Runoff Formation in a Tile-drained Agricultural Basin of the Harz Mountain Foreland, Northern Germany

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Abstract: By taking two different tile-drained agricultural basins with porous aquifers in the lowlands of northern Germany as examples, it is demonstrated with an integrated study approach that this type of basin responds similarly to an input as forested mountainous basins with dominant fractured rock aquifers in the central European highlands do. The control mechanism is local rise of pressure heads of aquifers starting with the infiltration process. It is shown that drain laterals in agricultural basins function like fractures and faults in those hard rock basins, i.e. as efficient drain pipe lines. This effect is amplified by hydraulic pressure transmission in the course of single input events, and additionally verified here with the help of artificial and environmental tracers. As a result stream flow is predominantly generated by exfiltrating groundwater. For this process drain laterals constitute fast hydraulic short cuts in the sense of preferential flow paths preferably in case that groundwater tables reach up to the level tile-drain networks.

Keywords: hydrograph separation; hydrological tracers; isotopes; dyes; groundwater; drain sampler

Runoff formation is a major ecohydrological process in both humid (Herrmann 1994) and dry regions (Newman *et al.* 2006). It chiefly controls turnover and composition of discharge waters as concerns quantity, quality and age by partitioning and mixing event and pre-event waters, and by mobilising the latter according to source area, origin and pathways which depend above all on actual hydraulic conditions. The complexity of physical processes which stand behind runoff generation on a small basin scale was recently acknowledged in a concept of future experimental research proposed by Herrmann *et al.* (2006). It shows that individual classical concepts used for stream flow generation (e.g. Buttle 1994; Beven 2006) merit altogether a re-evaluation, which means that they should be considered or not for inclusion in more integrated, i.e. holistic and interdisciplinary approaches of small basins, so-called ICA (Integrated Catchment Approach; Herrmann *et al.* 2001).

As compared to forested hard rock basins like Lange Bramke (Figure 1), runoff formation under tile-drained agricultural conditions is still not sufficiently investigated. However, as a matter of fact, related turnover processes of water and dissolved matter transport cannot be understood by taking only soil water movement into account. This was a main result of a most comprehensive collaborative agro-ecological research centre in Bavaria (FAM Munich; http://fam.weihenstephan.de/indexalt.html) that ended in 2003. Another important interdisciplinary collaborative project was earlier under Technical University Braunschweig (TUBS) in the 80ies of the last century (Richter *et al.* 1996). One of the two study basins is Krummbach (P1; 0.87 km^2) which is located in the northern Harz Mountains foreland at about 30 km south of Braunschweig (Figure 1), with Ohebach sub-basin (P4; 0.32 km^2) as a focal study site where orthic to gleyic luvisols and cultivation of sugar beet and winter wheat prevail. Krummbach-Ohebach is since closure of the project monitored by the TUBS Department of Hydrology and Landscape Ecology (DHLE). Hydrological monitoring in the other agricultural study basin Eisenbach (Figure 1) with dominant (gleyic) arenosols located in a complex pattern of morainic and sandy outwashed plain substrates, ended in 2003. Several selected results from that basin support the findings in Ohebach on which the main focus will be put here. However, the starting point for this paper will be Lange Bramke where major conclusions summa-

Name	Area (km^2)	Elevation range (mean)	Basin type	Bedrock soils	Vegetation	References
Lange Bramke – Harz Mts	0.76	543–700	forested, mountain	paleozoic sandstones and shales, podzolic cambisols	90% Norwegian spruce, 10% grassland	Hermann et al. (1989, 2001, 2006, 2007, 2008) Holko et al. (2001, 2002, 2006) Maloszewski *et al.* (1999) Hermann (1994, 2004) Hermann and Schöniger (1992) Schöniger (1991) Schöniger and Hermann (1990)
Krumbach – Northern Harz Foreland	15	112–333	agricultural, hilly	quaternary sediments; clayey soils(loess),	100% arable land	Hermann (1999, 1994) Hermann *et al.* (1997) Tischer (1995)
Ohebach	0.885	117–156				
Eisenbach – Southern Lüneburg Heather	4.24	62–119	agricultural, hilly	sandy moraines, cambisols	70% arable land, irragated, 15% fallow land	Hermann (1994, 1999) Hermann and Ueberschär (1993) Kim (1997) Schöniger (1998)

Figure 1. Hydrological study basins of the Department of Hydrology and Landscape Ecology (DHLE) at Technical University Braunschweig (TUBS) in northern Germany

rised in HERRMANN (2002, 2004) and HERRMANN *et al.* (2007) about contributing physical runoff formation processes were successively discerned through decades of experimental research by the GHLE in which the use of hydrological tracers played an important role.

The runoff formation process

The following conceptual suggestion for runoff formation or stream flow generation as the eco-hydrological target process in geo-hydrological research is the synthesis of own experimental findings not only in Lange Bramke but also in other mountainous environments with dominant confined and semi-confined fractured rock aquifers (cf. HERRMANN 2004), lowland to hilly environments including Valdai hills with porous aquifers (HERRMANN *et al.* 1997), and of many foreign experiences and suggestions. Accordingly, runoff formation can be split into three separate partial processes:

Infiltration with saturation of top soils (initial saturation), compression of the capillary fringe and percolation

With the effective infiltration capacity of the soil matrix achieved, infiltration water quickly drains preferably through macropore systems towards greater depths. Dye tracer experiments show that even macroscopically homogeneous soils have lots of preferential flow pathways once a broad infiltration front established through matrix flow (e.g. SCHUMANN 2004). As to agricultural irrigation systems, ponding irrigation seems to cause quicker and more efficient response to of water fluxes travelling through preferential pathways than sprinkler irrigation does (SCHUMANN *et al.* 2004). Similarily should behave storage and transport of dissolved matter such as agrochemicals in the unsaturated zone. Compression of the capillary fringe may initiate pressure transmission as suggested by STAUFFER *et al.* (1981) through the unsaturated zone (UZ) that allows hydraulic aquifer reactions actually without mass transfer in an initial phase.

