Hard Rock Hydrosystems (Proceedings of Rabat Symposium S2, May 1997).
IAHS Publ. no. 241, 1997

Modelling flow and transport processes in fractured rock groundwater systems on a small basin scale

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Abstract Some major steps towards a hydrogeological model for simulating flow and transport processes on a regional scale are being developed by taking a small catchment area of fractured Palaeozoic rock in the Harz Mts, northern Germany as an example. It is shown that identification of relevant hydrological processes and hydraulic parameters is necessary to develop respective conceptual modelling tool system, i.e. combined FE groundwater flow models (ROCKFLOW; FEFLOW), GIS facilities and choice of adequate boundary conditions. Reliable data from traditional and tracer hydrological (environmental isotopes, dyes), hydrogeological (geological and tectonic survey, drilling cores) and hydraulic investigations (aquifer tests, groundwater level records) permit first runs of the modelling system for 3D but nonstationary case. Numerical solutions of this kind are concluded to be relevant for both ecohydrological science and water quality and quantity management practice, and for respective risk analysis and decision making.

INTRODUCTION

This study aims at demonstrating a hydrogeological concept model for simulating flow and transport processes in fractured rock aquifers, and to apply it to small catchment basins of <10 km^2 in the Harz Mountains, Germany which should be representative for forested Central European Palaeozoic rock areas. Respective model has to be based on aggregated process knowledge to guarantee transferability under similar conditions. However, it has to consider local circumstances which are relevant to adequately describing the specific flow and transport processes on the small scale.

The proposed hydrogeological concept model which is made up by the working steps as demonstrated in Fig. 1 has been developed for the regional scale mainly by making use of the indispensable knowledge gained in several small catchments in the course of more than one decade. The model is being based on the following assumptions:

- for the upper fractured rock aquifer phreatic conditions are being assumed until 50 m of depth, and confined below;
- Darcy's law is valid by considering decreasing conductivity with depth;
- groundwater recharge is area comprising;
- about 80% of total area runoff originates from fractured rock aquifers;
- the unsaturated soil zone contributes little to total runoff, and overland flow is negligible.

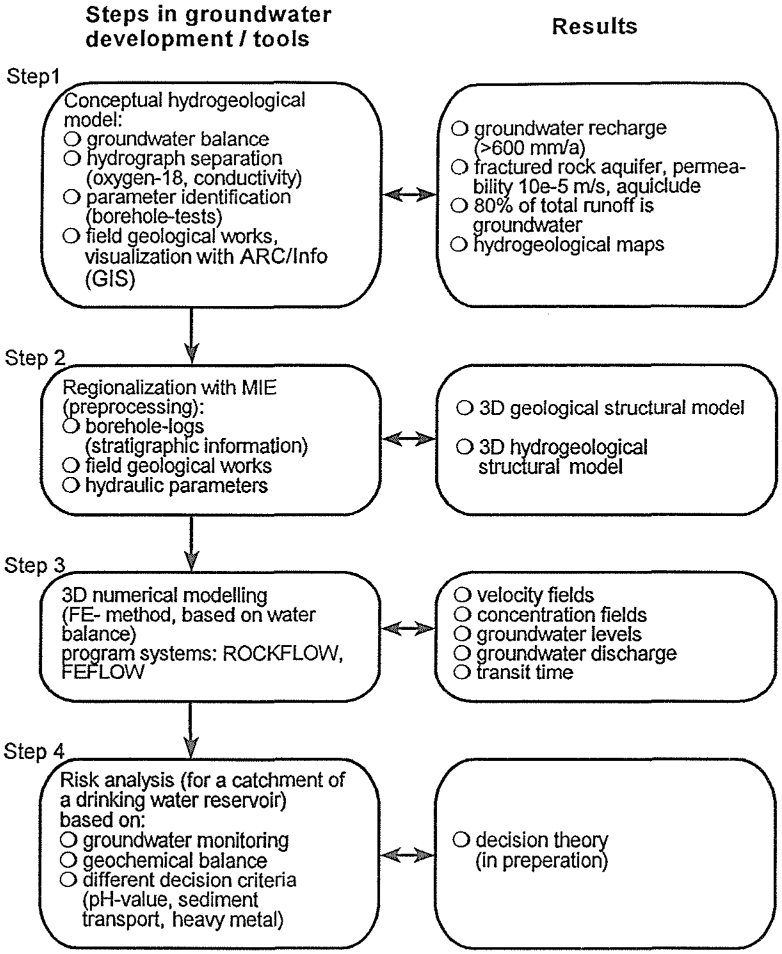

Fig. 1 Schematic hydrogeological concept model.

