RUNOFF FORMATION IN A SMALL MOUNTAINOUS BASIN DOMINATED BY A FRACTURED ROCK AQUIFER: RESULTS FROM THE TRACER-BASED INTEGRATED CATCHMENT APPROACH (ICA)

A. Herrmann, S. Schumann

Technical University Braunschweig, Institute of Geoecology,
Department of Hydrology and Landscape Ecology, Braunschweig, Germany
a.herrmann@tu-bs.de

Introduction

Hydrological processes control storage, turnover and pathways of water and dissolved matter in watershed environments. Therefore, understanding the governing process pattern is absolutely necessary for adequate protection and management of water resources that constitute an essential partial complex of ecosystems. Still, big knowledge deficits exist as far as origin, pathways and age of discharge contributing waters are concerned particularly on the single event time scale. Runoff formation, as the most complex eco-hydrological key process, should be studied preferably on the small scale of headwater basins. This scale is commonly associated with terms like overland flow, inter- or saturated flow, thus surface-near lateral flow processes which are specifically linked to each other. Runoff components of this site-specific category and the system hydrological concepts related to those were widely demonstrated in the anthology by Beven (2006). However, such synthetically-oriented views of precipitation-runoff processes may lead to wrong illustration of reality.

To overcome the methodical restrictions that are set to usual water balance investigations an Integrated Catchment Approach (ICA) was successively developed during the past 25 years in the Lange Bramke basin, Harz Mountains, Germany (Hermann et al., 2001). It applies the use of natural and artificial tracers to common methods. Since Lange Bramke will dispose of a 60 years discharge data series in 2009, the basin is also a study object for future hydrological trends and simulations in the climate change context. In this presentation the benefits from tracer hydrology analysis are demonstrated with respect to runoff generation studies and the related partial processes studies like flood hydrograph generation, groundwater exfiltration and recharge. The results also allow physical explanations for hydrological behaviour during statistical extreme years described by Schumann & Herrmann (2008) in a paper presented at the same conference.

Experiments

Lange Bramke basin covers an area of 0.76 km^2 and an altitude range from 540-700 m a.m.s.l.. 90% of the area is forested with 55 years old Norwegian spruce. The unsaturated zone (UZ) is made of forest soils on silty materials which are of solifluidal origin, rich in skeleton and that cover the weathered and fractured/fissured bedrock. The saturated zone is made up by Lower Devonian sandstones, quartzite and slates (fractured rock aquifer FRA), and by boulders, debris and gravels in the valley filling of the basin centre (porous aquifer PA). The present instrumentation for the measurement of hydrological, climatological and hydrogeological parameters is shown in Figure 1. Special focus is put upon groundwater experiments and groundwater monitoring under the confined/semi-confined FRA bearing

