Chapter 8

Hydrological Function of a Midlatitude Headwater Peatland

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Additional information is available at the end of the chapter

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Abstract

Peatland represents quite significant phenomenon in the headstream areas of Czech rivers. Considering the fact that these areas are crucial for streamflow generation process, it is very important to study the mechanism of runoff formation in a peatland and its hydrological function. Natural runoff process is affected by man already by its birth, thus in headwaters where numerous procedures related to runoff retardation and water retention increase in headstream areas could be realized. To understand and clarify the runoff generation process and the effect of various physicogeographic factors on its dynamics, the detailed analyses were carried out in the Vltava River headwaters (sw. Czechia) in recent years. It was necessary to consider the evaluation of peatland retention capacity, its hydraulic communication with draining watercourses and of runoff regime variability during various hydroclimatic conditions. The big attention was focused on findings of a runoff dynamics dependence on the groundwater table in the peatland and of the runoff chemistry and balance using isotopic hydrology methods. Natural tracers were applied at sprinkling plots to identify preferential flow and runoff formation at two opposite hillslopes in this peaty mountain headwater.

Keywords: headwater, peatland, peat bog hydrological function, hydrological extremes, runoff formation, retention potential, Vltava River, Šumava Mts., automatic stations, experimental catchment, oxygen isotopes, tracer experiment, dye

1. Introduction

Mountain peat bogs and peatland represent a significant phenomenon in headwaters of Czech rivers. They occupy a considerable part of the area where the outflow is formed. The study of the hydrological conditions of the most exposed parts of the Czechia therefore requires a very detailed field survey and study of the composition of peatland, its background, development, and hydrological function. These are the areas where the streamflow is generated and then transformed. These headwaters are crucial for the lower parts of river basins from the runoff point of view and in the sense of increasing extremity of climatic and hydrological features. Recently, these effects have been increasingly observed and their effects are mainly attributed to processes related to climate change, also in the mid-altitude part of the European continent.

In the context of catastrophic floods and extreme droughts that have occurred in recent years on the Czech territory, there is an urgent need of solving of issues dealing with protection against hydrological extremes, not using just classical engineering methods. There is a new protection strategy focusing on gradual increase of river catchment retention capacity including its headwater regions where numerous procedures related to runoff retardation could be realized. However, the realization of such measures must be preceded by a thorough research of these areas, not only in terms of hydrological, but also soil or vegetation point of view. It calls for an interdisciplinary concept of research and a comprehensive understanding of the existence of this phenomenon from many perspectives.

Suitable conditions for the research realization at present are related to the mid-latitude Vltava R. headwaters (sw. Czechia) representing the core zone of frequent extreme runoff events with high heterogeneity in terms of physicogeographic and socio-economic aspects. Due to the significant existence of peatland phenomenon in this area, detailed assessment of peat bogs hydrological function, its retention capacity and hydraulic communication have been done in order to evaluate its retention potential. Both classical hydrology approaches and modern methods were used to answer actual questions.

2. State of the art

A number of foreign and domestic projects have solved the matter of peat bog hydrological function but no one has been fully comprehensive. Opinions on their function, already appeared in the second half of the twentieth century, vary a lot. Ferda [1] made the detailed analysis of various approaches to tackle these questions in the Šumava Mts. On the base of "theory of sponge," that occurred in the late 1960s, peatland was distinctive for its significant water retention and discharge regulating ability, and for its discharge heightening ability in dry periods. Other studies from the late 1970s then confirmed the peat bogs retention capacity and show that the only possible way to increase the retention capacity is to lower groundwater level (GWL) by means of drainage. Since that time, the issue of hydraulic communication between peat bog complexes and draining streams (incl. procedures of drainage) has become a field of broad debates among experts (e.g., [2–7]). An interesting and detailed study of the literature covering opinions on both sides can be found in the paper of Holden et al. [8]. Conflicting results presented in the abovementioned papers depend on the different physicogeographical conditions. However, in general, acquired findings proved significant runoff variability of watercourses draining peatland areas. It can be said that the peatland influence on hydrological regime balance had been quite overestimated in the past.

The same result was acquired in the study area of the Vltava R. headwaters in Šumava Mts. [9–13]. Papers show a significantly negative influence of unaffected peatland on a runoff process from its variability point of view. This mountain range has the largest peat bog areas in the Czechia as well as in Central Europe. The existence of large amounts of peat bogs in this area is caused by a humid climate and by optimal relief configuration [14]. The influence of peat land on water quality in watercourses is assessed as unambiguously negative, while intensity of the effect is related to its area and volume in a catchment. Waterlogged areas in Central Europe are formed mostly in flat areas or shallow valleys (e.g., in Biebrza, Poland [15], or in western Slovakia [16]) but climatic and hydrological conditions are different from those of mountainous peat bogs. Quite similar conditions for upland peat bog development can be found in Scandinavia and Scotland. Therefore, it is better to compare hydrological processes within the Šumava Mts. peat bogs to those in Scottish or Scandinavian waterlogged areas.

The influence of peat bogs on hydrological processes has also been discussed with respect to the effect on water quality, especially the ionic structure of water in periods of high or low discharges [17–21]. In dry periods, runoff from peat bogs decreases or becomes almost intermittent. This results in improvement in the quality of the water in the streams draining the peat bog. This was confirmed by studies carried out by Ferda et al. [22] and others [23–25]. However, during spring snowmelt and summer rainfall totals, decline in water quality is observed as peat bog complexes are fully saturated. In case of water release during dry periods, this would be expected to result in decreased quality.

Defining the environment in which hydrological processes take place is quite complicated. Determination of basic hydrological processes using information about the qualitative composition of water is inconvenient and the concept of surface runoff is not sufficient. Hydrogeochemical approaches are suitable to explain the streamflow generation process and to understand the mechanism of water retention in a catchment. Since the theory of so-called "effective precipitation "[26] was accepted, the hydrological response of runoff to causal rainfall has been extensively studied. Despite this, the real mechanism of water behavior underground has not been so clearly described [27]. The absence of such detailed data results in simplified assumptions and insufficient description of complicated processes such as causal aspects of runoff generation. Rainfall-runoff transformation requires additional data that can be obtained using a natural indicator. This information can be provided by a combination of isotope and geochemical approaches [28, 29]. This new dimension to hydrological studies has proven extremely simple and superior to previous theories [27, 30]. Using information about isotopic structure within the soil, subsurface water and causal precipitation amount, proportion of these phases in extreme runoff episode based on isotope concentration in the outflow can be determined. However, mechanism causing this exchange is not completely known [29, 31]. Water can often move apart through isotopically and geochemically specified spaces, channels, or be retained [32]. These spaces are not space-homogenous, and their contribution over time to the proportion of runoff is not necessarily constant [33].

The main anthropogenic changes in the Šumava Mts. peat bog complexes have been caused by efforts of draining and drying. Peat bogs have been traditionally drained for the purpose of peat exploitation, agricultural land cultivation, or increase in wood exploitation in waterlogged forest areas. Nevertheless, the extent of surface drains was already considerable at the turn of the nineteenth and the twentieth century. However, the major period of drainage digging was in the 1970s and 1980s of the twentieth century. Nowadays, the drainage systems are still visible. Stocktaking researches have displayed that drainage has affected almost 70% of peat bogs in the Šumava Mts. [34]. The open system of drains causes especially: fast surface flow, steeper culmination, and higher fluctuations of GWL [35]. Performed restorations can improve these aspects and consequently increase the GWL by several centimeters in a year [36]. A research from Schachtenfilz in the Bavarian Forest has confirmed that restoration measures increased GWL and decreased its fluctuation [34]. Since 1998, a complex restoration program has been implemented in the area of the Šumava National Park. The program is primarily aimed at a general improvement of disturbed water regime in the peat bog area [37]. A concept of so-called "target water level" has been exercised during the restoration in the Šumava Mts. The method is based on determination of necessary water level, which is particular for each peat bog and which is desirable to be achieved by restoration measures. The necessary water level can be described as a maximal tolerated decline of water in a ditch under the dam head, which is bearable for a given type of a peat bog [38].

Peat bogs are physically and ecologically adapted on the depth of GWL. The depth has a great significance for ecological niches of vegetative species and hence even for peat development [39]. The response of GWL on an exercised restoration is usually very fast; nevertheless, the changes in water chemism and consequent reactions of peat bog species are very slow. Peat bog vegetative species are vulnerable and sudden changes of pH factor or changes in the amount of nutrients after exercising restoration can also have negative effects. Peat bog restoration consequently includes stabilization and increase of GWL and a repeated habitation of the standpoint by peat bog species. It is thus important to limit the amount of water drain [40].

3. Study area

The subject area is located within the upper Vltava (Moldau) R. basin, the left tributary of Elbe River, in Central Europe (see **Figure 1**). Headstream part of this basin, where experimental research was undertaken, represents an area with the significant existence of a phenomenon of a peatland that is of mountainous type, mainly fed by atmospheric precipitation. Although the studied area is mountainous, its exposure in the planed and highly exposed part of Šumava Mts. gives it a flat watershed character favorable for the existence of high moor. The catchment is formed by a typical old-aligned surface with an altitude varying between 1.100 and 1.300 m a.s.l. From the geological point of view, according to the tectonic zoning, the basin belongs to the area of Moldau-Danube elevation. Within the various parts of this area, a number of specific experimental catchments were chosen. Their area and slope are similar with the exception of the Rokytka Brook basin, which is slightly flatter. They also have similar soil and vegetative conditions, and most of the area was influenced by a bark beetle infestation. The biggest difference is the extent of peat soils which represents the main reason that why these comparable experimental basins were chosen. All catchments have been monitored several years by installed water level gauges in their closing profiles.

