

# Identification of Surface Runoff Source Areas as a Tool for Projections of NBS in Water Management



Jiří Jakubínský, Vilém Pechanec, Ondřej Cudlín, Jan Purkyt, and Pavel Cudlín

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**Abstract** The location of surface runoff source areas is one of the most important information for the conservation of water resources, their sustainable management as well as mitigation of the frequency of extreme hydrological phenomena. The location of the surface runoff source areas in the landscape affects not only the hydrological and sediment regime of the watercourse itself, but also some physico-chemical properties of the water. The exact parameters of the hydrological and sediment regime are the result of a number of variables – mostly soil properties, morphometric parameters of the terrain, and the level of anthropogenic influence, but

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also the type of surface cover. This research deals with the relationship between types of habitats (in terms of their qualitative properties – e.g. naturalness of the habitat, diversity of structures, sensitivity of the habitat to external interventions, etc.) and their impact on runoff processes in the landscape; i.e., the extent to which the habitat type can affect the soil water retention and infiltration capacity, and thus runoff processes. The creation of habitats with an identified positive effect on the hydrological regime (mitigation the frequency of drought and flash floods), or the creation of conditions suitable for the natural formation of these habitats, can be considered as a good example of nature-based solutions for water management. Within a study area in the Czech Republic, a medium-sized watercourse catchment with forest-agricultural landscape, a newly developed water retention model LOREP was applied. This model takes into account a multiple-flow regime, providing more accurate results than previous models. The analysis revealed that there are several types of natural or close-to-nature habitats able to retain a significant amount of rainwater, even in soils with limited retention capacity. A possible increase in the area of these habitats may indirectly contribute to the mitigation of hydrological extremes and the increase of surface water quality.

**Keywords** Environmental modelling, Habitat structure, Soil water retention, Surface runoff, Water resources

## 1 Introduction

The hydrometeorological conditions of a given place primarily contribute to the formation of surface runoff. Precipitation and evapotranspiration are spatially and temporally variable factors, which usually represent one of the fundamental impulses leading to the creation, change or extinction of surface flow in the landscape. These factors represent the key variables influencing the formation of extreme hydrological situations – not only flood events, but also drought episodes, which the Central European region is increasingly facing [1–3]. While the long-term flow regime is mainly shaped by the climatic conditions of the river basin (e.g., the prevailing climate conditions), sudden changes in the hydrological characteristics of the stream are the result of the current meteorological situation and direct anthropogenic influences. Apart from the extreme weather conditions there is also a number of other factors influencing the surface runoff formation, such as the soil saturation driven by antecedent precipitation, and other characteristics related to the physical–geographical properties of the landscape. The extent of surface runoff within the river basin depends on the rate of infiltration of rainwater, namely determined by the soil water retention capacity and partly also the degree of rainfall interception by vegetation [4].

The relationship between the hydrological regime of watercourses, the natural conditions of a given river basin, and the impact of human intervention in the

landscape have been discussed by a number of authors, in order to quantify the influence of individual factors on runoff processes [5–9]. Since vegetation (and especially forest cover) directly affects the precipitation–runoff processes and also acts as a protective cover for soil surface, it represents an important segment of the landscape, affecting the current and long-term water balance of the area. The relationship between the ecological status and structure of vegetation cover and the hydrological regime has been analysed by many authors [10–13]. The general conclusion is that forest stands and soil properties significantly modify the culmination and shape of the hydrograph of the precipitation–runoff episodes (the response time is delayed and the peak flood is lower); in addition to the physical geographical conditions of the river basin itself, these mainly include the composition of the forest, its age and health status of individual trees or the management practices used [10].

Compared to forest stands, agricultural land contributes in a greater extent to the overall impact on surface runoff characteristics. The gradual transformation of the original, highly diversified natural landscapes into the current large monotonous blocks of arable land represents the most significant change that has affected the rural landscape [14]. The great land cover and land-use change called as “green revolution” can be described as a turning point in global land management, which refers to, among other things, a fundamental change in the hydrological conditions of the affected environment (and indirectly also the water regime of most streams). An example of a European country where a very significant change in the land-use took place during the twentieth century is the Czech Republic. The change of land-use is also connected with the drainage of large areas, which was carried out due to efforts to cultivate the land using heavy machinery and to establish the collective agricultural systems [15]. According to Štěřba et al. [16], in the second half of the last century, more than 600,000 ha of land were drained in the Czech Republic (especially wetlands and waterlogged soils) in which the case study presented in this chapter was carried out. Land reclamation (i.e. change in soil utilization) affected practically the entire territory of the republic, especially the headwater areas, in which the original waterlogged soil caused difficulties during the conversion from non-agricultural to agricultural land [1]. Similar issues related to land-use change and its impacts on the hydrological regime have also been addressed in other European countries [17–20]. The main negative consequence of land-use change related to the land drainage and its cultivation was the hydromorphological degradation of the river network, the disruption of which was subsequently reflected in the hydrological regime. The increase in the rate of water runoff and the imbalance of flows during the year led to many changes in the morphological and ecological parameters of the river environment (especially related to the channel incision). The secondary – although not less significant – impact of agricultural activity on the river network is the deterioration of the biochemical quality of water, due to the flushing of harmful substances from cultivated land.

