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Anthropogenically altered runoff processes in a waterlogged headwater catchment within the National Park Hunsrück-Hochwald, Germany

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Abstract

This study is concerned with an initial investigation of anthropogenically altered runoff processes in a headwater catchment within the National Park Hunsrück-Hochwald (Germany) that is characterized by slope bogs and waterlogged soils. The examined area is crossed by a dense network of trenches, which were established in the course of forestry operations in order to utilize these waterlogged areas. An evaluation of the drainage network's influence on runoff processes is attempted using water gauges and GIS-based analyses of the subcatchments. Results of the water year 2016 and a heavy rainfall event show that gauges in the study area react quickly to precipitation inputs and that water is retained only for a short time. The magnitude of runoff recession even in short dry spells permits the conclusion that the already merely residual slope bogs are endangered. The partial results of this study can serve as an instrument for rewetting actions as they allow spatially and temporally high resolved statements about the influence of drainage networks. Furthermore, this study is embedded in a long-term monitoring of hydrological processes and represents a first component of a detailed process-measurement taking place.

Zusammenfassung

Die vorliegende Studie beschäftigt sich mit einer initialen Grundlagenuntersuchung zu anthropogen veränderten Abflussprozessen in einem durch Hangmoore und Staunässe geprägten Oberlaufeinzugsgebiet innerhalb des Nationalpark Hunsrück-Hochwald in Deutschland. Die untersuchte Fläche ist mit einem dichten Netzwerk von Entwässerungsgräben durchzogen, welches im Zuge der forstwirtschaftlichen Nutzung angelegt wurde, um staunasse Areale nutzbar zu machen. Anhand von Pegeldaten und auf Basis von GIS-basierten Untersuchungen der jeweiligen Teileinzugsgebiete wird versucht, eine Beurteilung des Einflusses der Entwässerung auf die Abflussprozesse zu treffen. Die Ergebnisse zeigen sowohl anhand des hydrologischen Jahrs 2016 als auch anhand eines Starkregenereignisses, dass die Pegel im Gebiet schnell auf Niederschläge reagieren und Wasser nur kurzzeitig in der Fläche zurückgehalten wird. Das Ausmaß, in dem Abflüsse selbst in kurzen Trockenphasen abnehmen, lässt den Schluss zu, dass die ohnehin nur noch residual verbreiteten Hangmoore in ihrem Fortbestehen gefährdet sind. Die Teilergebnisse dieser Arbeit können perspektivisch als Instrument für Wiedervernässungsmaßnahmen dienen, da sie zeitlich und räumlich hoch aufgelöste Aussagen über den Einfluss der Entwässerung zulassen. Zudem ist die vorliegende Studie in ein Langzeitmonitoring der hydrologischen Prozesse eingebettet und stellt einen ersten Baustein einer detaillierten Prozesserfassung dar.

Keywords headwater catchment, bog hydrology, bog drainage, bog rewetting, Rhineland-Palatinate

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1. Introduction

The National Park Hunsrück-Hochwald, established in 2015 and situated in South-Western Germany in the federal states of Rhineland-Palatinate and Saarland, features shallow slope bogs (synonymous with hanging bogs), transitional bogs and heavily waterlogged mineral soils as a characteristic and unique soil hydrologic feature. These areas are recharged by stagnating water that accumulates close to the surface in landscape depressions, forwarded by an infiltration-reducing solifluction-layer that was formed during the Pleistocene (*Klauck* 1985; *König* et al. 2016; *Reichert* 1975; *Steingötter* 2005). That is why they do not appear extensively but only in a patchy pattern on the slopes of the quartzite ridges situated in the area. In the course of forestry operations, which began in the 19th century and involved planting of extensive spruce stands, waterlogged areas were drained with the help of an extensive network of trenches (*Burggraaff* and *Schultheiß* 2016; *Schultheiß* 2016).

As a consequence, interflow that formally recharged the slope bogs and featured rather slow flow velocities is being converted into superficially and fast flowing water. Thus, two major anthropogenic alterations of the local runoff dynamics are caused: in the first place, precipitation input runs much faster through the affected headwater catchments, leading to extremely narrow and short-timed runoff peaks, especially in the course of heavy rainfall events. Secondly, the areal water retention is severely reduced, as the soil water is being drained out of the residual waterlogged areas (c.f. e.g. similar studies by *Ahti* 1980; *Robinson* 1980, 1986). This effect is apparent particularly in dry spells when a significant drop of discharge in trenches and natural streams is observable. While dropping discharge seems normal in dry spells, the magnitude of the reduction indicates a drying-out of the slope bog areas in a way that not only prohibits the current growth of peat moss but also endangers the remaining slope bogs (*Zemke* et al. 2016a; *Zemke* et al. 2016b).

As the detailed research of the local hydrological processes began in 2015, this study can only deliver a first insight into the actual dynamics taking place. It is part of a research program in the National Park that focusses on the preservation and restoration of the endangered slope bogs and their unique hydrological and biological features. In order to evaluate and manage rewetting actions taking place, which mainly comprise of sealing trenches, a dense network of gauges was installed in trenches, ditches and natural streams. They deliver runoff data helping to identify trenches that need treatment as a priority, for instance if the obtained values indicate notably effective drainage caused by a specific trench.

Therefore, the aim of the current study is to analyze runoff patterns of the water year 2016 (United States Geological Survey definition: 1 October 2015 to 30 September 2016) in selected slope bogs and natural streams in order to interpret them against the background of climatic boundary conditions and catchment-specific properties such as trench-network density and percentage of waterlogged area. The latter were derived from extensive GIS-analysis of the observed subcatchments. The interpretation focuses on a single event with high daily precipitation sum as well as on a comparison between winter- and summer-months. A concluding discussion questions the role of rewetting actions and the role of drainage networks on the basis of available literature sources.

2. Used material and methods

2.1 Study area

Research took place in the Traunbach headwater catchment, situated on the southern slope of the Erbeskopf, the highest peak (816 m.a.s.l.) in the state of Rhineland-Palatinate (*Fig. 1*).

The examined area (6.7 km^2) covers the northern part of the Traunbach headwater catchment, a tributary of the river Nahe with a total catchment area of 64.9 km^2 and a stream length of 19.2 km. Therefore, the study area covers roughly 10% of the catchment area. A vegetation mapping using aerial images and field mapping conducted by *Küster* (2016) shows the dominant land cover of the observed area (*Fig. 2*; *Table 1*).

Based on the modified results of *Küster* (2016), about three-fourths of the study area features forests as dominant vegetation with an even ratio between deciduous and coniferous forest. Open landscapes represent areas with dominant ferns, former common pastures and a generally incomplete tree canopy. Merely two percent of the investigated area exhibited peat mosses as dominant vegetation. That is caused by the generally patchy pattern of the waterlogged soils and the land-use change that converted many slope bogs mostly into coniferous forest stands (*Table 1*).