Quick rise of groundwater table corresponding to increase of groundwater potential

Fluid mechanical effects from mass transport through pulse pressure transmission and pure (free) flow through fissures, fractures and macropores of UZ initiate almost spontaneous area-wide increase of subsurface pressure heads as a response to basin input from precipitation and equivalent melt water (HERRMANN 2004; HERRMANN *et al.* 2006, 2007). In the non-stratified case of substrates without relevant mass displacement through interflow the subsurface water transport can be split up into two partial processes: vertical seepage in UZ and lateral groundwater flow in the underlying saturated zone (SZ). STAUFFER *et al.* (1981, 1992) found that under controlled homogeneous

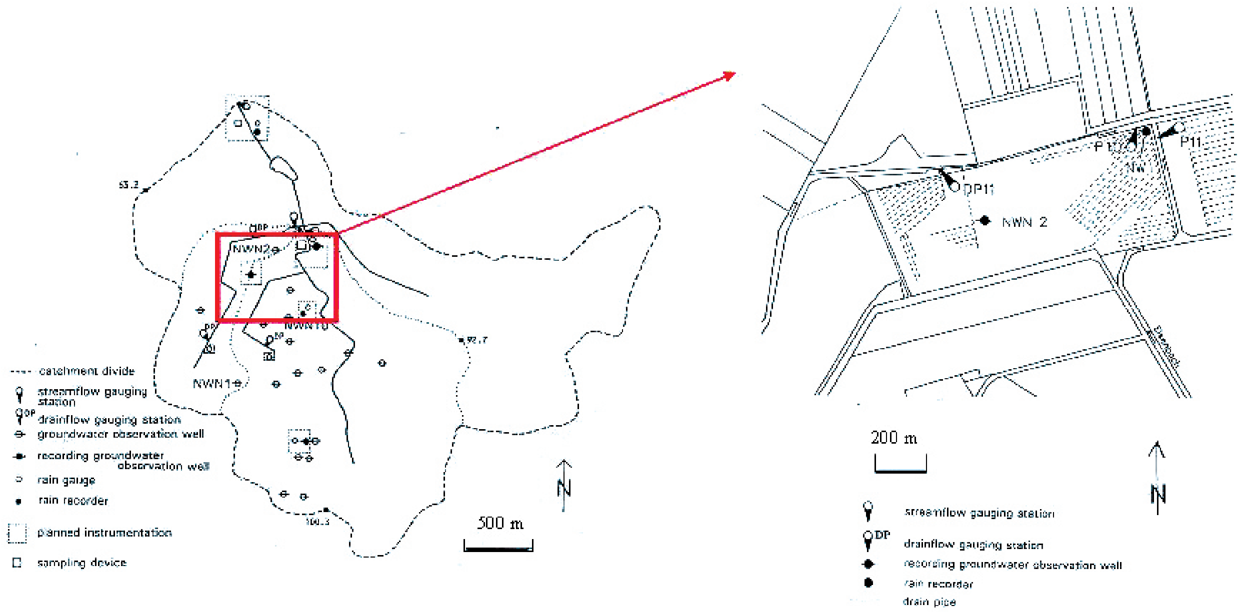


Figure 2. Eisenbach basin, Southern Lüneburg Heather, with sub-basin P10 (0.87 km²)

conditions compression of the capillary fringe is a main cause of the pressure transmission process. Natural environments suggest similar effects, although widely extended compression of the capillary fringe as a main condition is hardly thinkable even on a small basin scale like Lange Brake which is built up by fractured bedrock. Therefore additional explanation is necessary in this case of mighty UZ of up to several tenths of meters which is made up of weathered bedrock on top that is underlain by non-weathered but heavily fractured rock (Lower Devonian sandstones, quartzites and slates). Unlike such hydraulically tricky case one can better imagine the mechanism of compressing capillary fringe for shallow porous lowland aquifers with pronounced macrospore systems like Krummnach or Eisenbach with similar quick groundwater table reactions upon actual basin input (Herrmann & Ueberschär 1993; see also below). However, the phenomenon described here has nothing to do with the air pressure-dependent oscillation as observed in unsaturated zones (e.g. Tesař *et al.* 2001).

As a result of pulse pressure transmission, groundwater tables raise thus initiating processes which are relevant for Step 3.

Groundwater exfiltration to stream channels

Final quick and efficient groundwater exfiltration, for which the whole wetted cross-section of the river bed which is hydraulically acting, is considered a combined effect of high hydraulic potentials and pressure transmission (cf. Step 2). This assumption is based on the fact that mass transfer alone does not explain the huge infiltration quantities which are necessary to generate a flood hydrograph under frequent low hydraulic conductivities of the substrates. On the other hand, water-bearing major faults may function as principal drain lines, thus playing an important role for quick groundwater transfer to stream channels in basins with fissured and fractured bedrock like Lange Brake. Groundwater flow in faults may even be turbulent (Maloszewski *et al.* 1999). To maintain the quantitative input/output balance, short-term groundwater losses during single events will be compensated without much delay, i.e. groundwater recharge is a permanent process throughout the year.

Preferential flow pathways through artificial tile-drains in agricultural lands with shallow groundwater systems or natural major water-bearing tectonic faults in hard rock basins might facilitate runoff formation because of the high flow velocities as compared to the matrix with much lower conductivity of several orders. The existence of preferential flow paths, of which the knowledge is important for assessing mass transports in UZ and SZ as mentioned under Steps 1–3, contrib-

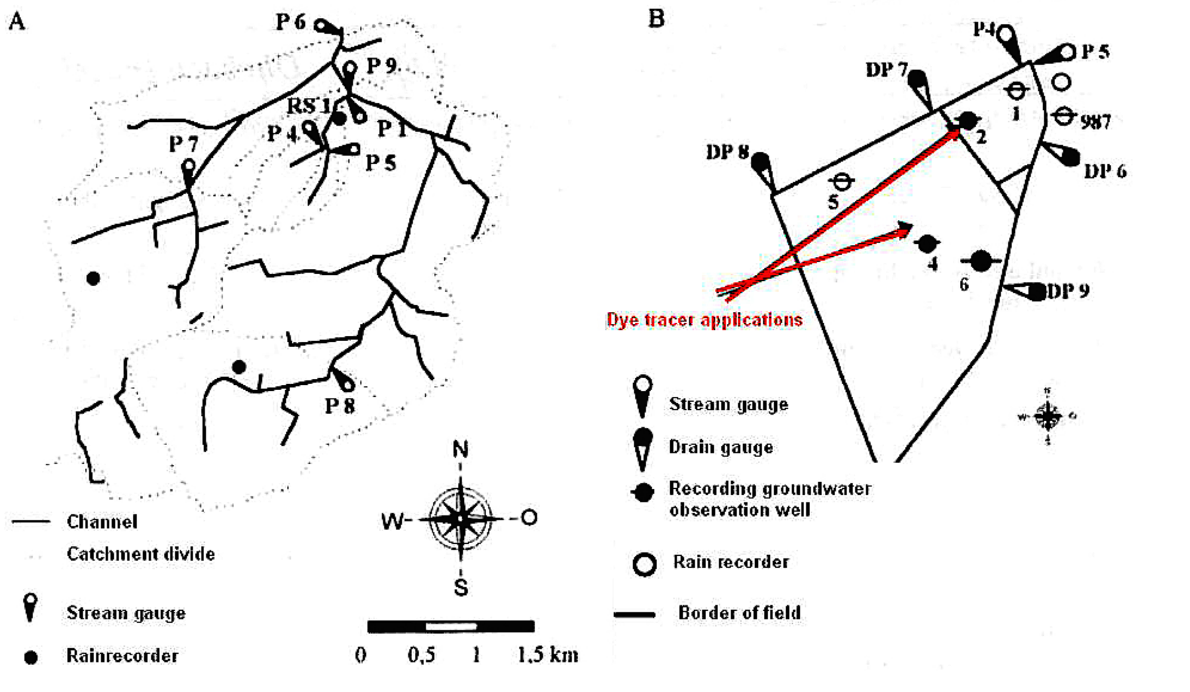


Figure 3. Krummbach basin, northern Harz foreland (left), with sub-basin P4 (0.87 km^2; right) (after Richter *et al.* 1996)