In the Rokytka B. basin, our "field laboratory," the peatland complex comprises several large and many small mountain peat bogs, which are surrounded by forest peat bogs, waterlogged

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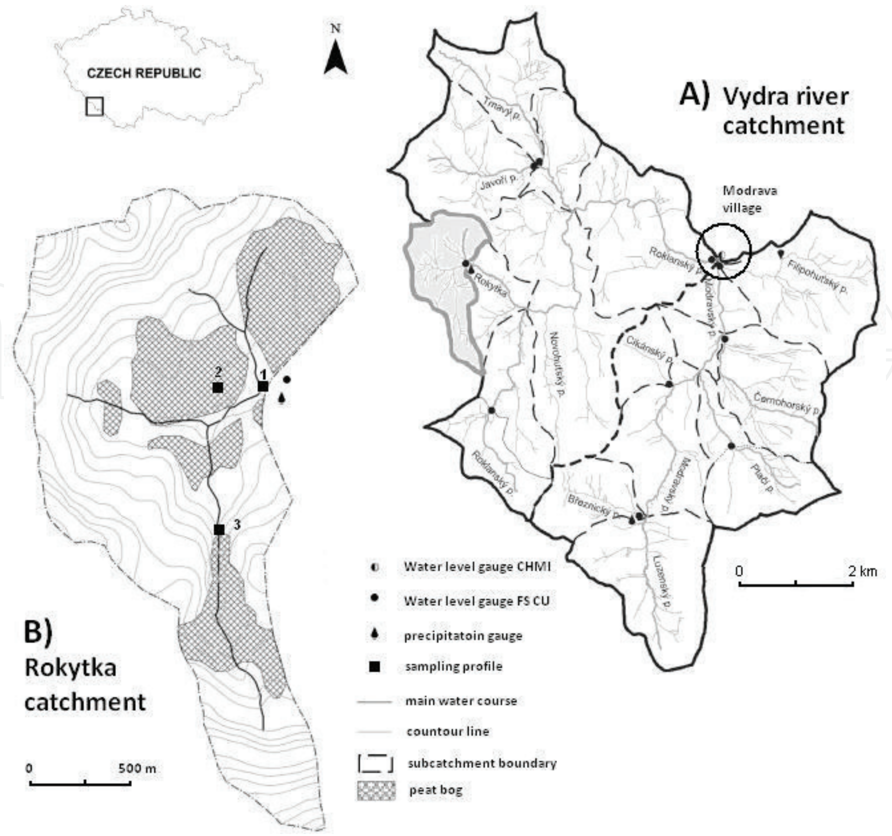

Figure 1. Localization of the study area incl. the CHMI (Czech Hydrometeorological Institute) and FS CU (Faculty of Science, Charles University in Prague) water stage recorders and automatic precipitation gauges within the Vltava R. headwaters. (a) Rokytka B. Experimental catchment within the Vydra River headstream area; (b) sampling profiles and the main peat bog complexes. Sampling profiles: (1) outflow, (2) peat bog lake, and (3) tributary.

pine stands and minerotrophic sedge peat bogs. According to the ZABAGED digital terrain model (the basic platform for geographical data of the Czech Republic) and to the TGM Water Research Institute DIBAVOD (digital basis for water management data), the experimental catchment of Rokytka B., down to the closing profile with installed water level gauge, has an area of 3.86 km^2. The total area of the main studied peat bog within the Rokytka B. catchment is almost 250 ha and its depth reaches up to 7 m. Maximum depth of the peat bog was measured in its central part. It represents historically the deepest analyzed profile in the whole Šumava Mts. with the oldest dating. The research of the Rokytka peat bog was also focused on a selected experimental drainage ditch as the anthropogenic impact, which is located in the northern part of the catchment, at 1.100 m a.s.l. It drains an area of 0.14 km^2. The drainage ditch was partially dammed by small restoration dams; partially it was left functional, with a depth of 1 m.

The bedrock is composed of weathered rocks, mainly granite. Soil conditions in the study area include the features of on-site Organosols, as described by Šefrna [41]. Local soils are typical for the area of Šumava Mts. with characteristic vertical sequence of several types of soil, with Histosols on the ridges and in basins. The largest area of the basin is covered by Entic Podzol, the second most common type of local soil is Histosol (about 26%). Lower part of the basin is filled with a relatively broad peat bog complex with quite significant cubic capacity up to 7.2 m depth. Number of peat bog lakes can be found here as well

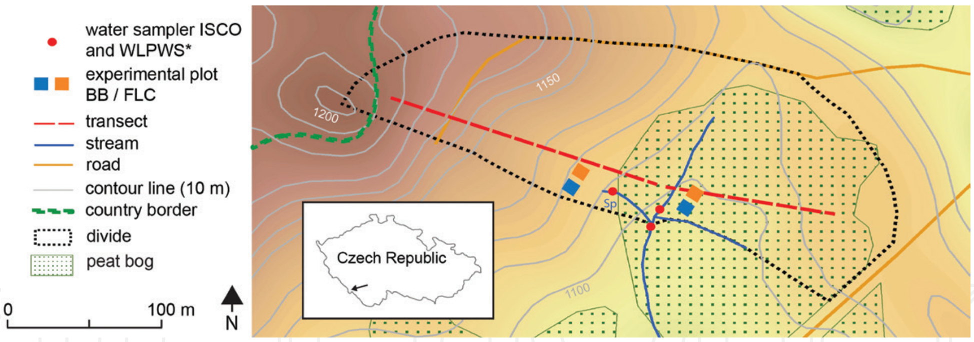

Figure 2. Overview of the Rokytka B. headwater test site (0.6 km^2); SpDspring; * water-level proportional water sampler [44].

(see **Figure 1 (b)**). In certain lower parts of the basin, Gleysols are spread out. To consider runoff conditions, water-saturated Organosols can be considered as extreme runoff accelerators. Their retention effect is not approved in the status of full water saturation, even if Organosols have a broad capacity for retention of water. Local vegetation is linked to peat bogs themselves, and forest. Peat bogs are surrounded by waterlogged spruce forest and minerotrophic sedge peat soils [42]. The rest of the forest vegetation is mainly composed of spruce with the addition of fir and beech, and is present predominantly on the south-facing slope. The forest has been influenced by the spruce bark beetle calamity.

To identify the runoff formation in detail using dye tracer experiments, the study site in the northern part of the Rokytka B. catchment was marked out (**Figure 2**). This second-order stream drains the area of 0.6 km^2 in the altitude between 1.100 and 1.260 m a.s.l. The test site can be divided into two parts represented by two opposite hillslopes with different soil types and vegetation cover. The mineral soil hillslope composed of a Podzol (PZ hillslope) is covered by beech stands at the upper hillslope zone and by dead spruce stands with healthy seedlings at the lower part. The soil profiles do not show a clear gradient toward the stream and are similar throughout the slope. Entic Podzol has been identified, with quite shallow organic top layer (<5 cm) and similar soil texture to a depth of about 1 m. Small parts of the PZ hillslope are covered by Haplic Podzol, but excavation is needed for proper identification. Neither there was a sharp transition between the mineral soil and the bedrock (well-weathered Gneiss or Granite) perceptible with electrical resistance tomography (ERT) measurements nor could a persistent GWL be detected. The organic soil hillslope is covered by a well-developed mountain peat bog (PB hillslope). The entire area consists of a mixture of various stages of decomposed peat. However, Acrotelm and lower Catotelm can be distinguished at depths ranging from 8 to 25 cm [43].

4. Materials and methods

To assess the hydrological balance and runoff formation in a peaty mountain headwater several methodical approaches and various data were used. Automatic stations for the variability monitoring of hydro-meteorological features and physiochemical parameters of surface water were installed in closing profiles of studied experimental catchments. Modern experimental hydrology also uses hydrochemical and geochemical approaches to explain the mechanisms which are related to water retention and runoff formation in headstream areas. Geochemical approach using stable oxygen isotope principle was applied to understand and clarify the streamflow generation processes in the highly peaty catchment. Contribution of water from peat bog areas to the total surface runoff has been assessed for unit hydrogram separation by means of anion deficiency. Tracers such as Brilliant Blue and Fluorescein-Sodium were used and applied at sprinkling plots to identify preferential flow and runoff formation at two opposite hillslopes in this peaty mountain headwater.

4.1. Monitoring of hydroclimatic conditions

The crucial means of obtaining high-quality data for consecutive analyses is represented by the functional system of automatic ultrasound or hydrostatic pressure water-stage recorders, climatic stations and shuttle precipitation gauges (**Figure 1**). Monitoring stations are provided by GSM module that can transmit data through GPRS network. Other modern equipment and methods were used in chosen experimental locations to determine rainfall-runoff relations. A number of experimental profiles also contained sensors for the observation of physiochemical parameters. This network, complemented by the Czech Hydrometeorological Institute (CHMI) state profiles, represents a crucial basis for precise analyses of a local runoff regime. In the profiles given, needful instantaneous discharge measurements using a hydrometric propeller or flow tracker were performed in order to construct accurate consumption curves with high confidence coefficients. Primarily, the influence of peat bog complexes on hydrological conditions was assessed by detailed comparison of runoff regimes in a number of chosen subcatchments with respect to diverse peatland extent and to other relevant physicogeographical parameters. Mechanism of a runoff formation (incl. recent peat bog revitalization processes) was studied primarily using basic hydrological statistics with particular attention to periods of high or low discharge rates. This approach was afterward complemented by much more predicative ion, carbon and oxygen isotope balance analyses (see Chapter 4.5).

