Hysteresis in semi-confined fractured rock groundwater-discharge relations related to runoff formation on a small basin scale

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Hysterese in Kluftgrundwasser-Abfluss-Beziehungen in Hinblick auf Abflussbildung in kleinen Einzugsgebieten

Zusammenfassung

Im Harzer Einzugsgebiet Lange Bramke wird geprüft, inwieweit die Hystereseschleifen für Piezometer-Abfluss-Beziehungen ein 3-stufiges Abflussbildungskonzept bestätigen. Dazu werden hochaufgelöste hydrologische und hydraulische Daten mit den Ergebnissen von Markierversuchen mit Umweltisotopen und Kunsttracern verglichen. Neben hydraulisch begründeten Hystereseentwicklungen im Uhrzeigersinn mit dem Abfluss als abhängiger Variabler sind häufig auch gegenläufige oder lineare bis exponentielle Verläufe vertreten. Die Ergebnisse überzeugen nicht, weitere Untersuchungen sind notwendig.

Schlagworte: Lange Bramke, Abflussbildung, Hysterese, Tracer.

Summary

By taking the 76 ha Lange Bramke basin, Harz Mts., Germany as an example, it will be tested to what extent hysteretic piezometric level-discharge relations confirm a hydraulically-based three-stage runoff formation concept. For this purpose, high-resolution hydrologic and hydraulic data series are checked together with the results of isotopic and artificial tracings. Hydraulically-sound clockwise, but also frequent anti-clockwise or even almost linear to exponential course of hysteretic loops are found taking discharge as dependent variable. Results are far from convincing, because hysteresis is in this context still little experienced.

Key words: Lange Bramke basin, runoff generation, hysteresis, tracers.

1 Introduction

In hydrology hysteresis is a common phenomenon the apperception of which strongly depends on filling stage of hydrological storages and intensities of the related input and output processes. To discover hysteretic relations between variables, high resolution in time and small-scale are favourable, mainly when intercalated complex fractured rock aquifer systems control water transfer towards discharge at basin outlet. Accordingly, for example piezometric table/hydraulic head-discharge connections might be hysteretic as a result of non-linear system reactions, as shown in Fig. 1. Unfortunately the valuable anthology of streamflow generation processes edited by BEVEN (2006) does not mention hysteretic behaviour as important hydraulic feature. Early protagonists for hysteresis in hydrology were MUALEM (1974, 1984) devising theoretical considerations, and DRACOS & STAUFFER (STAUFFER et al., 1981, 1992), who also run lab experiments. A main purpose of this contribution is to show to what extent the Lange Bramke experiments provide the data for studying the hysteresis phenomenon in respect to runoff formation process.

2 Basin and methods

Lange Bramke basin is located in the Harz Mts., in Northern Germany. The surface area is 76 ha, altitude ranges

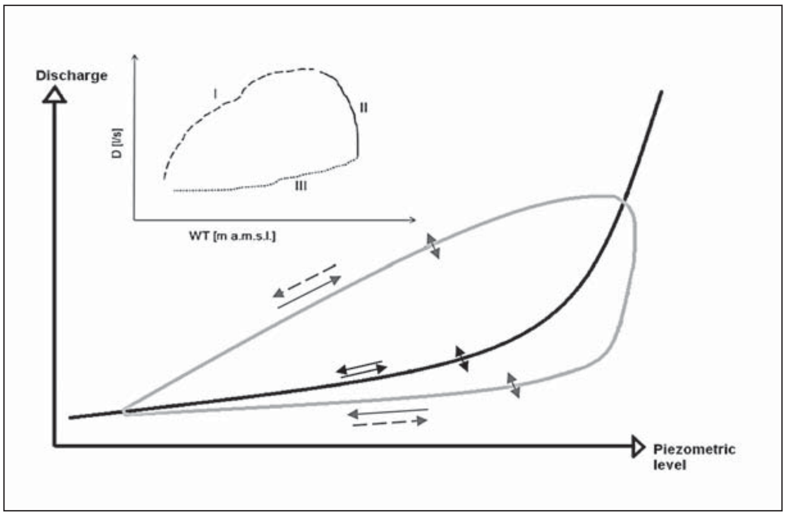

Figure 1: True clockwise hysteretic loop (top; from SCHÖNIGER & HERRMANN, 1990) with sequence rising (I) and recession limbs (III) and steady-state (II) of flood hydrograph, 16–19 July 1997; schematic loop as found in Lange Bramke basin (bottom)

