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The use of tracer hydrological time parameters to calibrate baseflow in rainfall–runoff modelling

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Abstract This paper discusses the use of tracer time parameters to calibrate the baseflow time concentration in a conceptual rainfall–runoff model. A comparison showed that the modelling approaches in tracer hydrology and rainfall–runoff modelling were mathematically equivalent. Therefore, it was assumed that tracer time parameters were suitable to calibrate baseflow runoff models. It can be shown that this is possible if the mobile and immobile water volumes in the groundwater system are considered. In a case study, the tracer time parameter of baseflow was 920 days. This value indicates the age of all water in the groundwater system and has no influence on the shape of the hydrograph. Recession analysis led to a turnover time of the mobile water in the groundwater system of 340 days. Coupling the water age and turnover time made it possible to simulate the baseflow with more detail. The calculated baseflow reflects correctly the dynamics of the groundwater system and the age of the baseflow.

INTRODUCTION

Many papers discuss the use of tracer hydrological techniques to obtain information on flow pathways or runoff components (for a review see Buttle, 1994) and on the age of water in hydrological systems (e.g. Maloszewski & Zuber, 1982; Stewart & McDonnell, 1991). Most studies which combine tracers and hydrological modelling use rainfall–runoff models to simulate streamwater chemistry (e.g. Christophersen *et al.*, 1990). The basic argument of these studies is that if it is possible to simulate both runoff and streamflow chemistry, then the model represents the hydrological system. Hooper *et al.* (1988) and Robson *et al.* (1992) used tracer techniques to calibrate or validate rainfall–runoff modelling.

The objective of this paper is not to describe how to achieve tracer hydrological information but to show how this information can be used to improve rainfall–runoff modelling. In particular, the use of tracer determined transit times to calibrate baseflow time concentration in conceptual rainfall–runoff models will be discussed.

METHODS

Water age definitions in tracer hydrology

To determine water ages of a hydrological system, mathematical models are used to relate the measured input and output tracer concentration. The main parameter of all

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models is the tracer time parameter. In tracer hydrology there are three different time parameters defined (Yurtsever, 1995). **Residence time** is the time elapsed since a labelled element enters the system and the time it is observed in the system. **Transit time** is the time spent by a labelled element between entry into and outflow from a system. **Turnover time** is the time it takes to exchange the total mobile water volume of the system under steady-state conditions: $T = V_{mob}/Q$, where T is the turnover time, V_{mob} is the mobile water volume, and Q is the flow rate.

It is important to note that the first two definitions relate to tracers, while the turnover time is only defined by the mobile water volume, regardless of its composition. Therefore, time estimates derived from tracers are only valid for the mobile water if the tracer is conservative and shows no chemical or physical retardation.

Stable isotopes like D or ^{18}O are widely used as tracers and show no chemical retardation since they are part of the water molecule. But the water molecules HDO or $H_2{}^{18}O$ are heavier than $H_2{}^{16}O$. This physical difference can cause retardation due to diffusion processes. This is especially true for double porous media like fractured rocks, where diffusion processes, in addition to advection and dispersion, influence the concentration of tracers. In this case the tracer diffuses from the mobile water in active fractures into the immobile water in the porous matrix of the rock, and *vice versa*. To account for this physical retardation and to relate the tracer time parameter to that of the mobile water, the mobile and immobile water volumes in the system have to be considered (Neretnieks, 1981):

$$\frac{T}{\tau} = \frac{V_{mob}}{(V_{mob} + V_{immob})} \tag{1}$$

where T is the turnover time, τ is the tracer time, V_{mob} is the mobile water volume and V_{immob} is the immobile water volume in the system.

In a qualitative interpretation, the turnover time T describes the dynamics of the mobile water in the system and governs the shape of the hydrograph. In contrast, the tracer time parameter τ explains the mean age of the total water volume in the system (V_{mob} + V_{immob}). The age of the water has no influence on the shape of the hydrograph. But exchange processes between the young mobile and old immobile water increases the age of mobile water. This is in addition to piston flow processes an explanation of the paradox how a hydrological system can react with a high dynamic, although the discharging water is at the same time old.