4.2. Runoff variability assessment

To assess the runoff variability in chosen profiles, classic hydrological statistics were used at the first step. To assess the degree of extremity in the ascending phase of a flood wave, the method of extremity indices was used [11]. In its first phase, it consists of the determination of the mean discharge of individual streams in the period before the flood wave (D-8 to D-2). The assumption is that this discharge would be reached in the following days if there were no causal situation. For the same period (D-8 to D-2), coefficient of variation (Cv1) from the mean hourly discharges was calculated. The calculated values give us a picture of the degree of fluctuation of individual streams in the period before the flood wave. In the second phase, the variation coefficient for the D-1 to DD period was calculated for each stream, referring to detected theoretical mean discharge of the stream in the period before the causal situation (D-8 to D-2) obtained by the above procedure. D-1 to DD period is the range in which the flood wave increased, culminated and decreased in this case. Calculated values of the coefficient of variation (Cv2) thus represent the rate of flood flow variability from their normal course, which would be theoretically reached without the flood situation. Mutual evaluation therefore provides a good picture of the extent of the flood wave extremity of individual streams in relation to their mean discharge. The use of this method is only applicable to certain flood situations, assuming similar causal conditions for all monitored streams. The following procedure was used to control and eliminate the possible distortion of values of the variability coefficient, depending on the duration of the peak flow and the wavelength on the individual streams. This consists in expressing the value of the mutual share of the maximum reached value of the 10-min discharge in the period D-1 to DD (hereinafter referred to as KP) and the mean discharge in the period before flood wave (hereinafter referred to as PP), in this case D-8 to D-2. The value obtained is referred to as the I_{EKP} peak flow extremity index (I_{EKP} = KP/PP).

4.3. Hydropedological survey

Detailed description of soil profiles and soil sampling for laboratory analyses was carried out. In general, soil retention capacity is measured using a number of methods. One of the most widely used is measurement by the neutron method, the method of retention curves [45], measurement of water isotopes change after passing through the soil [46], and other techniques. Gravimetric method, used in our research, still has many advantages. The most important thing is the simplicity of this method, little time-consuming, and it can be used to evaluate multiple factors at once (soil type, vegetation, etc.). Moreover, in many cases, this method provides results that are more accurate. The retention capacity of the individual parts of the bog was compared with the GWL. Between GWL and surface runoff from the bog, its relation with respect to other factors such as precipitation amount was assessed.

4.4. Groundwater level observation

Groundwater level measurements were implemented during the period from August to October 2014 [47]. This period was crucial for the evolution of GWL within the year. The GWL was measured manually in tubes which were inserted into the peat to a depth of 1–1.5 m. The water level was measured in lines which were copying parts of the drainage ditch. Thus, a regular net with 27 GWL measurement points, placed in regular distances, was created. The GWL was measured from the surface. For this purpose, particular segments were created from the measuring areas, and the GWLs were then compared with each other within the scope of the individual sections and lines (see **Figure 3**). The line 1 was divided into part A and part B for better accuracy. Part A is located directly to restoration dams, and part B is placed in area which is not affected of restoration measures. At each point, 28 values of GWL were measured. Further, particular level changes were statistically evaluated in the scope of individual sections and lines to better demonstrate the dependence of GWL fluctuation on the distance from a drainage ditch, or from restoration dams. Data of GWL from an automatic station in Rokytka peat bog were also used. At first, the whole dataset was analyzed by basic statistical characteristics and data testing. For distribution of measured values of GWL in various intervals, box plots were used. Statistical characteristics variance, correlation coefficient and directive deviance were calculated in software Stat-Soft Statistica. GWL fluctuation was put into context with particular significant factors of rainfall-runoff process, such as potential evapotranspiration. In this research, Penman-Monteith equation was used for the determination of daily potential evapotranspiration [48]. The antecedent precipitation index API [49] was also applied and calculated for five previous days. The index is used for determination of catchment saturation and it expresses the influence of precipitation which occurred in previous days to the given date. It thus demonstrates the ability of a catchment to absorb more precipitation.

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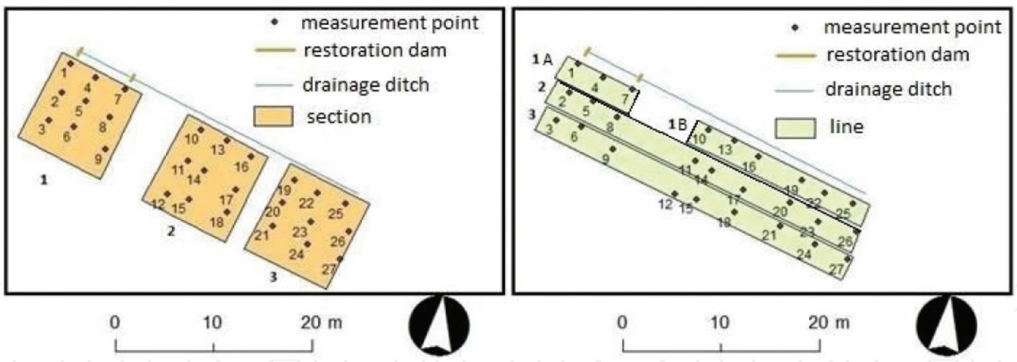

Figure 3. The scheme of particular measurements of GWL and of the segments where the GWL was measured.

4.5. Geochemical analyses

Precipitation and surface water sampling for chemical and isotope analyses was carried out in monthly and two-weekly time steps, respectively, with respect to the whole discharge range, in order to obtain data from extreme episodes such as thaw, snowmelt, rainfall and drought. Precipitation amount and its isotopic composition (δ^{18} O-H_2O) were measured in the adjacent catchments of Roh and Doupě, which have very similar characteristics and are close to the study area. Surface water sampling was carried out in three different sampling profiles: outflow profile (water level gauge), bog profile (organogenous lake) and inflow profile (tributary). The study catchment was closed by the automatic ultrasound hydrological gauge for continual discharge monitoring. The principle of $^{18}O/^{16}O$ fractionation was used for runoff formation modeling. It can be applied due to the uniqueness of the $^{18}O/^{16}O$ isotope ratio of each source—precipitation, subsurface water, surface water—at a particular time. The symbol “delta,” used to express the $^{18}O/^{16}O$ isotope ratio, represents the relative proportion of measured $^{18}O/^{16}O$ to a standardized $^{18}O/^{16}O$ proportion (Standard Mean Ocean Water) [28, 30]. Simple model (incl. the inputs from the bog and tributary) was applied to calculate the contribution of the bog to the Rokytka B. outlet. Due to similar signals of δ^{18} O-H_2O in the bog and precipitation total, it was not possible to assess the input of direct precipitation separately. Water balance of the Rokytka B. experimental catchment stems from a mass balance [50]. The contribution of the bog to the Rokytka B. runoff was therefore calculated on the basis of the following equations:

$$Q_O\,\delta^{18}\,O_O = \sum Q_i\,\delta_i = Q_B\,\delta^{18}\,O_B + Q_T\,\delta^{18}\,O_T \quad (1)$$

$$p = Q_B / Q_O \quad (2)$$

$$p = \left(\delta^{18}\,O_O - \delta^{18}\,O_T\right) / \left(\delta^{18}\,O_B - \delta^{18}\,O_T\right) \times 100 \quad (3)$$

where $\delta^{18}\,O_O$ is the outflow isotopic composition, $\delta^{18}\,O_T$ is the tributary isotopic composition, $\delta^{18}\,O_B$ is the bog isotopic composition, p is the relative contribution of bog water (%) and Q is the discharge in observed profiles.

4.6. Dye tracer experiments

The dye tracer experiments were carried out at the mineral soil hillslope and organic soil slope of the Rokytka B. headwater during baseflow conditions. At each hillslope, two 1.5 m x 1.5 m plots were sprinkled with both dyes (Brilliant Blue (BB), CAS#3844–45-9, concentration 5 g L^{-1}; Sodium-Fluorescein (FLC), CAS#518–47-8, concentration 2 g L^{-1}). All sprinkling plots were located at the transition between the concave, lower part of the hillslope and riparian zone in the vicinity of the stream [43]. The overall sprinkling time at each plot was ~ 2 h in order to simulate a rainfall intensity of 20 mm h^{-1}. These amounts and intensities represent a heavy rainfall storm in the Šumava Mts. Excavation of the FLC sprinkling plots followed out. After about 4 h sprinkling, exposing of soil profiles and the photography of FLC-stained soil structures were performed under short-time UV illumination (410 nm). As FLC is strongly light sensitive, it was carried out at night [51]. Pictures of the soil profiles were taken during the excavation with a digital Micro Four Third camera with a crop factor of 2.0 under daylight conditions beneath a shading tarp to avoid direct sunlight and shadow effects in case of the BB plots. Pictures at the FLC plot were taken at night with the same camera. Each FLC soil profile was illuminated separately with two light sources (500 W Halogen lamp, 27 W UV LED lamp) to visualize fluorescent FLC-stained soil structures similar to Gerke et al. [52].

The dye-stained flow patterns for both dyes BB and FLC at all soil profiles were analyzed according to a method described by Weiler and Flühler [53]. This method was originally developed for analyzing BB. Therefore, the color space of photographs is converted from the Red-Green-Blue (RGB) color space taken by the camera sensor into the Hue-Saturation-Value (HSV) color space. It was afterward classified and spatially analyzed with an algorithm written in IDL code [54]. This procedure was applied for both dyes (BB and FLC), thus for two different groups of photographs. To detect and analyze FLC in the soil profile photographs similarly to the BB photographs, the dye detection routine in the original IDL code was adapted for optimal FLC identification [43].