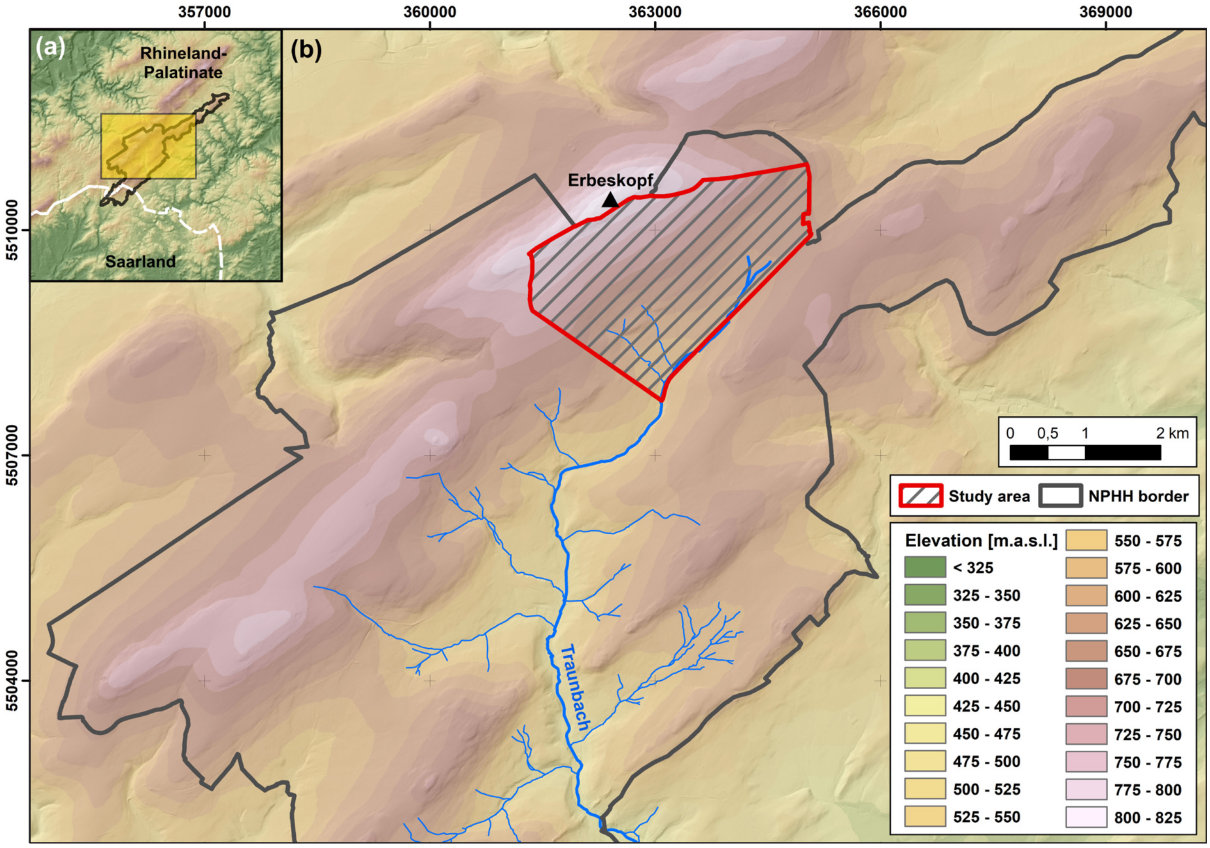

Fig. 1 *(a) National Park Hunsrück-Hochwald (NPHH) within Rhineland-Palatinate and Saarland (Germany); (b) study area within NPHH-borders. Source: Own elaboration*

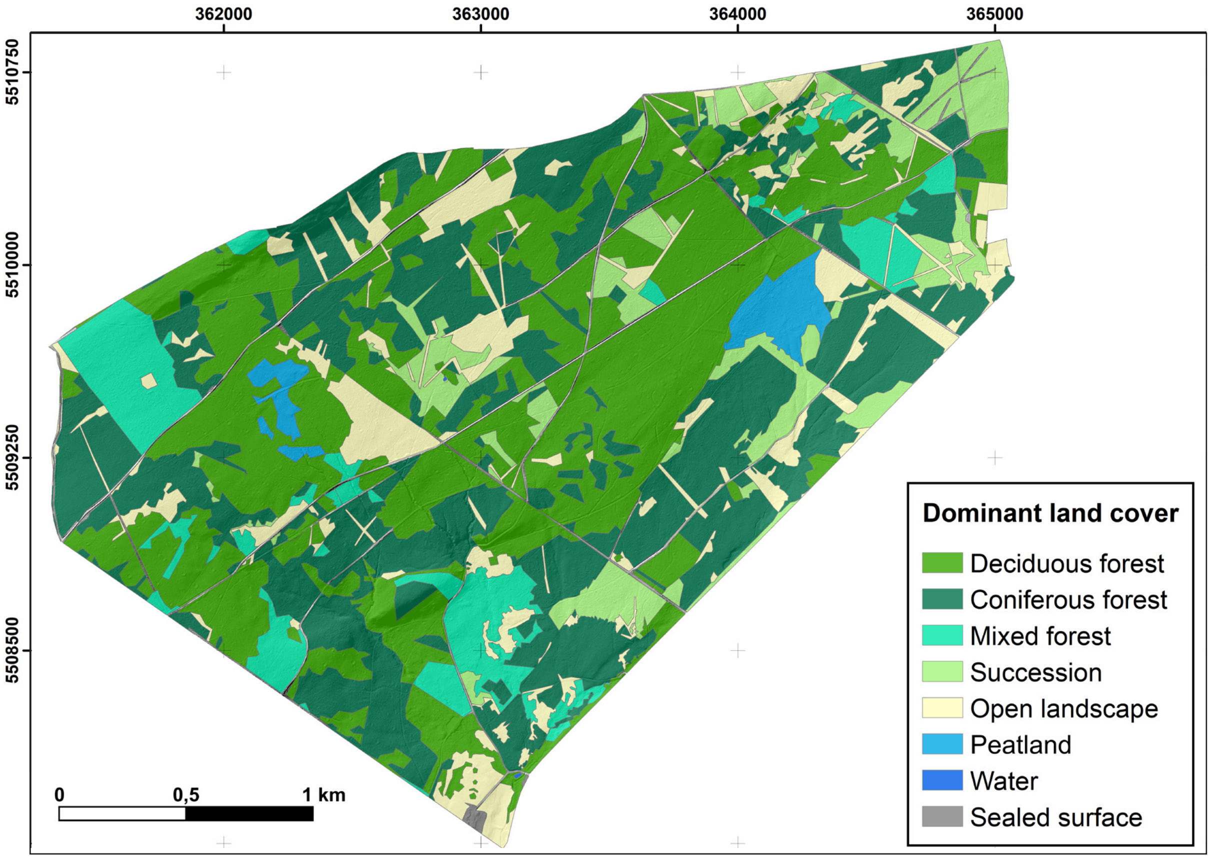

Fig. 2 *Dominant vegetation of the study area: Traunbach headwater catchment within the National Park Hunsrück-Hochwald. Source: Modified according to Küster (2016)*

Table 1 Absolute and relative land cover of the study area. Source: Modified according to Küster (2016)

Dominant vegetation	Area [km²]	Percentage [%]
Deciduous forest	2.37	35.4
Coniferous forest	2.24	33.4
Open landscape	0.70	10.6
Mixed forest	0.54	8.1
Succession	0.52	7.8
Roads and skid trails	0.17	2.6
Peat mosses	0.13	2.0

A dataset of the soil water regime obtained by the forest management planning of Rhineland-Palatinate and based on the classification presented in *AK Standortskartierung* (2016) shows that waterlogged soils concentrate along surface incisions or small scale basin structures (*Fig. 3*).

Areas with extremely waterlogged soils tend to be situated at the bottom of the hillslope because of accumulating soil water. Thranenbruch and Riedbruch are good examples for this kind of slope bogs. A second possibility for extremely waterlogged sites are natural incisions where interflow accumulates and triggers the growth of peat mosses. That is the case in Langbruch, Casparsbruch and Tierchbruch. The latter is a prime example for this type of bog, as the elongated form retraces a slope incision (cf. *Fig. 3*). There are fully developed bogs with peat thickness > 0.4 m. *Scholtes* (2017) describes extensive peats with a mean thickness of 0.3 – 0.6 m and maximum depths of 2 m and more in the observed area. However, the patchy occurrence of waterlogged sites leads to a closely spaced existence of slope bogs, transitional bogs, spring fens and more or less extremely waterlogged mineral soils (*Scholtes* 2002, 2017). Own investiga-