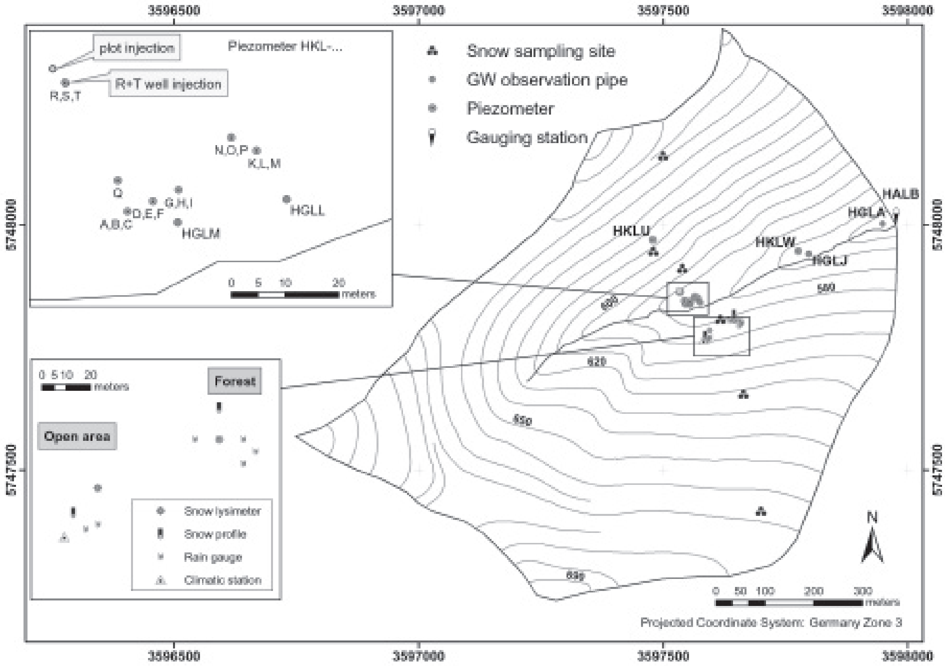

Figure 1. Topography and instrumentation of the Lange Bramke basin

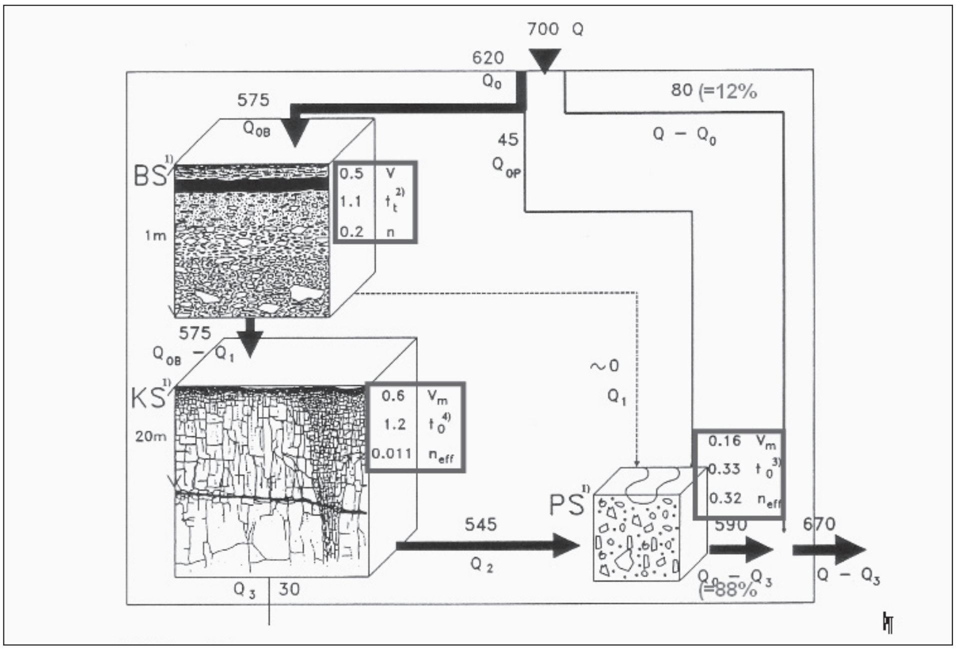

Figure 2. Hydrological basin model for Lange Bramke with mean annual water fluxes [mm WC] and hydraulic reservoir features (from Herrmann, 2008)

BS (here: UZ) = Soil water reservoir ($A_{Eo\ BS}$=0.71 km²); KS (FRA) = Fractured rock groundwater reservoir (transition from BS corresponds to partially unsaturated upper disruption zone; $A_{Eo\ KS}$=0.76 km²)

PS (PA) = Porous groundwater reservoir ($A_{Eo\ PS}$=0.05 km²)

Q = Water flux [mm/a]; V; V_{im} = Total volume; volume of mobile water [10^6 m³]; t_t; t_o = Mean transit time of tracer; mean transit time of water [a]; n; n_{eff} = Total porosity; effective porosity difficult hydrogeological conditions. Since 1980 regular and single event-based water samples of precipitation, snow cover and snow cover outflows, soil- and groundwater and discharge were analysed for 0-18, H-2 and H-3 contents to allow isotopic hydrograph separations and calculations of mean transit times and of other hydraulic parameters. Special campaigns with the application of artificial tracers (dyes, salts, deuterium) in piezometers as well as on terrain surface were performed to discover and confirm hydraulic connections and determine travel times.

