

## **Improving hydrological process modelling by coupling a rainfall–runoff model with tracer techniques**

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**Abstract** In the last few years remote sensing and GIS have been intensively used to improve rainfall-runoff modelling with reasonable success. Due to the powerful information which tracers provide about hydrological systems they can also be used for improving rainfall-runoff modelling. In this study tracer techniques helped to understand the turnover of water in the study basin. It was possible to determine the contributing reservoirs and transit times. With this information the modelling results were verified and simulated runoff components were allocated to physical reservoirs. Additionally, problems in modelling were detected. The comparison between modelled and tracer transit times of the groundwater component showed a remarkable difference.

### **INTRODUCTION**

The problem areas in hydrological modelling include (a) process understanding, (b) parameter estimation, (c) scales and (d) model validation (Todini, 1988; Beven, 1989; Bonell, 1993; Leavesley, 1994). A better physical understanding of hydrological processes and their interactions is needed. Physically based parameters are needed to describe the processes on different scales. Due to the complexity of nature, model parameters always represent an integration or average of spatial heterogeneity. But the laws of lumping parameters at the basin scale are still not known (Beven, 1989). Hydrological models tend to over-parameterization so that the parameters used show a degree of interdependence. Therefore, equally good simulations can be obtained with different parameter sets.

New approaches like remote sensing and GIS are widely used to meet the problems (b) and (c) (e.g. Ott *et al.*, 1991; Su *et al.*, 1992). However, these methods predominantly provide surface describing parameters. In contrast, tracer techniques supply vertical insight into hydrological systems and help to understand the processes and interactions involving the turnover of water in basins. With this information the dominating processes for runoff generation and their runoff components can be evaluated. Therefore, parameters determined by tracer techniques show a high potential for the use in hydrological process models.

The present study was undertaken to investigate the improvement of hydrological modelling with the aid of tracer determined information. The procedure was as

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follows: (a) modelling of the rainfall-runoff process with an existing model, (b) determination of runoff components and transit times with tracer methods, (c) comparison of the results of modelling and tracers, and (d) improving modelling with tracer information.

## STUDY SITE

The Brugga basin (40 km<sup>2</sup>) is located in the Southern Black Forest, southwest Germany. The bedrock of the basin consists of gneiss. It is covered by soils and debris of varying depth. At the bottom of the slopes the debris cover is ~10 m at maximum. The catchment topography is strongly variable with an elevation varying by more than 1000 m. The basin is characterized by high plains (20% of the basin area), steep slopes (75%) and narrow valley floors (5%). The mean annual precipitation amounts to 1750 mm, generating a mean annual discharge of approximately 1250 mm. Snow accumulation in winter, snow melt in spring and evapotranspiration during summer, govern the long-term annual discharge pattern. The catchment is widely forested (75%). About 23% of the basin is used as grassland and less than 2% is sealed.

## METHODS

The modular-designed, semi-distributed and physically based Precipitation-Runoff Modelling System (PRMS) (Leavesley *et al.*, 1983; Leavesley & Stannard, 1990) is used. Each process of the hydrological cycle is expressed in the form of physical laws or empirical relationships. Hydrological Response Units (HRUs) represent the spatial heterogeneity of the hydrological system in the model. Each HRU is homogeneous in its response to precipitation and different to other HRUs. The catchment is divided into HRUs based on basin characteristics such as slope, exposure, vegetation, soil properties and precipitation distribution. Water and energy balances are computed for each HRU. The hydrological system is conceptualized as a series of reservoirs (Fig. 1). Since tracer hydrology provides parameters for runoff generation the representation of runoff formation in PRMS is described as follows. Surface runoff is computed using a contributing area concept. The percentage of each HRU contributing to surface runoff is a function of soil moisture and rainfall amount. Water infiltrating to the soil zone decreases the soil moisture deficit until field capacity. All water in excess of field capacity is routed downward to the groundwater reservoir. Groundwater flow is computed as a linear function of groundwater storage. Subsurface flow occurs when the groundwater recharge exceeds a definable rate. All water in excess of the groundwater recharge rate is inflow to the subsurface reservoir. Subsurface flow is computed as a nonlinear function of subsurface storage. Subsurface flow is considered to be water in the saturated-unsaturated and groundwater zones that is available for relatively rapid movement to the river (Leavesley *et al.*, 1983).

