

# A new, physically-based, numerical runoff generation model system for study of surface–shallow groundwater relationships and system reactions to environmental changes

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**Abstract** A new concept is presented for modelling streamflow generation on a small basin scale. It is based on process knowledge realised using the Integrated Catchment Approach (ICA), and the FEFLOW software package for numerical groundwater flow simulation. The study relates to the Lange Bramke research basin in the Harz Mountains, Germany. First simulations for steady-state confirm the drain line function of the major cross-faults. A main future perspective concerns the coupling of FEFLOW with MIKE11 for calculation of groundwater exfiltration rates into defined individual channel sections.

**Key words** Harz Mountains, Germany; numerical groundwater modelling; runoff generation; fissured rock aquifer; hydraulic conductivity

## INTRODUCTION

During storms, groundwater can be a dominant component of runoff in many regions under different climatic conditions. This has been shown by environmental tracer studies (Herrmann, 1997). It means that groundwater recharge is appropriately high in such cases. An open question is how possible changes of hydrological boundary conditions due to global warming will influence the physical processes that govern the event-based turn-over of water and matter in environmental systems (Herrmann, 2004). Furthermore, dynamic hydrological systems have often been modelled with unrealistic process simplification, i.e. with a number of numerical methods that are not physically-based, but solve a set of ordinary differential equations.

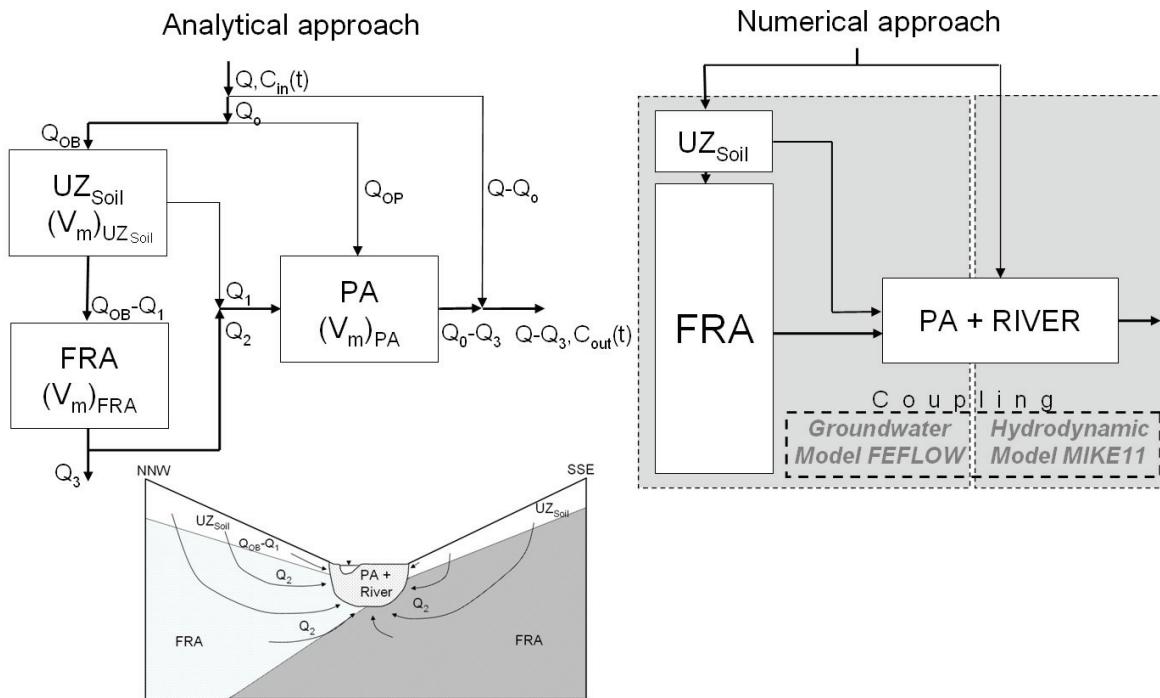
At the small basin scale, runoff formation is a primary ecohydrological process. The study of runoff formation has a long tradition as shown in the compilation of benchmark papers by IAHS (2006), but the use of integrated hydrological system approaches still plays a marginal role. Hence, a new tool for the study of runoff generation was developed that considers the holistic ecohydrological Integrated Catchment Approach (ICA; Herrmann *et al.*, 2001), which is based on combined field experiments and numerical modelling, and which has meanwhile become good practice. The tool allows for integrated water management systems for drinking water reservoirs and environmental protection at least in mountainous Central European hard rock regions of Palaeozoic age. The approach fits the IAHS PUB (Predictions in Ungauged Basins) activities and perspectives.