Abbildung 1: Reale rechtsdrehende Hystereseschleife (oben) mit Folge von auf- (I) und absteigendem Ast der Hochwasserganglinie am 16.–19. Juli 1997 (III) und Beharrungszustand (II) (aus SCHÖNIGER & HERRMANN, 1990); schematische Beispiele aus der Langen Bramke (unten)

between 540–700 m a.m.s.l. The basin is to a 90 % forested with 60-year-old Norwegian spruce und is made up of a dominant semi-confined aquifer of quartzite, sandstones, slates, and a minor porous aquifer of valley filling.

As a result of the integrated study approach which was developed for Lange Bramke since the 1980s including natural and artificial tracer experiments, hydrogeological investigations and monitoring of main water fluxes (SCHUMANN & HERRMANN, 2010), a three-component runoff formation concept was developed in which hysteretic effects as portrayed in Fig. 1 play a great role. Hydrologic background is that on the average only 10 % of total discharge is direct flow or event water, and 90 % is indirect or pre-event water with a mean transit time of about two years. Interflow is almost zero. The question is therefore how to verify these huge subsurface quantities independently from isotopic hydrograph separation.

3 Runoff formation concept

The proposed hydraulic mechanism controlling streamflow generation begins with rising hydraulic heads and pressure transmission through the unsaturated zone as soon as the infiltration process and compression of the capillary fringe occur, and is combined with quick aquifer reactions but actually without much mass transfer (HERRMANN & SCHUMANN, 2009) (Stage 1). In Stage 2, fluid mechanical effects due to mass transport through pulse pressure transmission und free flow cause growing subsurface pressure heads. Mass displacement in the underground can therefore be split into (i) vertical seepage due to the efficiently draining macropore systems in the unsaturated and (ii) lateral groundwater flow in the saturated zones. Final Stage 3 is a combined effect of high hydraulic potentials and pressure transmission because mass transfer alone cannot explain remarkable groundwater exfiltration rates in case of widely low hydraulic conductivity. To maintain the quantitative input-output balance groundwater recharge in the order of considerable 650 mm/a is a permanent process throughout the year considering 1,200 mm/a in areal precipitation.

3.1 Experimental findings

Both storm and snowmelt events are subject to similar physical processes (HERRMANN & SCHUMANN, 2009). Fig. 2 gives an example where in response to 60 mm of rain within two days in February 2002 sharp and spontaneous piezometric reactions of 3 m rise at piezometer HKLU located midslope in the centre of the basin, 0.2 m at HKLQ in basin centre toeslope position, and 1.2 m at HKLW toeslope at basin outlet, along with pronounced flood hydrograph formation are observed. However, frequent anti-clockwise hysteretic loop as represented by HKLQ – hydraulic patterns are frequently changing within individual events – are not easy to understand and need further explanation, whereas clockwise rotational sense is mainly caused by exfiltrating groundwater under pressure. This explanation agrees quite well with the pursued multi-stage runoff generation concept. In Fig. 3 examples for other rainstorms are shown. Furthermore, peak discharge often occurs before maximum pressure heads at piezometers, like here at HKLU and HKLW, which is also hard to figure from the hydraulic