To measure the accuracy between observed and calculated runoff the efficiency  $R_{eff}$  defined by Nash & Sutcliffe (1970) was used as the objective function. The values of  $R_{eff}$  range from  $-\infty$  to 1, while a value of 1 indicates exact agreement between observed and simulated runoff.

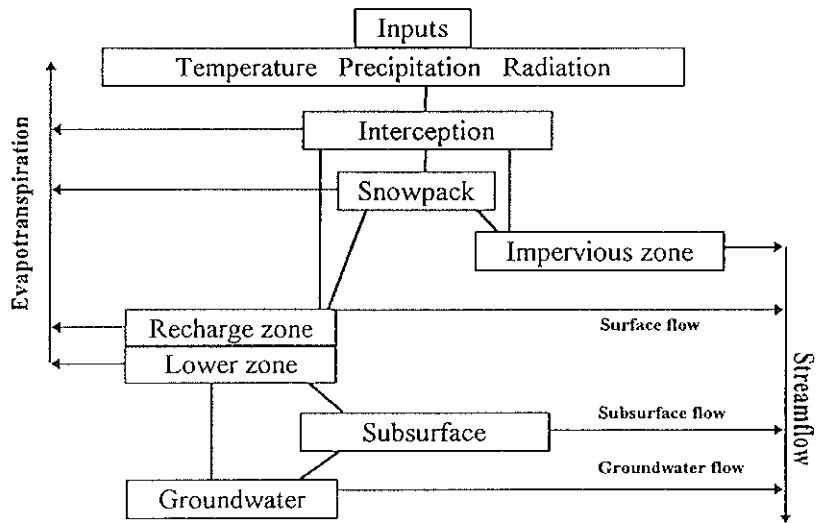


Fig. 1 Flow chart of PRMS (Leavesley *et al.*, 1983).

For the tracer hydrological investigation, end member mixing analysis was used to determine the runoff components (Sklash & Farvolden, 1979, Buttle, 1994).  $^{18}\text{O}$  and silica were used as tracers. The mean transit times of water for different reservoirs were calculated using the amplitude damping between  $^{18}\text{O}$  input and output graphs (Maloszewski *et al.*, 1983) at different sample sites.

## MODEL APPLICATION

The major processes in the Brugga basin are snow accumulation in winter, snowmelt in spring and evapotranspiration in summer. These processes are strongly influenced by basin properties such as elevation, slope, exposure and land use. 25 HRUs were delineated using GIS IDRISI overlay procedures. The dominating soil properties were also determined for every HRU. The HRUs obtained are unconnected areas. Most HRUs consist of various aggregates of pixels distributed around the study basin. This artificial catchment representation is possible because in the daily mode PRMS does not consider routing from a HRU to a channel segment or basin outlet.

Two different records were available to simulate rainfall-runoff. The first record is a ten year time series (1975–1984) which was used for initializing, calibrating and validating the model. The second record is a nine month time series. Intensive tracer hydrological investigations were carried out in the Brugga basin during the second period (July 1995–April 1996). This record was used for model validation and for comparison between model simulations and the results of tracer techniques.

## RESULTS AND DISCUSSION

The calculated values fit the observed discharge with reasonable success (Fig. 2). For the ten year period the objective function  $R_{eff}$  is 0.86. For the short period the model also explains the runoff variations quite well (Fig. 3). The same parameters determined

