Runoff generation following a prolonged dry period

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HYDROLOGY

Research need

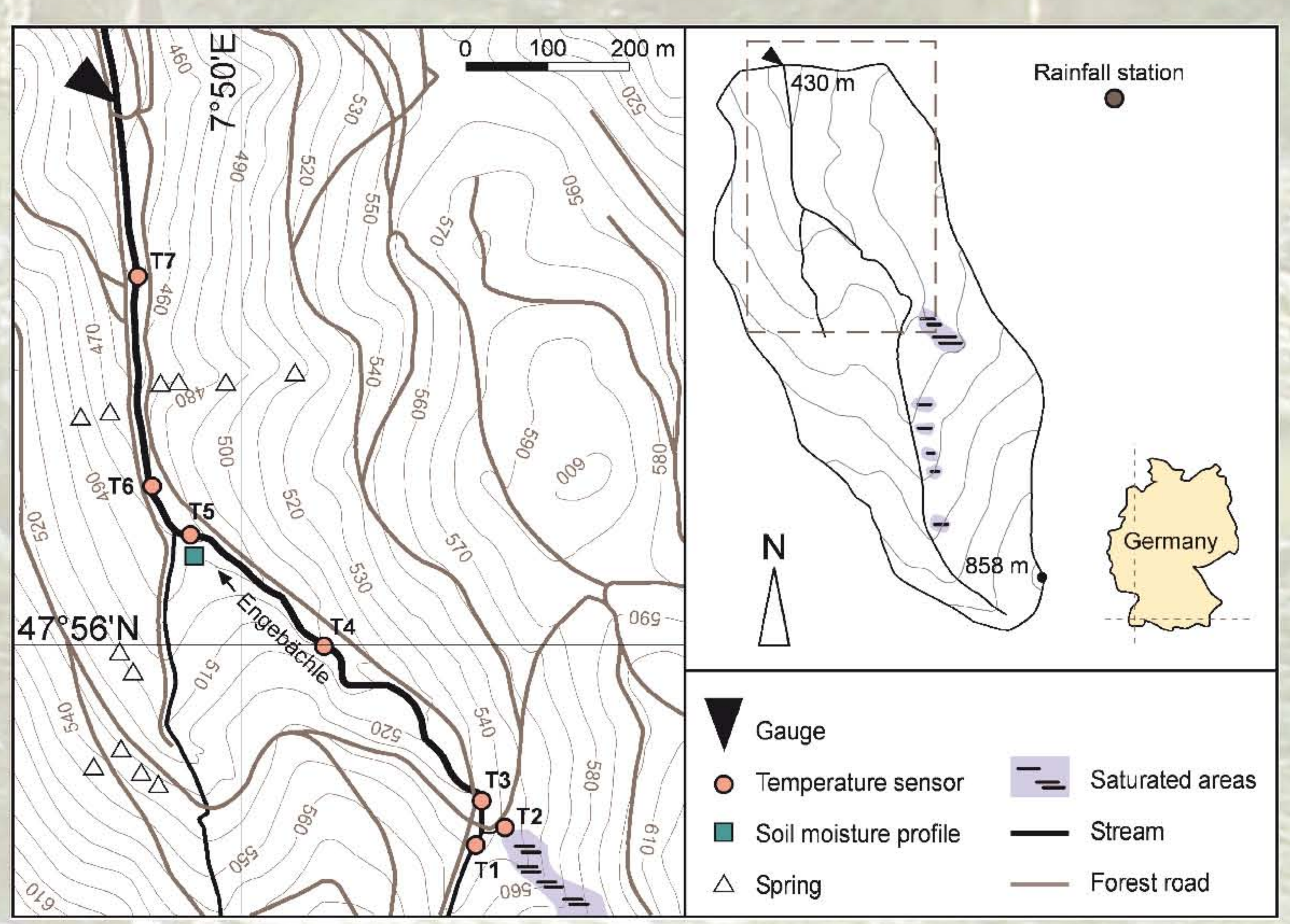
At the hillslope scale, individual runoff generation processes and hydrological connectivity strongly depend on wetness state. Thus, a significant **change of runoff response** may be expected **after an intense drought period**. However, existing knowledge is limited, at least for forest headwater catchments.