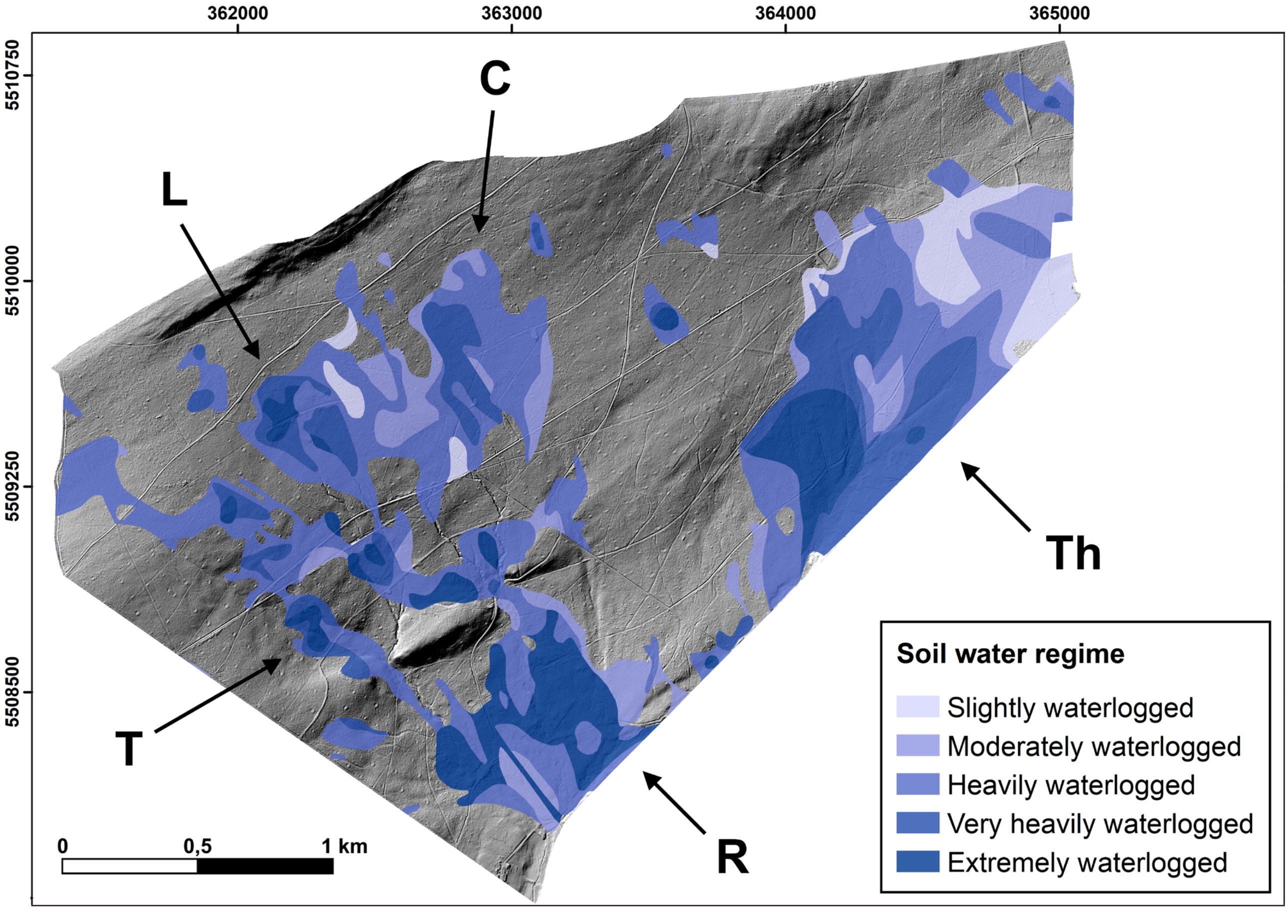

Fig. 3 Waterlogged areas and slope bog complexes of the study area, modified according to forest management planning of Rhineland-Palatinate (LfU RLP 2014). Soil water regime based on AK Standortskartierung (2016), representing classes slightly waterlogged – extremely waterlogged. Major bog areas are indicated: C = Casparsbruch, L = Langbruch, R = Riedbruch, T = Tierchbruch, Th = Thranenbruch. Source: Own elaboration based on LfU RLP (2014) and AK Standortskartierung (2016)

tions presented in *Hahn* et al. (2017) revealed (Mollic) Planosols, Haplic Podzols and fully developed bogs in direct vicinity to each other while the thickest peats showed a strong spatial correlation with very heavily and extremely waterlogged sites.

Another important factor for interpreting hydrological processes are the local climate boundary conditions. Climate data was obtained from the weather station in Hüttgeswasen (650 m.a.s.l.), operated by the Dienstleistungszentrum Ländlicher Raum of Rhineland-Palatinate (DLR RLP). It is located just about 100 m to the east of the study area (UTM E365155, N5510140; cf. upcoming *Fig. 6*), delivering in-situ data directly out of the observed catchment suitable for determining precipitation input. The weather station was established on 1 January 2009. Therefore, the whole dataset covers roughly eight continuous observation years (*Fig. 4*).

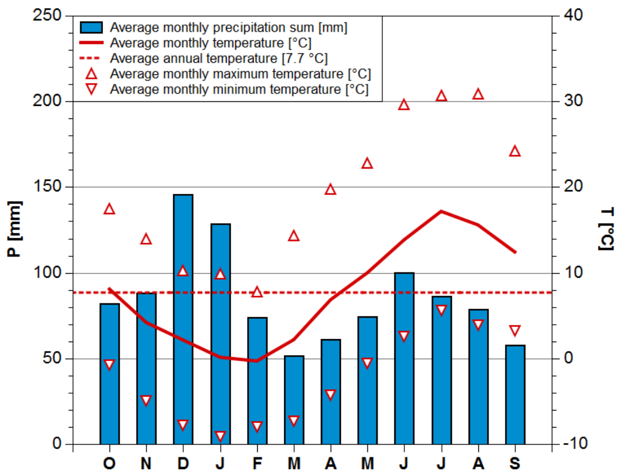

Fig. 4 Monthly-value climograph for the weather station Hüttgeswasen (650 m.a.s.l.), covering the water years 2009-2016. Source: Own elaboration based on DLR RLP (2017)

Mean annual temperature in Hüttgeswasen is 7.7 °C with a rather strong seasonality. While there are average monthly temperatures around 0 °C during December till February, summer temperatures reach almost 18 °C with possible maxima of >30 °C. Average precipitation sum is 1025.9 mm·yr^{-1} with January and December as most rain-laden months. Nevertheless, both summer and winter half-years show balanced rainfall sums, as 56% of the annual rainfall fall upon the winter half-year (Oct - Mar), while 44% fall upon the remaining months. Heavier rainfall in the summer usually consists of convective rainfall events during thunderstorms. Therefore, dry and hot periods change over to short but intensive rainfall events in quick succession.

2.2 Instrumentation and data analysis

2.2.1 Digital mapping of trenches and other linear structures

Linear structures like trenches, forest roads and their side ditches or skid trails were mapped using a high-precision digital elevation model (DEM) with a spatial resolution of 1 m^2 provided by the land surveying state office of Rhineland-Palatinate (LVermGeo RLP). In a first step, all linear patterns that were considered to be a hydrologic relevant feature were marked within the dataset (*Fig. 5*).

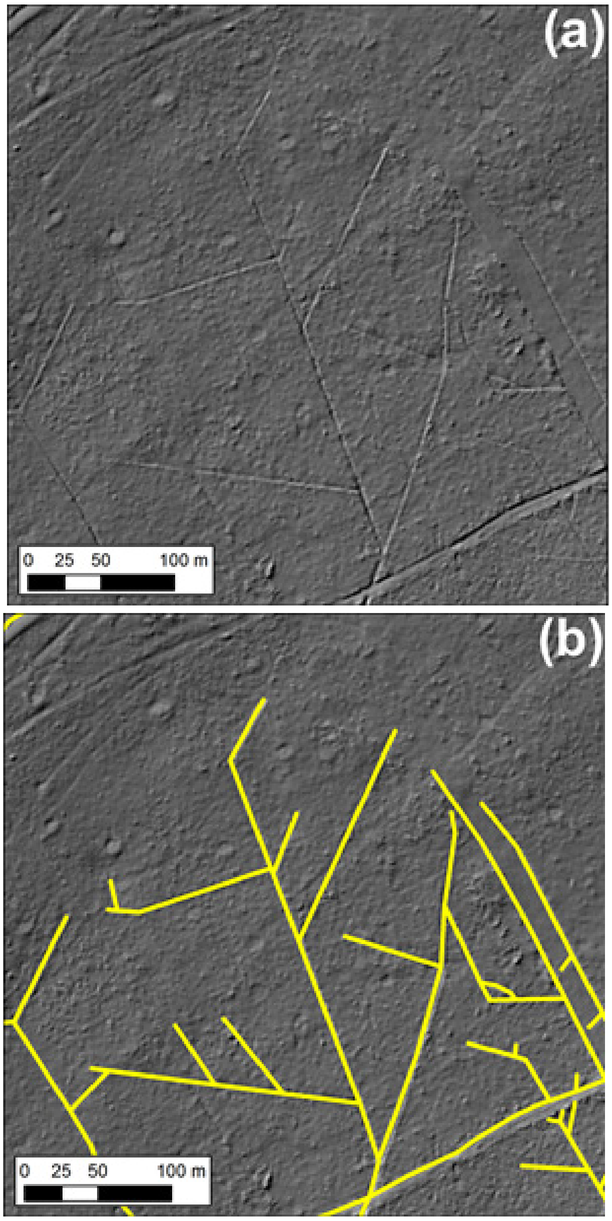

Fig. 5 Example for mapping linear structures with the help of a digital elevation model (DEM). (a) DEM raw data; (b) digitalized linear features. Source: Own elaboration