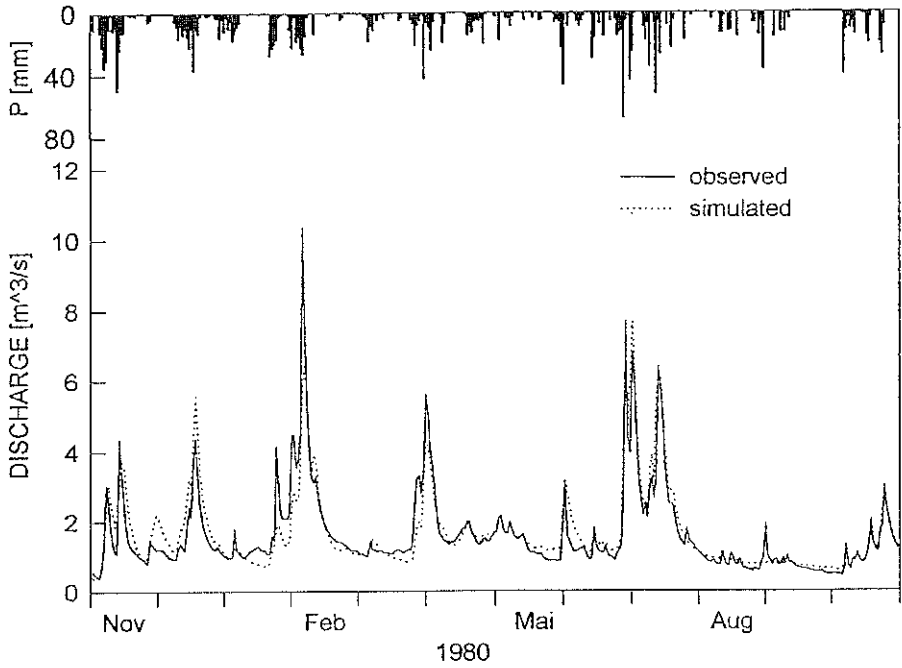


Fig. 2 Observed and simulated runoff, and precipitation of the Brugga basin for the hydrological year 1980.

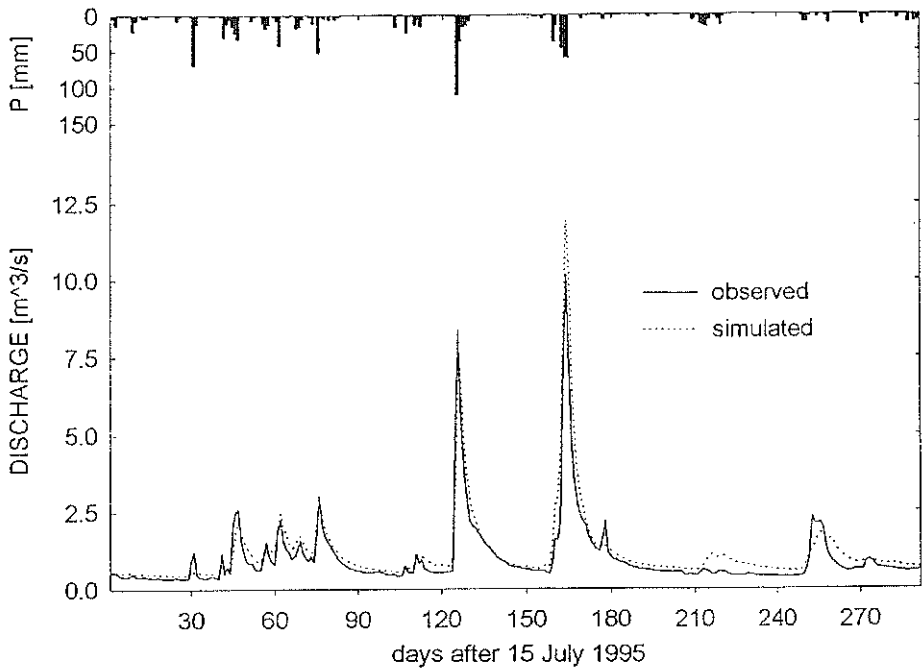


Fig. 3 Observed and simulated runoff, and precipitation of the Brugga basin from 15 July 1995 to 30 April 1996.

for the calibration period of the ten year record were also used to simulate the 1995/1996 record. The simulated runoff components show a high contribution from the debris cover during high flow periods. For event days number 150–210 the subsurface contribution was 68.1%, while the groundwater reservoir provided 30.9% of the total runoff volume (Fig. 4). The surface runoff contribution is very low (1% for event days number 150–210).

In low flow periods the total amount of runoff is supplied by the groundwater reservoir. The recession coefficient of the linear groundwater reservoir is equal to that determined in spring during low flow. The recession coefficient leads to a storage constant of 120 days for the groundwater reservoir. The storage constant is equal to a turnover time (Yurtsever, 1995), so that the simulated turnover time or residence time for the groundwater flow is 120 days.