utes to explain quick response of runoff to a basin input impulse not only by pressure transmission, but also by preferential mass transfer. A suggestion by Beven (1989) could at least momentarily close the gap between experimental findings and their explanation and simulation. His alternative explanation for rapid velocity of subsurface flow in high relief area and stratified (or layered) case applies where aquifer input moves downslope at kinematic wave velocity which can be several times higher than Darcy flow, and may be used as hydraulic model algorithm.

To conclude, one should not lose touch with two things: (i) Groundwater recharge, which guarantees the subsurface mass balance in the long-term, is a highly variable process in space and time as runoff formation is. Groundwater recharge is a permanent process preferably utilising efficiently draining macrospore and fissure systems. As we learnt from Lange Brake basin the transition zones between loose weathering materials on top and unweathered but fractured bedrock at bottom of vertical flow systems do obviously not constitute any serious hydraulic barrier for vertical water fluxes. (ii) Runoff formation is an extremely complex hydraulic process system as compared to other processes in hydrology. It seems that only an integrated experimental ICA approach as propagated by Herrmann *et al.* (2001) and recently acknowledged by Uhlenbrook (2005) guarantee a better understanding of related partial processes as a basis for future adequate process oriented numerical modelling.

In connection with the main present topic the following question arises: Do tile-drained agricultural basins with unconfined porous aquifers

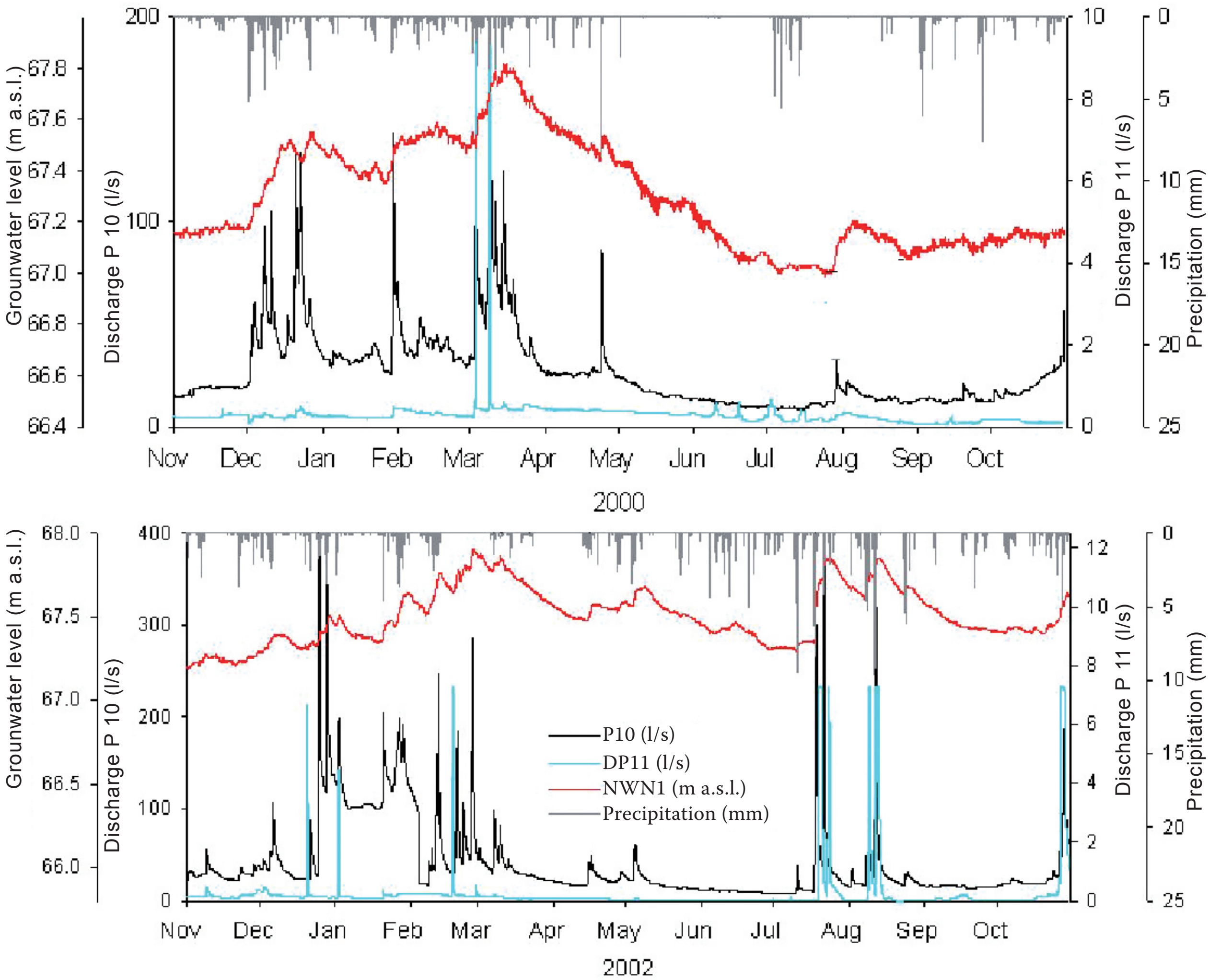


Figure 4. Stream flow (P10), drain flow (DP11), groundwater table (NWN1) and precipitation in Eisenbach basin during the hydrological years 2000 (top) and 2002 (bottom) (for locations see Figure 2)

behave in principle like forested mountainous basins with dominant semi-confined to confined fractured rock aquifers with respect to streamflow generation? If this is the case one can profit from the experiences in hard rock basins, and the following hypotheses are relevant and should be verified in the agricultural loose substrate basins: (1) surface runoff plays a greater role, depending on cultivated plants; (2) drain laterals may function as preferable pathways for seepage and groundwater; and (3) hydraulic heads control groundwater exfiltration into streams and groundwater under unconfined porous aquifer conditions similarly like the confined fractured hard rock case.