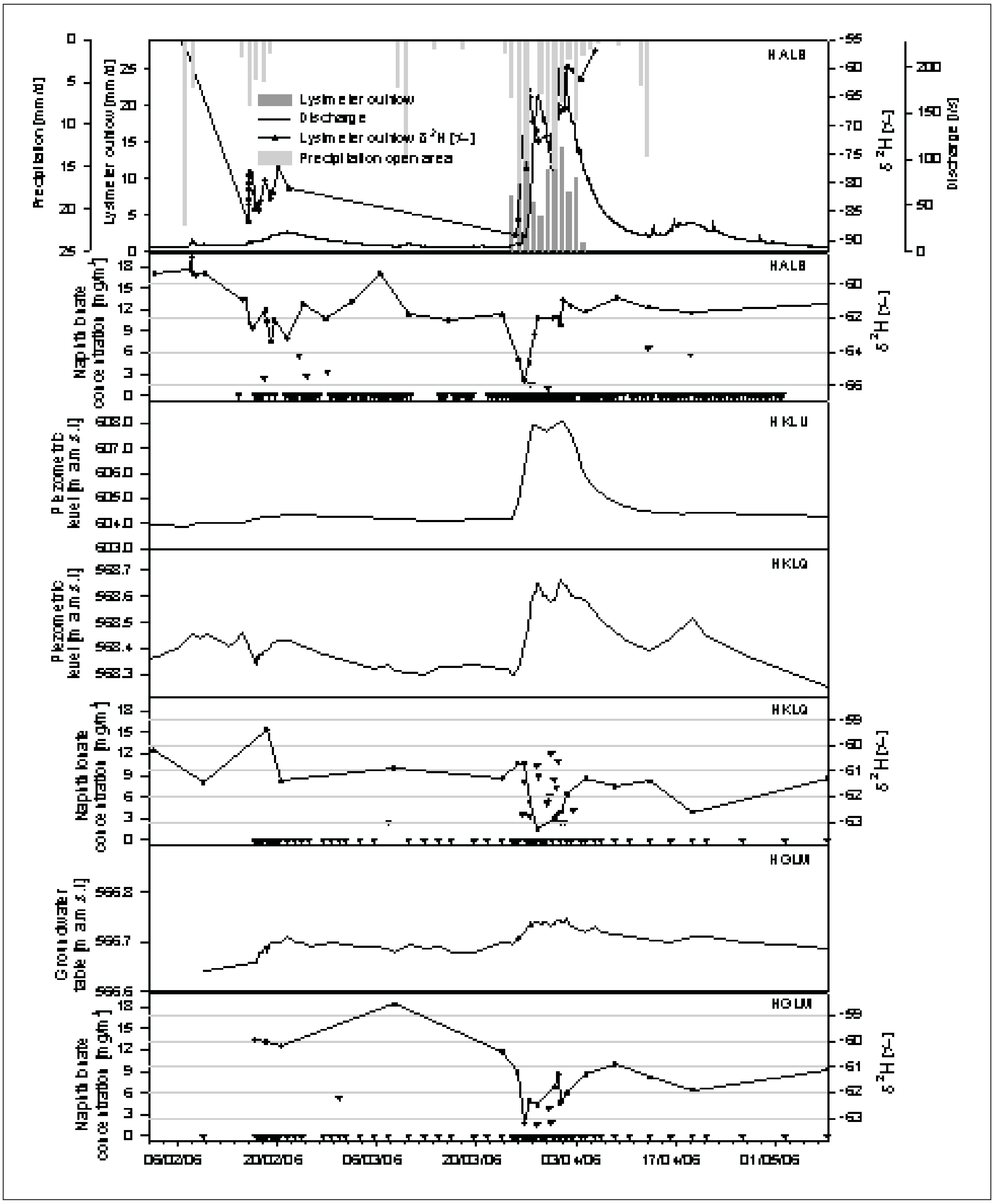

Figure 3. Hydrological conditions in Lange Bramke basin from February to May 2006 (for locations see Figure 1): Open area precipitation; forest lysimeter outflows with deuterium contents, discharge of Lange Bramke stream; groundwater tables at piezometers HKLU and HKLQ and at observation pipe HGLM, deuterium contents (right ordinate: dots and lines) and naphthionate concentrations (left ordinate: triangles) at stream gauge HALB, piezometer HKLQ and groundwater observation pipe HGLM (after Thies 2007)

Results

Figure 2 compiles the conceptual hydrological model of Lange Bramke basin with its three main storages (compartments; BS, KS, PS) and relevant water fluxes. Research findings concern flow rates and hydrological and hydraulic storage features. The following experimental results are remarkable:

Lateral interflow is negligible. Direct runoff is only 12% of total on the average as determined with O-18 and tritium. UZ and FRA are short-cut by distinct preferential flow paths, which enable fast percolation of the infiltration water, a result that was traced with dyes. The mean transit time of groundwater is 2.0 yrs. This was calculated based on tritium values and the application of an age distribution flow model. Though this is a quite short mean transit time, it is still long enough to buffer acid input waters. On the single event time scale, extraordinarily small direct flow portions are confirmed to exist, i.e. event water corresponds very often to less than 1% of the actual rain or meltwater input. The spontaneous reactions of groundwater flood hydrograph formation, is an independent indication of preparedness of the FRA system for increased groundwater exfiltration fluxes to the stream channels. Accordingly, groundwater is by far the dominant runoff component during flood events where the water-bearing major cross faults functioning as efficient subsurface drain channels. As a consequence, groundwater recharge that maintains the quantitative balance between input and output is a permanent process and about three times higher than assessed by conservative methods.