5. Results

5.1. Hydroclimatic conditions

In order to assess characteristics of runoff regime and hydroclimatic conditions, hydrological year 2008 was chosen. This year was very average in the sense of hydrometeorological features in recent years. Year 2008 was chosen also because of the fact that cooperation with the Czech Geological Survey (CGS) on geochemical analyses started this year ([55], see Chapter 5.5). The total amount of precipitation in the Rokytka B. catchment in this year was 1485 mm. The seasonal course of $\delta^{18}O\text{-}H_2O$ in precipitation was very consistent. Rokytka B. represents typical hydrological behavior of streams in the central Šumava Mts., with peak flows occurring in April and May during snowmelt (**Figure 4**). The annual discharge was 0.18 $m^3 s^{-1}$, so the studied year, 2008, showed an average value. Potential evapotranspiration was calculated using the Penman-Monteith Equation [48] from the set of 2007–2014 data. Evapotranspiration data varied little within the year, with a maximum movement of around 100 mm $month^{-1}$, see **Figure 4**. Observed data were homogenized and deemed representative for consecutive analyses. To evaluate general features of rainfall-runoff regime, mean daily and monthly discharges were calculated.

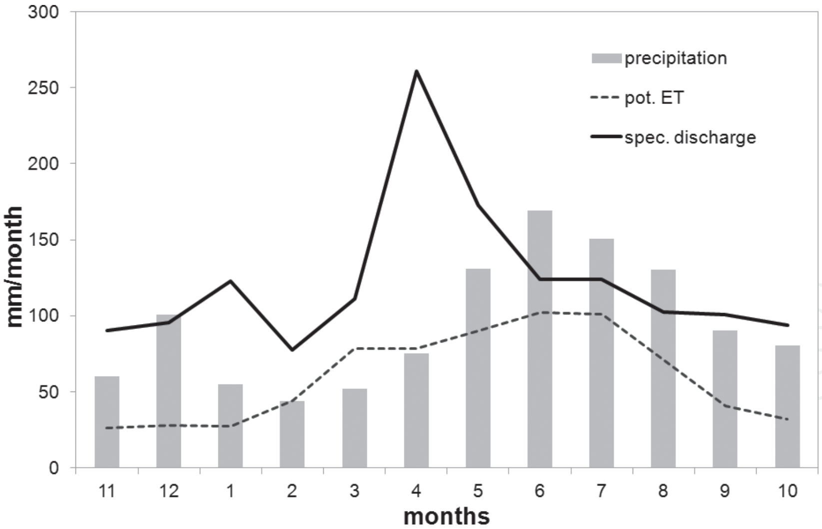

Figure 4. Mean monthly precipitation, specific discharge and potential evapotranspiration (pot. ET) in the study catchment of Rokytka B.

Studied year 2008 was from this point of view determined as an average year (**Figure 4**). The time series show a typical course every year with occasional exception related to thaws. Total runoff (1437 mm) was comparable to the measured amount of precipitation (1485 mm). The precipitation amount did not include water from snow during winter, so it seems quite low compared to the discharge. Higher rate of total precipitation was probably caused also by horizontal precipitation such as fog or frost. In general, the contribution of horizontal deposition in the area of Šumava Mts. is estimated at a minimum of 10%. Most elevated locations, incl. the Rokytka B. catchment, should have a higher horizontal deposition of around 15% [56–58].

5.2. Runoff regime variability

Based on hydrological time series analysis carried out within the upper Vltava R. basin, Kocum [12] determined the significant dependency of runoff variability on a peatland extent in a catchment. Continual records of instantaneous discharge offer an extraordinary database that is unique. Homogenized data can serve as an input for comprehensive analyses of ascending and descending phases of flood waves, and of minimum runoff episodes during dry periods. Detailed statistical analysis of daily, monthly, and yearly time series identified significantly higher runoff variability in the Vydra R. basin. This part of upper Vltava R. basin represents quite peaty area, compared to the nonpeaty Křemelná R. basin. Runoff variability in experimental subcatchments was assessed using the peak flow frequency analysis with respect to the different rates of discharge (**Figure 5**). Analysis of runoff reaction to causal rainfall amount during several rainfall events was also used. These analyses of extreme runoff phases (peak flow frequency method, e.g., [59] or [60]) showed much higher frequency of peak flows and their shorter reaction to causal precipitation total (i.e. lower water retention potency) in the case of highly peaty areas (Rokytka B.). Therefore, it can be said that there is more distinct runoff variability of streams draining peatlands and peat forming soils [61, 12].

Extremity of a hydrologically significant runoff event and specific p-g conditions in individual catchments were subjected to correlation analysis which was based on the method of extremity

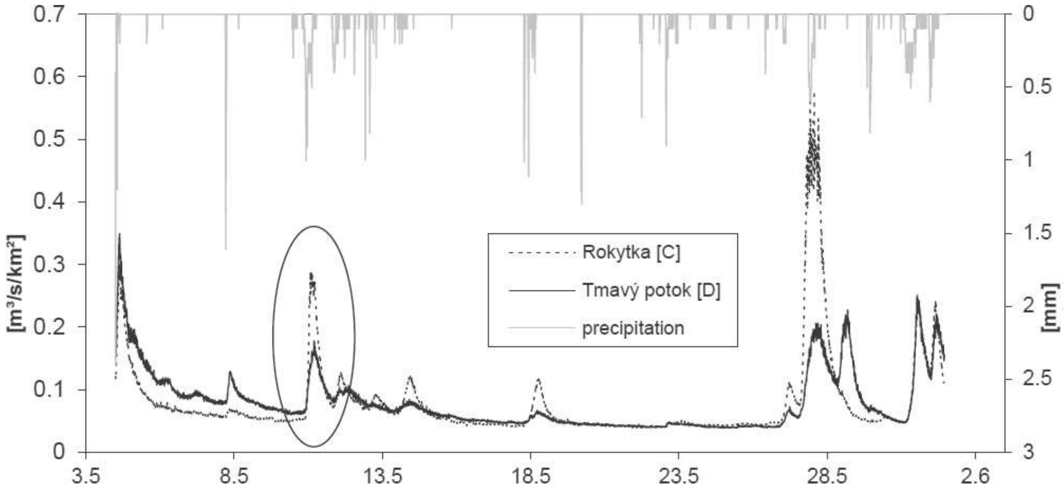

Figure 5. Specific discharge of Rokytka B. (C; 23.1% peat bog extent) and Tmavý B. (D; 2.3%) in May 2013.

indices and on the p-g parameters of the studied catchment. Similar index was used for estimating 100-year flood flows in unobserved catchments [62, 63]. The analysis shows that the extremity of the flood flow is affected mainly by a peat bog extent and by a catchment shape.

5.3. Retention capacity of peatland

Literature suggests that the landscape in the Czech conditions is able to accommodate up to 400 mm of water, an average of 40–90 mm [64, 65]. When considering the average groundwater table (GWL) bogs in the experimental catchment represent areas with the smallest retention capabilities. Retention values are similar to those found in shallow soils (about 140 mm excluding the actual humidity). Considering the lowest GWL bogs represent a significant retention areas within the catchment (230 and 267 mm). Since GWL is higher than its average value for three quarters of a vegetation period, peatland represents within the catchment the area with the smallest retention capacity. However, it is questionable whether the actual moisture measurement was sufficient. In terms of hydrological features, peatland therefore has crucial influence on the retention potential in the landscape [66].

5.4. Evaluation of the influence of peat bog restoration measures on the groundwater level

The variability of GWL represents an important factor of the evaluation the peat bog retention potential. Two different episodes were selected for the evaluation. The first one, the **episode of an intensive precipitation** (55.4 mm), was analyzed between the September 11, 2014 and September 15, 2014 at the Rokytka catchment. It is obvious that GWL along the drainage ditch shows a high amplitude (see **Figure 6**). With longer distance from the drainage ditch, the GWL increases and its change during an episode decreases. The level is the highest in the section close to restoration dams. Their influence is perceived as positive, as they raise GWL. They also have a stabilizing effect. However, the results also imply that in a certain distance from restoration dams, their effects can no longer be seen and GWL fluctuates naturally as in the

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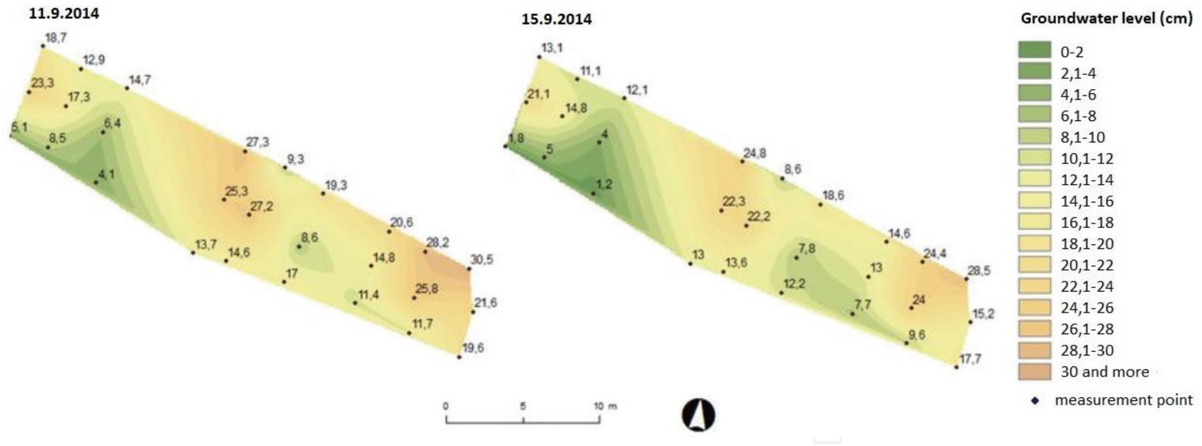