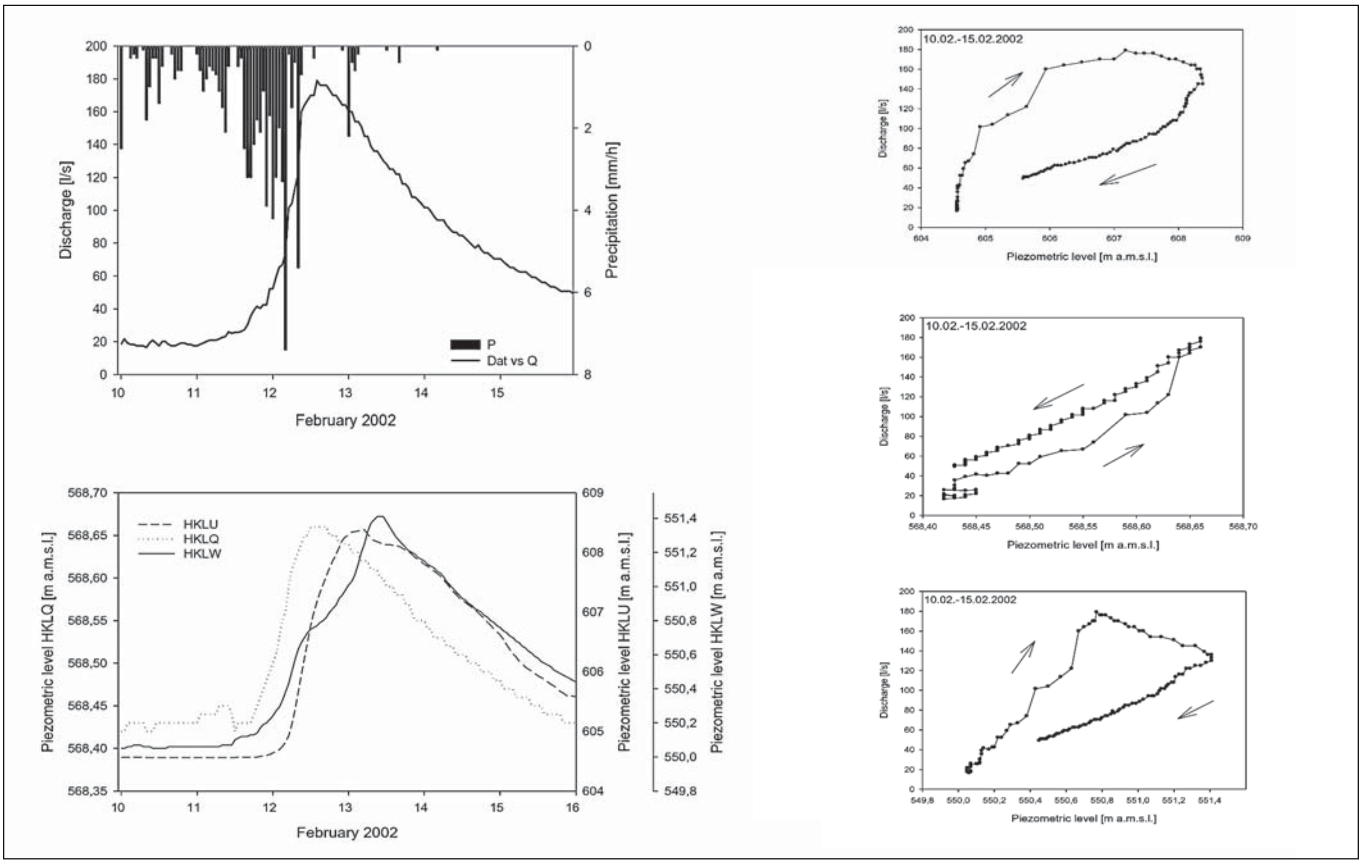

Figure 2: Precipitation, discharge, piezometric levels and hysteretic loops for three piezometers HKLU, HKLQ and HKLW during the storm event of 10–15 February 2002

Abbildung 2: Niederschlag, Abfluss, Piezometerstände und Hystereseschleifen an drei Piezometern HKLU, HKLQ und HKLW während des Starkregenereignisses vom 10.–15. Februar 2002