With the help of generated maps, a subsequent field mapping of these structures was facilitated. It was possible to identify even old trenches or trails that were not clearly recognizable anymore by using a combined approach including GIS and field mapping. Not only the position of the linear structures, but also the repair of the trenches and ditches was recorded including their exact measures (width, depth, sloping), plant cover, profile structure and cross section morphometry based on a check list introduced by *Schultheiß* (2014) for a similar study conducted in the neighboring Soonwald area. Therefore, it was possible to generate a complete digital register of all hydrologic relevant structures within the examined area.

2.2.2 Runoff measurements

A dense network of gauges was established in order to allow data collection with a high spatial resolution. Overall, 15 continuously recording water gauges (Type OTT Orpheus mini) with a sampling interval of five minutes were installed in selected trenches and natural streams. Moreover, discontinuous measurements took place at over 50 measuring posts, located mostly in trenches (*Fig. 6*). The latter were only sampled in phases with high runoff-sums, especially after heavy rainfall events or snowmelt, as the respective trenches usually fell dry in the remaining periods.

However, this study mainly focuses on two gauges, one located in the Tierchbruch slope bog (T) and one located underneath a culvert of a side ditch (D), passing under a forest road. It is part of the drainage network of the Langbruch situated upslope of the gauge. In order to provide a better interpretation of the datasets, hydrographs of the Traunbach, the receiving natural water course, are also presented for two locations. One is situated directly in the valley floor below the slope bogs (TB1), the other one is a water gauge run by the state environmental office of Rhineland-Palatinate (LfU RLP). It is situated in the village of Aben-

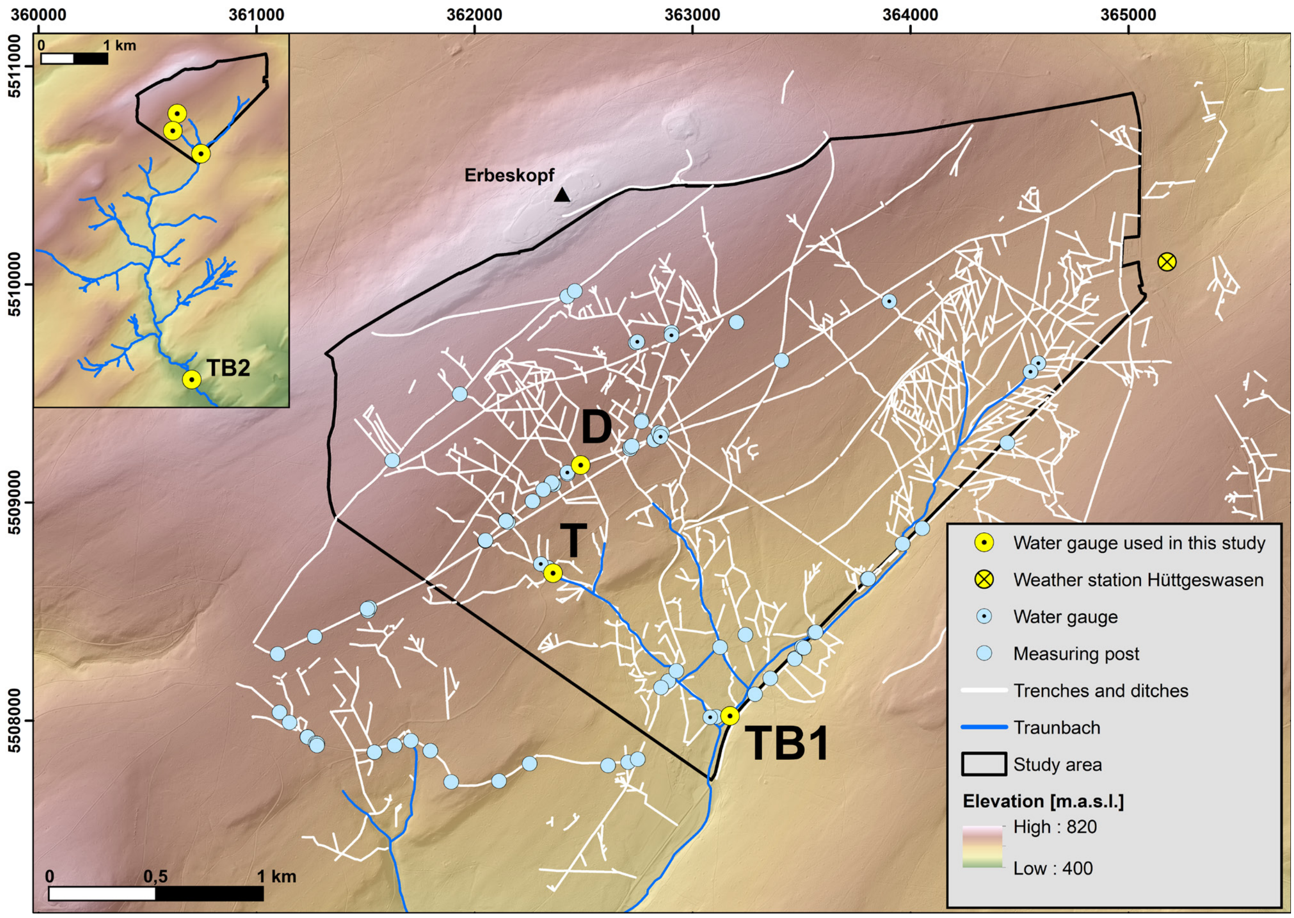

Fig. 6 *Location of all water gauges and measuring posts in and around the study area. The location of weather station Hüttgeswasen and the digitalized trench network are also indicated. Water gauges used in this study are Tierchbruch (T), side ditch (D) and Traunbach 1 (TB1) as well as Traunbach 2 (TB2) situated 6 km downstream of TB1. Source: Own elaboration*

theuer, approximately six kilometers downstream of the study area (TB2). TB2 is used mostly as a test gauge, showing runoff patterns in a higher spatial context. Because of the catchment size of TB2, datasets of trench networks and soil water regime have not been accomplished yet. That is why no detailed data obtained by using GIS-based analysis (cf. Section 2.2.3) but only hydrographs are shown for TB2. In order to provide a comparability between different-sized catchments, the specific runoff (q) [$l \cdot s^{-1} \cdot km^{-2}$] was used.

Specific runoff was analyzed using basic statistical methods. In order to evaluate the dataset scattering, average (μ), standard deviation (σ) and coefficient of variation ($c_v = \sigma/\mu$) were calculated and compared. Additionally, a correlation-analysis was conducted, trying to identify water gauges that correspond with each other. To choose the correct correlation coefficient, a Kolmogorov-Smirnov test (KS test) was performed, testing if all datasets were normally distributed. These operations were carried out using IBM SPSS Statistics 24.

2.2.3 GIS-based analysis of subcatchments

Subcatchment-areas for every gauge were determined using the Hydrology-Toolset of ESRI ArcGIS 10.3. With the help of the digitalized trenches, it was possible to generate flow paths that represent the actual spatial runoff patterns in the observed headwater catchment. The existing DEM was edited in terms of erasing culverts out of the surface model by burning the underlying ditches into the DEM. These culverts would have led to significantly altered spatial runoff patterns as the hydrologic GIS tools ignore trenches and ditches covered by an overlying soil layer. Using these corrected flow paths, it was possible to calculate the overground catchment areas of each water gauge. This areal data was used to crop all georeferenced datasets of soil water regime, land use, morphometry and anthropogenic structures to the extent of each subcatchment, resulting in detailed, site-specific spatial datasets. Because of the known subcatchment area, specific runoff (q) [$l \cdot s^{-1} \cdot km^{-2}$] could be calculated in the first place.