It is also necessary to mention that, although runoff processes are influenced nowadays by a number of anthropogenically conditioned factors, some extreme water levels cannot be eliminated even by the best management of water resources

or landscape planning. Although the overall ecological status of the river basin has a significant impact on the occurrence of floods, the main stimulus remains atmospheric precipitation and its parameters in agricultural catchments. According to Pithart et al. [21], it is obvious that, with increasing precipitation, natural conditions and level of anthropogenic influence decreases; for example, while after a 20 mm precipitation a river basin may capture up to 75% of the rainwater under optimal conditions, with a total precipitation of 100 mm or more, the captured amount may be less than 10% of the precipitation (based on measurements made in a medium-sized river basin in an agricultural landscape). The ecological status of the river basin has a significant effect on the formation of water runoff for precipitation amounts approximately up to a recurrence interval of 10–20 years; in the case of catastrophic precipitation events with a longer recurrence interval, the influence of the landscape significantly decreases [21].

Another factor that significantly affects the runoff generation process whose effect is not possible to completely eliminate is the presence of urban areas and impermeable surfaces. In addition to the fact that built-up areas reduce the water retention capacity of the landscape, urban areas reduce water evaporation [22] and also accelerate the water runoff flowing downslope [8, 23]. The most common cause of the accelerated runoff of water is the straightening of riverbeds, channel deepening and especially the concrete revetment of river banks. These features are typical for watercourses affected by the so-called urban stream syndrome [7, 24–26].

The most widespread measures to mitigate the impacts of hydrological extremes – especially flood situations – in the past were in general technical adjustments directly in the actual riverbeds, i.e., straightening, channel fortification, and incisions. These measures often had another equally important goal, namely to improve the soil permeability and thus increase its agricultural potential. However, in connection with the increasingly frequent impacts of climate and environmental change, the negative aspects of the implemented technical measures began to appear. Drained and compacted soil, which also leads to loss of connectivity between the watercourse and groundwater, began to be extremely prone to drying up at a time of gradually rising air temperatures and the unbalanced distribution of precipitation over time [27]. Only in the period with a significantly increased number of these hydrological extremes (after a period of numerous flash floods and the subsequent long period of drought) the need to implement other types of measures that could contribute to alleviating these hydrological extremes began to be demanded in most parts of Europe. Appropriate solutions could include the so-called nature-based solutions, which are defined by the European Commission [28] as measures inspired by, supported by or copied from nature. Within the water management sector, these are mainly “natural flood management” and “natural water retention measures”. According to Hartmann et al. [29], these are targeted interventions to improve water retention by plants (interception) and their evapotranspiration as well as the infiltration of water into the soil, and to support the formation of ponds and wetlands; the measures are intended to restore the connectivity of rivers with their surroundings. Although these measures are important in the entire area of the river basin, the vast majority of these interventions are usually concentrated in the area of river

landscapes, as narrow strips lining watercourses, which have the potential to accumulate not only rainwater but also water from the riverbed at elevated water levels, and thus significantly support the flood protection function of current landscapes. In order to ensure the positive effect of the mentioned measures (i.e. to reduce the frequency of hydrological extremes), it is necessary to implement them in areas that are as large as possible, which may require the cooperation of private landowners. However, the landowners are usually not interested in this type of measures, as they very often reduce crop yields, and some solutions also present certain technical complications in terms of land management [30]. One of the tools to stimulate the interest of landowners in the implementation of water retention measures could be various subsidy titles provided by the governments [31]. A certain solution that would help a society to realize the importance of the discussed measures is to express the financial value of individual ecosystem services provided by the landscape (for example, flood control, water storage, soil erosion prevention, and climate stabilization) in optimal conditions in terms of the impact on the hydrological regime [32].

Proposals for nature-based solutions to alleviate hydrological extremes assume a relatively detailed knowledge of local runoff processes and the main variables that affect the hydrological regime of the area. The use of various environmental models seems to be very effective in identification of surface runoff generation areas, especially erosion–accumulation modelling techniques, based on the outputs of which it is possible to identify localities that are prone to surface runoff generation and especially localities with some potential to experience the mentioned extreme phenomena. Most of the existing hydrological models use a digital terrain model (DTM) and information on selected soil characteristics that affect water transport within the soil profile (e.g. infiltration capacity and soil water retention capacity) as background data. These data are supplemented by information concerning the land-use; in particular, the land cover type, the crop rotation and applied sowing procedures in the case of agricultural land. Since the mentioned nature-based solutions that can be implemented in the catchment area also include, in general, a change in the nature of land cover, information on the impact of individual habitat types on runoff processes is one of the key features that should be reflected in landscape management. Thus, this study analyses the influence of different vegetation structures on local hydrological regime.