## RUNOFF FORMATION STUDY CONCEPT

The concept of the runoff generation study (Fig. 1) consists of combining experimental and modelling components, and establishing classical water balances on different time scales with the highest resolution for single runoff events. Hydrological and hydraulic input data are determined as required for calibration and validation of the numerical model. The relevant water fluxes for the study system are also calculated. Their successful quantification (expressed as basin averages in Herrmann *et al.*, 1989) together with the appropriate hydraulic parameter values like mean transit times for the three subsurface storages, mark the starting point for this concept. Another precondition was the progress in numerical modelling at small space and time scales in the 1990s.

The new model is based on the following physical process pattern: streamflow generation is activated by a rainfall or meltwater input pulse that mobilizes water and solutes in subsurface storages. Once the infiltration process begins, water and solutes can be exported, and the recharge process is initiated.

The new approach aims to quantify near surface water gains and subsurface soil and groundwater losses on a small basin scale by analysing simple cases in the Lange Bramke basin



**Fig. 1** The runoff formation concept with analytical solution of relevant water fluxes and subsurface storages (left) and numerical approach with spatial discretization (right).

where overland flow is negligible and the unsaturated zone (UZ: soil and upper weathered and fractured/fissured bedrock) is non-layered. In this case the interflow is close to zero. The channel flow originates predominantly from groundwater in the saturated zone (SZ: fractured/fissured bedrock). It is assumed, that UZ and SZ have shortened preferential flow paths. This enables fast percolation of infiltrating water and hence groundwater recharge throughout the year. Information on the origin, age and pathways of the water fluxes that cause channel inflow and generate flood hydrographs are required at a sufficient resolution in space and time.

## EXPERIMENTS AND MODELLING

Isotope and experimental hydrological data as well as hydraulic data were collected in the Lange Bramke research basin, area  $0.76 \text{ km}^2$  and altitude 540–700 m a.m.s.l., that is located in the Harz Mountains, Germany. It has been monitored since 1948. The basin is 90%forested by Norwegian spruce, resulting in negligible surface runoff. The wet valley floor, fire breaks aligned perpendicular to slopes, and forestry roads represent open areas. The basin has a fissured Lower Devonian rock aquifer (FRA) of sandstones, quartzite, slates and has a minor porous aquifer (PA) in the valley bottom. Experiments with artificial tracers showed that UZ and SZ are connected through preferential flow paths which indicate that SZ is just a transient storage with respect to runoff generation, and that major cross faults function as natural drain lines that favour quick and efficient groundwater exfiltration (Maloszewski *et al.*, 1999).

Topography and basic instrumentation in the Lange Bramke are shown in Fig. 2, and the geology in Fig. 5. In this context, 4" and 2" ( $1'' = 2.54 \text{ cm}$ ) piezometers were installed in FRA, and 1" in PA. The deepest piezometers are HKLU (55 m) and HKLT (25 m). Six piezometric triplets of 5 m, 10 m and 15 m depth (HKLA,B,C to HKLR,S,T) were installed for hydraulic and artificial tracer experiments. HKLQ and HKLW are 15 m deep. In contrast, 1" groundwater pipes in the shallow PA of the valley filling are only up to 4 m deep. HKLQ, U and W are recorded with automatic pressure transducers.

In the conceptual hydraulic basin model (Fig. 1) UZ is treated as a transient zone, which can be described by a specific transfer function. The SZ resembles a fissured rock aquifer (FRA) model system which is characterized within the GIS based FE FEFLOW programme package