3. Results

3.1 Subcatchment characteristics

Subcatchment characteristics derived from GIS-calculations show the spatial pattern and the percentage of waterlogged sites for each of the gauges within the study area (*Fig. 7, Table 2*).

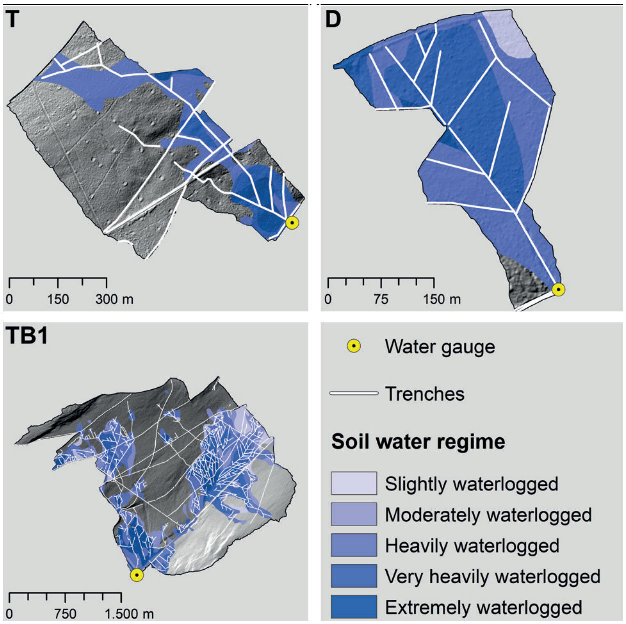

Fig. 7 *Spatial distribution of waterlogged soils and trenches within the surveyed subcatchments. Water gauges: Tierchbruch (T), side ditch (D) and Traunbach 1 (TB1). Source: Own elaboration*

Table 2 *Subcatchment characteristics: Catchment area, soil water regime and trench network. Water gauges: Tierchbruch (T), side ditch (D) and Traunbach 1 (TB1). Source: Own elaboration*

	Subcatchment		
	T	D	TB1
Elevation [m.a.s.l.]	648	687	574
Subcatchment area [km^2]	0.33	0.06	5.40
Terrestrial [%]	69.7	4.8	61.0
Slightly waterlogged [%]	-	4.3	2.7
Moderately waterlogged [%]	0.1	-	6.3
Heavily waterlogged [%]	19.7	48.5	16.0
Very heavily waterlogged [%]	6.4	40.2	8.3
Extremely waterlogged [%]	4.1	2.1	5.7
Length ditches and trenches [km]	3.8	1.6	63.9
Trench network density [$km \cdot km^{-2}$]	11.5	25.5	11.8

Although the size of the subcatchments differs between 0.06 and 5.4 km², there are still striking similarities between subcatchments T and TB. Both feature a comparable percentage of terrestrial soils with no significant signs of waterlogging. Also, their trench network density is almost the same, both showing about 11 km·km^{-2} trenches. In contrast, subcatchment D comprises almost entirely waterlogged soils with only 5% terrestrial soils. As a consequence, the trench network density is 27 km·km^{-2}. Generally, there is a strong dependency between soil water regime and trench network density. When only considering soil water regime classes 'waterlogged' and 'terrestrial', calculating trench network density for each subcatchment and soil water regime class is possible. Apparently, waterlogged areas in each of the subcatchments have a comparable and throughout higher trench network density (*Table 3*).

Table 3 Trench network density differentiated between waterlogged and terrestrial soil water regime. Water gauges: Tierchbruch (T), side ditch (D) and Traunbach 1 (TB1). Source: Own elaboration

	Subcatchment		
	T	**D**	**TB1**
Trench network density 'terrestrial' [km·km^{-2}]	7.5	19.3	5.1
Trench network density 'waterlogged' [km·km^{-2}]	20.8	25.8	22.1

A closer look at the dominant land cover, respectively the dominant vegetation, reveals that the majority of the subcatchment areas features forests as dominant land cover (*Table 4*). As stated in the introduction, one major motivation for draining slope bogs was to establish sites were spruce stands could be cultivated. The ratio between coniferous and deciduous stands against the background of the soil water regime underlines that waterlogged sites exhibit much more coniferous stands, a non-natural vegetation, indicating the strong anthropogenic impact on slope bogs in the study area (*Table 5*).

Subcatchment D is an exception as the Langbruch slope bog always was one of the most difficult areas with regard to draining because of strong and steady interflow conditions. Historical maps made by the respective forest districts at that time indicate that it was not possible to establish spruce stands (*Schultheiß* 2016). That is why the deciduous forests represent one of the most natural sites in the study area when viewing at the dominant vegetation. Another indicator for this state is the rather high percentage of peat moss land cover (cf. upcoming *Table 6*). Nevertheless, the subcatchment is still severely impacted by drainage networks (cf. above *Fig. 7*).

Table 4 Dominant land cover of the subcatchments. Water gauges: Tierchbruch (T), side ditch (D) and Traunbach 1 (TB1). Source: Own elaboration

	Subcatchment		
	T	**D**	**TB1**
Deciduous forest [%]	47.9	-	35.0
Coniferous forest [%]	36.4	73.2	38.9
Mixed forest [%]	7.7	9.2	4.7
Succession [%]	0.6	-	7.9
Open landscape [%]	7.3	5.1	8.8
Peat mosses [%]	-	12.3	2.0
Other [%]	2.3	-	2.8

Table 5 Land cover percentages of deciduous and coniferous forests, differentiated between soil water regime. Water gauges: Tierchbruch (T), side ditch (D) and Traunbach 1 (TB1). Source: Own elaboration

		Subcatchment		
		T	**D**	**TB1**
Terrestrial	Deciduous forest [%]	61.2	4.2	51.5
	Coniferous forest [%]	22.7	-	30.2
Waterlogged	Deciduous forest [%]	13.8	72.8	10.9
	Coniferous forest [%]	65.3	-	51.0

3.2 Climatic boundary conditions, water year 2016

Water year 2016 showed a total precipitation sum of 942.9 mm and an average temperature of 8.3 °C (*Fig. 8*). Compared to the existent weather data available for weather station Hüttgeswasen (*Fig. 4*), water year 2016 was hotter and drier than the average (*Table 6*).

The longest period of consecutive rain days (16 days) was measured from 2 January 2016 to 17 January, 2016. Here, a precipitation sum of 78.2 mm was recorded. This does not seem surprising as January was the averagely second wettest month in the dataset of 2009 to 2016. The longest consecutive period without any rainfall documented lasted eleven days from 9 to 20 March 2016. Rainfall occurred on 206 of 366 days with a mean rainfall sum of 4.6 mm·d^{-1}. The highest daily precipitation sum was gauged on 30 May 2016, amounting to a total of 42.3 mm·d^{-1}.