To develop and realize the proposed model concept a considerably large number of special investigations was necessary on a small basin scale to identify relevant hydrological and hydraulic processes and parameters, i.e. topographical, pedological and geological surveys, hydraulic (pumping, slug and bail) tests, isotope hydrological and geochemical hydrograph separations, dye tracer experiments, and groundwater hydraulic system characterization which require a team of specialists.

For realization of the model concept in Fig. 1 apart from mentioned field experiments for parameter identification the combined use of a groundwater flow model with GIS is necessary where the GIS constitutes the visualization tool for the acquainted space and object data which are imported by the groundwater model through an interface, and combined with the dynamic, i.e. time-dependent data series.

EXPERIMENTS

Study basin

The study basin where the proposed model concept has been tested is Große Schacht (51°44'N; 10°26'E) of 9.6 km^2 and 341-861 m a.m.s.l. which is situated in the Harz Mts, Lower Saxony, northern Germany. Große Schacht is a headwater catchment of the Sösetalsperre drinking water reservoir. Lithology is made up by Upper Devonian and Lower Carboniferous diabase, quartzites and siliceous schists and slates. In connection with considerable tectonic disruptions of the lithofacies units which led to faulting, heavy fracturing and dislocations versus upright positions, distinct horizontal alternations of slightly and strongly conducting bedrock can be observed, with the smallest tecto-lithological conductivity units being not wider than 30 m (cf. Fig. 3).

Podsolic brown earths of up to 40-60 cm of depth and shallow regosols are the dominating soils which have developed on extended allochthonic Pleistocene solifluidal materials on slopes and valley bottom. Major vegetation is Norwegian spruce (*Pinus abies* karst.). Slopes are steep, with main inclinations between 10° and 15°.

Since 1990 the hydrological network comprises several gauging stations, rain gauges, a climatic station and six fully supported 4" piezometers of up to 55 m depth. Discharge at the main outlet is being observed since 1941. From 1990 to 1994 special attention concerned the hydrobiogeochemical behaviour of the catchment, and use of environmental isotopes oxygen-18 (^{18}O) and tritium (^{3}H) as well as pH-value and electrical conductivity as tracers for hydrograph separation and mean groundwater transit time determination.

Results

Specific runoff is for Große Schacht about 30 l s^{-1} km^{-2}, thus ranging in the order of most Central European highland watersheds. A major hydrological finding also with respect to water quality is that more than 80% of total runoff which is an input to Sösetalsperre reservoir is groundwater with a more or less long subsurface passage. Consequently, its mean transit time amounts to 1-4 years as determined from ^{3}H, and the contribution of actual event water to 10-15% on the average as found from ^{18}O and geochemical measurements (Sommerhäuser, 1994). Both isotope hydrological findings have formerly been confirmed in well-known Lange Bramke catchment of the same region (Herrmann *et al.*, 1989), and also on a global scale (Herrmann, 1997). However, this also means that overland flow and interflow are both of very minor importance for the systems under consideration, and that on the other hand atmospheric pollutants from precipitation and dry deposition are being largely buffered during the underground passage as can be also concluded from long-term pH observations (Groth, 1984).

As a main result of the long-term analyses of piezometer levels, quick responses are being observed upon rain and snowmelt events as demonstrated with Fig. 2. However, depending on tecto-lithological conductivity unit these reactions may

