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RESEARCH AND OBSERVATORY CATCHMENTS: THE LEGACY AND THE FUTURE

Investigation of subsurface connectivity and subsurface stormflow in low mountain ranges—Findings from the two research catchments Obere Brachtpe and Bohlmicke (Germany)

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Abstract

The two small research catchments *Obere Brachtpe* (2.6 km^2; 50.989986, 7.752013) and *Bohlmicke* (1 km^2, 51.079319, 7.892988) are located in the Rhenish Massif, a low mountain range in Germany. Land use in both catchments is dominated by pasture land, spruce stands and mixed forests. Mean annual temperature is 9.1°C, and mean annual total precipitation is 1250 mm, with 15%–20% of the annual precipitation falling as snow. The geology is characterized by sandy silty clay shale from the Lower and Middle Devonian. Loamy Cambisols derived from periglacial slope deposits, complemented by Leptosols and Stagnosols, are the most prominent soils in the catchments. Long-term hydrological datasets of precipitation, throughfall, discharge, groundwater levels and soil moisture (at different soil depths) in a high temporal and spatial resolution are available for further scientific analysis. Both catchments were monitored within the time period 1999 and 2009, in order to understand how the antecedent soil moisture, stratified soils (periglacial cover beds) and topography (slope form) impacted the subsurface connectivity, and the subsurface stormflow generation - a dominant runoff generation process in humid mountainous catchments. Detailed physically based investigations on runoff processes were carried out, and the obtained results helped to better understand subsurface stormflow generation and subsurface connectivity dynamics. The process knowledge gained, which was presented at several conferences, as well as publications, was the basis for the discussion of open questions within the scientific network 'Subsurface Stormflow - A well-recognized, but still challenging process in Catchment Hydrology' (2016–2021), and the research unit 'Fast and invisible: conquering subsurface stormflow through an interdisciplinary multisite approach' (2022–2025), both financed by the German Research Foundation (DFG).

KEYWORDS
double peak hydrograph, groundwater, hillslope hydrology, runoff generation, soil moisture, subsurface connectivity, subsurface stormflow, topography

1 | INTRODUCTION

In mountain catchments in humid climates, subsurface flow (SSF) is a widespread process in runoff generation (Bachmair & Weiler, 2014; Blume & van Meerveld, 2015; Chifflard et al., 2008; Weiler et al., 2006). According to the definition of Chifflard et al. (2019), SSF develops in vertical structured soils where the bedrock, or a less permeable soil layer, is overlaid by a permeable soil layer, and vertical percolating water is deflected more or less in a lateral direction due to the slope inclination.

When the groundwater table rises into more permeable soil layers, and water laterally flows through the more permeable layers into the river, SSF can also occur ('transmissivity feedback mechanism'; Bishop et al., 1990). SSF is also known in hydrological literature as: shallow subsurface runoff, interflow, lateral flow or soil water flow, which reflects the different underlying process concepts based on the experience developed in various experimental studies and modelling approaches in different environments, and at different spatial and temporal scales (Weiler et al., 2006). Nevertheless, SSF has a clear influence on runoff generation at the catchment scale (Becker, 2005; Chifflard & Zepp, 2008; Graeff et al., 2009; Zillgens et al., 2007), and on the development of recent floods (e.g. in central Europe in 2002 and 2013; in central and western Austria in 2005; Markart et al., 2015). Moreover, SSF is also responsible for example, the transport of labile nutrients or pollutants into the surface water bodies (Zhao et al., 2013), which underlines its further importance for aquatic ecosystems, and makes an accurate process understanding essential. In this context, knowledge regarding subsurface hillslope-stream connectivity is essential for understanding and predicting runoff and stream water quality. This connectivity could be very dynamic due to various hydrological conditions, and occurs when hillslopes become hydrologically connected to the stream by subsurface water flow (Blume & van Meerveld, 2015). To understand processes and factors controlling subsurface stormflow, and subsequently subsurface connectivity, the two small research catchments: *Obere Brachtpe* and *Bohlmicke*, which are part of the network European Representative Basins (ERB; IHP/HWRP-Working Group 'FRIEND/ERB', Herrmann & Schumann, 2010), were instrumented. The catchments feature typical characteristics (soil type, relief, climate, etc) that lead to subsurface stormflow and connectivity, and provide the opportunity to conduct intensive process research, at different spatial and temporal scales.