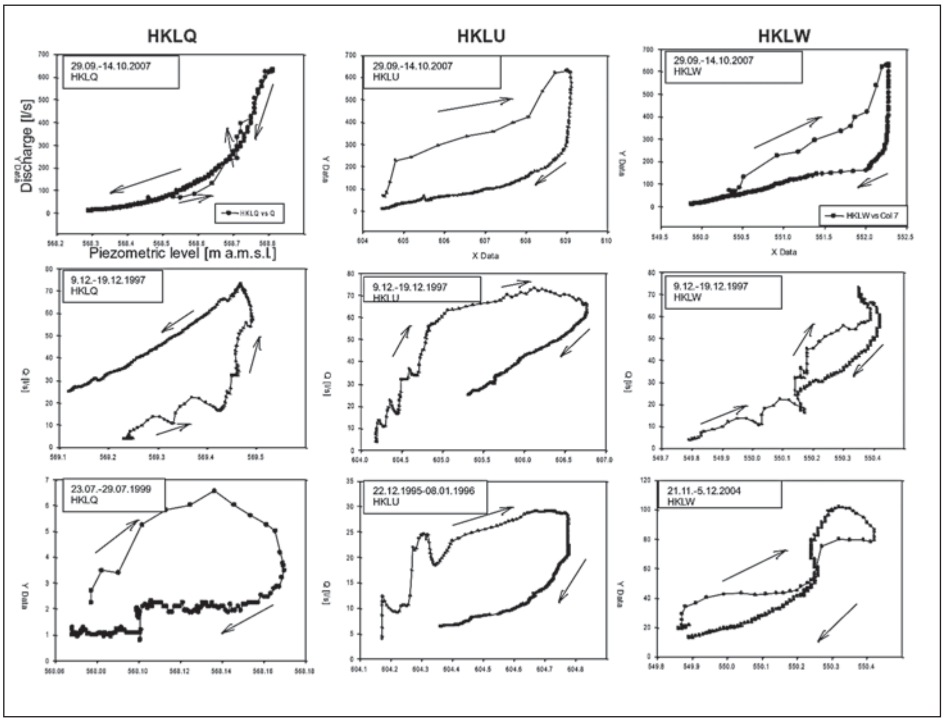

Figure 3: Typical hysteretic loops for discharge/piezometric levels at three different sites

Abbildung 3: Typische Hystereseschleifen für Abflüsse/Piezometerstände an drei verschiedenen Stellen point of view. The question is whether the hydraulic concept assumed here for Lange Bramke can be considered valid for similarly structured watersheds with confined fractured Paleozoic rock aquifers in Central and Eastern Europe.

On the other hand, isotopic and artificial tracings confirm fast mass transfer which starts with areal infiltration and is controlled by the respective pressure heads in the fractured rock aquifer and groundwater exfiltration. Hence groundwater discharge might be higher than traditional methods pretend. The snowmelt and rain on melting snow cover events in Fig. 4 was ultimately discussed in detail in HERRMANN & SCHUMANN (2009) but under different emphasis can serve as example. In summary, the information taken from the stable environmental isotope deuterium (H-2), which was captured with the aid of a 1 m² snow lysimeter in the experimental forest stand in the centre of the basin, is that isotopically light meltwater is infiltrating the unsaturated zone and percolating towards the fractured rock at HKLQ and to well HGLM in porous aquifer, and is finally observed in the streamflow HALB. The message from naphthionate concentrations injected to the fractured rock aquifer at 10 m depth at about 25 m from HKLQ on 16 February 2006 is that they appear at the same sites indicating the groundwater exfiltration flux. Hence, the tracer technique contributes verifying hydraulic findings as a main requisite for the pursued three-stage runoff formation concept.

3.2 Categorisation of hysteretic relations

Attempts of classifying hysteretic discharge-piezometric level relations serve for identification of probable hydraulic pattern in the runoff formation mechanism. For this purpose the hysteretic coefficient k was defined:

$k = \Delta D_{max}/(D_{peak}-D_{initial})$

with D for discharge; k = 1 stands for perfect circular loop.