## **2 Identification of Runoff Source Areas Using Environmental Modelling Techniques**

### ***2.1 Characteristics of the Study Area***

The study area is the Dřevnice River basin, located in the eastern part of the Czech Republic, near the state border with Slovakia (see Fig. 1). The basin has an area of 438.2 km<sup>2</sup> and especially the headwater area is characterized by a relatively rugged

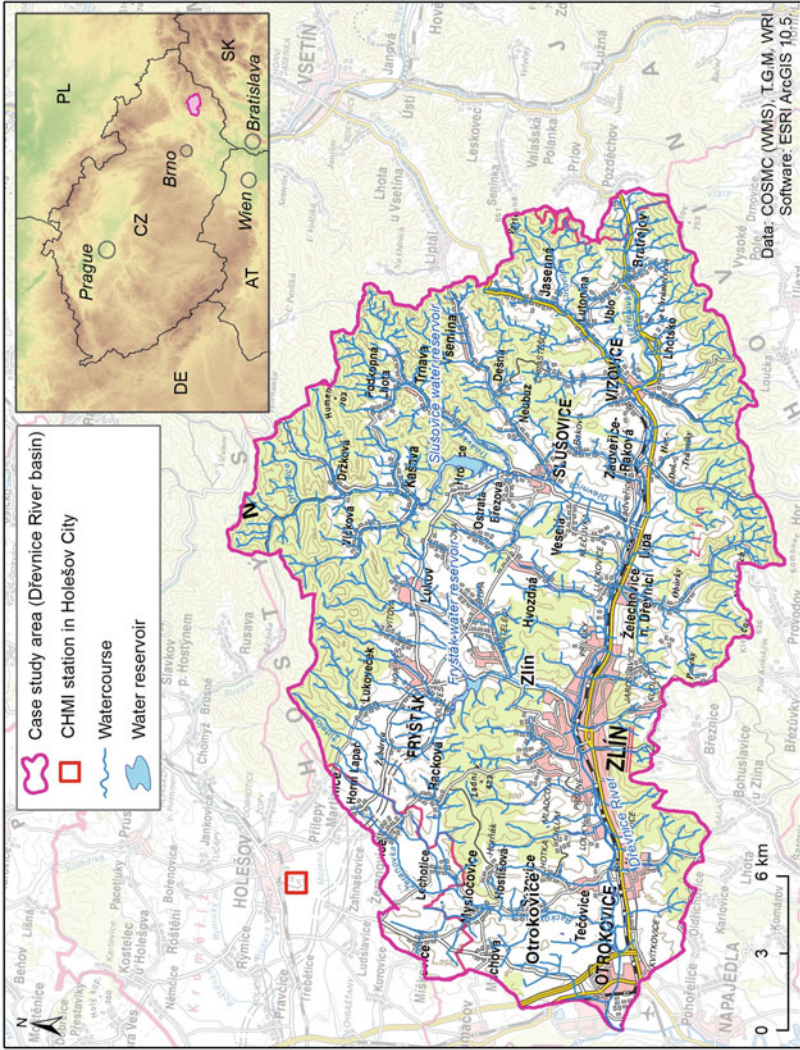
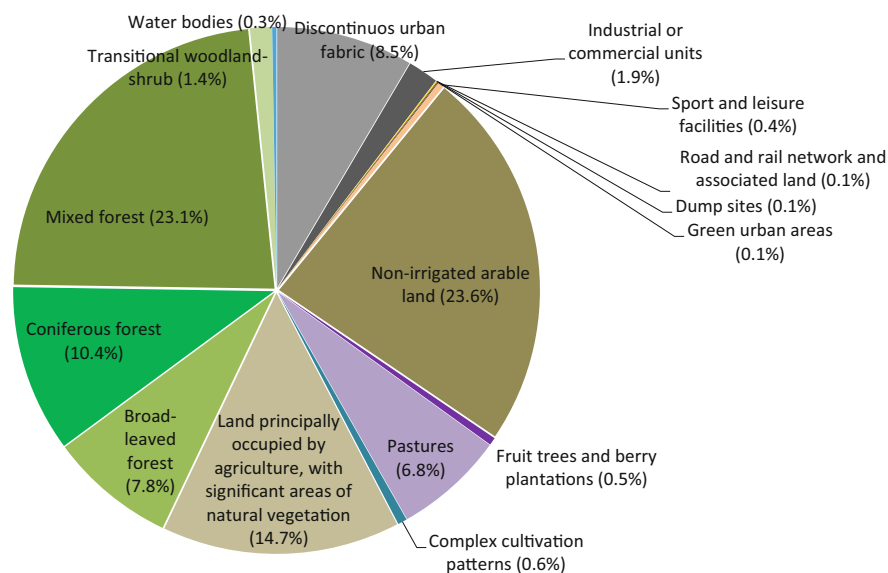


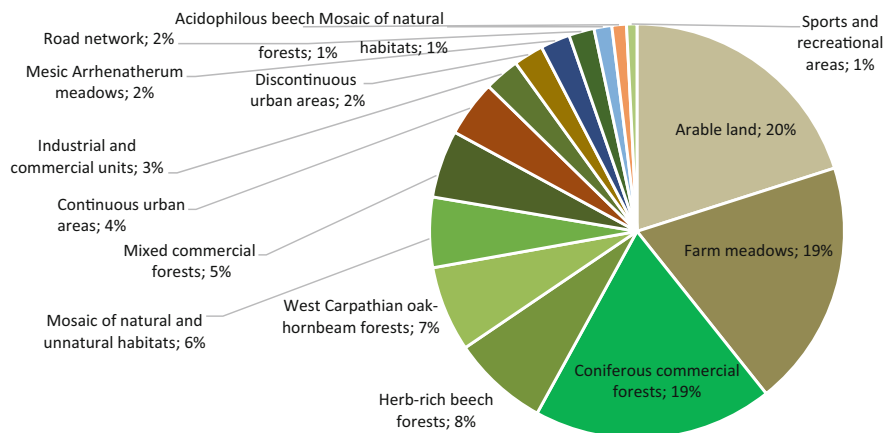
Fig. 1 Dřevnice River basin located in the eastern part of the Czech Republic



