Integrated Methods in Catchment Hydrology—Tracer, Remote Sensing and New Hydrometric Techniques
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Integration of tracer information into the development of a rainfall–runoff model

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Abstract A conceptual rainfall–runoff model has been developed for the mountainous Brugga basin (39.9 km^2) situated in the Black Forest, southwestern Germany. This model contains an extensive, physically realistic description of the runoff generation, considering seven unit types each with characteristic dominating runoff generation processes. The processes are conceptualized by different linear and nonlinear reservoir concepts. Tracer concentrations (i.e. dissolved silica) are attributed to reservoir outflows, according to tracer hydrological investigations. A study period of 20 months showed a reasonable agreement between simulated and observed discharge. The simulated amounts of different runoff components also agreed well with calculations based on measurements of natural tracers. The tracer simulations were less accurate, whereas the general behaviour of the tracer concentrations and short time periods were modelled well.

INTRODUCTION

On the one hand, tracer methods provide excellent tools for examining runoff generation processes. Tests using artificially injected tracers allow insight into the runoff generation processes at the hillslope scale. The use of natural tracers such as isotopes or geochemical tracers provides valuable information about runoff components and their formation and dynamics at the catchment scale. On the other hand, rainfall–runoff models have also improved in recent years. Increased computer capacities have made it possible to develop distributed physically-based models (e.g. SHE model; Abbott *et al.*, 1986). However, the enormous spatial variable 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 readily available for most applications. Attempts to incorporate hydrochemical data for such a model have been performed (Bergström *et al.* 1985; Lundquist *et al.*, 1990). Unfortunately, these models have only simple runoff generation conceptualizations, which are usually much poorer than knowledge of the processes based on field studies. Therefore, the objective of this study is to combine suitable methods, such as tracers and rainfall–runoff models, to develop a process-oriented model, which incorporates the results of runoff generation studies using tracer methods.

MATERIALS AND METHODS

Study site and runoff generation processes

The study was performed in the mountainous Brugga basin (39.9 km^2), located in the

Southern Black Forest, southwestern Germany. The mean annual precipitation is 1750 mm, generating a mean annual discharge of 1200 mm. About two thirds of the precipitation in the upper parts falls as snow. The bedrock consists of gneiss and anatexits, covered by soils and drift of varying depths. The basin is widely forested (75%) and the remaining area is pasture; urban areas are below 2%.

Tracer investigations and field observations showed that fast runoff components are generated on saturated areas and on steep highly permeable slopes covered by boulder trains. Slow runoff components originate from the fractured hard rock aquifer and the deeper weathering zone. The major part of the area (60.3%) is covered by periglacial deposits. Here macropore flow occurs, soil water displacement takes place, and perched groundwater tables can spread above less conductive layers. This mainly results in delayed runoff components depending on the antecedent moisture content (Leibundgut & Uhlenbrook, 1998). The contribution of fast, delayed, and slow runoff components was calculated according to measurements of natural tracers to be 10%, 67.5% and 22.5%, respectively (Lindenlaub, 1998).

TAC model

General The TAC model (tracer aided catchment model) 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 the further modules were adapted from other conceptual models. The spatial discretization was based on a delineation of zones, each with characteristic dominating runoff generation processes (Rutenberg *et al.*, 1999) and elevation zones. The model uses a daily time step and simulates discharge and concentrations of examined natural tracers (e.g. dissolved silica or ^{18}O) by using basinwide precipitation, temperature and potential evapotranspiration.

Snow and soil routine The model input variables precipitation and temperature are varied for each elevation zone according to the measured increase or decrease with elevation. This specified input has to pass a snow routine, which is based on a degree-day method (e.g. Bergström, 1992). Then the precipitation or snowmelt water is transferred to a soil routine, which was adopted from the conceptual HBV model (Bergström, 1992). The advantage of this routine is that water can run off even if the soil storage is not saturated. This corresponds to the soils in the basin which contain numerous macropores. The same soil routine was used for the respective zones in the following runoff generation routine, but its parameterization depended on the particular soil properties of each zone.

Runoff generation routine Seven zones, each with characteristic dominating runoff generation processes, were distinguished. Each zone obtained a model input depending on its elevation and areal extent. Thus, all model computations of the following reservoir concepts were performed in this (semi-)distributed way; only the underlying fissured aquifer reservoir was computed in a lumped manner. Four of the seven reservoir concepts are presented in Fig. 1; the other three are simple linear reservoirs.