Figure 6. Changes of GWL during a selected episode of intensive precipitation between the September 11, 2014 and September 15, 2014. The given numbers in the graph represent measured GWL in centimeters on a given day.

peat bogs, which are not influenced by a drainage. It is also evident that the decreases or increases of GWL are very variable, and there are noticeable differences between individual points (up to 6.4 cm), in spite of the fact that it is a small homogenous area. On the contrary, in areas near restoration dams, the GWL was increasing very gradually and a similar increase was reached at all the measurement points. Another observed episode was during a **dry period**, when there was only 1.4 mm of precipitation from the September 2, 2014 to September 7, 2014 (see **Figure 7**). The smallest changes of GWL in a period with low precipitation were reached in the middle line of the observed area (3 m from the drainage ditch). It is interesting that in this episode, rather big amplitudes can be found, even in the area of restoration. It can be caused by the fact that before the period of drought, the GWL was very high, precisely right under the surface; hence, following decreases could have progressed faster there. The biggest difference between water levels is significant again and it is even up to 9.2 cm during the monitored 5-day range. It has been confirmed repeatedly that in the areas located further from restoration, the GWL is distinctly lower, and, moreover, there is a remarkable and fast fluctuation of GWL, which is not beneficial for the evolution of mountain peat bogs [47].

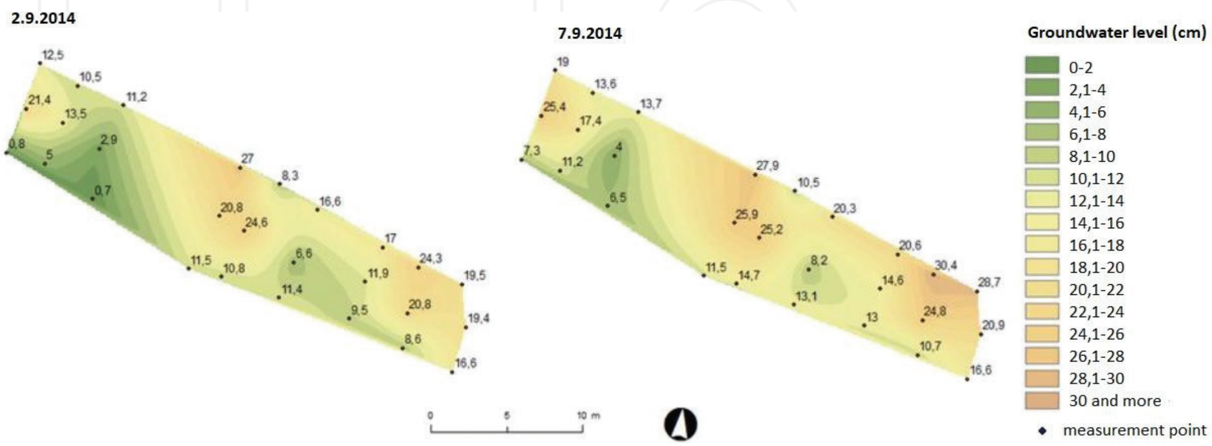

Figure 7. Changes of GWL during a selected episode of drought between the September 2, 2014 and September 7, 2014. Given numbers in the graph represent measured GWLs in centimeters on a given day.

5.5. Runoff chemistry and balance

Peat bog: Water in the Rokytka peat bog had low dissolved solids concentrations. Seasonal profile of δ^{18} O-H_2O (see **Figure 8**) was similar to that for precipitation, as it represents the main source of water in the bog. The hydrogen ion concentration (pH) in bog water is predominantly regulated by total organic carbon (TOC). This concentration shows quite strong seasonal profile related to evaporation and organic matter production (high TOC in summer and low TOC in winter period). Naturally higher content of organic acids along with a low total mineralization results in low pH and low alkalinity of water. Nitrates can be observed in the bog only in winter, while their source is represented by winter precipitation.

Tributary: Study catchment of Rokytka B. is supplied with a number of tributaries. However, two of them are the most significant. Since they show very similar chemistry, due to the fact that both affluents showed very similar chemistry, data from that with higher discharge were analyzed. Total mineralization of Rokytka B. was higher than in the bog. Its δ^{18} O-H_2O profile was more balanced as shown in **Figure 8**. The δ^{18} O-H_2O balance is a result of the prevailing supply of groundwater. Only in periods of higher precipitation, Rokytka B. can contain water from shallow soil horizons with a higher TOC content. Hydrogen ion concentration of Rokytka B. was significantly dependent on discharge and the profile of affluent discharge was very similar to that of brook itself. Increased concentration of TOC was probably related to the production of organic substances during the summer period. There was no significant correlation between TOC and pH.

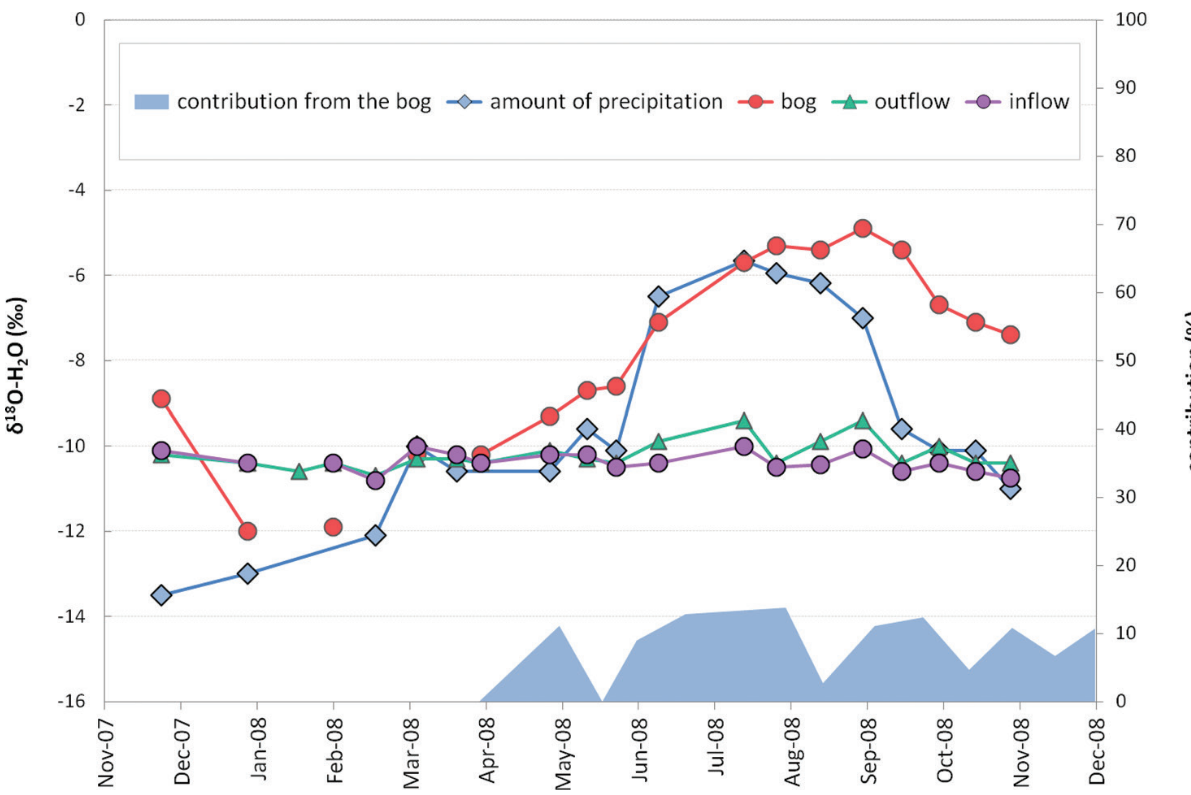

Figure 8. Profile of δ^{18} O-H_2O in surface water and precipitation in the Rokytka B. catchment for the hydrological year 2008; the y-axis shows the relative balance contribution of bog water to the total runoff from the catchment.

Outflow: Chemistry of Rokytka B. in the closing profile looks very similar to the chemistry of the main affluent. On the base of the results (see **Figure 8**), it is clear that the contribution of bog water to the outflow of Rokytka B. was negligible, ranged not more than about 10% of total runoff outside the winter period. During winter, the bog contribution was insignificant and the total runoff was formed only by tributaries, that is, underground water. General character of chemistry of Rokytka B. comes mainly from water sources that have been in contact with mineral soils, even during the period of increased runoff (see stable $\delta^{18}O$-H_2O, **Figure 8**). A strong argument for claiming that the main sources of Rokytka B. runoff are represented by its tributaries, which are mainly supplied by groundwater, is that, compared to the bog, there was also a high concentration of cations in the brook. Regularly increasing TOC concentrations are most likely from the riparian zone, where TOC is washed off during the increased runoff period. Production of seasonal organic matter would also have some influence [55].

5.6. Identification of runoff formation using dye tracers

Near-surface flow in the NW direction toward the stream was revealed by the visual survey of the soil surface in the vicinity of the BB sprinkling plot. Brilliant Blue was detected in a small, water-filled depression 10.5 m downslope from the sprinkling plot. The BB stained flowpaths went from the NW side of the sprinkling plot and followed mostly lateral preferential flow structures formed by decomposed trees or roots. They did not strictly follow the terrain gradient. This lateral preferential flowpath was identified as the main direction of subsurface flow.