Objectives

Apply different methods to characterize a change in runoff generation following a prolonged dry period in a forest headwater catchment:
(1) use water temperature sensors to study **runoff generation mechanisms at dry conditions**,
(2) analyse **continuous rainfall-, runoff- and soil moisture records**,
(3) study nine consecutive after-drought runoff events by **hydrograph separation**,
(4) collect weekly **water quality samples**.

Study area / Methods

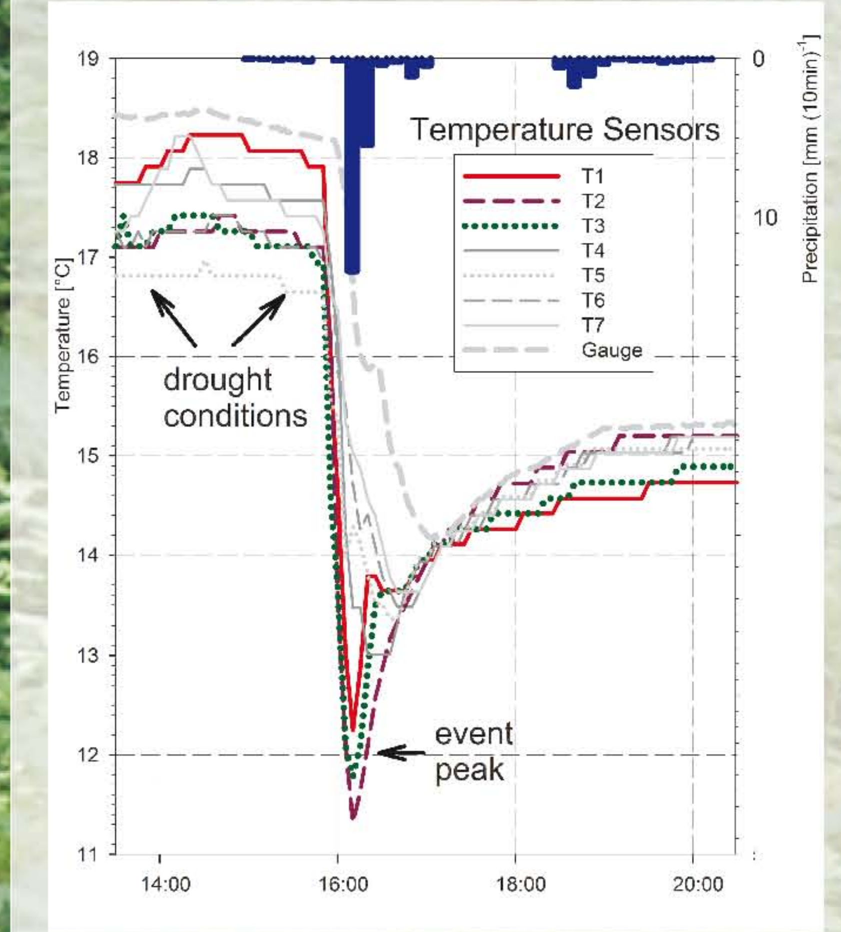
Basin Engebächle: 1.53 km^2
Black Forest Mountains, Southwest Germany
Altitude: 430 - 858 m a.s.l.
Geology: metamorphic rocks / periglacial drift
Soils: Dystric cambisols, sandy loam, stony
Vegetation: 100% forest
Mean annual precipitation:1100 mm
Saturated areas by diffuse groundwater discharge



Rainfall intensities were measured by the PLUVIO weighing raingauge (OTT Messtechnik). **Streamflow** was measured by a metal V-notch weir, 33 cm wide at its top. A soil profile on a steep hillslope close to the stream was equipped with four capacity type **soil moisture probes** (ECH2O, Decagon Devices, Inc.). These were located at depths of 40, 65, 80 cm below surface down to the weathered bedrock at a depth of 1.15 m. **Water temperature sensors** (Optic StowAway Temp logger, Onset Computer Corp.) were placed at seven points along a 1.2 km channel reach. To capture the contribution of saturated area runoff, temperature sensors were placed immediately up- (T1), downstream (T3) and within (T2) an extended saturated area. For 15 weeks (03/06 - 27/09/2005) rainfall and streamflow were sampled in a weekly time interval. **$^{18}O/^{16}O$-isotope ratios** were determined by mass spectrometry (Delta-S, Finnegan Mat), **chloride** and **nitrate** concentrations by ion-chromatography (Dionex DX-500), and **silica** by photometry (Aquamate, Spectronic Unicam).