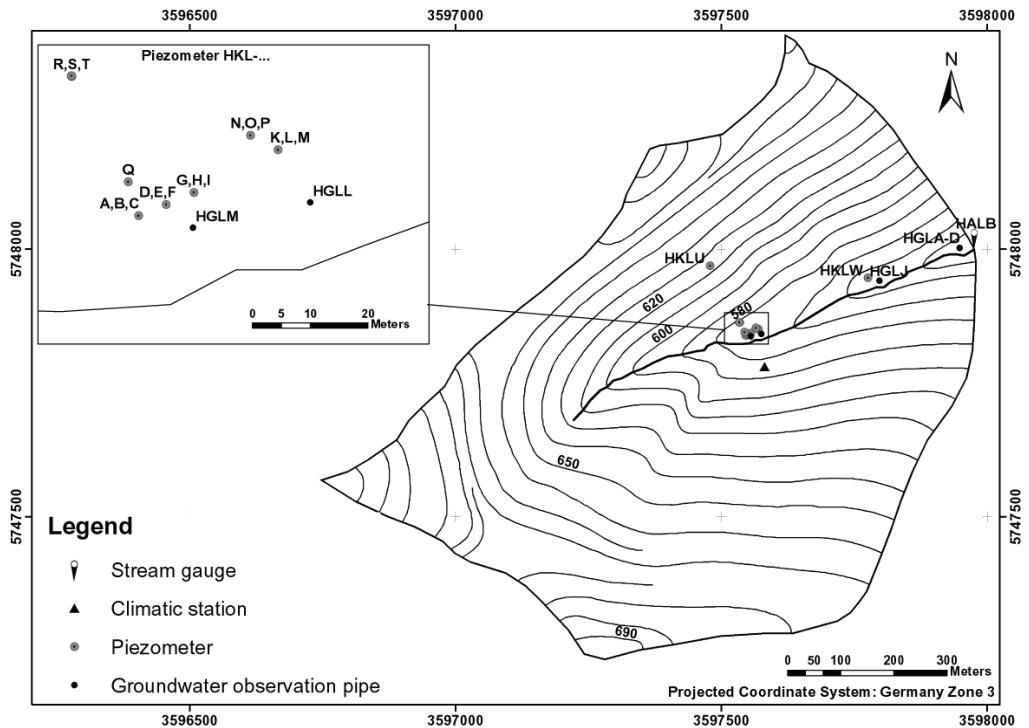


Fig. 2 Topography and instrumentation of the Lange Bramke research basin, Harz Mountains, Germany.

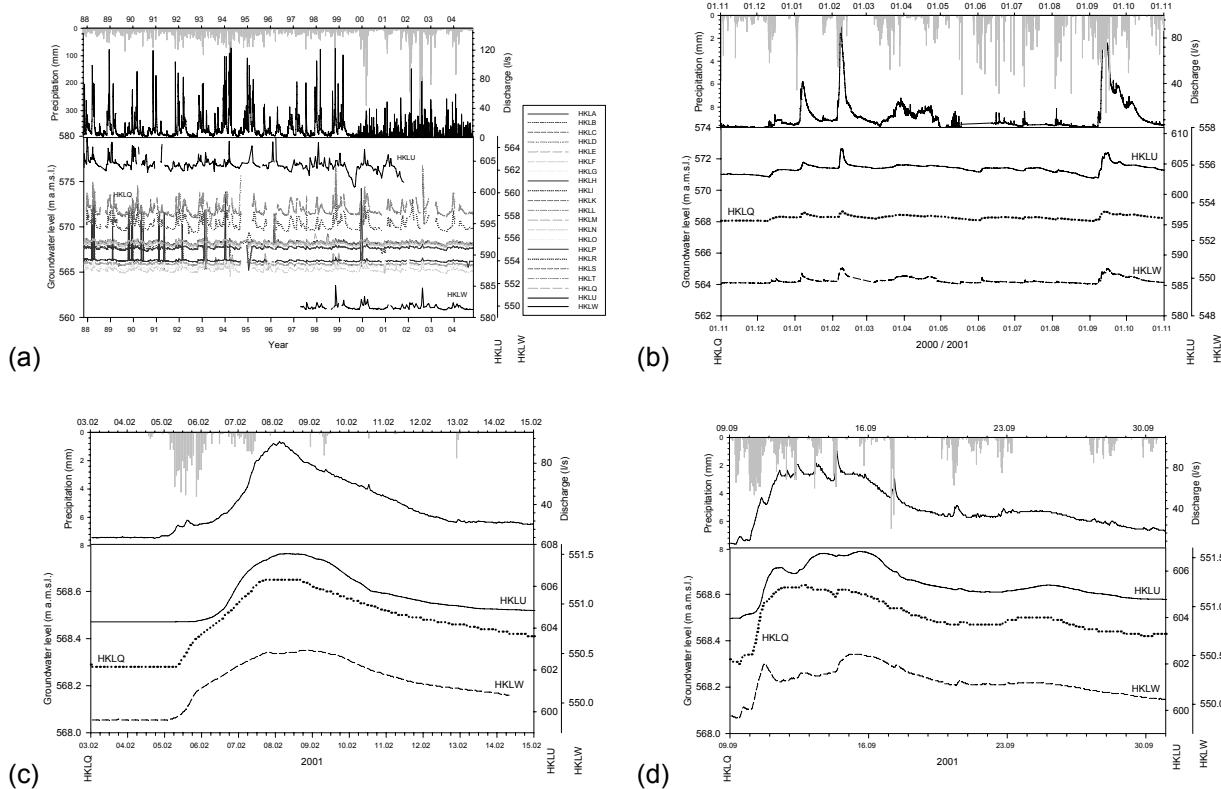
(Diersch, 2005), that allows simulation of the groundwater flow and transport. To quantify and verify the simulated groundwater exfiltration volumes along the main flow channel, FEFLOW will be coupled with the surface water software MIKE11 channel and wave propagation model in the near future by means of a special interface manager.