**Fig. 2** Prevailing land-use categories in the Dřevnice River basin (based on the CORINE Land Cover 2012 dataset)

relief. In terms of land-use, it is a predominantly forest–agricultural to agricultural landscape, which is divided by a relatively dense network of rural settlements. Non-irrigated arable land (23.6%) and mixed forest (23.1%) comprise the dominant type of land-use; urban areas cover almost 10% of the river basin. The Dřevnice River basin also includes a relatively large urban area, concentrated around the city of Zlín (located in southern edge of the river basin). Detailed information on the type of land-use in the Dřevnice River basin is presented in Fig. 2. An overview of the 15 most represented types of habitats is given in Fig. 3. The plain consists almost exclusively in the floodplain of the Dřevnice River and several of its major tributaries, while a large part of this flat area with fertile soil is covered by urban or industrial areas and transport infrastructures. The area is severely affected by soil erosion through water, which reaches a value of almost  $30 \text{ t ha}^{-1} \text{ year}^{-1}$  in on non-forested steep slopes [33].

The average annual air temperature in the region ranges from 7 to  $10^\circ\text{C}$ , and the total average annual rainfall is 600–1,000 mm [34], depending on the specific location within the river basin. In the headwaters, cambium soils are the predominant soil type, whereas in downslope areas and in the western part of the river basin, the Luvizems and brown soils are dominant. The Dřevnice river floodplain and floodplains of some larger tributaries are formed by gley alluvial soils (the soils occasionally fully saturated with water). More than two-thirds of the area consist of highly rugged terrain (with an average terrain slope of more than  $5^\circ$ ), which together with a specific geological subsoil (Flysch formation) significantly affect the hydrological regime of local watercourses (especially in terms of accelerating runoff). The



**Fig. 3** Fifteen most frequent habitats (both natural and unnatural) in the Dřevnice River basin (using data from [37])

Dřevnice River originates in the highlands located in the north-eastern part of the basin at 560 m above sea level (a. s. l.) and empties into the Morava River (177 m a. s. l.) near Otrokovice city, 42.3 km from the spring area. The average long-term discharge at the mouth to the Morava River is  $3.15 \text{ m}^3 \text{ s}^{-1}$  [35]. There are two dams located in the basin. One is the Slušovice water reservoir, situated directly on the Dřevnice River with a total retention volume of 9.95 million  $\text{m}^3$ , the main purpose of which is flood protection and ensuring minimum ecological flows in dry periods. The second dam is the Fryšták water reservoir on the Fryštácký Brook, which has a volume of 2.95 million  $\text{m}^3$  and was implemented for the same use as the Slušovice dam. The Dřevnice River basin is relatively prone to the occurrence of floods, either by summer floods caused by long-lasting rains or flash floods, which typically affect especially smaller watercourses and tributaries of the Dřevnice River. The largest floods recently recorded in the study area were observed in 1987, 1997, 2006, and 2010 [36], with residential houses always being flooded and property damages caused. Due to frequently recurring floods, technical flood protection measures were implemented in various parts of the river basin, especially within the Zlín City (see the example in Fig. 4).

## 2.2 Modelling of the Surface Runoff Source Areas

In order to analyse the water retention capacity of soils in the study area, a recently developed LOREP model [38] was applied. The LOREP model is a tool for the identification and spatial localization of areas with low water retention capacity, allowing to work with a structured catalogue of non-technical measures (e.g., implementation of grass belts in arable land, and change in sowing procedures) to





**Fig. 4** Flood dike delimiting the polder area (on the right side), as an inundation area of the Dřevnice River on the outskirts of Zlín City, Czech Republic

increase and support the water retention function of the landscape. One of the main advantages of the LOREP model is the ability to capture multiple flows in sloping terrain, which many other hydrological models do not allow (they work only with single flow direction – i.e. runoff from one pixel to a neighbouring pixel with lower altitude). The model is based on the use of GIS technology and available hydrological equations. The whole model consists of four consecutive steps: (1) the determination of the volume of territorially specified direct surface runoff (runoff caused by and directly following a rainfall or snowmelt event), (2) the spatial delineation of hydrological zones of the basin (i.e. spatial distribution of sites with higher ability to retain rainwater), and (3) the localization and determination of causes of low water retention capacity.

The procedure for the computation of territorial-specific surface runoff is based on a combination of specific functions in GIS, hydrological equations of the runoff curve number method and spatially distributed unit hydrographs. The LOREP model was developed in Python and designed for ArcGIS Pro. The input data are expressed as a grid of pixels in agreement with the rules of raster representation in ArcGIS. The spatial resolution is chosen to be high enough to allow identification of the influence of linear features on the surface runoff volume.