The variety of k coefficients derived for storms in Lange Bramke is remarkable. In times with absolutely higher piezometric levels like in winter season or after a sequence of subsequent events, differing fracture porosity, conductivity and transmissivity will create additional percolation, pressure head and exfiltration pattern effects. Hence, changes in pro-

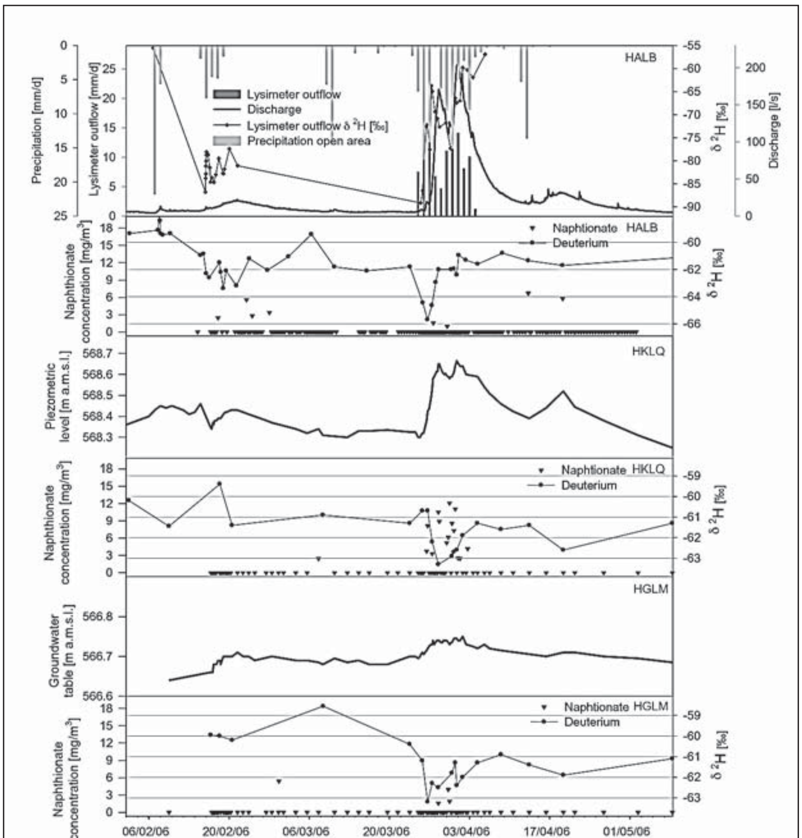

Figure 4: Naphthionate and deuterium concentrations in streamflow at basin outlet HALB, at piezometer HKLQ and at HGLM in porous aquifer, with groundwater levels; open area precipitation; discharge and forest snow lysimeters outflow with deuterium contents during snowmelt with rain March/April 2006 (after HERRMANN & SCHUMANN, 2009)

Abbildung 4: Naphthionat- und Deuteriumgehalte im Abfluss Lange Bramke (HALB), bei Piezo-meter HKLQ und HGLM im Porenaquifer, mit Grundwasserständen; Freiland-Niederschläge, Abflüsse und Lysimeterausflüsse im Wald mit Deuteriumgehalten während Schneeschmelze mit Regen im März/April 2006 (nach HERRMANN & SCHUMANN, 2009)