## RESULTS

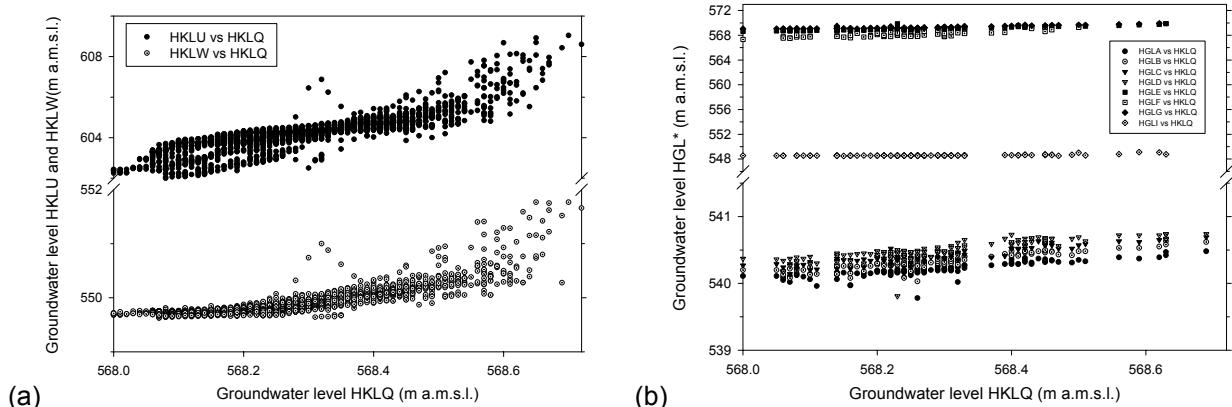
The results here concentrate on the runoff relationships with the fissured rock groundwater that is known to be the main streamflow generating component of the system. Discharge and water tables of the confined to semi-confined FRA react similarly in the long-term and for single events, but they vary in individual detail depending on the given inputs (Fig. 3). Accordingly, FRA can be considered and modelled as one hydraulic system. The closely corresponding groundwater table relationships for the fissured aquifer verified by the piezometers recordings shown in Fig. 4(a) strengthen this finding, whereas Fig. 4(b) proves the intercalated hydraulic position of PA as a transfer storage with a mean transit time of three months as compared to >3 years for FRA (Herrmann *et al.*, 1989). The groundwater–discharge relationships have frequently been found to be hysteretic, i.e. higher discharges are observed at given groundwater tables for the rising than for the falling limbs of the same hydrograph (Herrmann, 2004).

As a consequence of these findings, runoff generation must be attributed to the dominant groundwater contributions of different ages that follow diverse pathways. The related processes correspond to three distinct development stages of streamflow generation as formerly proposed by Herrmann (1994): (1) infiltration causes saturation of the top soils that results in compression of the capillary fringe; (2) the rise of groundwater tables, i.e. of groundwater potential; and (3) increase of groundwater exfiltration into channels through pressure transmission and combined groundwater ridging and macropore flow (see Buttle, 1998). Many event analyses confirm these stages which were hence introduced into the conceptual model system in Fig. 1. Furthermore, isotope findings show that annual groundwater recharge is about three times the amount determined by traditional methods (Herrmann *et al.*, 1989).