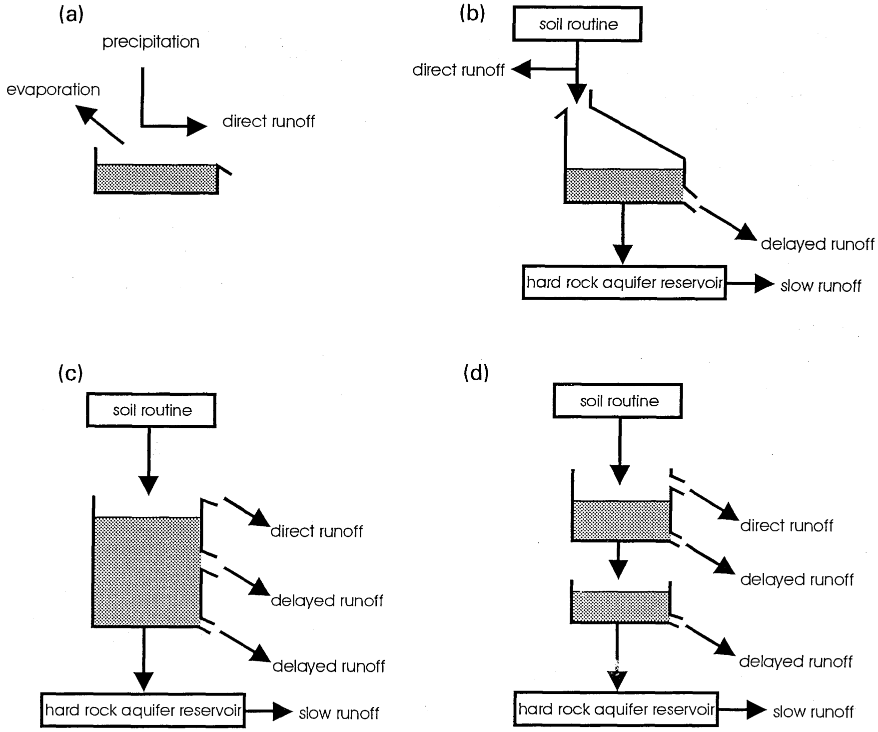

Fig. 1 Four different reservoir concepts of the runoff generation routine: (a) saturation overland flow, (b) groundwater ridging, (c) transmissivity feedback, (d) perched water table.

On saturated areas, saturation overland flow is computed. The rainfall or snowmelt water runs off directly after filling a reservoir, which considers losses due to interception and microtopographic depressions (Fig. 1(a)). Evaporation empties this reservoir.

In flat, incompletely saturated, near-stream zones the groundwater ridging process is assumed. In these zones the groundwater table and the capillary fringe are close to the surface and a little infiltrating water is sufficient to cause a relatively strong rise of the groundwater table. This is responsible for an efficient displacement of near-stream groundwater (delayed runoff). In TAC, this process is conceptualized by a single reservoir, which is linear until the reservoir content exceeds a threshold (Fig. 1(b)). Then the reservoir outflow becomes nonlinear. If the reservoir content exceeds a second threshold, the reservoir "overflows"; i.e. the water from the soil routine runs off directly. This corresponds to a rise of the water table to the surface and an initiation of saturation overland flow. A constant loss to the fissured aquifer is also considered.

On steep slopes covered by boulder trains, fast lateral subsurface flow occurs (direct runoff) if the contribution to the underlying hard rock aquifer is exceeded. This is computed by a single linear reservoir, with a constant loss to the fissured aquifer reservoir.

In some parts where the periglacial drift cover is not stratified, the hydraulic conductivity increases the closer the groundwater table rises to the surface (higher conductive layers become active; "transmissivity feedback"). This is conceptualized by a single reservoir with three outflows, which become active when the reservoir content exceeds certain thresholds (Fig. 1(c)). All reservoir outflows are modelled linearly.

The main part of the basin is covered by a stratified periglacial drift cover (Rutenberg *et al.*, 1999). Here the runoff generation is characterized by perched aquifers, which spread on top of less conductive layers (i.e. a compacted soil layer or the soil bedrock interface) during larger events. This is modelled with two serial reservoirs, where the maximal percolation rate from the upper to the lower reservoir is defined by one model parameter (Fig. 1(d)). The upper reservoir has two outflows, representing the fact that the discharge in the perched aquifer increases considerably when the water table comes closer to the surface (similar to Fig. 1(c)). The lower reservoir stands for the less conductive layer and provides only a delayed runoff component.

Tracer investigations showed that slower runoff components are generated on areas covered with moraines and on the remote hilly uplands. Both areas are conceptualized each with a simple linear reservoir. A constant loss to the fissured aquifer reservoir is taken into account for both areas.