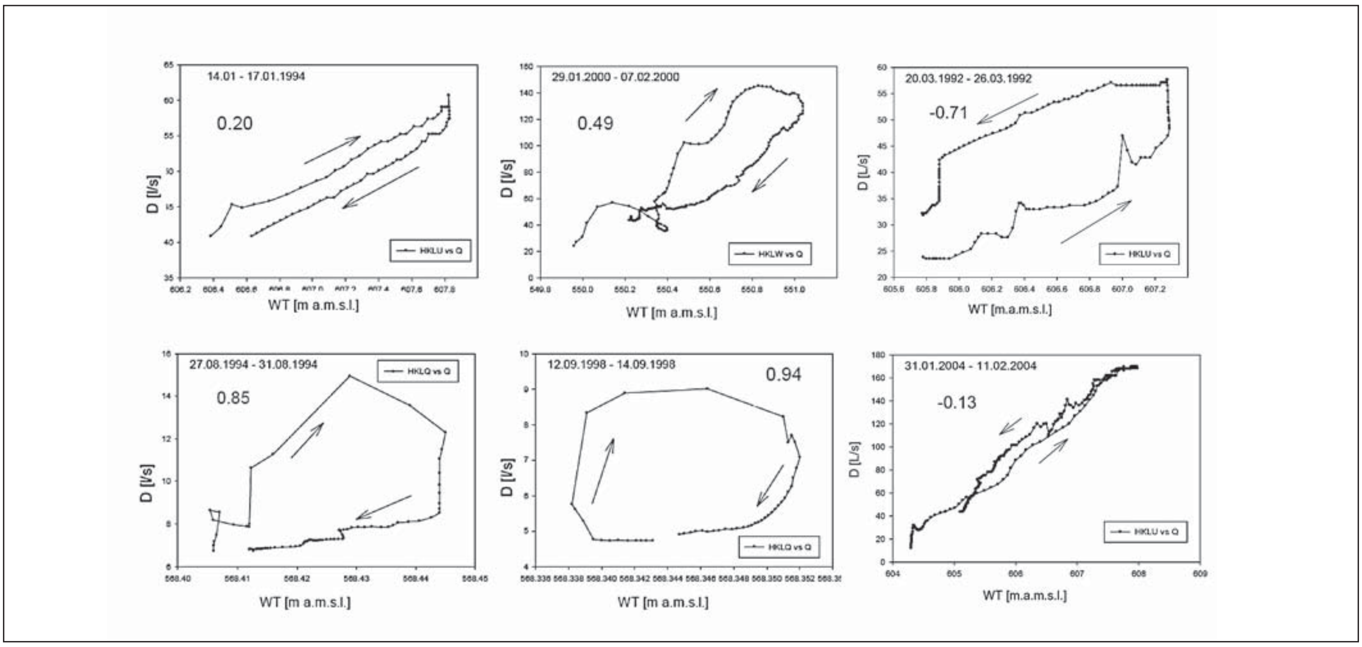

Figure 5: Examples of positive and negative hysteresis coefficients k
Abbildung 5: Beispiele für positive und negative Hysteresekoeffizienten k

cess boundary conditions are presumed to create diverse hydraulic and hydrologic basin response. Hence, neither any piezometric threshold level expressing hysteresis trends can be found, nor statistically significant time lags between precipitation, discharge or piezometric level peak values which could help to classify hysteretic discharge-groundwater relations in an understandable way (Prilop, 2009). Accordingly, at HKLQ anti-clockwise rotation prevails in winter, and clockwise in summer when the smaller events dominate. At HKLU, clockwise rotations reign but mainly in winter. The same is observed at HKLW in both half-years.

4 Conclusion

In the pursued three-stage runoff formation concept an explanatory option for anti-clockwise hysteretic effects might originate in the assumed compression of the capillary fringe established by Stauffer et al. (1981) as a main condition for the first stage. The original approach was then refined by Stauffer et al. (1992) as a so-called hysteretic storativity concept and again confirmed with a sandbox experiment in the lab. But for the nature example of Lange Bramke it is difficult to distinguish between the two overlying hysteretic effects of the unconfined capillary zone and the confined aquifer. Although propagated by Stauffer et al. (1992), the inclusion of this storativity concept in an integrated groundwater model is a tricky task as can be concluded from the intricate master thesis by Schneider (2009) at ETH Zurich which was looked after by Fritz Stauffer, and where Processing Modflow served as implemented groundwater model.

However, the hysteretic concept finally helps to understand better some complex hydraulic process patterns like runoff generation, but results are far from convincing. In this context the variety of small research basins which were assembled in an open inventory under the auspices of the German IHP/HWRP Committee in 2009 (http://www.euro-friend.de/) is a basis for exchange of practical knowledge and scientific results, and to come into cooperation on the issue.

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