The modelling technique itself consists of several consecutive steps:

**Table 1** Curve number (CN) categories reflecting antecedent precipitation index for 5 preceding days (API5) (according to [44]). Three categories of CN number are commonly determined for the purpose of refining the antecedent precipitation index, based on prevailing conditions

CN number category	API5 – out of growing season [mm]	API5 – during growing season [mm]
I	<13	<36
II	13–28	36–53
III	>28	>53

1. Creation of the necessary GIS layers, capturing the current land-use and hydrological characteristics of soils (an overview of all data sources used is given in Table 1),
2. Reclassification of input data into individual categories according to the runoff curve number (CN) methodology,
3. Determination of CN for individual landscape patches (homogeneous in terms of land-use),
4. Modification of CN after taking into account the antecedent precipitation index – API5 (volume of rainwater from the previous 5 consecutive days preceding to the day with the analysed precipitation event),
5. Calculation of current soil loss values (IaA),
6. Calculation of runoff height and soil water retention capacity.

The CN method is a recognized and globally used approach developed by the American Soil Conservation Service (SCS) in 1954 and documented for the first time in the National Engineering Handbook [39]. The general starting point of the methodology is the assumption that the ratio of the runoff volume to the total of torrential precipitation is equal to the ratio of the volume of water retained during runoff to the potential volume that can be retained. The potential volume of water retention depends on the soil type, surface cover, cultivation method, and previous conditions of soil moisture and vegetation [40]. Water drains can occur only after the initial loss, which is caused by interception, infiltration, and surface retention. The standard CN curve method is used to determine the runoff curve numbers according to U.S. Soil Conservation Service [41]. Individual CN curve values are available for each land-use category based on land-use type, cultivation method, hydrological conditions, and the hydrological groups of soils. Precisely defined categories are described in detail in the methodology itself [41].

The last distinguishing factor is the hydrological group of the soil: A, B, C or D. Based on CN numbers, the runoff height and the volume of water drained from the area can be estimated. With knowledge of the CN, the maximum water retention  $A$  [mm] can be calculated from the following equation:

$$A = 25.4 \times \frac{1,000}{\text{CN} - 10} \quad (1)$$

Therefore, if the torrential rain exceeds 20% of the calculated maximum water retention, the height of the drained water  $H_R$  can be calculated as (for  $H_P > 0.2A$ ):

$$H_R = \frac{(H_P - 0.2A)^2}{H_P + 0.8A} \quad (2)$$

where “ $H_R$ ” is the runoff height (mm), “ $H_P$ ” is the total of the causal precipitation measured in 24 h (mm), and “ $A$ ” is the maximum water retention (mm).

### ***2.3 Identification of Runoff Source Areas in the Dřevnice River Basin, Using the LOREP Model***

Using the above modelling approach, the runoff height and the related water retention ability of the landscape for the entire study area were computed. Our method involved the modelling of the hydrological response of the Dřevnice river basin to a causal precipitation of a total of 42 mm (during approximately 6 h of precipitation on 13 May 2020), evenly distributed over the entire area of the river basin. The previous precipitation conditions of the given locality were considered in the calculation –API5 took the value of 51.10 mm. This is based on the effect of the total precipitation in the previous days on the soil’s ability to retain further precipitation. A five-day total referred to as antecedent precipitation index (API) is commonly used [42], and was divided into three categories in this study according to the precipitation volume (see Table 1 for CN values verified for the Czech Republic). CN values were based on the spatial intersection between the soil hydrological groups and the agricultural and forest areas. By distinguishing the hydrological conditions into good, medium, and poor (respecting the methodology of SCS [41]), three variants of the layer were created. The CN value was assigned to the records according to the conversion table [43]. Since 1971, a specification of the CN values according to antecedent moisture conditions has appeared in the National Engineering Handbook (SCS 1971). Clarification of the initial losses preserves the calculated CN numbers of the mean hydrological conditions and the maximum retention resulting from them. The current value of initial losses is specified on the basis of the total precipitation in previous days. Instead of a fixed 20% of the maximum possible water retention, as in the standard SCS methodology [41], the actual value of the initial losses is calculated using the total precipitation of the last 5 days. Adjusting the initial losses has a direct effect on the change in the runoff height and outflow volume.

The meteorological station nearest to the study area (operated by the Czech Hydrometeorological Institute) is located in the town of Holešov, at a distance of about 5 km from the boundary of the basin at the closest point. The values of API5 in the growing period before the selected precipitation event (as of 13 May 2020) were taken from this station. The input data concerning total precipitation in the area of

interest correspond to real conditions, as these are data related to a selected precipitation event that occurred during Spring 2020. The selected precipitation represents an above-average precipitation event in this region – an average maximum amount in individual precipitation episodes is 38.5 mm for the period 1961–2019 and average monthly total precipitation is 52.3 mm for the same period [34]. In addition to meteorological data, information on terrain properties and surface cover is very important when solving the problem of rainfall–runoff processes; this especially includes morphometric (e.g. terrain fragmentation, slope) and morphological features (soil structure, soil depth and its particle size distribution, and other properties of the soil-forming substrate). In general, the key information includes the infiltration capacity of the soil and its maximum water retention capacity, which are characteristics that are significantly affected by anthropogenic activities, whether through the compaction of the topsoil by heavy agricultural machinery or its complete covering with artificial materials (construction of buildings, road networks and other related infrastructure) [45].