Runoff formation in tile-drained agricultural basins

The study of runoff formation in tile-drained basins by DHLE-TUBS concentrates on two locations in the lowlands of northern Germany: Eisenbach and Krummbach-Ohebach basins (cf. Figure 1).

EXPERIMENTS

Experimental designs and instrumentations were similar in the two basins. (cf. Figures 2, 3, 5 and 8). Streams/channels are equipped with Venturi flumes (Eisenbach P10; Krummbach P1) or V-notch weirs (Krummbach P4) with digital water table recording from pressure transducers, and tile-drain samplers with V-notch weirs and float gauges. Groundwater tables are meanwhile digitally recorded with pressure transducer systems and precipitation with digital rain recorders. Registration intervals are generally 15 min. The experiments in Eisenbach basin were completely stopped in 2003 due to financial problems in connection with maintenance and frequent defective measuring equipment related to age which caused less reliable data and data gaps. In Krummbach basin, measurements are still active but reduced to sites P1, P4, DP 7, DP8 and piezometers 4/6 in 1996. In 2004 piezometer NKG 4 was given up and was removed to site NKG 6 as the farmer wished.

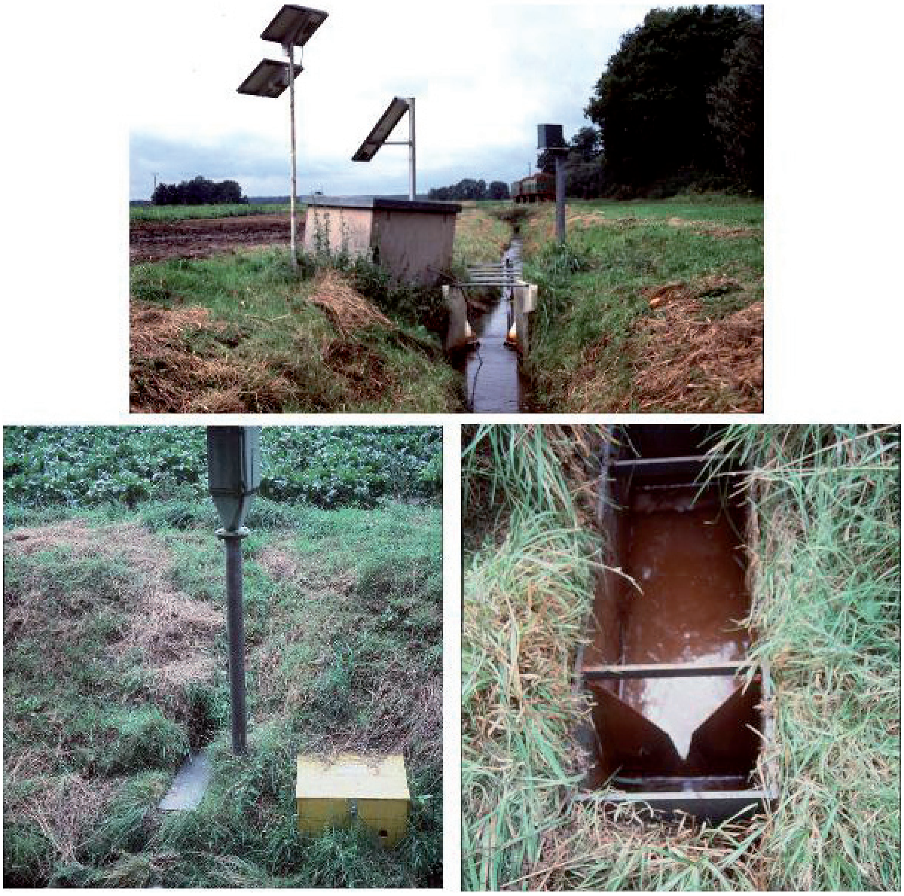
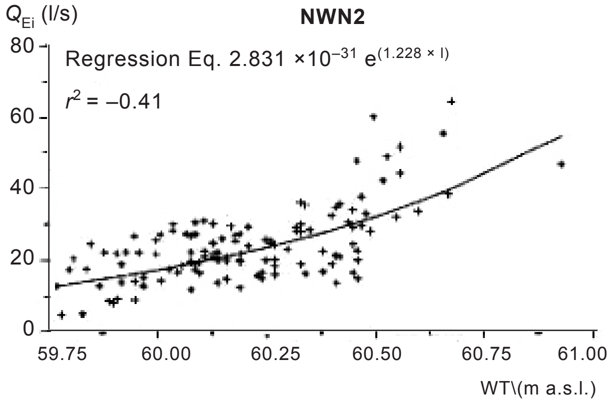
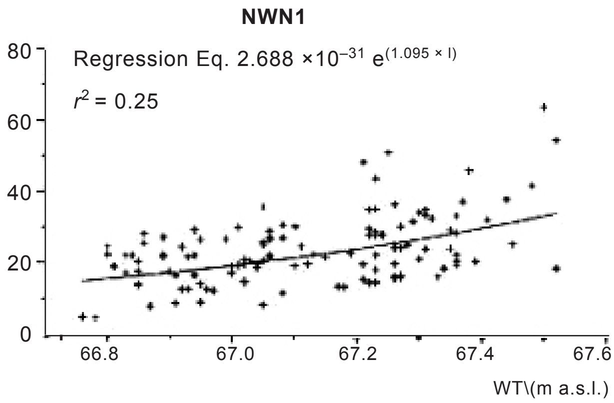


Figure 5. Eisenbach basin: Venturi flume at gauging station P10 (top), weir of drain sampler DP11 (bottom right) together with recording unit (bottom left)





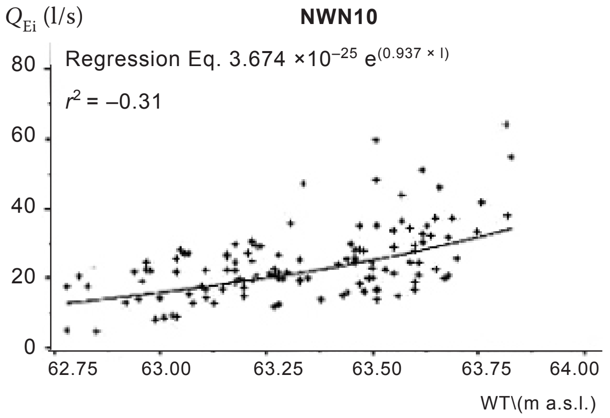


Figure 6. Eisenbach: Discharge (Q_{Ei}) at P10 vs. groundwater tables (WT) at selected wells located at 100 m (NWN2), 190 m (NWN10) and 350 m (NWN1) from gauging station P10 (for locations see Figure 2) for weekly values between January 1989 and August 1992 (from Herrmann & Ueberschär 1993)

Natural processes in the Eisenbach basin are influenced by irrigation measures with groundwater during growing seasons. However, although legal irrigation rates per area unit exist real irrigation water quantities are not exactly known. In those parts of Krummbach basin which are of interest here irrigation is not relevant.