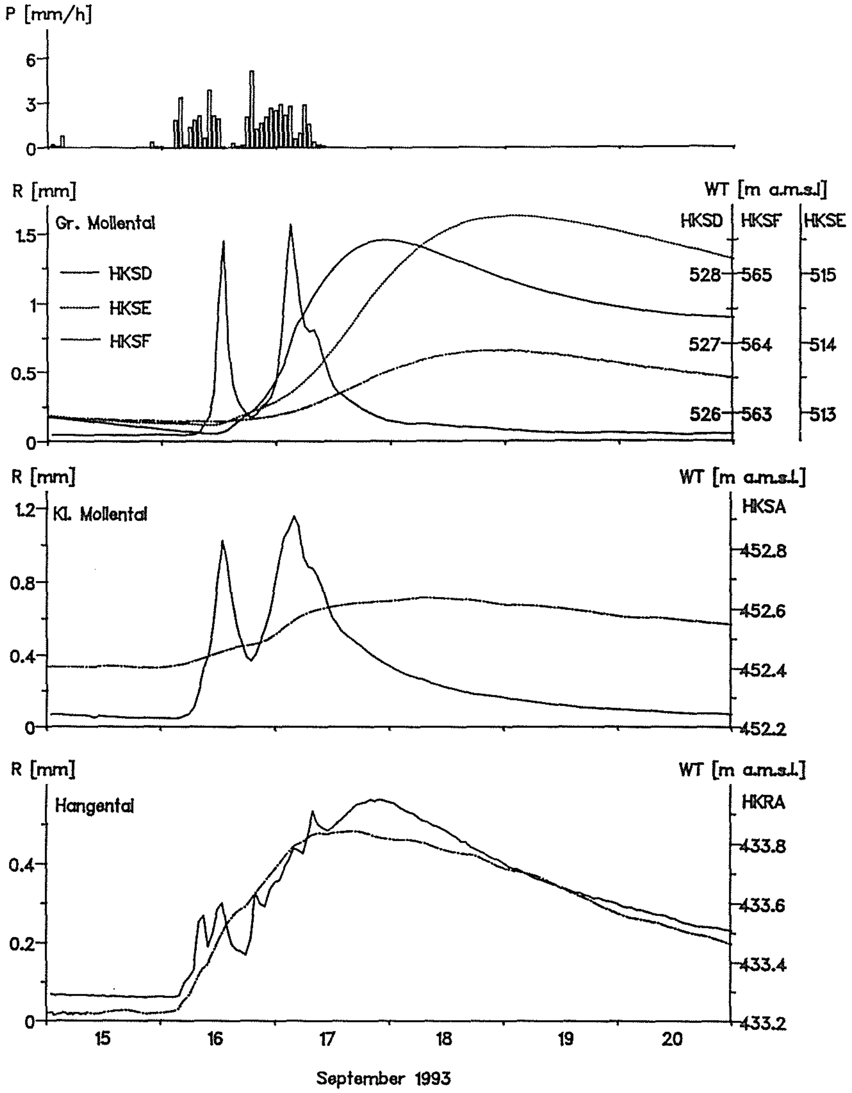

Fig. 2 Precipitation (P), runoff (R) and groundwater tables (WT) for different river-near observation wells for three small Söse sub-catchments and storm conditions from 15 to 20 September 1993.

considerably differ as shown here. The diverging reaction times and amplitudes are closely related to these units.

From the diverse field and laboratory experiments the runoff formation process can be considered for headwater areas in fractured Palaeozoic rock as follows:

- Actual precipitation and snowmelt water infiltrates the upper soil storage, which is being drained rather effectively through macropore systems of pores, cracks, skeleton/soil contact areas, and root and animal channels all leading to deeper horizons.

- Deep seepage of gravitative infiltration water is going through continuous fracture systems of the unsaturated zone without any serious delay at the soil/bedrock interface.
- Rapid seepage is directly controlling areal rises of fractured rock groundwater tables even during the input event that, however, differ according to hydraulic conductivities. But in this context one should also consider pressure-induced water table rises due to the increased pressure head with the infiltration process in case where conductivities do not explain quick response through mass transfer alone (Herrmann, 1994). The dye tracer experiments which were performed in Lange Bramke and Großes Mollental of Große Schacht basin have shown distinct preferential flow patterns in tectonic fissures and faults.
- Growing local pressure heads cause groundwater exfiltration increase and, therefore, flood hydrograph formation as an integrated subsurface basin effect. Since traditional Hortonian flow and system hydrological interflow, too, are negligible under these circumstances, most runoff formation concepts available are not applicable in this case.