The tracer hydrological runoff component analysis showed that four reservoirs provide the majority of the runoff in the Brugga basin. The direct component contributes up to 45% during the first hour of an event. But its importance decreases rapidly during the event, so that the upper debris cover contributes 65–75%, and baseflow 25–35%, of runoff for the whole event. The baseflow contribution originates in the lower debris cover (10–15%) and the fractured gneiss (85–90%). Transit times vary from hours up to a decade for the different reservoirs (Table 1). Detailed information on the evaluation and results of the tracer hydrological experiments are given in Lindenlaub *et al.* (1997).

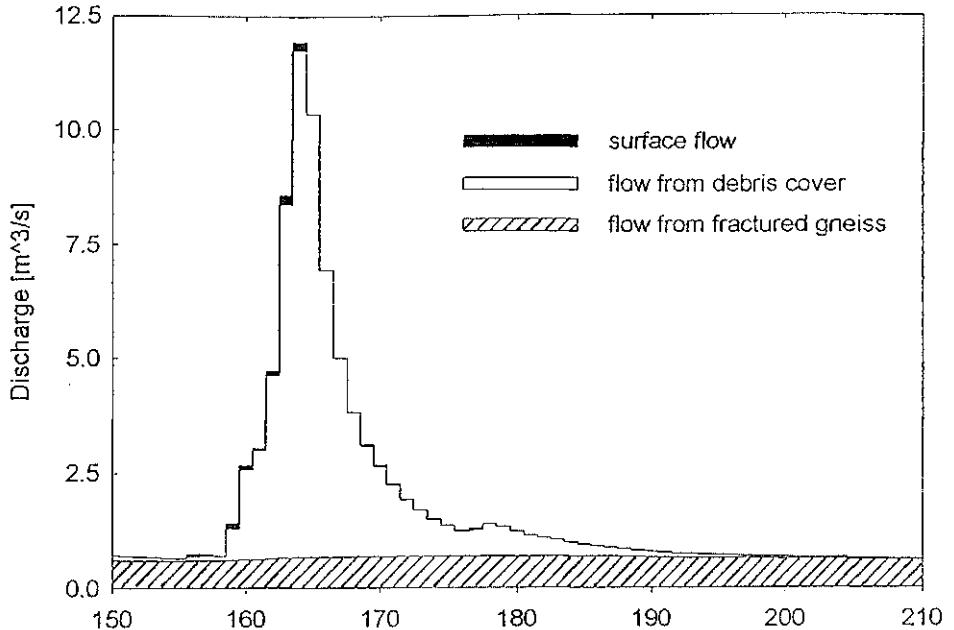


Fig. 4 Simulated runoff components for event days number 150–210.

## CONCLUSIONS

The comparison shows that the PRMS model allows the simulation of runoff components determined by tracer techniques with reasonable success. Due to the

**Table 1** Runoff components, reservoirs and their tracer hydrological characterization (Lindenlaub *et al.*, 1997).

Runoff component	Tracer behaviour	Reservoir location	Transit time	Quantification
Direct runoff	Dilution by event water, decrease in pH and electrical conductivity	Surface	Hours	Up to 45% during short periods
Weekly component	Decrease in silica	Upper debris cover	Days to week	Up to 65–75% during events
Base component	Annual pulsation of $^{18}\text{O}$	Lower debris cover	1–2 years	10–15% of baseflow
Delayed base component	No reactions in silica and $^{18}\text{O}$	Crystalline bedrock	10 years	85–90% of baseflow

conceptualization of PRMS it was not possible to model two different baseflow components. For simulation, lower debris cover and fractured gneiss must be considered as one single reservoir. Additionally, the simulated residence time of water for the baseflow component differs strongly from the tracer results. This is due to the ratio of mobile and immobile water in the lower debris cover and fractured gneiss. While isotopes reflect the age distribution of the mobile and immobile water, the storage constant of the linear storage concept represents only the dynamics of the mobile water.

The use of tracer techniques helps to understand the turnover of water in the study basin. It was possible to determine the contributing reservoirs and respective transit times. With this information the modelling results could be verified, and simulated runoff components could be allocated to physical reservoirs. Finally it can also be concluded that by coupling hydrological models with tracer hydrological techniques a step can be made in solving all of the problem areas (a) to (d) mentioned at the beginning of this paper.

Further work will consider greater flexibility in the use of more than three runoff components and improvements in the transit time simulation.

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