2 | SITE DESCRIPTION

The findings on subsurface connectivity and subsurface stormflow were obtained in the two small research catchments: *Obere Brachtpe* (2.6 km^2; 382–425 m a.s.l.) and *Bohlmicke* (1 km^2; 350–502 m a.s.l.), located in the Rhenish Massif, a low mountain range in Germany (Figures 1 and 2) (Chifflard et al., 2018). Land use in both catchments is dominated by pasture land, spruce stands and mixed forests. Mean annual temperature is $\sim$ 9.1°C, and mean annual total precipitation $\sim$ 1250 mm, with 15%–20% of annual precipitation falling in the form of snow. The geology is characterized by sandy silty clay shale from the Lower and Middle Devonian. Loamy cambisols derived from periglacial slope deposits, supplemented by leptosols and stagnosols, are the main soils in the basin. Periglacial cover beds are a typical example of stratified soils that are common across most Central European low mountain ranges, and typically consist of three (upper, middle and lower) layers. These layers vary in their pedophysical and sedimentological properties due to the solifluidal formation processes integrating different material (eg. autochthonous material, aeolian input) during the Pleistocene, when these low mountain ranges were unglaciated periglacial regions. In both catchments, the upper layer is of loose soil bulk density, and rich in macropores. The intermediate layer has a higher bulk density than the upper layer, and differs in clast content and thickness from the upper layer, according to topographic location. The basal layer is rich in clasts aligned parallel to the slope inclination, and is characterized by high bulk density, which in turn has the effect that water percolating vertically is blocked and forced to flow laterally (Chifflard et al., 2008).

3 | INSTRUMENTATION AND MEASUREMENTS

Long-term hydrological datasets of precipitation, throughfall, discharge, groundwater levels and soil moisture (at different soil depths) at a high temporal and spatial resolution are available (*Obere Brachtpe*: 1999–2009; *Bohlmicke*: 2000–2007). The catchment Obere Brachtpe (elevation range: 382–425 m a.s.l.) is a headwater catchment of the catchment Hüppcherhammer (47.2 km^2), where stream water levels have been recorded since 1967 (Hüppcherhammer; 313 m a.s.l.) and between 1999 and 2009 (380 m a.s.l.; Obere Brachtpe) (Chifflard et al., 2018). Mean discharge (MQ) is $\sim$1.24 m^3/s or 828 mm/year (Hüppcherhammer; 1967–2014) and $\sim$ 0.078 m^3/s or 965 mm/year (Husten: 2001–2009). At these two gauging stations, the water level was measured by a bubble gauge and H-Flume, respectively. At the Bohlmicke gauge, a water level-discharge relationship was used to evaluate the discharge [average: 0.007 m^3/s; 2000–2007]. To check the calculated discharge, the discharge was measured manually at monthly intervals, and compared with the calculated values; no differences were found during the entire period under investigation. In both catchments, soil water status was measured automatically (10 min-interval) by tensiometers at different soil depths (20–200 cm) and at different slope positions, within three typical slope forms [convergent (upper slope, middle slope, foot slope, riparian zone), divergent (foot slope) and planar (foot slope, upper slope)]. The bases of the tensiometers positioned along the various the various soil horizons, and the three periglacial cover beds ranging from: 20 cm (typically Ah-horizon; upper layer), to 60 cm (typically Bv-horizon; upper layer), 90 cm