Comparison of linear lumped parameter models used in tracer hydrology and rainfall–runoff modelling

In tracer hydrology and in rainfall–runoff modelling the mathematical approaches used are linear lumped parameter models. The comparison of the approaches to determine tracer time parameters and to simulate runoff concentration in rainfall–runoff modelling shows that both fields use equivalent models (Table 1). The mathematical formulation, parameters, and units of the Exponential Model (EM) are equal to the Linear Storage (LS), and the Dispersion Model (DM) is equal to the Diffusion Wave (DW). This implies that the parameters determined by tracer hydrology must be suitable for the calibration of the runoff concentration in rainfall–runoff modelling.

Table 1 Linear lumped models used in tracer hydrology and rainfall–runoff modelling, parameters and units.

Tracer hydrology	Rainfall–runoff modelling
EM	**LS**
$g(t)=\frac{1}{\tau}\mathrm{e}^{-t/\tau}$	$h(t)=\frac{1}{T}\mathrm{e}^{-t/T}$
τ: tracer time parameter (T)	T: recession constant or turnover time (T)
DM	**DW**
$g(t)=\frac{1}{t\sqrt{4\pi(D/vx)(t/\tau)}}*\exp\left[-\frac{(1-t/\tau)^2}{4(D/vx)(t/\tau)}\right]$	$h(t)=\frac{1}{t\sqrt{4\pi(D/vx)(t/T)}}*\exp\left[-\frac{(1-t/T)^2}{4(D/vx)(t/T)}\right]$
D: dispersion ($L^2\,T^{-1}$) v: mean flow velocity ($L\,T^{-1}$) x: mean flow distance (L) τ: tracer time parameter (T)	D: diffusion wave parameter ($L^2\,T^{-1}$) v: mean flow velocity ($L\,T^{-1}$) x: mean flow distance (L) T: turnover time (T)

In a comparison of the two different mathematical approaches—EM or LS on one side and DM or DW on the other side—the models DM or DW show a higher flexibility than the models EM or LS. In Fig. 1 the reaction functions of both model groups are plotted normalized to the tracer or turnover time. Since EM or LS have only the time parameter, the corresponding reaction function can only be plotted as a single curve. In contrast, the models DM and DW contain a second parameter (*D*/*vx*) and therefore, it is possible to plot optional curves. Because of its higher flexibility, DW was tested to simulate the baseflow time concentration in an existing rainfall–runoff model.

Rainfall–runoff modelling

The rainfall–runoff modelling and tracer investigations were carried out in the mesoscale (39.9 km^2), mountainous Brugga basin in southwest Germany. In the study

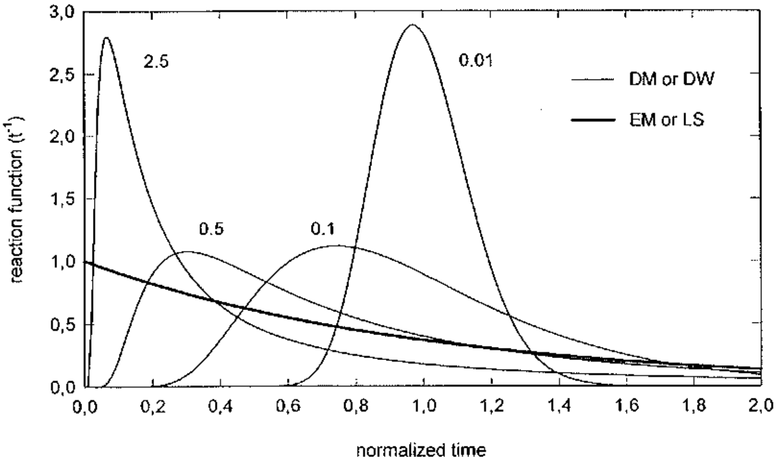

Fig. 1 Comparison of time normalized reaction functions of DM/DW for different *D*/*vx* and EM/LS.

catchment an underlying fractured gneiss provides the main part of the baseflow. For a more detailed description see Lindenlaub *et al.* (1997).

Due to its high flexibility of model alterations, the deterministic and semi-distributed model PRMS (Leavesley *et al.*, 1983) was used in the framework of MMS (Leavesley *et al.*, 1996) to simulate the rainfall–runoff process. Four steps were conducted: (1) Calibration of the unaltered model using LS for baseflow simulation. Unknown runoff generation and concentration parameters were calibrated using model inherent mathematical optimization techniques. (2) Substitution of LS by DW and simulation of the runoff process with the same model parameters as in step (1). Comparison of simulation results between step (1) and (2). (3) Determination of baseflow tracer time parameter using ^{18}O and the turnover time using recession analysis techniques; and (4) calibration of the baseflow time concentration with the tracer time parameter.