Good hydrological system knowledge and data availability allowed the application of FEFLOW to a small basin with a dominating fissured rock aquifer for the first time. The progressive 1-D to 3-D mesh generator enabled the fracture system to be simulated as shown in



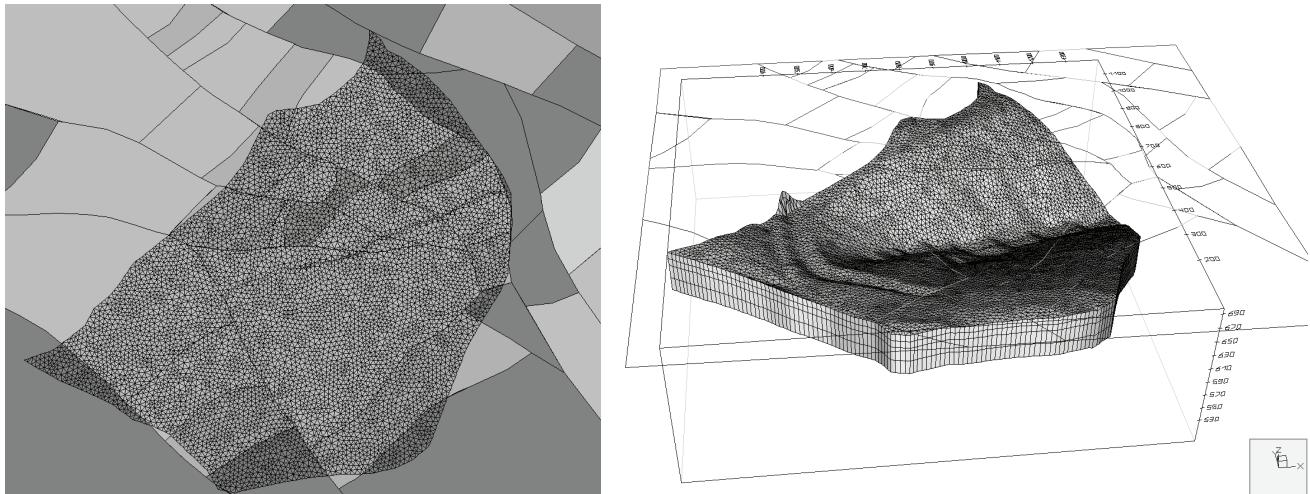
**Fig. 3** Lange Bramke basin: precipitation, discharge and fissured rock groundwater tables measured manually and automatically (HKLQ, -U, -W) (a) for 1987–2005; (b) for 2001 (only HKLQ, -U, -W); and for single precipitation-runoff events in 2001 with rain on snow (c) and rain (d).



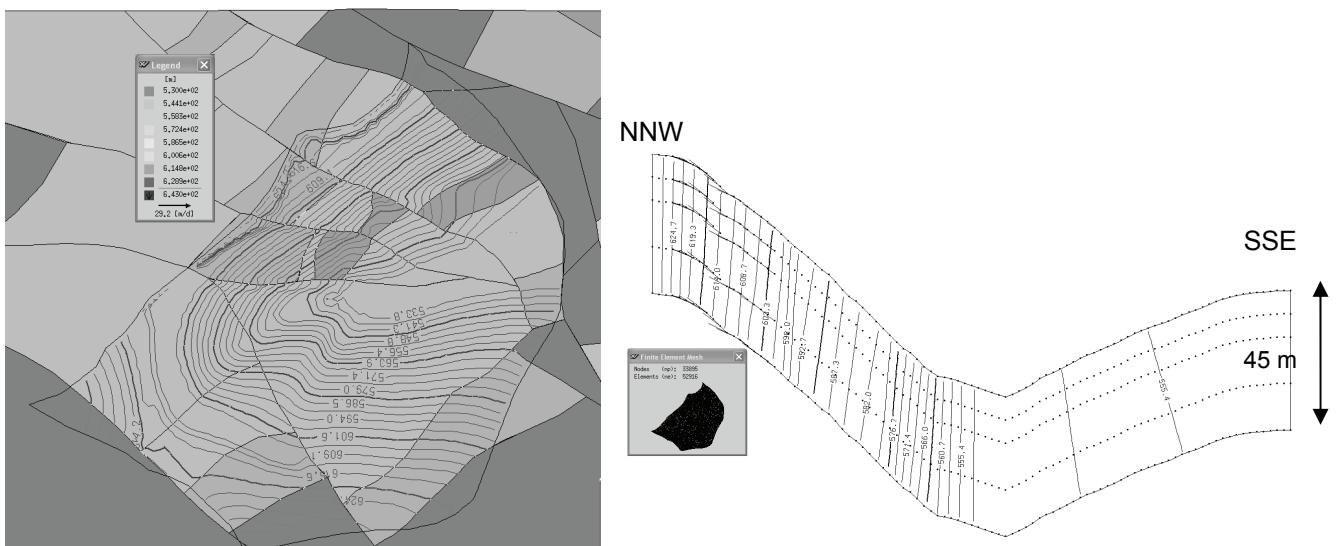
**Fig. 4** Groundwater table relationships in respect to HKLQ for FRA piezometers HKLU and HKLW in 2000–2005 (a); and between FRA HKLQ and PA (HGL\*, manual measurements) piezometers (b).