Overall, two periods with remarkably dry months were recorded: December 2015 and January 2016

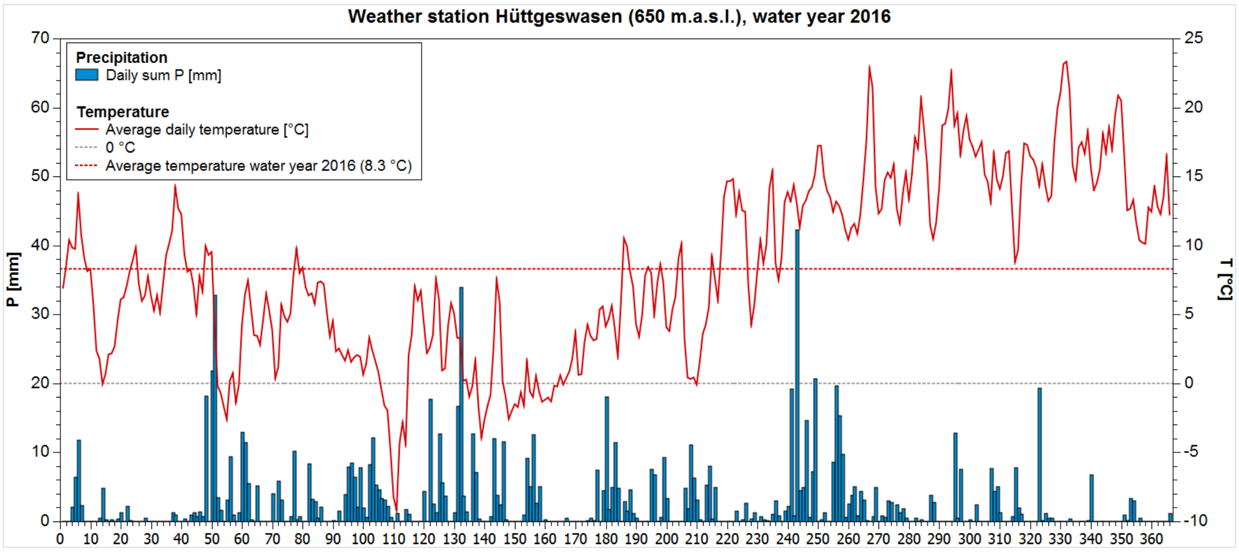

Fig. 8 *Daily-value climograph for weather station Hüttgeswasen (650 m.a.s.l.), water year 2016. Source: Own elaboration based on DLR RLP (2017)*

Table 6 *Average monthly temperature (T), monthly precipitation sums (Sum P) and comparison with average values of 2009-2016 (values in brackets) for weather station Hüttgeswasen. Source: Own elaboration based on DLR RLP (2017)*

Month	Avg. T [°C]	Sum P [mm]
Oct 2015	6.5 (-1.5)	33 (-49)
Nov 2015	6.0 (+1.8)	124 (+36)
Dec 2015	5.3 (+3.2)	54 (-91)
Jan 2016	0.8 (+0.6)	107 (-22)
Feb 2016	1.2 (+1.5)	131 (+57)
Mar 2016	1.5 (-0.6)	85 (+33)
Apr 2016	5.4 (-1.5)	75 (+14)
May 2016	10.8 (+0.8)	95 (+21)
Jun 2016	14.2 (+0.3)	136 (+36)
Jul 2016	16.4 (-0.7)	36 (-50)
Aug 2016	16.0 (+0.4)	52 (-27)
Sep 2016	14.9 (+2.5)	16 (-42)
Total	**8.3 (+0.6)**	**943 (-83)**

were two consecutive months with lower precipitation sums than the average and late summer (July-September) constantly showed low precipitation sums. Concerning average temperatures, the winter months were comparatively mild. November 2015 to February 2016 showed values higher than the average of 2009 to 2016. The whole summer months and especially September 2016 were hotter than the weather station's average. Overall, only 41 days with an average temperature below 0 °C were measured with one distinct cold snap in the second half of January 2016. As only little precipitation was recorded during this period, snow cover was relatively scarce, limiting the impact of snow melt on the hydrographs.

3.3 Runoff patterns

3.3.1 Hydrographs, water year 2016

Hydrographs for all gauges show different runoff patterns over the course of the water year: October and November 2015 exhibit minimal specific runoff values for gauges TB1 and TB2, representing the rather empty water reservoir of the catchments at the end of summer (*Fig. 9*).

By the end of November 2015, triggered by the first heavy rainfalls and reduced evaporation caused by falling temperatures (cf. *Fig. 8*), an increasing catchment discharge developed, culminating in a phase with highest q-values, persisting from January until March 2016. During this phase, water gauges T and D were installed (28 January 2016), henceforward providing an insight into smaller slope bog catchments. With rising temperatures during March 2016, q decreased significantly, although March 2016 was by trend colder and wetter than the average (cf. *Table 6*). Presumably, this runoff recession was initially caused by the already mentioned phase without precipitation lasting from 9 March until 20 March 2016. This result is a strong hint towards a disturbed water retention. An intact slope bog and/or waterlogged area should withstand such a short dry spell – especially that early in the course of the year – without such a drastic recession of runoff rates because of the charged soil water storage after rain-laden winter months. In fact, the dense drainage network prohibits a sustainable soil water recharge and leads to distinct and narrow runoff peaks each time a precipitation input occurs (*Fig. 9*).

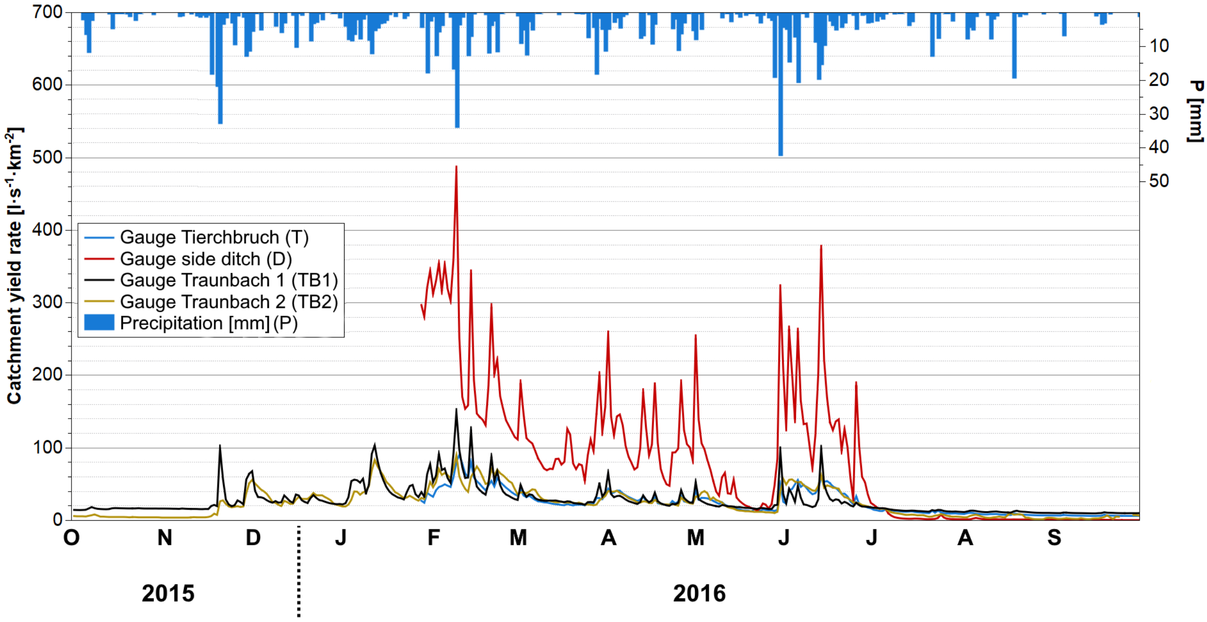

Fig. 9 Hydrographs and daily precipitation sums for water year 2016. Source: Own elaboration

April to July 2016 depicts a phase of rising temperatures with an increasing probability of convective precipitation events (cf. Section 3.2). Here, high runoff rates are even more bound to singular rainfall events. Even short dry spells lead to a notable q-decrease as there is a much higher evaporation on hand. Additionally, growing vegetation exerts influence as it extracts water out of the soil. After July 2016, even rainfall events are not reflected in the hydrographs anymore. High average temperatures and the continuous draining lead to a complete emptying of the extensive water storage. It is apparent that water gauge D features runoff lower than all other gauges from then on while it previously exhibited much higher rates. Water gauge D is the most upslope situated (cf. *Table 2*), that is why it is possible that this shift from highest to lowest runoff is a consequence of least catchment area and therefore catchment water storage capacity. Still, it is again a hint towards runoff conditions that endanger the residual slope bog's growth requirements with regard to sufficient soil water content.

Both TB1 and TB2 show similar q-values throughout the year with TB1 featuring narrower and higher peaks during rainfall events, an effect that is most likely caused by the smaller catchment size. In contrast, TB2 exhibits longer recession phases after rainfall events. Even though catchment size is smaller than those of TB1 and TB2, gauge T features similar yield rates. Only water gauge D reveals significantly higher average runoff (*Table 7*).