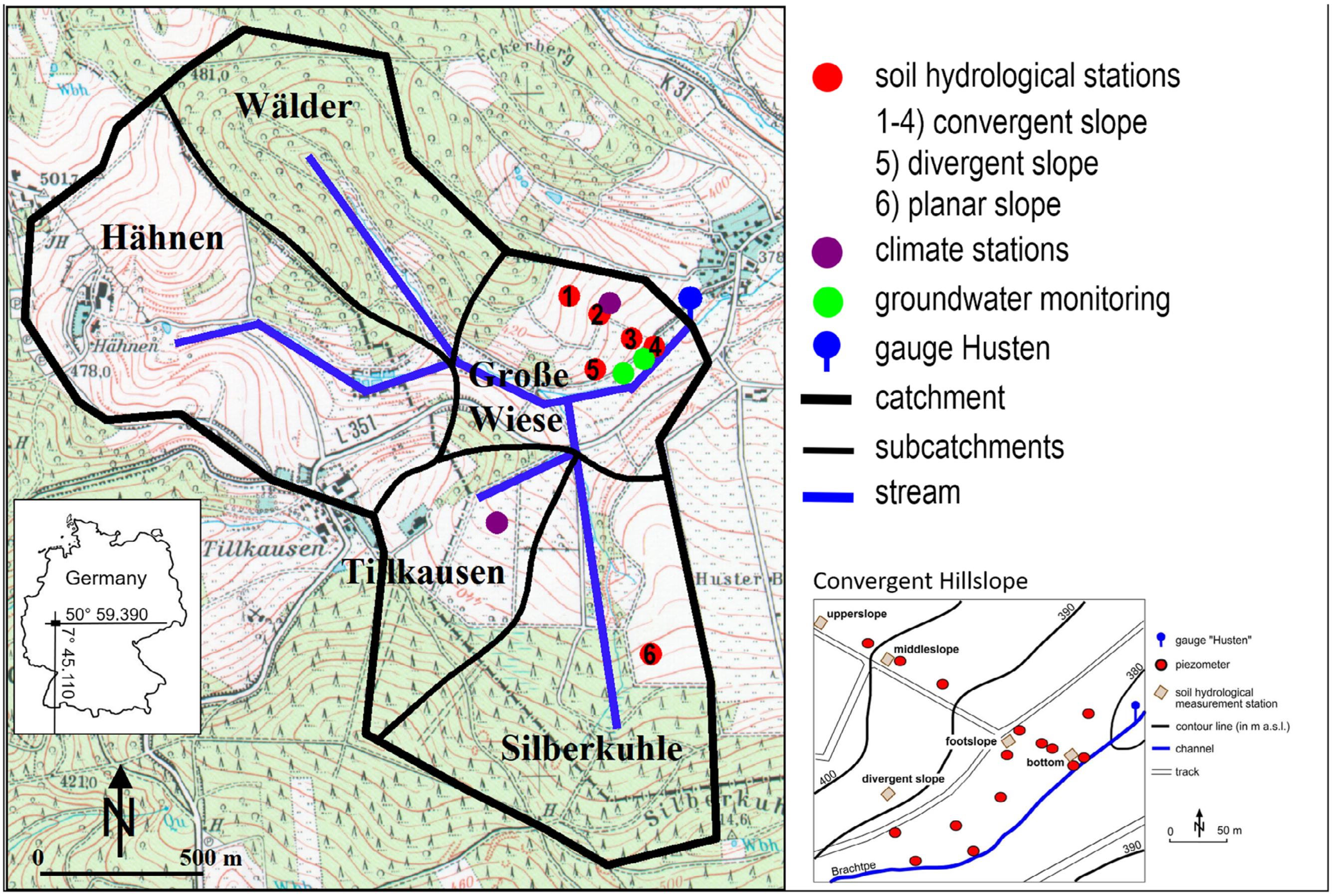

FIGURE 1 Location of the study catchment Obere Brachtpe (modified after Chifflard et al., 2018)