RESULTS AND DISCUSSION

Step (1) The model performance for the validation period (15 July 1995 to 30 April 1996) was good (Fig. 2(a)). The accuracy of fit was assessed during high flow periods using the model efficiency r_{eff} calculated with measured and simulated runoff (Nash & Sutcliffe, 1970) and during low flow using log-transformed runoff values ($r_{log\ eff}$). The model efficiency values r_{eff} and $r_{log\ eff}$ are 0.91 and 0.83 (Table 2). Values close to 1.0 indicate minor differences between measured and simulated runoff. The turnover time of baseflow was 160 days.

Step (2) The use of DW to simulate baseflow time concentration decreased the model performance insignificantly (Table 2, Fig. 2(b)). These simulation results were obtained using the same turnover time as in step (1) and a $D/vx_{modelling}$ of 2.0. For values of $D/vx_{modelling}$ between 0.5 and 2.0 the reaction function of DW is close to LS (Fig. 1) and therefore similar simulation results were obtained. Obviously, the model

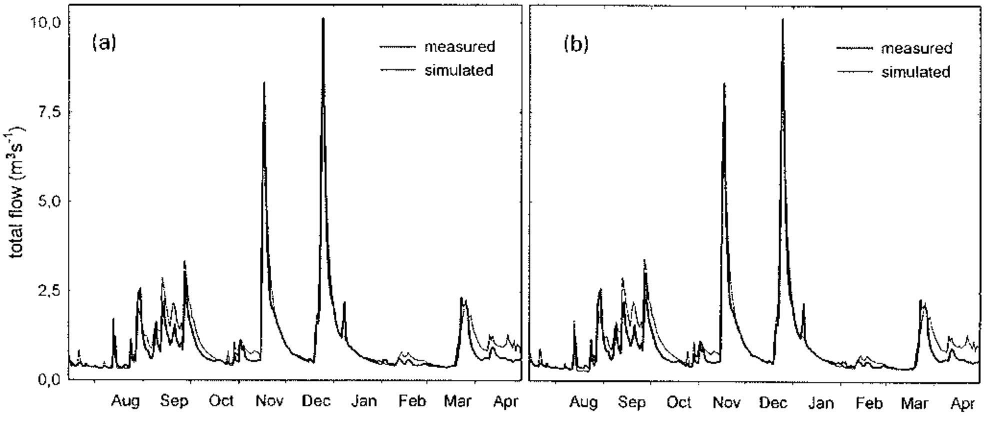

Fig. 2 Measured and simulated total flow using (a) LS and (b) DW for baseflow simulations.

Table 2 Baseflow time parameters and simulation accuracy according to Nash & Sutcliffe (1970) for steps (1), (2) and (4).

Step/Model	Baseflow parameters	r_{eff}	$r_{\mathrm{log\,eff}}$
(1) LS	T = 160 days	0.91	0.83
(2) DW	T = 160 days, D/vx = 2.0	0.90	0.82
(4) DW	T = 340 days, τ = 920 days, D/vx = 1.5 ν_{mob} = 1.0%, ν_{immob} = 1.7%	0.89	0.79

performance of DW is at least equal to that of LS. This illustrates the capability of DW to model baseflow runoff.

The comparison of the simulated baseflow runoff between LS and DW shows a quicker reaction of DW to input (groundwater recharge) and also a steeper recession during low flow (Fig. 3). In contrast, LS reacts more harmoniously and shows a slower recession. This suggests the choice of DW in catchments with shallow, reactive groundwater bodies.

Step (3) The transit time of the baseflow was determined from ^{18}O data from three springs which discharge mainly water from the fractured gneiss. EM and DM gave equally good fits to the data. The transit time for the three springs are 720 days, 900 days and 1140 days with an arithmetic mean of 920 days (Lindenlaub, 1998). D/vx_{tracer} was 0.5. The turnover time was determined using the recession analysis package DIFGA, which is based on the LS approach (Schwarze *et al.*, 1994). Altogether four different storages could be determined. The slowest reacting storage was considered as the fractured gneiss storage. That turnover time is 340 days.