Fig. 5 as a block of fractured rock with discrete, oriented fractures and a fault network. The parameters of the 2-D fracture elements derived from analytical solutions for tracer experiments in Maloszewski *et al.* (1999) for preliminary steady-state flow simulations, i.e. with all boundaries and material data including conductivity as time-constant were: cross-section area  $1.0 \text{ m}^2$  (est.), conductivity  $1.00\text{E-}04 \text{ ms}$ , compressibility  $1.00\text{E-}04 \text{ m}^{-1}$ , in-transfer rate/out-transfer rate  $8.57 \text{ day}^{-1}$  (est.). The “cubic” Darcy Law was used which governs flow and pressure gradient relationships in the case of flow in individuals fractures, which is assumed as flow between two parallel and smooth plates. The vertical fractures are represented as discrete quadrilateral 2-D feature elements which are integrated in a FE mesh of over 50 000 six-node triangular prisms.

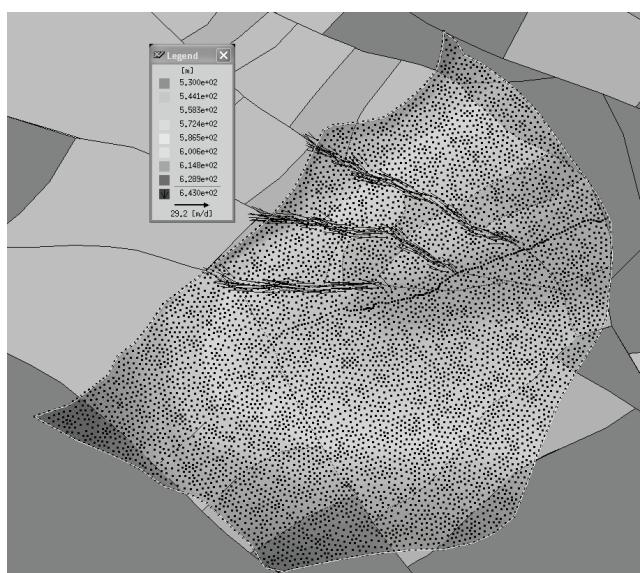
The simulated distribution of the hydraulic head is shown, together with the corresponding equipotential lines in Fig. 6. One should note the deep 45 m circulation of groundwater in the



**Fig. 5** Finite element mesh with mesh refinement of faults and geological background map (left) in 3-D with four layers and top slice reflecting the DTM (right).



**Fig. 6** Steady-state hydraulic head of FRA from FEFLOW (left) and equipotential lines (right).



**Fig. 7** Continuous flow velocities and velocity vectors (cf. legend) in FRA as calculated from FEFLOW and concentrating on the left slope area.

faults. This was confirmed 15 years ago by electromagnetic VLF-R measurements on water-bearing cross-fault structures (Herrmann *et al.*, 1989). The head isolines allows for the estimation of the (regional) meso-scale groundwater flow pattern.

