attributed to the different runoff components generated in the runoff generation module. Consequently, the simulation of the tracer concentration in the model discharge is possible. The quality of the TAC results was assessed by the agreement of the simulated and observed tracer concentrations as well as by the goodness of fit of the runoff simulation.

Model application and model validation

For the model application a calibration and validation period was considered (split sample test; Refsgaard and Storm, 1996). For both periods a good agreement between the simulated and observed discharge was reached. To evaluate the model performance the model efficiency, $R_{eff}(Q)$, (Nash and Sutcliffe, 1970) was computed (where $R_{eff}(Q) \cap [-\infty; 1]$ and 1 means for a perfect fit of the simulated and observed discharge). For the calibration period $R_{eff}(Q)$ amounted to 0.77, and the model efficiency using logarithmic runoff values, $R_{eff}(\log Q)$ to 0.84. $R_{eff}(\log Q)$ is more suitable to evaluate the simulation of low flow, and values occur in the same interval as $R_{eff}(Q)$. For the validation period, the model efficiencies amounted to 0.73 and 0.83, respectively. The general runoff dynamics were described adequately; the mean and low flows were simulated particularly well. The simulations of high flows are poorer; peaks are partially over- or underestimated.

The application of TAC in different subbasins and a neighbouring basin yielded also good results. For these applications, the model input data precipitation, temperature, evapotranspiration and the spatial delineation of unit types with the same dominating run-

Table 1: Results of the TAC applications in the Brugga basin, different sub-basins (Katzensteig, Buselbach and St. Wilhelmer Talbach) and the neighbouring Zastler basin; as statistical measure the model efficiency $R_{eff}(Q)$ according to Nash and Sutcliffe (1970) is given.

	Brugga 40 km²	**Katzensteig** 1.4 km²	**Buselbach** 6.1 km²	**St. Wilhelmer Talbach** 15.4 km²	**Zastler** 18.4 km²
$R_{eff}(Q)$ (without re-calibration)	0.767	0.616	0.689	0.849	0.650
$R_{eff}(Q)$-*specific* (re-calibration)	–	0.678	0.708	0.859	0.692
$R_{eff}(Q)$-*Brugga runoff zones* (using the spatial delineation of the Brugga basin)	–	0.587	0.704	0.834	0.671

off generation processes were calculated for each basin separately. In a first step, the parameter set that was optimised for the Brugga basin was applied directly to the other basins. Only the spatial delineation of zones with the same dominating runoff generation processes was modified for each basin. The direct transfer of the parameter set yielded about the same model performance as the parameter sets, which were optimised in each basin (Table 1). Consequently, it can be stated that the determined parameter set is suitable not only for the Brugga basin but also for the other basins. The lower model efficiency values for the Katzensteig and Zastlerbach basin are due to problems with the input data. In general, the modelling results on a daily basis were at least as good as the simulations using other models in the basin (e.g. TOPMODEL, Güntner et al., 1999a; HBV, Uhlenbrook et al., 1999; PRMS, Mehlhorn, 1999).