The second value affected by the total precipitation in previous days is the indicator of the initial loss. Mishra et al. [46] investigated on data from the U.S. Department of Agriculture Agricultural Research Service (USDA-ARS) Water Database. This database contains data on total precipitation and direct runoff in small river basins in the USA. They worked with many models, of which the most accurate results were achieved by the modified Mishra–Singh model (MMS) determined by the following equations:

$$IAa = \frac{\lambda + A2}{CN - A + M} \quad (3)$$

$$M = \frac{((API5 - 0.2A) \times A)}{(API5 + 0.8A)} \quad (4)$$

where  $IAa$  is the current value of the initial losses (mm),  $\lambda$  is a coefficient of individual partial losses (cm),  $A$  is the potential water retention derived from CN numbers (mm),  $M$  is the soil moisture from antecedent precipitation (%), and  $API5$  is the total precipitation in the previous 5 days (mm).

The fact that linear landscape features (such as lines of trees, indicating the riparian vegetation along the streams) can be a part of land-use analysis and represents one of the key benefits of the model. This is possible because high-resolution raster data (with a pixel size of 5 m) was used, and because the modelling focused on the hydrology of small basins (it was not necessary to work with extremely large datasets). List of all the datasets and their sources used for modelling is given in Table 2.

Freely accessible images of the Sentinel 2 satellite, captured on 18 April 2020, were used as input data to create a layer with spectral reflectance information. On the Sentinel portal [47], the image with the least extensive coverage of clouds over the study area was selected from the products available. The images were uploaded to

**Table 2** List of data sources used in the case study area

GIS layer	Data source	Data publisher	Scale	Type of classification
Land-use	Open street maps (OSM)	OSM individual contributors	1: 2,116	Each polygon has its own attribute
Hydrological soil groups (HSG)	Map of HSG	Research Institute for Soil and Water Conservation	1: 5,000	Four soil groups – A, B, C, D; according to the infiltration rate
Typological forest units	Regional forest development plan; forest typological map	Institute of Forest Management (IFM)	1: 10,000	Typological classification system of IFM
Spectral reflectance	Sentinel 2 imagery	European space Agency	10–60 m/ pixel	12 spectral bands
Aerial images	World imagery	Digital globe	1 m/ pixel	Raster data
River basin boundary	Hydrological division – river basin of IV. Stream order	T.G.M. Water Research Institute	1: 10,000	Vector data
Habitat map	Habitat mapping layer	Nature Conservation Agency of the Czech Republic	1: 10,000	Vector data, 165 habitat types

**Table 3** NDMI intervals based on moisture conditions (according to [48])

Moisture conditions	Level of moisture conditions	NDMI interval
Dry	1	–1.0–0.0
Moderate	2	0.0–0.2
Wet	3	0.2–1.0

SNAP software, in which the resolution of the bands had to be unified. After unifying the band resolution to 10 m and creating a connection of the images into a mosaic, the Normalized Difference Moisture Index (NDMI) was calculated according to the following equation:

$$NDMI_{S2} = \frac{(Band_{8A} - Band_{11})}{(Band_{8A} + Band_{11})} \tag{5}$$

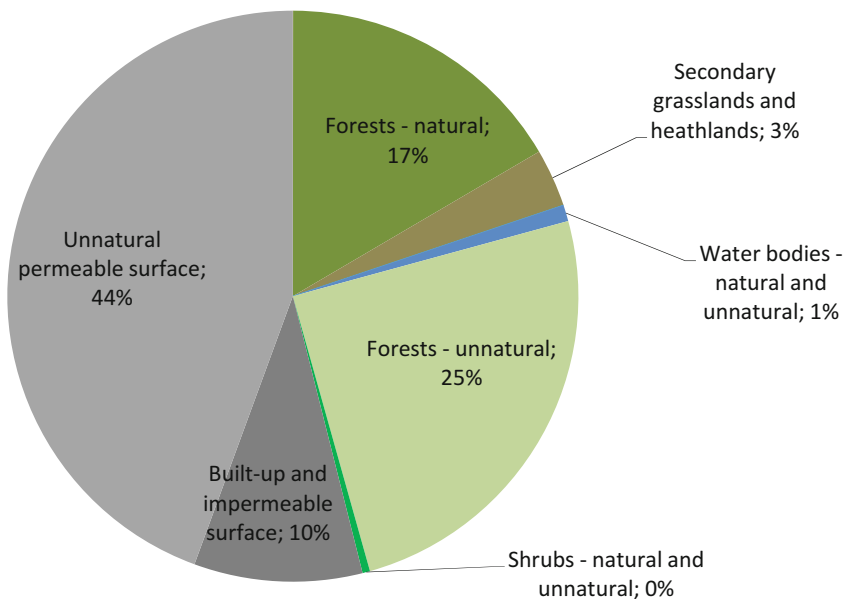
After calculating the NDMI values, the output raster was exported to the ESRI ArcGIS Pro software. This software ensured the conversion of the raster into polygons and the classification of pixel polygons into three levels of the current moisture conditions (Table 3).