Table 7 Average q, standard deviation (σ) and coefficient of variation (c_v) for all water gauges. Water gauges: Tierchbruch (T), side ditch (D), Traunbach 1 (TB1) and Traunbach 2 (TB2). Source: Own elaboration

	Subcatchment			
	T	**D**	**TB1**	**TB2**
Avg. q [$l \cdot s^{-1} \cdot km^{-2}$]	23.8	84.0	26.8	23.5
σ q [$l \cdot s^{-1} \cdot km^{-2}$]	16.7	96.0	19.7	19.1
c_v q [%]	70.3	114.3	73.4	81.6

Regarding variability of runoff rates, water gauge D again shows exceptional values. While gauges TB1, TB2 and T hold standard deviations between 16.7 and 19.7 $l \cdot s^{-1} \cdot km^{-2}$, conditioning variation coefficients between 70.3 and 81.6%, water gauge D shows much higher variabilities. Here, a standard deviation of 96 $l \cdot s^{-1} \cdot km^{-2}$ is on hand, therefore even leading to a $c_v > 100\%$ (114.3%). In order to evaluate if daily q-values correspond between all water gauges, a correlation analysis was conducted. KS-testing of all datasets revealed non-normally distributed datasets. Therefore, only the Spearman correlation coefficient was allowed to use (*Table 8*).

All of the daily runoff values exhibit significant, strong correlations > 0.9 between each other. That is a strong indicator for fast water transport from the upper catchment (D, T, TB1) to the lower stream section at TB2, as runoff peaks at TB2 are usually measured within the same day they occur at the other measurement sites, generating a strong correlation. While this correlation between the adjacent upstream-gauges was expectable, throughout strong correlations between upstream- and downstream-gauges reveal a quick water delivery out of the study area. A graphical analysis of the dependencies between daily q-values measured at the Traunbach and in trenches provides a better insight into dataset-scattering (*Fig. 10*). A second advantage is that a separation between upstream (TB1) and downstream (TB2) values is possible.

Table 8 Spearman correlation coefficient for average daily specific runoff rates. All correlations are significant at 0.01 level. Water gauges: Tierchbruch (T), side ditch (D), Traunbach 1 (TB1) and Traunbach 2 (TB2). Source: Own elaboration

	Subcatchment		
	T	**D**	**TB1**
D	0.957	-	-
TB1	0.951	0.975	-
TB2	0.964	0.935	0.907

Regression curves for each gauge show a rather linear regression between TB2 and the other gauges and logarithmic regressions between D, T and TB1. It is apparent, that gauge D shows a wide scattering against the background of TB2, as the latter is reacting much more damped on precipitation events rather than showing fluctuating values. However, when compared to TB1, there is still a recognizable 'upslope signal' conserved in the q-values of TB1, as apparently better corresponding values are on hand.

3.3.2 High-intensity rainfall events

Rainfall events with high intensities (daily precipitation sum > 20 mm) offered a good opportunity to evaluate the runoff processes regarding their response characteristics to short-timed and intense precipitation. They deliver clear and distinct input signals, therefore allowing a direct connection between runoff peaks and rainfall events. In the water year 2016, five days with precipitation sums > 20 mm occurred (*Fig. 11*).

Three of these days fell upon the winter half-year (19 November and 20 November 2015, 9 February 2016), the remaining two days (30 May and 5 June 2016) featured typical thunderstorm events caused by labile atmospheric stratification. Especially 30 May featured an extraordinary daily precipitation sum of 42.25 mm. It is discussed within this study as a prime example for hydrograph response to heavy rainfall events. A thunderstorm struck the study area between 2:00 a.m. and 7:00 a.m., generating a rainfall sum of 30.8 mm in this five-hour period (*Fig. 12*).

All water gauges within the study area responded very quickly with increasing runoff rates compared to q-values before the rainfall event. That is partially linked to the formation of fast Hortonian Overland Flow, as the soil body certainly was not capable to infiltrate that amount of precipitation over such a short period. Water gauge D showed the quickest and most extreme reaction with a discharge peak of 673.4 $l \cdot s^{-1} \cdot km^{-2}$, 15-times increased compared to the lowest runoff before the rainfall event, measured at 0:00 a.m.

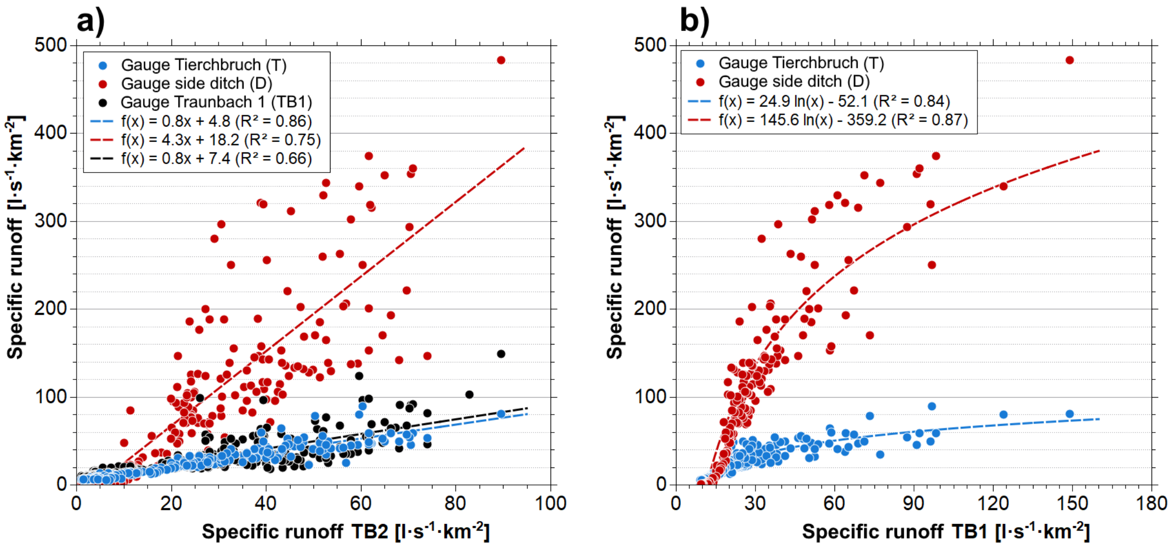

Fig. 10 Dependency of daily specific runoff between Traunbach (TB) and trenches (D, T) on the basis of a) downstream-gauge TB2 and b) upstream-gauge TB1. Source: Own elaboration

Considering the mean daily q of gauge D (319.7 $l \cdot s^{-1} \cdot km^{-2}$; cf. *Fig. 9*), it is evident that this specific ditch reacts so fast to high intensity rainfall events that the quick decrease of catchment discharge leads to daily runoff rates which mask short-timed extreme values. That is a strong argument for high temporally resolved measurements in order to detect flow responses to precipitation inputs. All other gauges show clear signals of increasing runoff but with slightly slower response time in case of TB1 (peak at 7:00 a.m.), while gauge T peaks around the same time as D. Gauge TB2 shows the highest runoff values at 5:00 p.m., providing a rudimentary hint at discharge passage times within the headwater of the Traunbach river. Runoff recession is generally quicker with decreasing catchment size. A secondary rainfall event at 12:00 p.m. triggers a weaker second peak with a comparable response time between rainfall and runoff increase at gauges T, D and TB1. Only TB2 shows a higher second peak (5:00 p.m.) after continuously rising runoff values starting at 6:00 a.m., culminating in an elongated recession hydrograph.

4. Discussion

It was possible to assess some distinct runoff patterns, even though only a comparatively short time period was examined. Gauges T and TB1 show almost the same specific runoffs during the course of water year 2016, with only minor differences concerning mostly longer latency periods of increasing runoff after rainfall events for TB1. That is most likely caused by larger catchment area and longer (inter)flow paths. Results also showed that gauge D featured by far the highest specific runoff values in conjunction with the most variable runoff. There are many possibilities why this gauge showed such a deviating runoff pattern. One underlying factor surely is the small catchment size that conditions more fluctuating runoff values. Though, existing studies clearly state an increase of fluctuant discharges with increasing percentage of bogs within a catchment area like in catchment D (e.g. *Janský* and *Kocum* 2008).