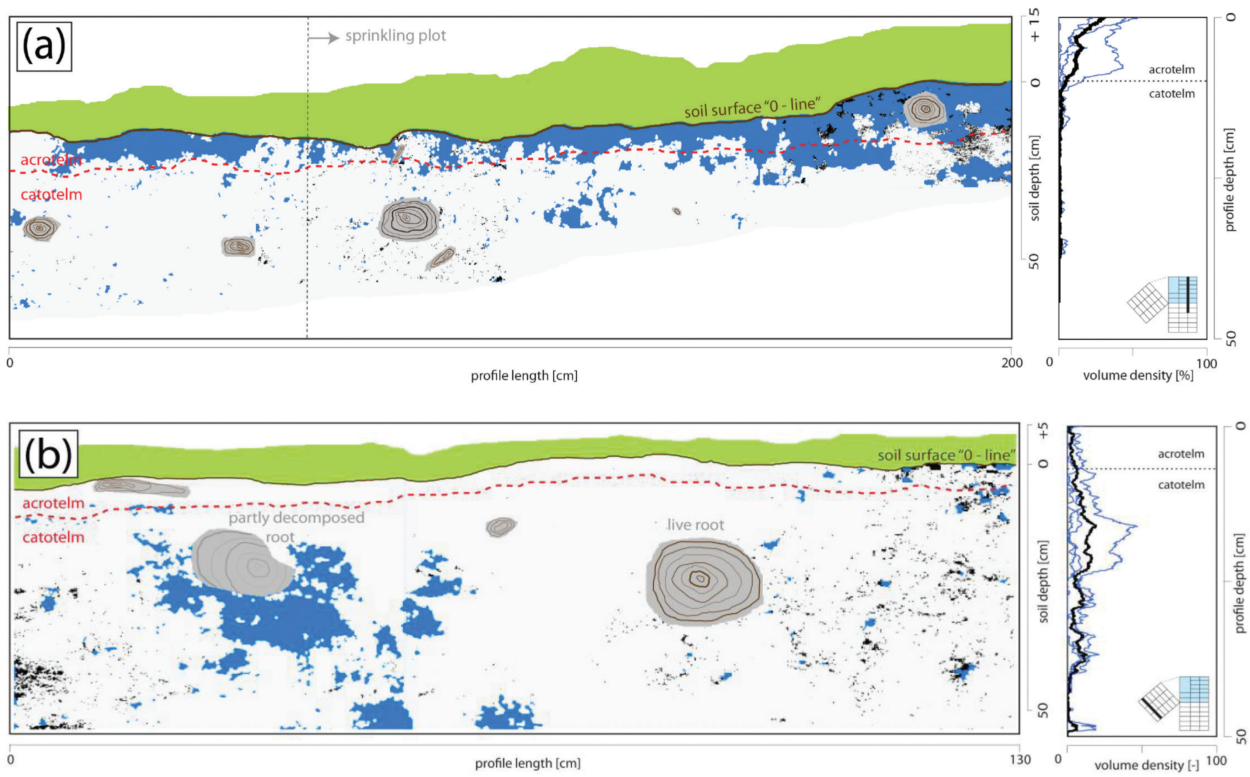

Figure 9. (a) Scheme of lateral soil profile (IL0.5) and (b) frontal soil profile (FD0.25) at the BB sprinkling plot PB3 at the organic soil hillslope (i.e. peat bog). The position of the profile is visualized in bottom right corner. Blue = BB dye, gray = roots, green = vegetation, black = unclassified shadows, red-dotted line = soil horizon dividing line. Charts on the right represent the vertical distribution of the volume density of the BB.

Smaller and less stained flowpaths were detected downslope from the sprinkling plot. BB was disappearing 2 m from the sprinkling plot. BB followed lateral soil pipes that were formed by decomposed roots or fallen trees. Undecomposed timber and healthy trees did not create such effective lateral preferential flowpaths. Accordingly, they had no significant impact on dye-stained patterns (see **Figure 9**). Major flowpaths of BB could be detected even several days after the dye application because BB created clearly detectable dye-stained patterns on the dark peat particles as well. The excavation of BB stained soil patterns at the organic soil hillslope (PB3) proceeded from two directions, NW and SW, following the stained flowpaths in the soil. Near the sprinkling plot, most of the dye was detected at the surface and in near-surface soil horizons, which correlates with Acrotelm (**Figure 9**). About 2.0 m downslope from the BB sprinkling plot at hillslope PB the dye-stained patterns diminished in the Acrotelm and were observed mainly in and around macropores in the Catotelm [43].

6. Discussions

Within the long-term project, *various approaches for the evaluation of hydrological balance* of mid-latitude mountain peatland and peat bogs were used. Classic statistical methods and modern research approaches were implemented in order to understand the real mechanism of the streamflow generation process in areas with significant peat bog phenomenon. The 12-year duration of the project entails the crucial findings that were used in this paper and complement the long-term time series of data from the state profiles. However, different approaches were not used throughout the whole period but in chosen terms. Application of all used methods in the whole period was not possible because of financial and personal resources, as well as the ongoing technology development. However, what was supervised very much in detail was always the choice of correct and relevant data base of needed parameters and suitable time periods. Combination of such corresponding analyses was crucial for complex outcomes that were presented. It has to be stated that every each methodology approach and acquired result casually supports and supplements one another. Such a broad and detailed study has never been carried out in this area and brings completely new findings that are minimally comparable with different types of peat bog complexes.

Thus, general solution of the issue of a *peat bog impact on the runoff process* is not possible. It depends on many factors, mainly on the type of a peat, on its condition and on the extent of anthropogenic influence. Opinions on the peat bogs hydrological function have undergone considerable development and are often contradictory. Generally, the hydrological importance of peat bogs has been overestimated in the past and cannot be regarded as flow regulators because draining streams show extremely high volatility. More controversial discussions within the foreign and domestic literature (e.g., [2, 5, 6]) can be found within the question of drainage of former ameliorative channels or its torrent control respectively. Based on research in the upper Vltava R. basin, it could be stated that it is crucial to take into account the specific characteristics of peat deposits and its surrounding natural conditions while evaluating the revitalization measures effect on runoff dynamics.

Within the literature, a number of *positive and negative examples* of the peat land influence on hydrological regime can be found. These contradictory claims can be paradoxically united. When

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the bog is drained, runoff variability decreases, but it leads to destruction in time by the bog succession. If GWL would be regulated and reduced in time of need, bog retention potential could be used without the threat of its existence. Periodical fluctuations of GWL in the bog are natural constituents of its development. Minimum time lag between the monitored GWL and surface outflow points to a negligible ability to absorb significant rainfall totals by the bog complex and to a minimum hydraulic communication between the bog complex and its draining stream.

Detection of natural tracers is a useful method to provide the key information in hydrological observation studies of catchment runoff formation. These methods use the different behavior of a small quantity of water molecules. Study of water dynamics by means of natural tracers is typically oriented on usage of oxygen (^{18}O) and hydrogen (^{2}H) isotopes [31]. Stable oxygen and hydrogen isotopes are elements that occur naturally, in variable concentrations, in the hydrological cycle. It provides the unique information about the water that enters a catchment in the form of precipitation, that retains in the catchment and that passes out in the form of runoff. Hypotheses and knowledge of runoff regime dynamics of studied areas gained on the basis of classical hydrological approaches were therefore confirmed by detailed hydrochemical and geochemical analyses. The application of this modern approach in such an optimal model catchment, such as the Rokytka B. catchment, appears as a legitimate shift in research. According to above stated fact, geochemical data show no significant hydraulic connection of the studied bog with the Rokytka B. bed. Moving at a maximum of around 10% out of winter period, as a consequence, the contribution of surface runoff by water from the bog is very insignificant. The predominant portion of underground water (forced out due to the pressure gradient) in total runoff was also confirmed by separation of each runoff component according to geochemical parameters. The problem of hydraulic communication between peat bog complexes and draining streams needs to be solved strictly with respect to local p-g conditions! As it was already said, these findings represent the first knowledge of such a focus in conditions of the Vltava R. headwaters. A similar study describing the use of stable oxygen and hydrogen isotopes was carried out on Uhlířská catchment in the upper part of Černá Nisa River basin in Jizerské Mts. [29, 67]. The prevailing share of subsurface water in the total runoff was confirmed, as in the case of the Rokytka B. study, by the separation of runoff components according to geochemical parameters. During the accelerated runoff, the proportion of water from the causal precipitation episode is gradually increasing, thus contributing to dilution of the draining water. The study of Šanda and Císlerová [67] shows that the drainage of this water is accelerated by the system of partial drainage bases of underground and groundwater in the form of artificial and natural forest gutters, chasms and saturated areas with an ongoing return flow. This course can also be observed in the case of selected catchments in the Šumava Mts. with the existence of nonrevitalized peat bog areas with melioration channels.

If we assess abovementioned outcomes from a hydrological point of view, we have to state following: In physicogeographical conditions of Vltava R. headwaters, peatland acts as a negative element for runoff transformation. Hydrological features of local waterlogged areas are disfavorable. Our primary hydrological assumption of insignificant impact of peatland on runoff dynamics, especially during extreme episodes (floods, droughts), was confirmed by acquired findings from geochemical analyses performed. Considerably weak impact of a peat bog on runoff was also supported by a high concentration of cations in the surface runoff compared to the bog. Much more significant contribution to surface runoff of Rokytka B.

has a groundwater from the basin. In general, very close correlations between pH and actual discharge in experimental profiles were found regularly. A reasonably close relationship was also observed in the closing profile of Rokytka B. catchment. Our research findings strongly support the fact that peatland areas within the studied catchment do not significantly communicate hydraulically with surface streams and their hydrological function is, in the concrete area of Vltava R. headwaters, insignificant [9, 11].