The flow through the fissured aquifer (slow runoff component) can be modelled with different lumped parameter models for tracer transport, which are described in detail by Maloszewski & Zuber (1996). The exponential piston flow model (EPM) was most suitable for the Brugga basin. The two fitting parameters were determined by ^{18}O investigations (Lindenlaub, 1998). For using these values in TAC, they have to be converted considering mobile and immobile zones in the fissured aquifer (Mehlhorn & Leibundgut, 1999).

All runoff components of the different reservoir systems are added to give the total simulated discharge. An additional runoff routing routine is not considered for the 39.9 km^2 Brugga basin, since it is assumed that the generated discharge reaches the outlet in the channel system within the simulation time step of one day. However, the integration of a routing routine for shorter time steps is possible. A constant tracer concentration is attributed to each reservoir outflow. Here the results of the tracer hydrological investigations of the different runoff components and source areas (Lindenlaub, 1998; Leibundgut & Uhlenbrook, 1998) are incorporated. The mean concentration of the reservoir outflows, weighted by the amount of each runoff component, gives the simulated tracer concentration in the total discharge.

Model application

All computations of the snow, soil, and runoff generation routine were performed separately for elevations zones with a vertical extent of 100 m. The distribution of zones with the same dominating runoff generation processes within one elevation zone is presented by Rutenberg *et al.* (1999). The mean temperature was determined from three meteorological stations and the areal precipitation was computed from measurements at four stations. The precipitation data were corrected for systematic measurement errors. The potential evapotranspiration was calculated using the approach of Turc & Wendling (DVWK, 1996). For tracer concentrations, the determined concentrations of dissolved silica for the different flow systems were used without further optimization (Leibundgut & Uhlenbrook, 1998).

The model was calibrated manually for the period 15 July 1995–1 April 1997 using a trial and error procedure. This was supported by using a Monte Carlo procedure where, for each model parameter, intervals were defined. The parameter values were determined randomly within the intervals. These intervals were based on field measurements and the application of other models. They were reduced gradually. To evaluate the model performance, three objective functions were used: the model efficiency, R_{eff} (Nash & Sutcliffe, 1970); the model efficiency using logarithmic runoff values, $\log R_{eff}$, for the runoff computations; and the coefficient of determination, r^2, to compare simulated and observed tracer concentrations. During the optimization the main objective was a good reproduction of observed discharge. The model was run on a daily base step; tracer observations were available weekly, except for the snowmelt period in spring 1996.

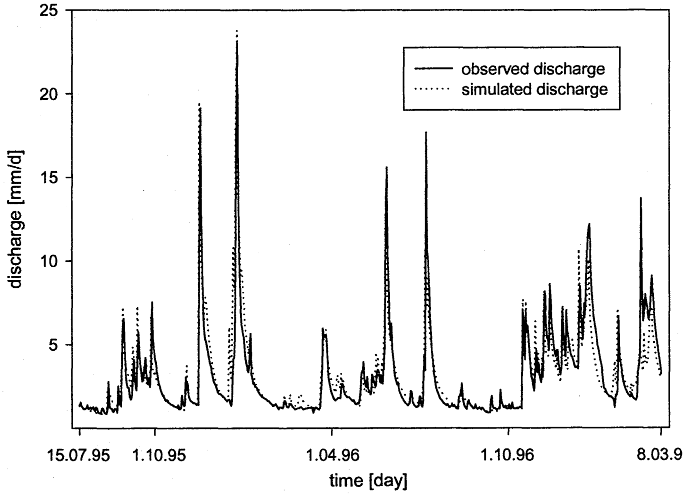

Fig. 2 Results of the discharge simulation using TAC for the period 15 July 1995–8 March 1997.

RESULTS

A good agreement between simulated and observed discharge was reached (Fig. 2). The model efficiency, R_{eff}, amounted to 0.767 and $\log R_{eff}$ to 0.835 for the investigated period. The general runoff dynamic is described adequately; the mean and low flows are simulated particularly well. The simulation of high flows is poorer, peaks are over- or underestimated. The contribution of fast, delayed, and slow runoff components amounted to 10.6%, 69.5% and 19.9%, respectively. This corresponds to the results obtained from ^{18}O measurements (Uhlenbrook, 1999).

The correspondence between simulated and observed silica concentrations in total runoff is less accurate compared to runoff simulations. For the whole period r^2 amounts to 0.29. However, for shorter periods a reasonable silica simulation could be found (Fig. 3). It is also shown that fast runoff components occur only for short periods and that delayed runoff components contribute the largest amount. The behaviour of slow runoff components is reasonably constant.