RESULTS

The results shown here refer to typical wetter or dryer hydrological years with many or only a couple of runoff events of different magnitude, and also without any serious data gaps. This paragraph concentrates possible process mechanisms as system reaction to basin input which lead to increased discharge at basin outlets.

Eisenbach

Figure 4 shows the hydrological conditions in the Eisenbach basin for the year 2000 with summer drought and groundwater table recession, and for continuously wet 2002 with less varying groundwater tables but on a higher absolute level. Respective measuring instruments used in the Eisenbach basin can be seen in Figure 5. One should notice that in times with very high groundwater tables like in March 2000 and July/August 2002 drain flow may be excessive. In this case groundwater tables reach up to the level of the tile-drains and lateral samplers which may therefore discharge huge quantities of groundwater. Frequently farmers are very surprised when they hear about this fact, although they might have got informed about groundwater-stream water table relationships in the channels long before constructing tile-drain networks in their fields by own observation. Respective mechanism will be discussed in more detail below under results for Krummbach basin.

The distinct synchronous reactions of groundwater tables and drain and stream flows upon single precipitation events let conclude that stream flow is to a large extent generated by exfiltrating groundwater into channels directly through channel walls, and indirectly through drain samplers under both wet and dry conditions. This means that single input-output events may be characterised by hydraulic short-cut between aquifer and channel through these two mechanisms: pipe flow and flux through macropores. In this context Figure 6 stands for another important finding, i.e. the subsurface system reacts as a whole thus reflecting continuous aquifer conditions, with the stream flow-groundwater table relations slightly correlating with distance from channel. Accordingly, stream flow increases with rising groundwater table. Supposed that groundwater table rise corresponds to growing groundwater potential, the latter should produce increased groundwater exfiltration fluxes into stream beds.

Highly resolved event data sometimes show what one should expect, i.e. stream flow-groundwater relations being hysteretic (Figure 6 right)! The mechanism standing behind this finding is local rise of pressure head that starts after Stauffer *et al.* (1981) with the infiltration process. For almost the first time under field conditions this phenomenon was identified in Lange Brake basin. Accordingly, discharge is strongly increasing with growing groundwater potential, thus causing the steep rising limb of the storm hydrograph, whereas the top portion of the recession limb is bound to still rising groundwater table on day two of the event, thus allowing continuation of large groundwater quantities to exfiltrate. The following flow recession is occurring on a still high absolute level with respect to the time that has passed since the initiating rain, and is accompanied by only slightly reducing groundwater potential.

Considering the instantaneous responses of groundwater table, drain flow and discharge to the rain input impetus by considerable 47.5 mm of rain in Figure 7 it is doubtful whether traditional runoff generation concepts as e.g. compiled by Freeze (1972) apply here, which would attribute the larger portion of the runoff surplus to overland

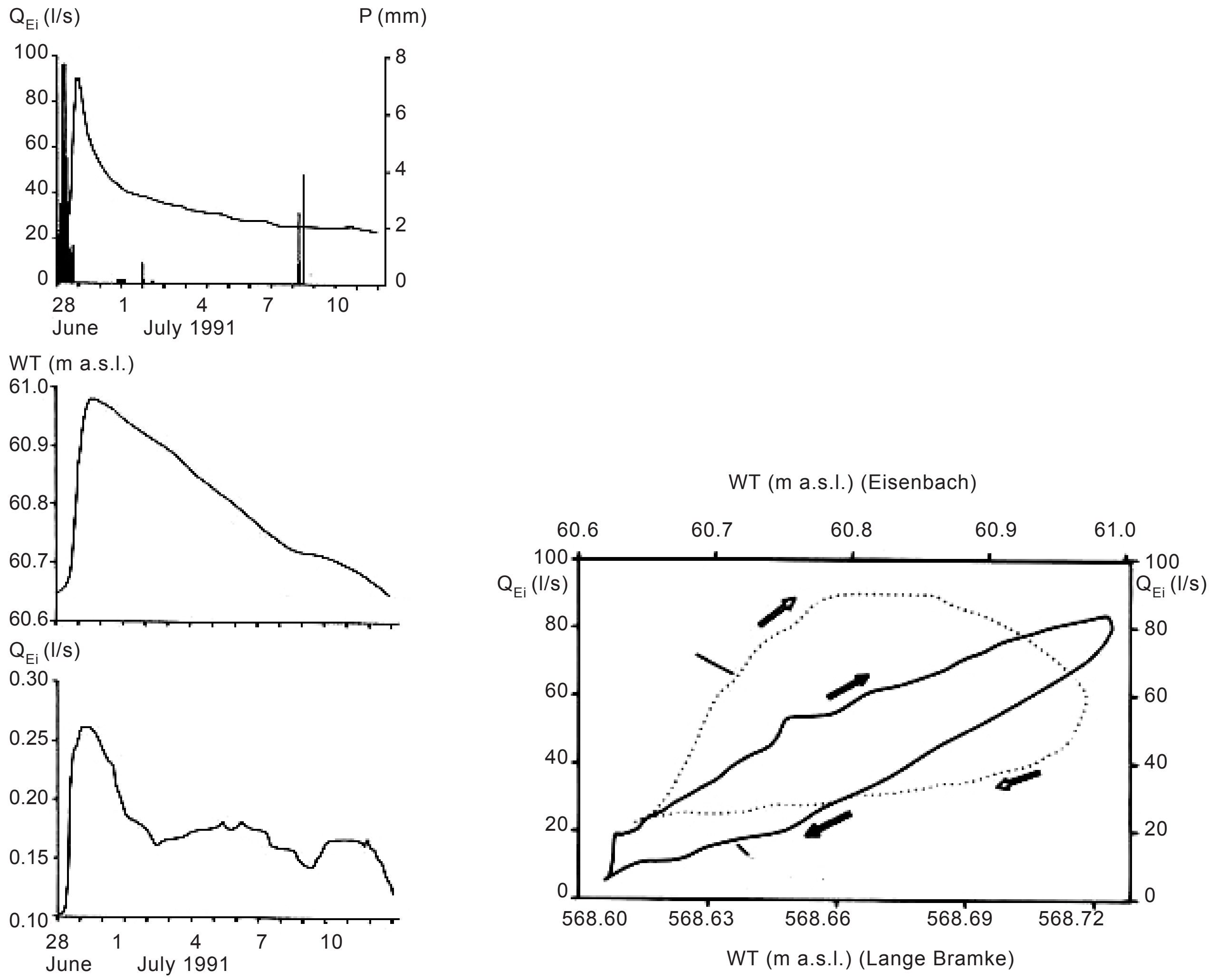


Figure 7. Eisenbach: Developments of precipitation (P) and discharge (Q_{Ei}) (top left) at P10, groundwater table (WT) at NWN2 (centre left) and drain flow (Q_{dr}) at DP11 (bottom left) for a storm event (for locations see Figure 2) with hysteretic loop for discharge-groundwater table relationship for the same event as compared to an example from Lange Bramke hard rock basin (right) (from Herrmann & Ueberschär 1993)