Within the research, the question of impact of ongoing *revitalization measures of the local peat bogs* (made by Šumava National Park management) on the runoff dynamics was opened. Its wholly satisfactory solution, although it should be decisive in the selection of measures to improve the runoff conditions in the area, does not yet exist. Significantly, higher extremity of flood situations was found out in cases of revitalized streams. Local revitalization process consists in damming of former ameliorative channels draining peat bogs. Detailed analyses approved that these revitalization measures stabilized runoff conditions in yearly course and had balancing effect during average runoff situations. In a number of experimental catchments, the presence of revitalization measures can also impact negatively on given flood event. Studies confirmed that revitalization adjustments in selected subcatchments had balancing effect on runoff conditions only to the certain level of its extremity. In most cases, runoff extremity was intensified as soon as the certain water-level stage (respectively discharge) was exceeded. To confirm the correctness of these statements and to correctly understand the functioning of this mechanism, broader data base is needed.

In peaty catchments, the retention ability depends mainly on the shallow depth of the phreatic zone in the peat bog, whereas the deep phreatic zone in the Podzol plays a minor role [13]. Peat bog areas are hypothesized to control storm runoff formation in these headwaters. Peat bogs can significantly contribute to stormflow when the peat is fully saturated, that is, storm events exceeding a threshold of 10–15 mm [68]. As mentioned above, according to a geochemical study based on 2 years of monthly stream water sampling [55], peat bogs contribute only 10% to baseflow at the outlet of the entire Rokytka B. catchment. However, some zones of a peat bog area, such as springs or soil pipe systems connected to the stream, exhibit high fluctuations in discharge [69]. This fact could explain the observed spiky storm hydrographs at the entire Rokytka B. catchment outlet (area of 3.8 km^2) and at the Rokytka headwater test site (0.6 km^2). Presented runoff fluctuations from peaty areas could be caused by surface flow (as observed within a field survey at the Rokytka peat bog), near-surface flow [7, 40] or subsurface stormflow in soil pipes [70, 40, 71]. Outcomes of Holden and Burt [72] at a blanket Peat site showed that near-surface flow (i.e., Biomat flow, BMF) up to the depth of about 10 cm can contribute more than 90% to the plot's outflow. Biomat flow can be defined as a lateral stormflow in the organic litter layer which has quite high porosity and high hydraulic conductivity in the topsoil [71]. Storm hydrographs at the Rokytka B. headwater are highly volatile and are characterized by quick and steep rising and falling limbs. The hydrologic response to rainfall events is fast and the recession to antecedent baseflow occurs rather quickly [43].

7. Conclusions

Based on acquired outcomes from time series statistical analyses, much more distinct runoff variability of streams draining highly peaty catchments in the Vltava R. headwaters (sw. Czechia), especially during extreme hydrological situations, was observed. This fact was

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confirmed by hydropedological, hydrochemical and geochemical approaches. Geochemical data show no significant hydraulic connection of the studied bog with its draining stream. The predominant portion of underground water in total runoff was also confirmed by separation of each runoff component according to geochemical parameters. However, this subject needs to be solved strictly with respect to local physicogeographic conditions. These conclusions correspond to the typical mid-latitude peat bog area in conditions of Czech mountainous areas. Their restoration measures carried out in recent years have a positive effect on GWL. It was proven that restoration decreases fluctuation and increases GWL, which is essential for a natural evolution of a mountain peat bog. Tracer experiments detected biomat flow, shallow lateral subsurface flow and mostly deep percolation at the Podzol hillslope. At the organic peat bog biomat flow at short distances and mostly lateral pipe flow following decayed tree-root systems with long lateral subsurface flow distances were recognized. It can be stated that bogs in the studied basin represent separate hydrological units with their own typical runoff regime, which does not contribute to the discharge curve balancing (during both floods and droughts), and that their hydrological function in this mountainous area is insignificant.

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References

[1] Ferda J. Hydrologický význam horských vrchovištních rašelinišť. Sborník ČSAZV – Lesnictví. 1960;**10**:835-856

[2] Conway VM, Millar A. The hydrology of some small peat-covered catchments in the Northern Pennines. Journal of the Institute of Water Engineers. 1960;**14**:415-424

[3] Burke W. Principles of drainage with special reference to peat. Irish Forestry. 1967;**24**:1-7

[4] McDonald A. Some views on the effects of peat drainage. Scottish Forestry. 1973;**27**:315-327

[5] Moklyak VI, Kubyshkin GP, Karkutsiev GN. The effect of drainage works on streamflow. In: Hydrology of marsh-ridden areas, Proceedings of the Minsk Symposium, June 1972. IAHS Studies and Reports in Hydrology. Vol. 19. Paris: Unesco Press; 1975. pp. 439-446

[6] Baird AJ. Field estimation of macropore functioning and surface hydraulic conductivity in a fen peat. Hydrological Processes. 1997;**11**:287-295

[7] Holden J, Burt TP, Cox NJ. Macroporosity and infiltration in blanket peat: The implications of tension disc infiltrometer measurements. Hydrological Processes. 2001;**15**:289-303

[8] Holden J, Chapman PJ, Labadz JC. Artificial drainage of peatlands: Hydrological and hydrochemical process and wetland restoration. Progress in Physical Geography. 2004;**28**(1): 95-123

[9] Janský B, Kocum J. Peat Bogs Influence on Runoff Process: Case Study of the Vydra and Křemelná R. Basins in the Šumava Mountains, Southwestern Czechia. Geografie - Sborník ČGS. 2008;**113**(4):383-399. ISSN 1212-0014

[10] Kocum J, Janský B, Čurda J, Česák J. Extremita odtoku v pramenné oblasti Otavy (řešení negativních dopadů klimatické změny). In: Vrabec M, Durčanský I, Hladný J, editors. Hydrologické dny 2010 - Voda v měnícím se prostředí. Sborník příspěvků ze 7. národní konference českých a slovenských hydrologů a vodohospodářů. Praha: Nakladatelství ČHMÚ; 2010. pp. 597-604. ISBN 978-80-86690-84-1

[11] Čurda J, Janský B, Kocum J. Vliv fyzickogeografických faktorů na extremitu povodní v povodí Vydry. Geografie – Sborník ČGS. 2011;**116**(3):335-353. ISSN 1212-0014

[12] Kocum J. Tvorba odtoku a jeho dynamika v pramenné oblasti Otavy. Praha. Dizertační práce: Přírodovědecká fakulta Univerzita Karlova v Praze; 2012. p. 206

[13] Vlček L, Kocum J, Janský B, Šefrna L, Kučerová A. Retenční potenciál a hydrologická bilance horského vrchoviště: případová studie Rokytecké slatě, povodí horní Otavy, JZ. Geografie. 2012;**4**:371-395

[14] Pošta P. Organogenní jezera v České republice. Magisterská práce. PřF UK, Praha; 2004. p. 119

[15] Wassen MJ. Hydrology, water chemistry and nutrient accumulation in the Biebrza fens and floodplains (Poland). Wetlands Ecology and Management. 1995;**2**:125-137

[16] Juráková M, Klementová E. Status and trends of the wetlands in West Slovakia. Slovak Journal of Civil Engineering. 2003;**3**:1-8

[17] Novák M. Huminové vody ve vodách údolních nádrží. Vodní hospodářství. 1955;**5**(4): 127-128

[18] Onderíková V, Štěrbová A. Prispevok k biologii a chemizmu Oravskej nádrže. Vodní hospodářství. 1956;**6**(2):46-51

[19] Novák M. Výzkum kvality vody v údolní nádrži Lipno. Vodní hospodářství. 1959;**9**(9): 378-383

[20] Freeman C, Evans CD, Montieth DT, Reynolds B, Fenner N. Export of organic carbon from peat soils. Nature. 2001;**412**:785-786

[21] Worrall F, Burt TP, Adamson JK. Controls on the chemistry of runoff from an upland peat catchment. Hydrological Processes. 2003;**17**:2063-2083

[22] Ferda J, Hladný J, Bubeníčková L, Pešek J. Odtokový režim a chemismus vod v povodí Horní Otavy se zaměřením na výskyt rašelinišť. Sborník prací HMÚ. 1971;**17**:22-126

[23] Hruška J et al. Role of organic solutes in the chemistry of acid-impacted bog waters of the western Czech Republic. Water Resources Reasearch. 1996;**32**(9):2841-2851

[24] Hruška J, Kohler S, Bishop K. Buffering processes in a boreal dissolved organic carbon - rich stream during experimental acidification. Environmental Pollution. 1999;**106** (1):55-65

[25] Oulehle F, Janský B. Limnologie a hydrochemismus v NPR Rejvíz. In: Jezera České republiky (Současný stav geografického výzkumu). Prague: Charles University in Prague; 2003. pp. 93-108

[26] Horton RE. The role of infiltration in the hydrologic cycle. Transactions - American Geophysical Union. 1933;**14**:446-460

[27] McDonnell JJ. Where does water go when it rains? Moving beyond the variable source area concept of rainfall-runoff response. Hydrological Processes. 2003;**17**:1869-1875

[28] Hoeg S, Uhlen BS, Leibundgut C. Hydrograph separation in a mountainous catchment - combining hydrochemical and isotopic tracers. Hydrological Processes. 2000;**14**: 1199-1216