The synchronous breakthrough curves of stable isotopes and dyes in both FRA and PA aquifers and the observed evolution of discharge during single events indicate a basin-wide pressure transmission followed by the mobilisation of groundwater thus the generation of flood hydrographs primarily composed by groundwater. The application of artificial tracers has also shown that the major cross-faults play an important role for the ground water transfer towards channels with flow velocities of up to more than 10 m/h indicating turbulent flow. With the FE software package FEFLOW it is possible to describe groundwater flow fields and exfiltration rates in the stream channel. In the near future respective model flood hydrographs will be simulated.

The spatial pattern of successive processes that determine runoff formation is as follows: (i) Infiltration with saturation of top soils and percolation; (ii) Rise of groundwater table, corresponding to an increase in groundwater potential; (iii) Groundwater exfiltration in faults and to stream channels. Fig. 3 stands exemplarily for process results that are described by the tracer hydrological ICA approach. The demonstration of the individual work steps that are necessary to be taken to reach such results and to explain the short-term turnover of water during single events is a main purpose of this paper.

Conclusion

The paper picks up the roles which isotopic hydrograph separation and mean transit time calculations, combined with artificial multi-tracer experiments and reliable hydrological and hydraulic background information play for hydrological process studies, numerical modelling and model calibration on a small basin scale. A long-term goal of the investigations is to meet the requirements of PUB (Prediction in Ungauged Basins) for this type of eco-hydrological systems. Using data from Lange Bramke means to profit from long term hydrological data series under very controlled local conditions and *vice versa* to allow for a process-based interpretation of statistical results based on a 60 years data series.

References

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