Figure 8. Krummbach basin (left): Venturi flume and weather station at gauging station P1 (top right), weir of gauging station P4 (bottom right)

flow and interflow, respectively, but much less to groundwater flow. The role which drain laterals may play for turnover and export of water and solutes in agro-ecosystems, was for the first time explicitly pointed out by Deverel and Fio (1991) and Fio and Deverel (1991). However they still did not consider the hydraulic short-cut between aquifer and drain laterals. As a result of the investigation in Eisenbach, the same phenomenon of local rise of pressure head seems to constitute a principal impetus for stream flow generation like in the Lange Brake hard rock basin, where major faults function as principle drain lines such as drain samplers do in the agricultural environment.

Krummbach

Measuring instruments used in the Krummbach basin can be seen in Figure 8. Figure 9 shows the hydrological conditions in the Krummbach basin for the year 2000 which differ distinctly from the situation in Eisenbach basin (cf. Figure 4) in the winter half year whereas both summer half years are characterised by permanent low flows and falling groundwater tables in both basins. The year 2004 was selected to demonstrate that the water tables which were measured parallel for a while at the two piezometers NKG4, which had to be given up, and NKG6 are representing the same aquifer system. In general in the two years considered all hydrologic system components in Figure 9 react synchronously on precipitation inputs. As a result of the parallel groundwater table measurements in 2004 NKG4 seems to respond more sensibly to the same input impetus than the new NKG 6. The stream flow-groundwater table relations in Figure 10 in principle confirm the Eisenbach finding in Figure 6. However, according to results for old position NKG4 threshold values seem to exist beyond which pressure heads lead to extreme exponential increase of the groundwater exfiltration flux into channels.

In order to verify the hypothesis that groundwater is the to a largest degree major component in streamflow formation two dye tracer experiments were performed in the Ohebach P4 catchment area which were designed with and accompanied by TUBS-DHLE. The two tracer application sites are marked in Figure 2. The conditions and results of the experiments were as follows:

Experiment 1: On 3 February 1995 100 g of eosin dissolved in 1 l of stream water were applied to one m² of terrain surface close to well NKG2 and exactly above a drain sampler. Afterwards additional 50 l of stream water were then distributed over the one m² plot. At the same time of tracer

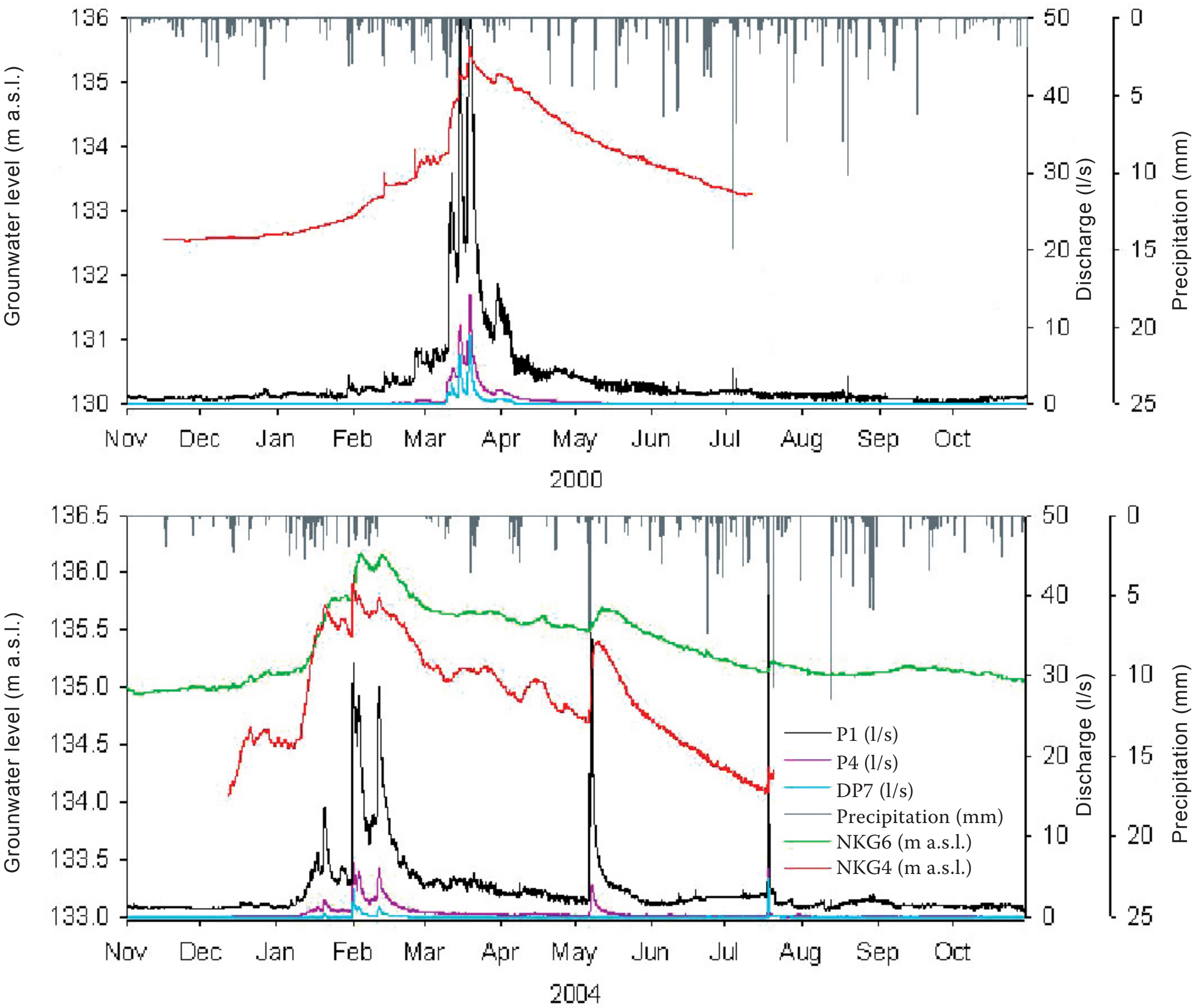


Figure 9. Stream flow (P1, P4), drain flow (DP7), groundwater tables (NKG4, NKG6) and precipitation in Krummbach basin during the hydrological years 2000 (top) and 2004 (bottom) (for locations see Figure 3)

application the groundwater table was on the same level of the tile-drains, i.e. at about 93 cm below surface. Water flow in the sampler was 0.173 l/s. 18 min after application tracer solution appeared in the channel (Figure 11), and 3.5 h after that 10% of the applied tracer mass was recovered from the channel flow. No tracer was detected in the groundwater of the adjacent well, which means no lateral tracer flux should exist.