Step (4) The tracer time parameter should be used to calibrate DW to simulate the baseflow time concentration. But as mentioned above, the tracer time parameter τ describes the age of the water and has no influence on the shape of the hydrograph. The turnover time T governs the hydrograph. The coupling of both time parameters using the relation expressed in equation (1) solved the problem. The mobile and

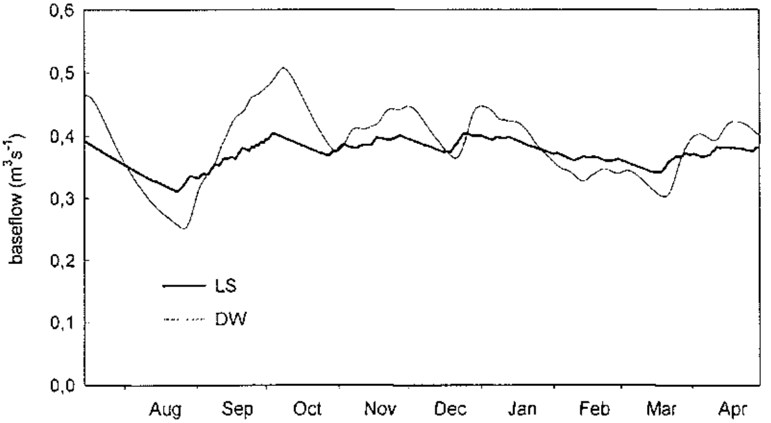

Fig. 3 Comparison of baseflows simulated with LS and DM.

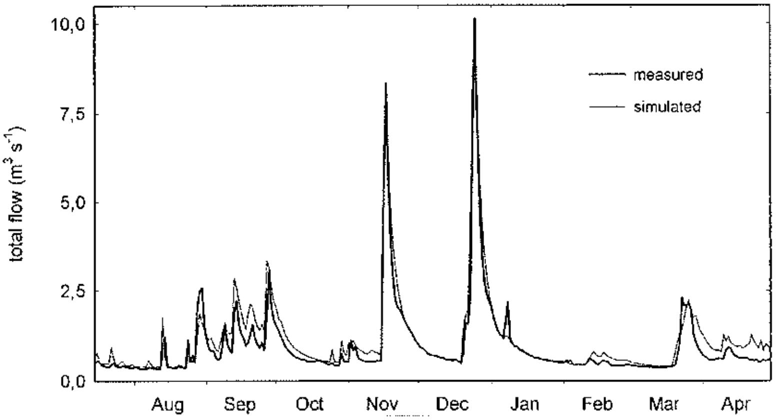

Fig. 4 Measured and simulated total flow using the coupled tracer time parameter to calibrate baseflow.

immobile water volumes were not known. Instead active fracture and inactive microporosities were used. The active fracture porosity was estimated as 1%. Considering both time parameters and equation (1) led to an inactive porosity of 1.7%; both porosity values seemed realistic.

Using both time parameters τ and T to calibrate the baseflow time concentration decreased the model performance insignificantly (Fig. 4). The r_{eff} and $r_{\log \mathrm{eff}}$ are 0.89 and 0.79, respectively (Table 2). The slightly worse result has low importance compared to the better description of the groundwater storage since now the dynamics and the age of the water are considered. Additionally, now the model was calibrated with parameters which were determined by independent methods and no mathematical optimization technique was used to improve the simulation results.

Problems arose with the use of the D/vx parameter. The tracer studies showed a D/vx_{tracer} of 0.5. Using this value in the rainfall–runoff modelling led to a poor simulation. Best results were obtained for a value of 1.5. The D/vx_{tracer} is not useful for modelling water flow because it describes not only the heterogeneity of the tracer flow field, but also diffusion effects of the tracer. For D/vx_{tracer} and $D/vx_{\mathrm{modelling}}$ a relation like equation (1) could not be found.

CONCLUSIONS

It can be concluded:

- It is possible to simulate baseflow time concentration with DW.
- Baseflow time concentration can be calibrated with tracer determined transit times, but then the mobile and immobile water volumes of the groundwater system have to be considered.
- The use of tracer time parameters leads to a more realistic description of the groundwater system since the age of the water and its dynamics are considered.
- In additional to remote sensing and GIS, tracer techniques also provide powerful tools to determine parameters for rainfall–runoff modelling.

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