[29] Šanda M. In: Vrabec M, Durčanský I, Hladný J, editors. Přirozené stabilní izotopy kyslíku a vodíku v hydrologii experimentálního povodí, Hydrologické dny 2010 - Voda v měnícím se prostředí. Sborník příspěvků ze 7. národní konference českých a slovenských hydrologů a vodohospodářů. Praha: Nakladatelství ČHMÚ; 2010. pp. 255-261. ISBN 978-80-86690-84-1

[30] Klaus J, McDonnell JJ. Hydrograph separation using stable isotopes: Review and evaluation. Journal of Hydrology. 2013;**505**:47-64

[31] Kendall C, McDonnell JJ, editors. Isotope tracers in catchment hydrology. Amsterdam: Elsevier Science B.V.; 1999. ISBN 13: 978-0-444-50155-4

[32] Kirchner JW. A double paradox in catchment hydrology and geochemistry. Hydrological Processes. 2003;**17**:871-874

[33] Šanda M, Kulasová A, Císlerová M. Hydrological processes in the subsurface investigated by water isotopes and silica. Soil and Water Research. 2009;**4**:83-92

[34] Bufková I. Naprava narušeneho vodniho režimu rašelinišť v národnim parku Šumava. Ochrana přirody. 2013;**2**:17-19

[35] Ballard CE, McIntyre N, Wheater HS, Holden J, Wallage Z. Hydrological modelling of drained blanket peatland. Journal of Hydrology. 2011;**407**:81-93. DOI: 10.1016/j.jhydrol.2011.07.005

[36] Worrall F, Armstrong A, Holden J. Short-term impact of peat drain-blocking on water colour, dissolved organic carbon concentration, and water table depth. Journal of Hydrology. 2007;**337**:315-325. DOI: https://doi.org/10.1016/j.jhydrol.2007.01.046

[37] Bufková I, Stíbal F, Mikulášková E. Restoration of drained mires (Šumava National Park, Czech republic). Proceedings 7th European conference on ecological restoration Avignon, France; 2010, pp. 23-27. DOI: 10.1007/978-90-481-9265-6_16

[38] Bufková I. Revitalizace šumavskych rašelinišť. Zprávy České Botanické Společnosti, Praha. 2006;**41**(21):181-191

[39] Kvarner J, Snilsberg P. Groundwater hydrology of boreal peatlands above a bedrock tunnel–drainage impacts and surface water groundwater interactions. Journal of Hydrology. 2011;**403**:278-291. DOI: 10.1016/j.jhydrol.2011.04.006

[40] Holden J. Peatland hydrology and carbon release: Why small-scale process matters. Philosophical Transaction, The Royal Society. 2005;**363**:2891-2913. DOI: https://doi.org/10.1098/rsta.2005.1671

[41] Šefrna L. Pedologická charakteristika povodí Otavy ve vztahu k povodním [online]. Charles University in Prague; 2004. Available from: http://hydro.natur.cuni.cz/zmeny_povodni/pdf/sefrna.pdf [Accessed 8 July 2009]

[42] Bufková I. Ochrana rašelinišť na Šumavě : aneb byly Rokytecké slatě první. In: Černý D, Dvořák L, editors. Weitfällerské slatě, Sborník výzkumu na Šumavě, 2, Vimperk, Správa NP a CHKO Šumava. 2009. p. 103

[43] Vlček L, Falátková K, Schneider P. Identification of runoff formation with two dyes in a mid-latitude mountain headwater. Hydrology and Earth System Sciences. 2017;**21**:3025-3040. DOI: 10.5194/hess-21-3025-2017

[44] Schneider P, Lange A, Doppler T. Development and evaluation of a water level proportional water sampler, American Geophysical Union, Fall Meeting 2013, abstract #H43H-1579; 2013

[45] Šanda M. Proudění vody v půdním profilu na svahu horského povodí. Doktorské disertační minimum. Praha: ČVUT; 1998. p. 12

[46] Zhang W et al. The impact of vegetation and soil on runoff regulation in headwater streams. Catena. 2011;**87**:182-189

[47] Doležal T, Vlček L, Kocum J, Janský B. Evaluation of the influence of mountain peat bogs restoration measures on the groundwater level: Case study Rokytka peat bog, the Šumava Mts., Czech Republic. AUC Geographica. 2017, [S.l.], july 2017. ISSN 2336-1980, doi: 10.14712/23361980.2017.11

[48] Penman HL. Natural evaporation from open water, bare soil and grass. Proceedings of the Royal Society. 1948;**194**:120-145

[49] Mishra SK, Singh VP. Soil Conservation Service Curve Number (SCS-CN) Methodology. Vol. 511. Dordrecht: Kluwer Academic Publisher; 2003

[50] Bůzek F. A rapid procedure for preparing Oxygen-18 determination in water samples. Isotopenpraxis. 1984;**19**:70-72

[51] Käss W. Tracing Technique in Geohydrology. Rotterdam: A. A. Balkema; 1998. p. 581

[52] Gerke KM, Sidle RC, Mallants D. Criteria for selecting fluorescent dye tracers for soil hydrological applications using Uranine as an example. Journal of Hydrology and Hydromechanics. 2013;**61**:313-325. DOI: 10.2478/johh-2013-0040

[53] Weiler M, Flühler H. Inferring flow types from dye patterns in macroporous soils. Geoderma. 2004;**120**:137-153. DOI: https://doi.org/10.1016/j.geoderma.2003.08.014

[54] Weiler M, Naef F. An experimental study of the role of macropores in infiltration in grassland soils. Hydrological Processes. 2003;**17**:477-493

[55] Kocum J, Oulehle F, Janský B, Buzek F, Hruška J, Vlček L. Geochemical evidence for peat bog contribution to streamflow generation process: Case study of Vltava R. Headwaters, Czech Republic. Hydrological Sciences Journal. 2016;**61**:2579-2589. DOI: 10.1080/02626667.2016.1140173

[56] Eliáš V, Tesař M, Buchtele J. Occult precipitation: Sampling, chemical analysis and process modelling in the Šumava Mts. (Czech Republic) and in the Taunus Mts. (Germany). Journal of Hydrology. 1995;**166**:409-420

[57] Tesař M, Eliáš V, Šír M. Preliminary results of characterization of cloud and fog water in the mountains of southern and northern bohemia. Journal of Hydrology and Hydromechanics. 1995;**43**(6):412-426

[58] Pavlásek J, Tesař M, Máca P, Hanková R, Hudečková K, Jačka L, Klose Z, Ředinová J. Ten years of hydrological monitoring in upland microcatchments in the bohemian Forest, Czech Republic. IAHS-AISH Publication. 2010;**336**:213-218

[59] Ahearn EA. Peak-flow frequency estimates for U.S. Geological Survey streamflow-gaging stations in Connecticut. Water-Resources investigations report, 03-4196. U.S. Geological Survey, East Hartford, Connecticut; 2003. 36 p

[60] Feldman AD. Flood Hydrograph and Peak Flow Frequency Analysis. Technical Paper. Davis, California: HEC; 1979. p. 28

[61] Kocum J, Janský B. Retence vody v pramenných oblastech Vydry a Křemelné – případová studie povodí Rokytky. In: Černý D, Dvořák L, editors. Weitfällerské slatě. Sborník referátů ze semináře 21.1.2009. Vimperk: Správa NP a CHKO Šumava; 2009. pp. 26-48. ISBN 978-80-87257-00-5, ISSN 1803-4470

[62] Šercl P. Vliv fyzicko-geografických faktorů na charakteristiky teoretických návrhových povodňových vln. Sborník prací ČHMÚ, sv. 54, ČHMÚ, Praha; 2009. 88 p

[63] Štěpánková R. Vliv fyzicko-geografického prostředí na vznik a vývoj povodní v povodí Berounky. . Disertační práce. Praha: PřF UK; 2004. p. 178

[64] Tesař M, Šír M, Zelenková E. Vliv vegetace na vodní a teplotní režim tří povodí ve vrcholové části Šumavy. Aktuality šumavského výzkumu, s. 2004;**2**:84-88

[65] Lichner L, Šír M, Tesař M. Testování retenční schopnosti půd. Aktuality šumavského výzkumu. 2004;**2**:63-67

[66] Vlček L. Retence vody půdou v experimentálních povodích se zaměřením na organozemě. Magisterská práce. Praha: PřF UK; 2011. p. 67

[67] Šanda M, Císlerová M. Transforming hydrographs in the hillslope subsurface. Journal of Hydrology and Hydromechanics. 2009;**57**(4):264-275

[68] Vlček L, Kocum J, Janský B, Šefrna L, Blažková Š. Influence of peat soils on runoff process: Case study of Vydra R. headwaters, Czechia. Geografie. 2016;**121**:235-253

[69] Holden J, Burt TP. Piping and pipeflow in a deep peat catchment. Catena. 2002;**48**:163-199. DOI: https://doi.org/10.1016/S0341-8162(01)00189-8

[70] Rizzuti AM, Cohen AD, Stack EM. Using hydraulic conductivity and micropetrography to assess water flow through peat-containing wetlands. International Journal of Coal Geology. 2004;**60**:1-16. DOI: 10.1016/j.coal.2004.03.003

[71] Gerke KM, Sidle RC, Mallants D. Preferential flow mechanisms identified from staining experiments in forested hillslopes. Hydrological Processes. 2015;**29**:4562-4578. DOI: https://doi.org/10.1002/hyp.10468

[72] Holden J, Burt TP. Hydrological studies on blanket peat: The significance of the acrotelm-catotelm model. Journal of Ecology. 2003;**91**:86-102. DOI: 10.1046/j.1365-2745.2003.00748.x