Results

Water temperature dynamics



For individual sensor location refer to map of study area

During the first after-drought runoff event, a mixing analysis with data from water temperature sensors (T1, T2, T3) illustrated the importance of runoff from the saturated area (SA):

T1 (upstream SA) + T2 (inside SA) = T3 (downstream SA).

At drought conditions prior to the event:
T1 = 18.2 °C, T2 = 17.4 °C, T3 = 17.4°C
=> **SA-runoff is the only source of streamflow at T3**.

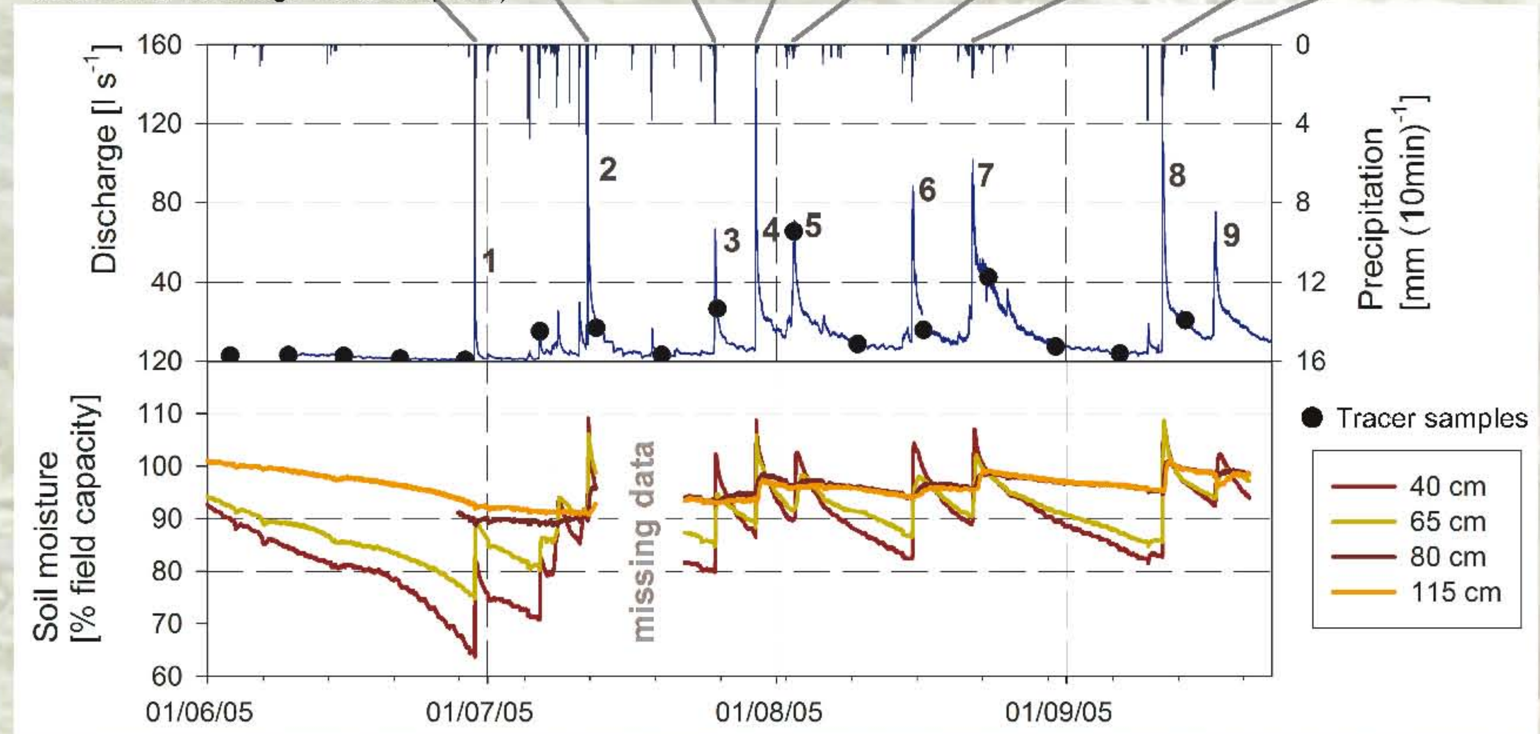
At the event peak:
T1 = 12.5 °C, T2 = 11.3 °C, T3 = 11.8 °C
=> **SA contributes approximately 60% of streamflow at T3**.