The identified runoff source areas were compared with land-use categories and also with the layer of habitats occurring in the river basin (Fig. 3). For this purpose, a habitat mapping layer according to the Habitat Valuation Method – HVM [49] was used. This layer contains all habitat types occurring in the Czech Republic, including habitats significantly affected by man or completely unnatural habitats.

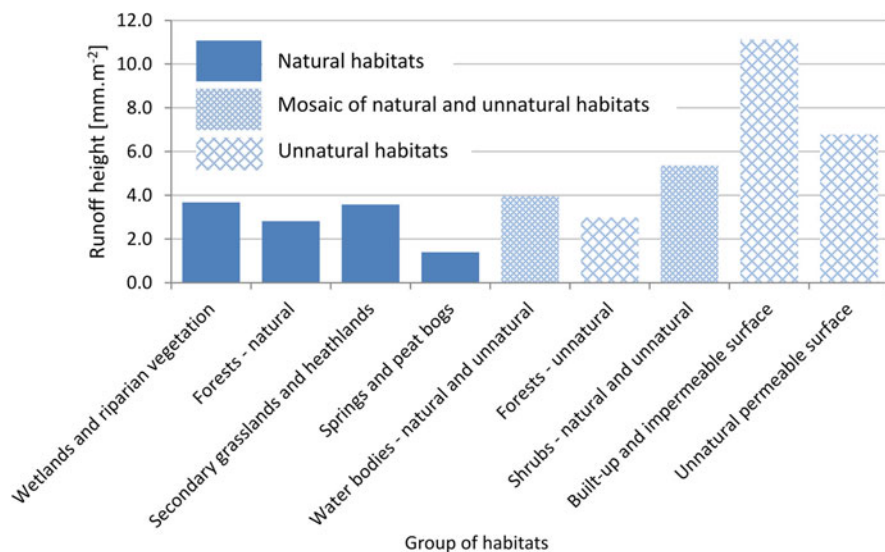
### 3 Results of the Soil Water Retention Modelling in the Case Study Area

#### 3.1 Surface Runoff Heights

Detailed information about the land-use types in the Dřevnice river basin was grouped into a total of nine categories according to their water permeability, and it was found that more than 70% of the area, it can be assumed that the permeability of the soil is not completely limited, although it is anthropogenically influenced (e.g. arable land, orchards, gardens, urban greenery and parks). The remaining 20% of the area, including natural or close-to-nature forests or scrublands, have a completely natural infiltration capacity. An overview of individual categories of land-use differentiated according to their water retention ability is given in Fig. 5. The study area was divided into two categories – “permeable” and “impermeable”, while the following categories of land cover were considered impermeable according to the CORINE Land Cover database [50]: continuous urban fabric, industrial or commercial units, road and rail network and associated land, and construction sites. In Fig. 3 these areas are included in the category of “built-up and impermeable surface”, which covers approximately 10% of the river basin. All other land-use categories were considered as permeable. Thus, permeable areas are represented in the river basin in a vast majority, although these are unnatural or nature-distant sites in many cases.



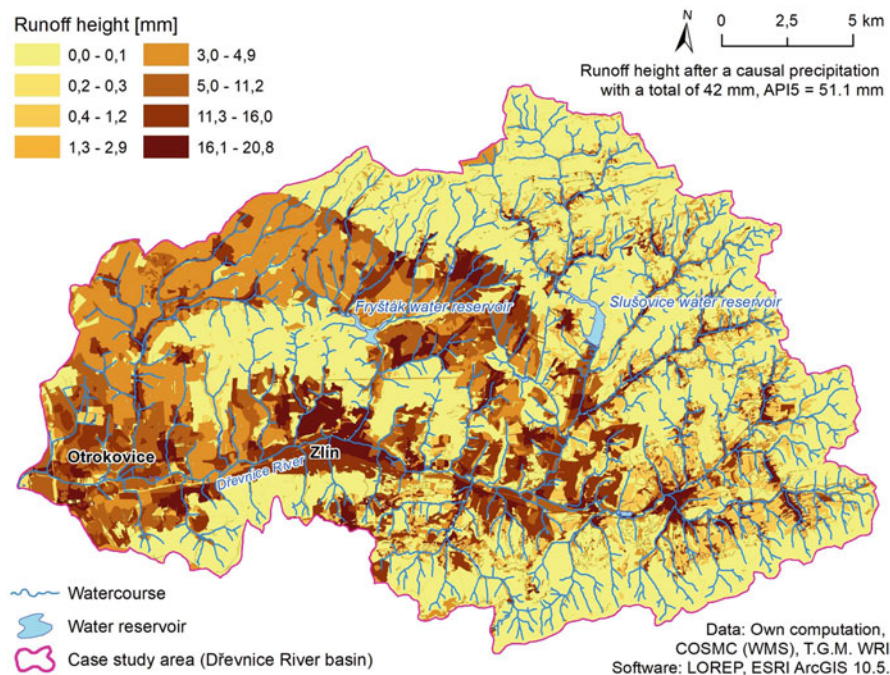
**Fig. 5** Individual land-use types merged according to their water permeability in the Dřevnice River basin