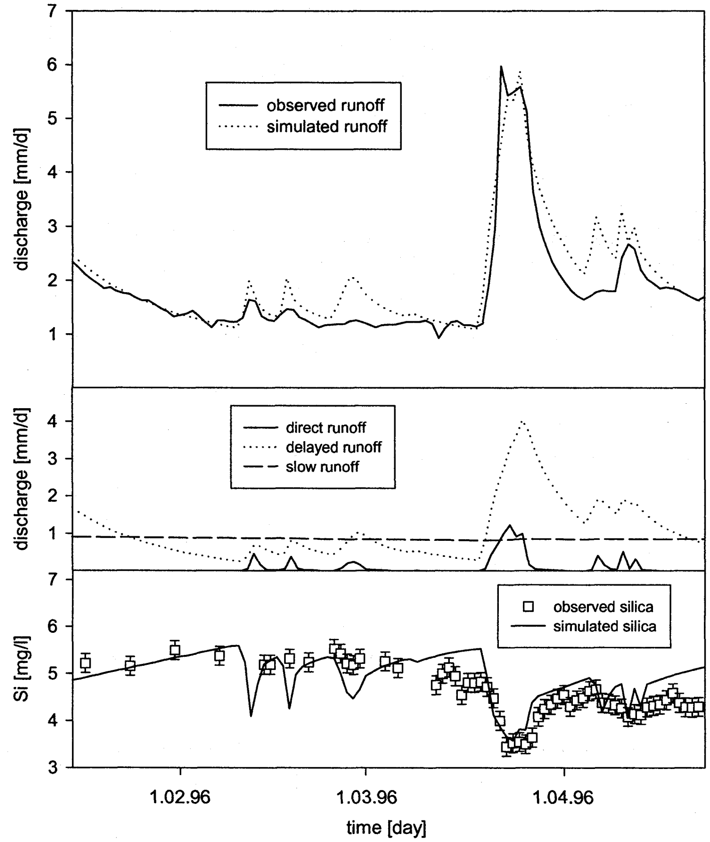

Fig. 3 Simulation of discharge (*top*), portions of the different runoff components (*middle*) and dissolved silica concentrations (observed concentrations with error bars, *bottom*) for the period 14 January 1996–23 April 1996.

DISCUSSION AND CONCLUSIONS

The less accurate simulation of high flows is caused by different reasons. First, the uncertainty of high flow measurements is larger. Second, the calculation of basinwide precipitation was not consistent because two rainfall stations had many data gaps, especially during winter. Last but not least, the use of daily time steps causes uncertainties in exact timing of the discharge. For snowmelt-induced events it is particularly difficult to determine the correct temperature for each elevation zone, which defines the melt rate. This is caused by daily temperature variations or temperature increases with elevation (temperature inversion). The influence of land use on temperature (moderation effect of forests compared to open-land use) is a third factor that modifies melting conditions. In a mountainous basin such as the Brugga, topography causes additional problems in calculating melt rates (aspect or shadowing effect).

The computed amounts of the runoff components agree well with calculated amounts based on ^{18}O measurements. The comparison of simulated and observed tracer concentrations offers an additional opportunity to assess the modelling concept.

The general dynamics of silica concentrations and the simulation of short periods is modelled fairly well considering the model was not calibrated for this objective. The accuracy of the simulations corresponds to results presented by Bergström *et al.* (1985) and Lundquist *et al.* (1990) for different hydrochemical parameters. One problem is the assumed constant behaviour of silica concentration, i.e. no temporal variations were considered for the different outflows of the reservoir systems. This was done because no systematic variations of silica concentrations were found (Leibundgut & Uhlenbrook, 1998). The poorer tracer simulations are partly caused by errors in discharge simulation. For instance, before the main snowmelt event in spring 1996, the model simulated three small events where little or no effect was observed in the discharge (Fig. 3). In reality, the falling precipitation was held in snow cover while the model simulated runoff. This is probably caused by an incorrect temperature regionalization. The errors of discharge modelling trace to silica modelling, i.e. the immediate activity of fast runoff components with low silica content caused an underestimation of silica concentrations. However, good discharge simulations resulted in adequate tracer simulations shown for the main snowmelt event (Fig. 3).

To conclude, the modelling concepts presented provide a realistic description of runoff generation in a mountainous basin. A tool was developed to simulate water and tracer fluxes within such a catchment. This approach shows how the results of tracer investigations can be integrated into rainfall–runoff modelling. Consequently, new possibilities for the assessment and validation of a modelling approach are introduced.

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