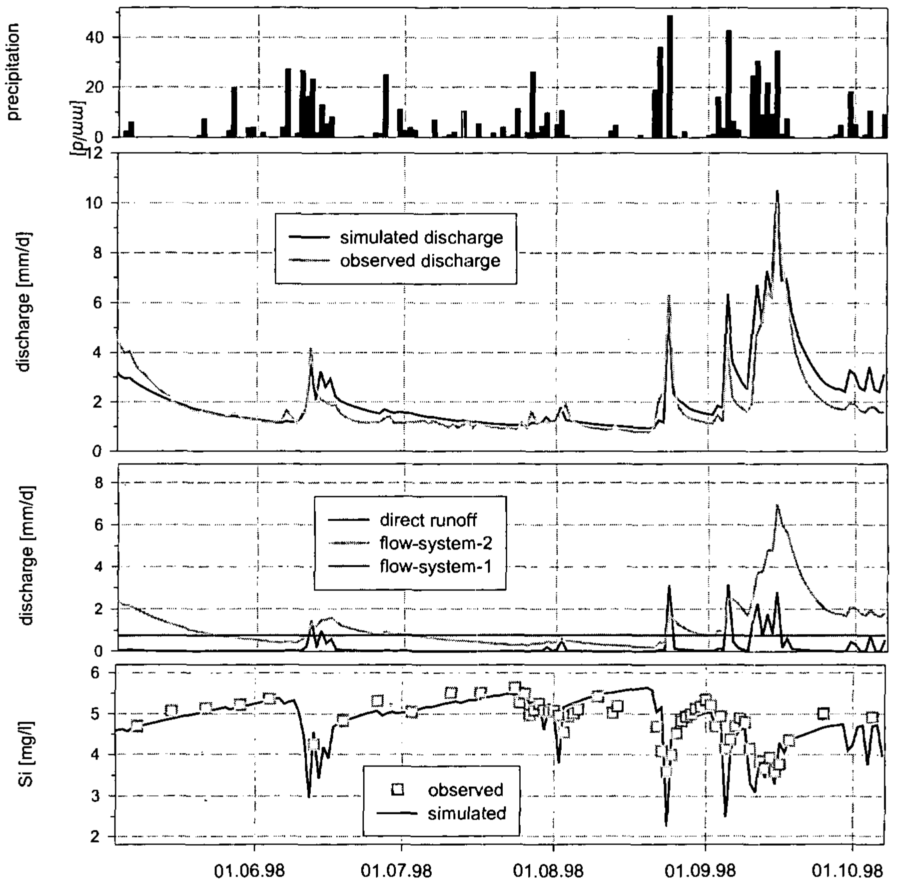

Figure 3: Measured basin wide precipitation (first), comparison of simulated and observed discharge at the Brugga gauging station (second), portions of the different runoff components (third) and comparison of observed and simulated dissolved silica concentrations (observed concentrations with error bars; fourth) for the period 03.05.98–07.10.98 (adapted from Uhlenbrook et al., 2000).

In a next step, an extensive model validation on internal stages and flows was performed using additional information (multiple-response validation). Therefore, snow height measurements, contribution of runoff components and silica concentrations were compared with the simulations at a spring and the basin outlet. The snow data showed the realistic simulation of snow accumulation and melt for one station. The correspondence between the simulated and observed silica concentration at the basin outlet is less accurate for the whole simulation period of 3.2 years compared to runoff simulations ($r^2 = 0.36$). However, for shorter periods good silica simulation could be obtained without any parameter optimisation (Figure 3; see also the simulation of a snow melt period in Uhlenbrook and Leibundgut, 1999). For the simulation at the spring the same order of goodness was reached. Last but not least, the model was validated using the portions of calculated runoff components. The analysis of the tracers oxygen-18, tritium and CFC on a monthly basis showed a similar composition of the three runoff components as the TAC simulations (Table 2).

Table 2: Comparison of the proportions of runoff components determined by tracer measurements in the Brugga basin (using oxygen-18, tritium and CFC measurements, see Uhlenbrook et al., 2000) and simulated with TAC.

	Runoff components determined by tracer measurements [%]	Runoff components simulated with TAC [%]
Near surface runoff	11.1	9.9
Shallow groundwater	69.4	66.6
Deep groundwater	19.5	23.5

Concluding remarks

The potential of tracer methods for identifying the runoff generation at a catchment scale was demonstrated. Source areas, flow paths, residence times and the contribution of different runoff components could be determined. Based on these findings, better process oriented modelling concepts can be developed. The modelling approach of TAC, which is based on the spatial delineation of unit types with the same dominating runoff generation processes and their conceptualisation with relatively simple routines, is suitable for an improved process-oriented modelling. Apart from classical hydrometric data (snow heights, runoff from sub-basins etc.) the potential of tracer methods for performing a multiple-response validation was demonstrated. Tracer concentrations or calculated runoff components can be used to validate or disprove a modelling concept. The bipartite approach with combined experimental and modelling research within the same project was successful and is recommendable for future investigations.

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