Event characteristics and hydrograph separation by EC

Event water percentage showed a decreasing tendency towards the end of the study period, although large uncertainty ranges were determined.

Event	1	2	3	4	5	6	7	8	9
Date	29/06	11/07	25/07	29/07	02/08	15/08	21/08	11/09	16/09
Rainfall amount [mm]	26.0	34.5	24.3	37.6	14.0	24.5	29.1	45.9	23.8
Maximum rainfall intensity [mm/h]	123.6	117.6	46.2	110.1	4.5	18.6	12.0	38.7	15.3
Total flow [m^3]	534	2975	1477	3749	2760	3235	6981	4510	2895
Peak discharge (l/s)	54.2	150.5	67.1	147.1	71.4	88.1	101.4	110.5	75.0
Separated event water by EC [% of total flow]	39.2 (26.6 - 52.5)*	38.9 (21.7 - 65.1)*	19.2 (17.9 - 20.4)*	16.1 (4.8 - 27.4)*	13.7 (6.6 - 20.9)*	17.4 (7.4 - 27.5)*	33.7 (14.1 - 57.1)*	16.6** (2.1 - 36.3)*	10.8 (5.8 - 16.0)*

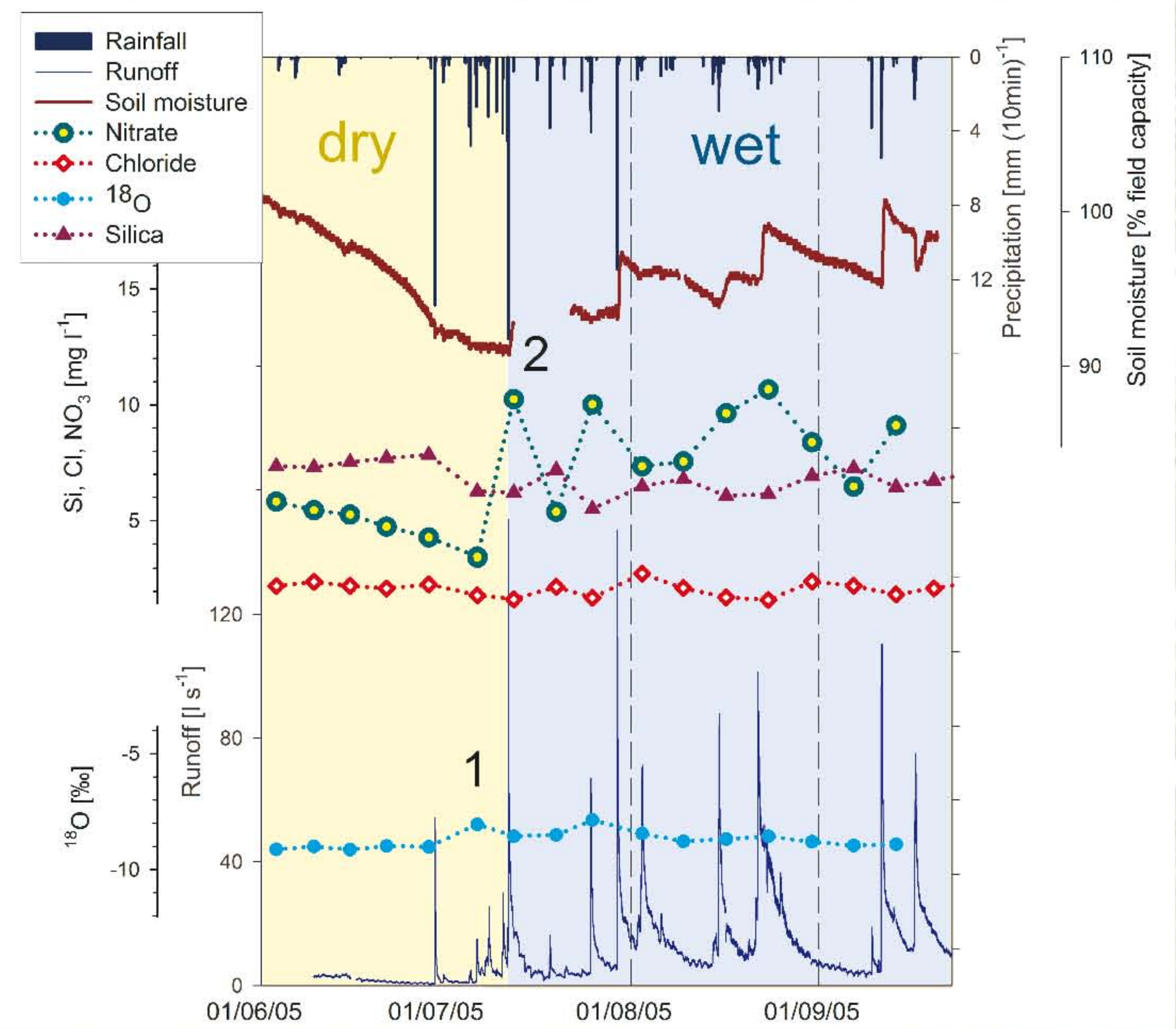
* Uncertainty ranges were determined following Genereux (1998)