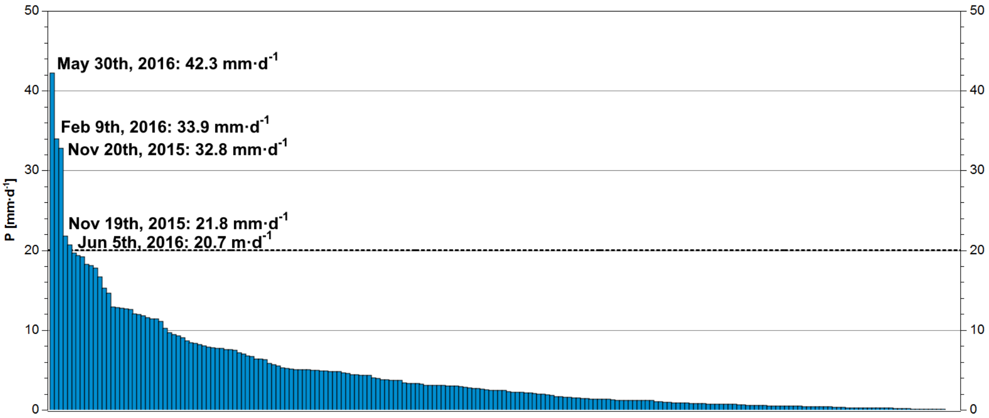

Fig. 11 Daily-rainfall sums of water year 2016, weather station Hüttgeswasen, sorted descending based on precipitation sum. Source: Own elaboration based on DRL RLP (2017)

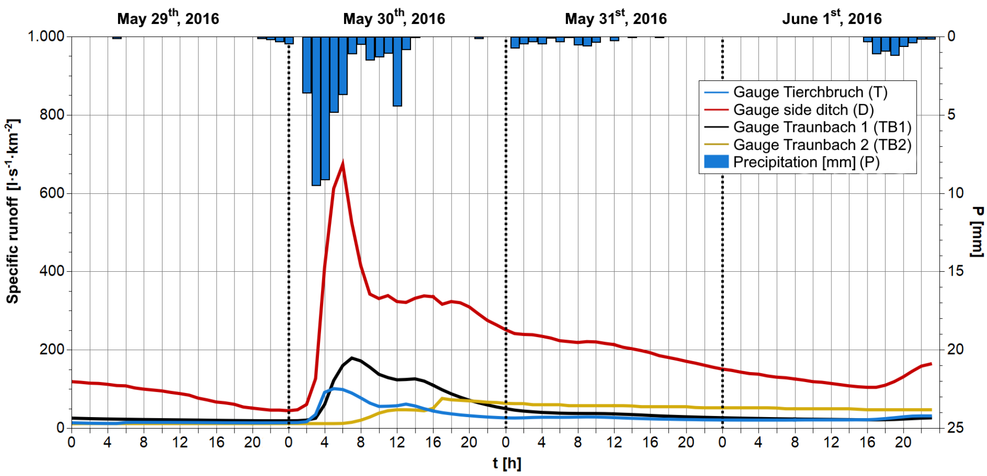

Fig. 12 Hourly specific runoff for water gauges Tierchbruch (T), side ditch (D), Traunbach 1 (TB1) and precipitation sum for weather station Hüttgeswasen 29 May to 1 June 2016. Source: Own elaboration based on DLR RLP (2017)

Luscombe et al. (2016) discuss the drainage effects explicitly for shallow bogs like those in the National Park Hunsrück-Hochwald. They try to investigate if a) local water table depth is controlled by size and position of trenches, and if b) the variability of rainfall-runoff response is proportional to the drainage channel size and attributes of the topographic catchment area. They point out that a dense trench network leads to spatially more heterogeneous and deeper local water tables and that they promote a higher variability of discharge – findings that can be verified for the gauges presented in this study.

Besides the direct and small-scale local effects of bog drainage, the question arises, which role bogs and waterlogged areas assume in the tangle of hydrological effects within a headwater catchment. *Holden* et al. (2004: 11) state that the "theory of a sponge", meaning that bogs function as a general water storage, has to be rejected because many studies showed that they do not generally function as a good water retention area. For blanket bog areas, it is even stated that "(…) baseflows are poorly maintained and runoff generated very quickly from the near-saturated hillslopes" (*Holden* et al. 2004: 11). Proceeding, *Holden* et al. (2004) even suggest that drained bogs might be a better alternative when it comes to flood prevention, as trenches provide a capacious soil water storage. Fully saturated bogs are furthermore described as areas with a quick runoff generation, as the surface-near water table provides the formation of overland flow or shallow interflow (*Janský* and *Kocum* 2008; *Vlček et al.* 2017).

These conclusions seem to question the approach of sealing trenches in order to preserve slope bogs as part of decentral water retention. But they have to be considered carefully because of many reasons. First of all, it is widely acknowledged that runoff processes in (drained) bogs are still poorly understood (*Ballard* et al. 2011; *Holden* et al. 2004; *Luscombe* et al. 2016). Processual dependencies seem to be site specific, even for singular gauges. For example, *Moklyak* et al. (1975) found out that there is no clear difference between drained and preserved bog areas. During and after drainage operations, gauges in their study area showed both increasing and decreasing discharges, delivering no clear conclusion. Secondly, when viewing at shallow bogs like in the National Park Hunsrück-Hochwald, there seems to be in fact a clearer tendency that drainage networks increase the generation of floodwater, especially when waterlogged sites are arranged in a spatially heterogeneous pattern like in the national park (*Allot* et al. 2014; *Grand-Clement* et al. 2015; *Holden* et al. 2006; *Luscombe* at al. 2016). Furthermore, one has to consider the fact that none of the existing studies discusses slope bogs in a steep headwater catchment. That is important because this site specific topographical factor leads to the assumption that water generally does not stay very long in those shallow bog areas. Their existence depends rather on a steady recharge than on a long termed water accumulation like in typical (blanket) bogs located at the lower slope of larger catchments. Therefore, it is not likely that a state of fully saturated soils – which would in fact generate runoff very quickly – has to be assumed as a frequent state for the slope bogs in the national park.

Additionally, modeling approaches carried out for the TB2 gauge by *Haag* et al. (2016) classified the catchment as dominantly interflow-fed. While this may be true for the catchment area as a whole, this detailed analysis of the drained subcatchments shows rather short latency periods between rainfall and runoff peaks. This suggests the conclusion that trenches and ditches accelerate the water flow by retransferring already infiltrated water into superficially flowing water. A process that *Tempel* et al. (2011: 120) addressed as "anthropogenic return flow". As it disturbs the steady recharge of soil water by draining the areas too fast, it is most likely that draining slope bogs in the national park has a negative effect on water retention. This assumed effect has to be monitored over a longer period of time to allow formulating more well-grounded principles concerning local hydrology, as the effects become noticeable only after a longer time period (*Green* et al. 2017; *Holden* et al. 2011).

Nevertheless, while this study focused on the actual hydrological responses, presenting a status-quo of the processes in the national park, there is a second aspect that has to be in mind in terms of slope bog restoration. Projects supported by the European Union (*Stiftung Natur und Umwelt Rhineland Palatinate* 2017) acknowledge a severely disturbed vegetation with only residual appearances of slope bogs in the national park. That is caused by drainage, leading to altered growth conditions. Even if long-term monitoring should prove that effects on discharge are scarce, an effective retention of soil water has to be accomplished in order to restore the natural vegetation.

5. Conclusions

Runoff patterns of selected slope bogs and waterlogged areas as well as those of natural streams were analyzed within this study. For the water year 2016, it was possible to derive distinctive patterns that give a strong hind towards anthropogenically altered processes taking place. Foremost, a quick runoff generation in the aftermath of heavy rainfall events was observed. This leads to the conclusion that a dominant part of the measured runoff was most likely fast surface runoff rather than dominant interflow, which would have been expectable for this specific catchment. Therefore, trenches and ditches function as hydrologic features accelerating the water flow by converting comparatively slow interflow into superficially flowing water, accordingly leading to anthropogenic return flow.

This also leads to a quick drainage of former waterlogged sites, even in short dry spells. Thus, even implications for ecological site characteristics have to be assumed. Primarily waterlogged sites become more terrestrial, eventually leading to habitats no longer providing sufficient growth conditions for peat mosses. Future results, involving the complete water gauge network and longer timespans, should provide an important component in understanding hydrological processes in this specific catchment.

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