Experiment 2: On 14 March 1995 80 g of eosin was applied in the same way but close to well NKG4, with the groundwater table at 131 cm lying distinctly below the surface and tile-drain levels. This fact and a minor sampler flow of only 0.019 l/s only explain that in the course of the four weeks following the application no tracer was recovered in the channel.

Finally, after the winter wheat harvest on 10 August 1995 soil material was sampled at both tracer application sites in different depths. The distribution of tracer mass with soil depth is shown in Figure 11. As a result, 75 g, corresponding to 75% of the tracer mass applied to the soil surface in February 1995 was still left in the soil, whereas from the March 1995 experiment it was even 73 g or 91%. In conclusion high groundwater tables by up to the level of tile-drains and main samplers favour quick transportation and export of solutes as such from agrochemicals. Under certain conditions this process may be accelerated due to abruptly rising groundwater tables during input events.

To complete the tracer hydrological study approach, an isotopic hydrograph separation was carried out (Figure 12) in order to back up the

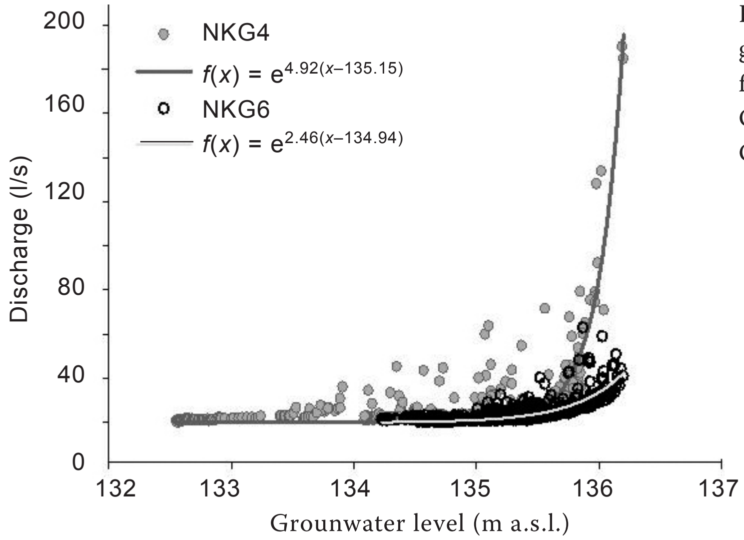
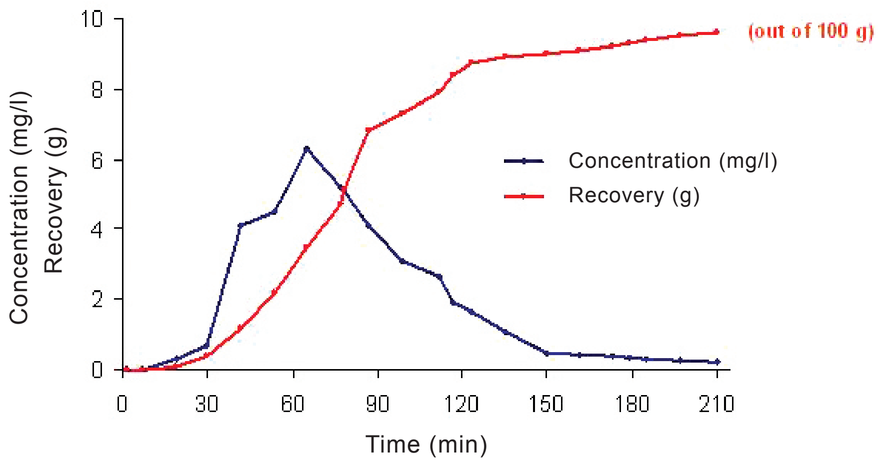


Figure 10. Krummbach: discharge at P1 vs. groundwater tables at wells NKG4 und NKG6 for weekly values between November 1999 to October 2004 (NKG4) and November 2003 to October 2006 (for locations see Figure 3)

hypothesis of hydrograph generation mainly by groundwater also in agricultural basins:

The storm runoff event in Figure 12 is a good example for combined use of electrical conductivity and the stable environmental isotope oxygen-18 for the separation of event water or direct flow from precipitation from pre-event underground water or indirect flow. According to the two-component-mixing model the average direct flow proportion is in the order of 10% for the whole period, and up to 20% at times of peak discharge. From these findings and the hydrological data and specific



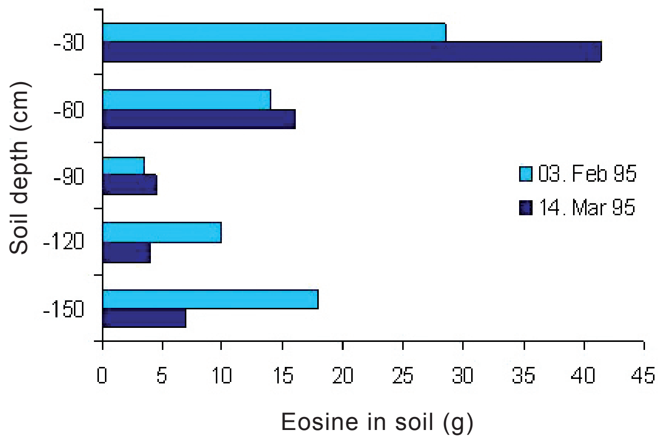


Figure 11. Breakthrough and mass recovery curves for eosin at stream gauge P4 originating from the 3 February 1995 experiment (top); eosin mass recoveries on 10 August 1995 in the soil profiles at the two sites of tracer application on 3 February and 14 March 1995 (after Schnug & Kücke 1996)