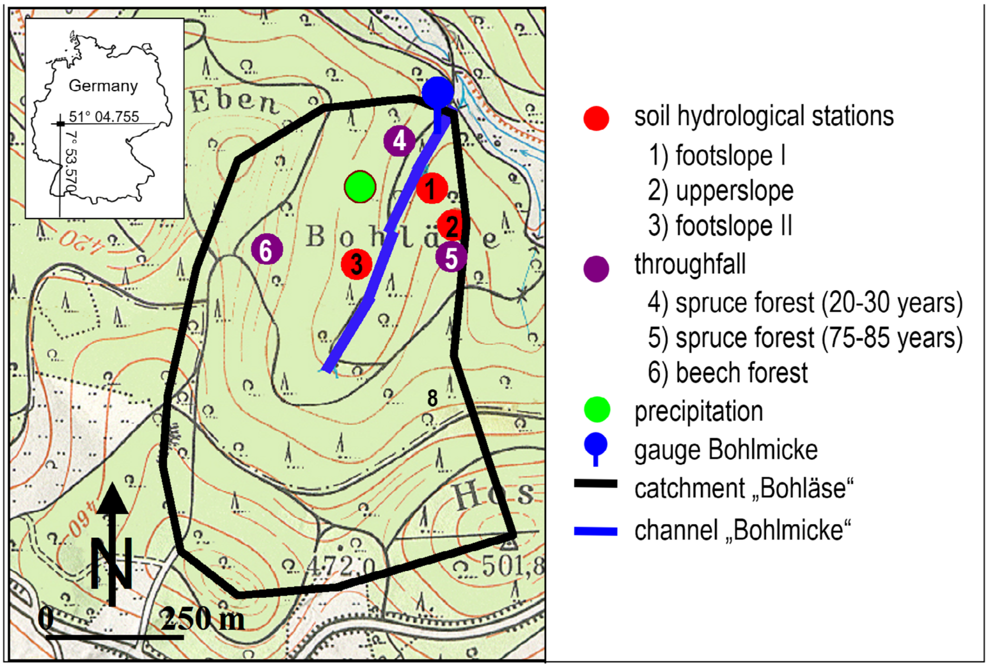

FIGURE 2 Location of the study catchment Bohlmicke (modified after Chifflard et al., 2008)

(typically Bv-horizon; intermediate layer) and 120 cm (typically ICv-horizon; basal layer). At lower slope positions, thicker Bv-horizons are present, which were formed mostly from colluvial material (Chifflard, 2006), in which the tensiometers were positioned at deeper soil depths. At the convergent slope (Obere Brachtpe), four soil moisture stations were arranged following a hypothesized moisture gradient, from upper to lower slope, whereas at the divergent and planar slope, the soil moisture stations were installed at the lower slope. The suction tension data were retrieved weekly, and the tensiometers also serviced at weekly intervals. The data were then checked for plausibility, with, for example, values outside the defined measuring range, or values indicating a groundwater level significantly above the ground surface being removed. In addition, readings that indicated that the tensiometers had fallen dry, as a result of soil air entering the tensiometers, were removed. Within the convergent and the divergent slope, groundwater levels were recorded automatically (10 min) and manually (weekly) by 14 piezometers equipped with pressure sensors. Similar to the gauging stations, groundwater levels were measured manually on a weekly basis to control the automatic measurements. Further investigations in both catchments included the exploration of subsurface structures by geophysical surveys (ground-based radar, geoelectric), the prediction of the spatial variability of soil moisture (Chifflard et al., 2004, 2006), the determination of soil moisture regimes (Chifflard et al., 2011) and the use of hydrochemistry data to detect components and source areas of subsurface runoff (Didszun et al., 2002).

4 | RESEARCH FINDINGS

In the two catchments, detailed physically based investigations on runoff processes have been carried out since 1999 (Chifflard et al., 2008, 2010, 2011, 2018; Chifflard & Zepp, 2008; Didszun et al., 2002; Moldenhauer et al., 2013; Rezzoug et al., 2005; Zepp & Herget, 2001). The results obtained in these two catchments helped to further understand how antecedent soil moisture, stratified soils (periglacial cover beds) and topography (slope form) impact subsurface connectivity and subsurface stormflow generation (Chifflard et al., 2008, 2019; Reiss & Chifflard, 2014). The process knowledge gained, which was presented at many conferences and in many publications, was the basis for the scientific network 'Subsurface Stormflow - A well-recognized but still challenging process in Catchment Hydrology' (https://www.online.uni-marburg.de/ssf/) (2016–2021), and the research unit 'Fast and invisible: conquering subsurface stormflow through an interdisciplinary multisite approach' (2022–2025), both financed by the German Research Foundation (DFG), as well as for the discussion of open questions regarding the subsurface stormflow generation (Blöschl et al., 2019; Chifflard et al., 2019).

In the catchment *Bohlmicke*, the results obtained at different spatial scales show that the periglacial cover beds have a strong influence on both soil-water dynamics on the plot scale, and runoff dynamics on the catchment scale. These results emphasize the importance of cover beds in the generation of subsurface runoff and, additionally, in subsurface connectivity in a subdued relief. It has to be highlighted that the basal layer shows a temporally variable influence on soil-water fluxes, dependent on antecedent soil moisture, the latter being defined as initial soil moisture at the onset of a runoff event. On one hand, the basal layer functions as a barrier for vertical water flow when soil moisture is low; while on the other hand, it is a preferential pathway for lateral subsurface runoff in the case of high soil moisture.