The flow velocity fields in Fig. 7 indicate the importance of the major cross-faults for basin turnover of fissured rock groundwater. The high fracture flow velocities of up to  $30 \text{ m day}^{-1}$  contrast with the extended low ones for matrix flow in the less disturbed bedrock. Hydraulic conductivities of the regular rock mass (two orthogonal families of small-sized quasi-parallel fractures) from *in situ* pump and slug tests range between  $2.20\text{E-}06$  to  $3.5\text{E-}05 \text{ m s}^{-1}$ , and in highly fractured zones near the top of the non-weathered bedrock and close to faults, are on the order of  $8.20\text{E-}05 \text{ m s}^{-1}$ . A previous multi-tracer experiment in the centre one of the three major cross-faults (cf. Fig. 7) helped to determine the average flow velocity to be  $12 \text{ m h}^{-1}$  which corresponds to turbulent flow (Maloszewski *et al.*, 1999) and agrees with the present modelling findings.

The results portray the functioning of major cross-faults as main groundwater drain lines. However, analysis shows that the exfiltration amounts from these faults are too little for the formation of single flood hydrographs. Hence, additional exfiltration volumes need to be included in the process, i.e. that which originates from the matrix flux of the less conductive bedrock. Therefore special emphasis must be paid to the transfer role of PA, i.e. on the coupling of the groundwater system and the main channel. This will be realised with the help of MIKE11 and the construction of 3rd Cauchy-type boundary conditions to assess the groundwater inflow rates separately from each channel section.

## CONCLUSIONS

The initial numerical modelling results show that fissured rock groundwater flow as a main streamflow generating component in the Lange Bramke basin is a reasonable hypothesis. An advantage of the physically-based numerical systems approach is that it allows for a regionalization of the runoff formation process with scarce data in the near future. This meets the requirements for Predictions in Ungauged Basins (PUB). However, further tracer experiments are needed to improve model calibration, and a stochastic fracture network model will be developed for the transfer and regionalization of results.

The more precise information on the variability of water availability in space and time during single precipitation–runoff events is of great interest to water management authorities and for environmental scientists. The modelling tools are found to be able to simulate a change in the physical process pattern. If these process changes are caused by climate change then the ecohydrological impact can be predicted by this model. Therefore the results may be used in planning strategies for appropriate counter measures to cope with climate change.

## REFERENCES

- Buttle, J. M. (1998) Fundamentals of small catchment hydrology. In: *Isotope Tracers in Catchment Hydrology* (ed. by C. Kendall & J. J. McDonnell), 1–49. Elsevier, The Netherlands.
- Diersch, H.-J. G. (2005) *User's Manual Feflow 5.2*. WASY GmbH, Institute for Water Resources Planning and Systems Research, Berlin, Germany.
- Herrmann, A. (1994) Ecohydrological research on a small basin scale: scientific approach of the runoff formation key process. *Beiträge zur Hydrologie der Schweiz* **35**, 83–95.
- Herrmann, A. (1997) Global review of isotope hydrological investigations. In: *Third FRIEND Report 1994–1997* (ed. by G. Oberlin), 307–316. Cemagref Editions, Antony, France.
- Herrmann, A. (2004) Runoff formation in mountainous environments and possible effects of global warming. In: *Studies in Mountain Hydrology* (ed. by A. Hermann & U. Schroeder), 1–12. IHP/HWRP Berichte 2, Koblenz, Germany.
- Herrmann, A., Schöniger, M. & Schumann, S. (2001) Integrated approach of investigating and modelling runoff formation considering information from environmental and artificial tracers. *Freiburger Schriften zur Hydrologie* **13**, 90–97.
- Herrmann, A., Koll, J., Leibundgut, Ch., Maloszewski, P., Rau, R., Rauert, W., Schöniger, M. & Stichler, W. (1989) Wasserumsatz in einem kleinen Einzugsgebiet im paläozoischen Mittelgebirge (Lange Bramke/Oberharz). Eine hydrologische Systemanalyse mittels Umweltisotopen als Tracer (Turnover of water in a small basin in Paleozoic highlands – Lange Bramke/Upper Harz Mts. A hydrological system analysis using environmental isotopes as tracers). *Landschaftsökologie und Umweltforschung* **17**, Braunschweig, Germany.
- IAHS (2006) *Streamflow Generation Processes* (Selection, Introduction and Commentary by Keith J. Beven). *Benchmark Papers in Hydrology*, IAHS Press, Wallingford, UK.
- Maloszewski, P., Herrmann A. & Zuber, A. (1999) Interpretation of tracer tests performed in fractured rock of the Lange Bramke basin, Germany. *Hydrogeol. J.* **7**, 209–218.