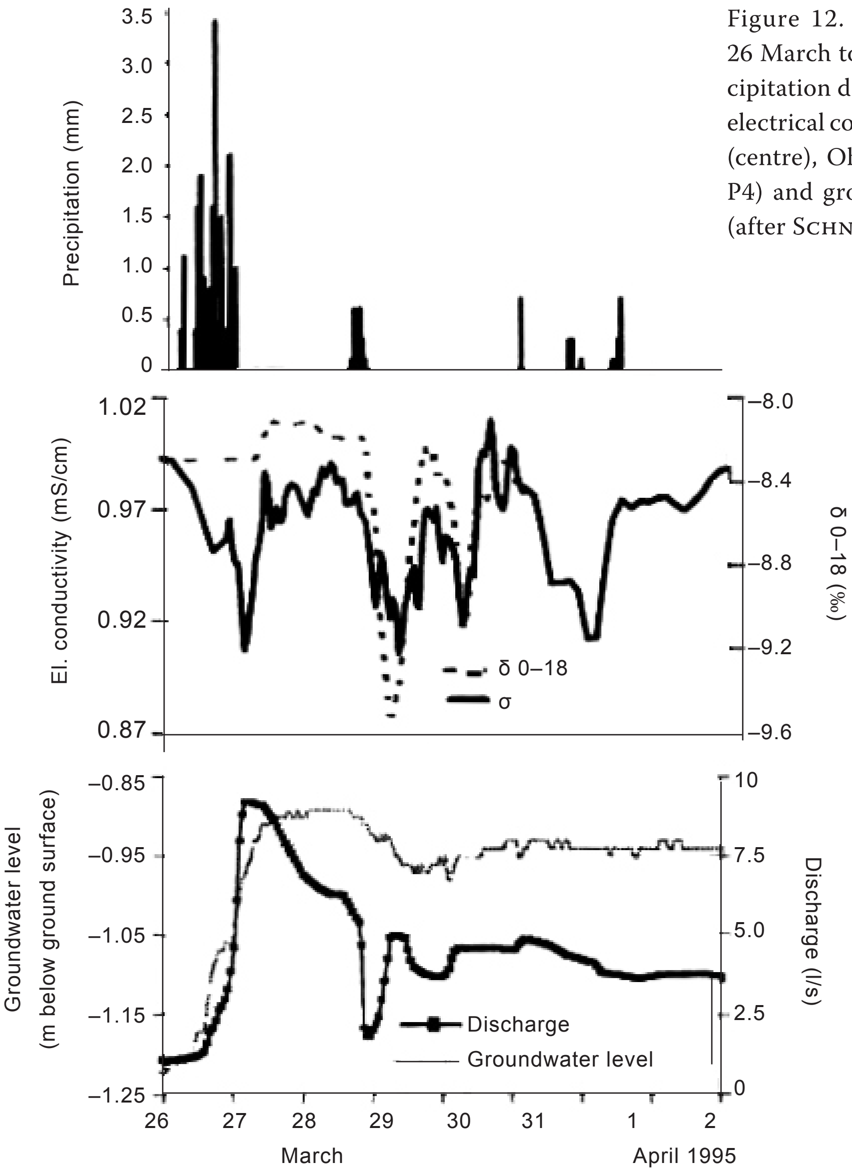


Figure 12. Storm event in Krummbach from 26 March to 2 April 1995: Developments of precipitation depth (top), O-18 contents ($\delta\ ^{18}O$) and electrical conductivity (σ) of the Ohebach channel (centre), Ohebach storm hydrograph (discharge P4) and groundwater tables at NKG4 (bottom) (after Schnug & Kücke 1996)

hydrological model assumptions the water fluxes in Table 1 can be calculated. The results confirm that event water plays only a minor role in stream flow generation. The whole discharge volume (= basin output) is for the calculation period only one third of the precipitation volume (= basin input). Only 3.7% of precipitation flux contribute to the hydrograph as direct flow component which

Table 1. Main water fluxes for a storm event in the Kummbach basin from 26 March–3 April 1995

Water flux	Volume (m^3)	Percentage
Precipitation	10 885 (= 23.5 mm WC)	100
Overland flow	80	0.7
Drain flow	2656	24
from precipitation	340	3
from groundwater	2316	21
Groundwater flow	543	5
Discharge	3279	30

corresponds to 13% of total flow. Accordingly, only a very minor portion of precipitation contributes to hydrograph generation as overland and drain flow with the latter passing through preferential flow paths of the macropore system of the soils. Groundwater is the main agent, but which is activated with the infiltration process starting. Accordingly, the by far largest precipitation amounts recharge the aquifer. Groundwater recharge is therefore considered a permanent process.

CONCLUSION

A main conclusion from the experiments discussed is that the traditional runoff formation concepts do not adequately translate turnover and transport of water and matter in agro-ecosystems of the type reported here. One reason for their limited ability to represent real processes is that shallow aquifer systems – confined or unconfined and made up by porous loose or fissured and fractured hard rock substrates – seem hydro-dynamically more specifically imbedded in the whole complex runoff formation process than in general assumed. Accordingly, by preference similar holistic, integrated approach on a small basin scale as was only briefly indicated here should be pursued to extend our knowledge in this field more purposefully.

As demonstrated the tile-drained agricultural basin type with porous aquifer responds similarly to a basin input as forested mountainous basins with dominant fractured rock aquifers do, i.e. under the two different aquifer conditions stream flow is predominantly generated by infiltrating groundwater. The driving force for quasi-spontaneous increase in groundwater exfiltration is pressure transmission once the infiltration process has started, combined with local rise of pressure heads. The exfiltration effect is amplified by the growth of hydraulic pressure in the course of single input events, and additionally verified here with the results from the application of hydrological tracers.

The major control mechanism, i.e. local rise of pressure heads is not only active close to channel beds and walls, but also along tile-drains, drain samplers and last but not least the walls of major faults in hard rock systems. Accordingly, the effects of these disruptions in the hydraulic systems of small basins are that they function as efficient drain pipe lines, thus representing hydraulic short cuts or preferential flow pathways. In tile-drained agricultural systems the efficiency of this pipe flow effect is increased when groundwater tables reach up to the level lateral drain networks. With these conclusions the hypotheses 2 and 3 which were put at the end of paragraph two can be confirmed as correct, whereas the more important role of overland flow in agricultural basins as compared to the forested as expressed under hypothesis 1 was not reconfirmed in this study. However, soil erosion is frequent in the two regions, and it mainly depends on rain quantity and intensity, and on cultivated plants.

To complete our knowledge further investigations are necessary which should take up the ICA (Integrated Catchment Approach) approach as propagated by Herrmann *et al.* (2001) in order to create a physical basis for future hydraulically-based numerical modelling and simulation of runoff formation in head water basins. In this context, according to the experiences of Herrmann *et al.* (2006, 2007) in cooperation with Maloszewski *et al.* (1999) tracer experiments are very helpful in verifying flow parameters and calibrating numerical hydraulic basin models.

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Received for publication January 29, 2008
Accepted after corrections March 25, 2008

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