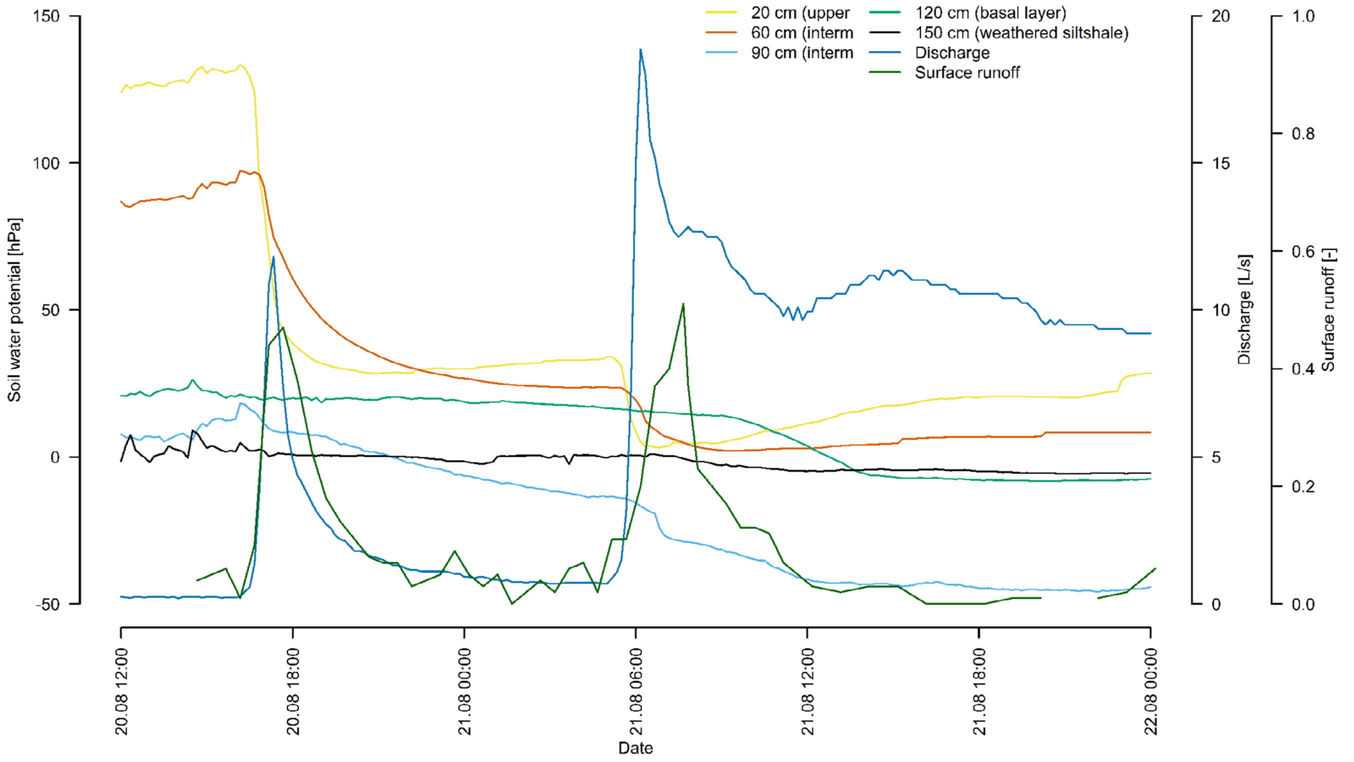

FIGURE 3 Discharge, soil water tensions in different soil depths (20, 60, 90, 120, 150 cm) and the portion of surface runoff based on hydrograph separation with dissolved silica (modified after Chifflard et al., 2008)

The temporal variability of subsurface connectivity between lower slope positions and the stream has been proven by the combination of tracer-hydrological (catchment scale) and hydrometric measurements (plot scale) during different rainfall/runoff events (Figure 3). This has shown that the intermediate and basal layers influence soil-water dynamics and runoff generation in different ways, depending on antecedent soil moisture (Chifflard et al., 2008; Moldenhauer et al., 2013).