Continuous rainfall, soil moisture and streamflow data

From 24/05 - 28/06/2005 only 24.5 mm of rainfall was recorded. This early summer drought caused an apparent soil moisture deficit in upper soil layers which was only balanced by intense July rainfalls. The **two lowermost soil moisture sensors showed retarded reactions**. Event responses at these sensors could only be observed from 11/07/2005 on, suggesting a gradual filling of deeper soil reservoirs. A similar pattern was apparent in recorded streamflow. Following the intense early summer drought with minimum baseflow, **Event 1** (29/06/2006) was characterized by **steep rising and falling limbs** of the hydrograph and almost no post-event increase of baseflow. Only **during the following events**, flow recession was gradually delayed and **baseflow recovered**.

Weekly water quality samples



Nitrate concentrations **showed minimum concentration** at 06/07/2005 and a **sudden increase thereafter (2). This closely corresponded to the response of the deepest soil moisture sensor.** A short, less intense drought period (26/08 - 09/09/2005) showed a similar decreasing trend in soil moisture and streamflow nitrate.
Chloride concentrations were continuously low without relation to moisture conditions. Compared to nitrate, **^{18}O-isotopes reacted quicker** (already on 06/07/2005 (1), at the minimum concentration of nitrate) and were most enriched when samples were taken at high discharge. Also **silica reacted quicker** than nitrate and showed dilution effects already in the first after-drought sample of 06/07/2005 (1).

=> Nitrate and soil moisture indicated transition from dry to wet

Conclusions

(1) Stream temperature directly showed the important **dual role of a permanently saturated area at drought conditions**: it (i) sustained baseflow and (ii) quickly responded to rainfall.
(2) Hydrograph separation suggested that **at dry conditions, storm runoff generation was dominated by event water**, predominantly from the surface (permanent saturated areas and forest roads). Only **during following rainfall events did subsurface runoff components regain their importance**, causing higher fractions of pre-event water and a longer term increase of base flow.
(3) Weekly samples of streamwater quality indicated changes in dominant runoff generation processes. ^{18}O-isotopes and silica documented the importance of new water during runoff events immediately after the drought. However, **a sudden increase of nitrate** was the only unambiguous water quality indicator for the **transition from a surface- to a subsurface dominated runoff response**.
(4) This turning point was corroborated by **deep soil moisture sensors** that **responded almost simultaneously**.

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