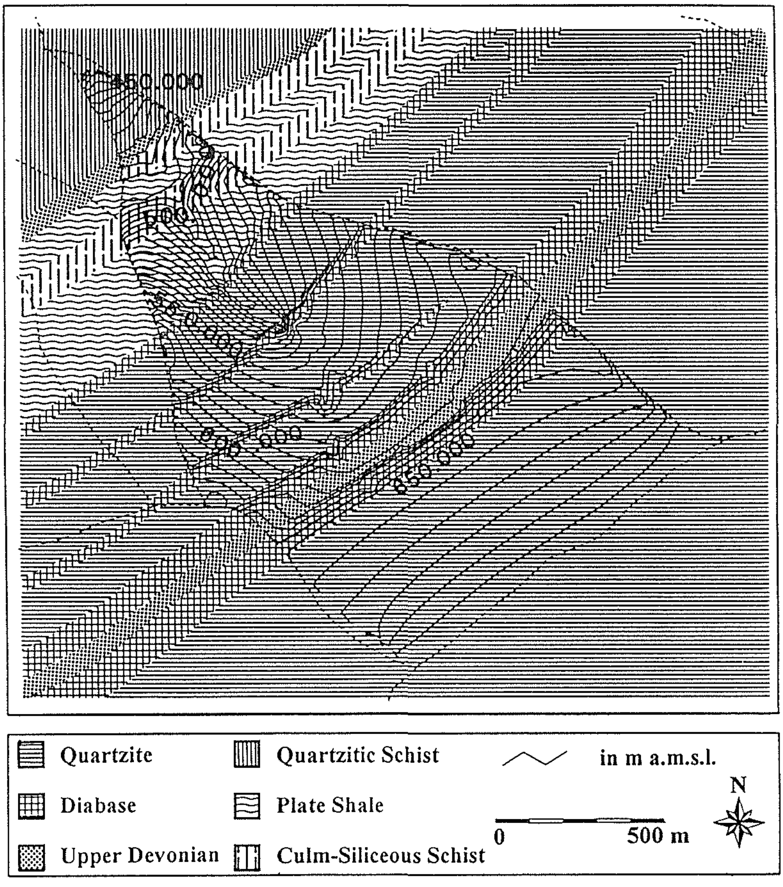

Fig. 3 Stationary groundwater flow simulation with FEFLOW for Großes Mollental sub-catchment for August 1994.

To summarize, the hydrogeological model concept is assuming quasi-homogeneous flow through the bedrock by taking into account conductivity ranges as determined from hydraulic aquifer tests in the tecto-lithological units. As a consequence, micro-structures such as fissures and fractures are also being averaged. However, conductive cross faults are being considered by selection of finer discretization.

GROUNDWATER FLOW MODELLING

Accordingly, these and further similar findings and assumptions for the region lead to the conclusion that numerical models are needed to simulate flow and transport processes adequately.

To fit extended quick groundwater reactions in the course of single precipitation-runoff events numerical simulations should consider free groundwater surface. A main scientific profit from the mentioned hydrological and hydraulic findings are applications of numerical FE groundwater models such as ROCKFLOW (Wollrath & Zielke, 1990) and FEFLOW (Diersch, 1996). Figure 3 shows a typical example of stationary groundwater flow simulation for Großes Mollental sub-catchment of 1.49 km^2 and 435-822 m a.m.s.l. where the passage through the unsaturated soil zone is being neglected. Results are quite reliable but only when considering the boundary conditions for free fractured rock groundwater surface (phreatic conditions). In a next step, preliminary simulation for nonstationary conditions after respective calibration by Schöniger (1996) seem quite promising, too.

Actually, main attention is being focused on numerical matter transport modelling by interpreting several dye tracer experiments available with the 3D groundwater model in a first step. Preliminary result is given in Szymanski & Schöniger (1996).

CONCLUSION

The resulting modelling system is interesting for both scientific and applied problems, i.e. ecohydrology and water resources and quality management also with respect to risk analysis and decision making in general (Ganoulis, 1994). After having successfully tested the nonstationary case unsteady conditions should be simulated in a next step to fit natural flow conditions much better. This would then also allow to solve at least the numerical problem of conservative tracer transport which is in natural environmental systems highly time-dependent.

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