In the catchment *Obere Brachtpe*, essential and fundamental findings on the impact of topography and soil moisture on subsurface connectivity and runoff generation were also obtained. The analysis of temporally high-resolution groundwater data in relation to the discharge of the receiving stream during several rainfall/runoff events has shown the influence of slope form, and the flat riparian zone on the runoff processes (Chifflard, 2006). Due to the convergent slope form, subsurface stormflow is concentrated at the bottom of the convergent hillslope. Because of the small slope inclination in the flat riparian zone, the velocity of subsurface water flow is reduced, and groundwater from the slope is transported to the channel with a time lag. As a consequence of this delayed groundwater flow, the runoff in the receiving stream increases again following the initial peak. According to the findings of (Chifflard et al., 2010), delayed peaks are a fundamental indicator of the contribution of subsurface runoff.

The influence of the antecedent soil moisture on runoff generation was quantified by multiple regression analyses of rainfall, pre-event discharge, single-point soil moisture profiles from representative locations and peak discharge, discharge duration, discharge volume, based on 137 single rainfall-runoff events (Chifflard et al., 2018; Chifflard & Zepp, 2008). The evaluation of the extensive dataset shows that the number of explanatory variables in the regression models is lower in winter (up to three variables) than in summer (up to eight variables), and higher for the mesoscale catchment (Hüppcherhammer) than for the small catchment (Husten) (up to two variables). In addition, it was shown that soil moisture data from selected key sites (plot size) in the small catchment improved the quality of the regression models constructed for the mesoscale catchment. This indicates the varying importance of the soil moisture, depending on which characteristics of the discharge are focused on. Based on this intensive data evaluation, it can be concluded that point data for soil moisture in functional landscape elements describe the system condition of catchments very well, and can provide valuable information for flood forecasting in mountain landscapes with subsurface runoff.

5 | OUTLOOK

The obtained results on subsurface stormflow generation and subsurface connectivity dynamics offer the possibility for advanced applications, not only in hydrology, but also in other disciplines such as: geography, soil hydrology, hydrochemistry or biochemistry. The recently accepted research unit 'Fast and Invisible: Conquering Subsurface Stormflow through an Interdisciplinary Multi-Site Approach' (DFG - FOR 5288/1) will take up this interdisciplinary approach, and investigate the genesis of subsurface stormflow, among others in these catchments, using a wide variety of additional methodological approaches of biology, soil science and geophysics. In terms of subsurface connectivity, a currently ongoing research project, financed by the DFG, will investigate the export of organic carbon from permanent and intermittent springs to headwater streams at different temporal scales. An additional interdisciplinary effort has recently started to integrate conceptual soil hydrology modelling into a transient finite-element groundwater model. The two catchments provide the database and necessary process understanding for further model development (Zepp et al., 2017). For all these research projects, experimental study areas provide not only hydrological datasets, but also detailed process knowledge, which continues to be necessary for advancing our current understanding of these and other hydrological processes.

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DATA AVAILABILITY STATEMENT

The comprehensive hydrological, pedological, biochemical and hydrochemical datasets obtained in these two small catchments, including, for example, highly detailed information on soil types, tracer measurements or spatial soil moisture values are available for further evaluation. Basic datasets, including time series of runoff of the three gauging stations (Hüppcherhammer, Obere Brachtpe, Bohlmicke), soil moisture of the eight plots - including all depths, groundwater levels of the 14 piezometers (in a weekly and 10 min-interval), as well as the meteorological dataset of the climate station at the convergent hillslope, are available from Chifflard and Zepp (2020). Obere Brachtpe Research Catchment - Hydrologic Data, HydroShare, http://www.hydroshare.org/resource/56763733d1194ea48a04449e4ca029ab/. The data are available as .xls files, in which the measured values are listed per time step, that is, the respective measuring interval and per measuring point. Each .xls file covers a period of 1 year. The time series have been pre-- cleaned, and can be used directly for further evaluations. For more information on additional available datasets, please contact the lead author: peter.chifflard@geo.uni-marburg.de.

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