**Fig. 6** Runoff heights for the nine land cover categories, driven by a causal precipitation of 42 mm (homogeneous throughout the basin)

Within the above-mentioned nine land-use categories, the surface runoff height was calculated in the next step of this study; i.e., the volume of rainwater draining in the form of surface runoff after the described causal precipitation of 42 mm, and  $API_5 = 51.10$  mm (see Fig. 6). The results confirmed that the largest amount of water drains from the built-up and impermeable surfaces. In these localities, on average, up to 11.12 mm of water drains after a causal precipitation, which means that approximately 239 m<sup>3</sup> of water drains in this form in the Dřevnice river basin (approximately 22% of the total surface runoff volume after the investigated causal precipitation). Another significant amount of water runoff is generated under an unnatural permeable surface (e.g., green urban areas, arable land, and pastures), from which about 6.79 mm of drains after causal precipitation. Due to its large area, the presence of unnatural permeable surfaces is a key element influencing runoff processes; in the entire river basin, almost 300 m<sup>3</sup> of water flows out of these areas – i.e., about 28% of the total runoff generated in the basin. Considering natural or near-to-nature land-use categories, the highest values of water runoff after causal precipitation were recorded in wetlands and riparian vegetation (3.68 mm) and secondary grasslands and heathlands (3.58 mm). Lower values were shown by natural and close-to-nature forest stands (2.82 mm) and springs with peat bogs (1.39 mm). In total, about 24% of the total runoff from the above-mentioned causal precipitation drains from the areas covered by natural or near-to-nature landscape in the Dřevnice River basin.

In terms of the spatial distribution of surface runoff within the Dřevnice River basin, it is evident that increased runoff values may occur, especially in the areas with a more developed floodplain, such as in Zlín and Otrokovice city, as well as in



**Fig. 7** Spatial distribution of runoff height in the Dřevnice River basin after a causal precipitation of 42 mm and an antecedent precipitation index (API5) of 51.1 mm

the Racková and Fryštácký brook basins (both right-hand tributaries of the Dřevnice river in the middle and lower part of the basin). In these sites, larger units with a relatively homogeneous land-use occur more often; at the same time, this is a significantly less fragmented landscape structure compared to the rest of the river basin. Although the lower slope gradient in this area should make a positive contribution to the lower runoff heights (as verified for example by [51]), intensive land-use dominated by non-irrigated arable land and discontinuous urban fabric has the opposite effect, and the runoff intensity is therefore relatively high. Based on Fig. 7, an obvious difference in runoff processes can be seen in the eastern and western part of the river basin, while for the western part, the conditions that have already been mentioned above apply (i.e., homogeneous blocks with a uniform land-use on less sloping land, which are, however, intensively utilized). In the eastern part of the basin, we can observe different processes. The considerable rugged relief and the presence of relatively deep valleys also determine the nature of land-use: individual sites with homogeneous land-use are significantly smaller, and the runoff height is therefore very variable. The lower runoff values are rather obtained in the headwater parts of the sub-basins present here, which are often forested and less inclined (the slope ranges usually from 5 to 10°). The outlined difference between the eastern and western half of the river basin is also evident when evaluating the density of the river network, which is affected by terrain; while in the western part it



**Table 4** Average soil water retention after a causal precipitation of 42 mm, computed for the nine groups of habitats/land cover categories

Group of habitats	Average soil water retention [mm]	% of a causal precipitation
Wetlands and riparian vegetation	38.4	91.5
Forests – natural	37.1	88.3
Secondary grasslands and heathlands	37.2	88.5
Springs and peat bogs	<b>39.1</b>	<b>93.1</b>
Water bodies – natural and unnatural	38.9	92.7
Forests – unnatural	37.3	88.9
Shrubs – natural and unnatural	36.2	86.1
Built-up and impermeable surface	<b>34.8</b>	<b>82.8</b>
Unnatural permeable surface	36.7	87.3

Extreme values are marked in bold

ranges between 0.2 and 1.4 km km<sup>-2</sup>, in the hilly eastern part, it acquires values between 3.0 and 3.5 km km<sup>-2</sup> [35].

For the nine defined categories of land-use, which differ in terms of their soil permeability and degree of anthropogenic influence, the average volume of captured water after a causal precipitation of 42.0 mm (homogeneous in the whole river basin) was further calculated (see Table 4). The analysis confirmed the working hypothesis, namely that natural or close-to-nature habitat types (land-use categories) will be able to retain the largest amount of rainwater and, conversely, the lowest water retention capacity will be provided by significantly anthropogenically affected habitats. It should be emphasized that habitats classified as “built-up and impermeable surface”, in addition to continuous urban areas, include habitats of “rocks and quarries” or habitats of “landfills and construction sites”, which maintain a certain water retention function (up to 83%); i.e., the water is still infiltrated and does not drain in the form of surface runoff.

We can summarize that after the causal precipitation of 42 mm, more than 18.4 million m<sup>3</sup> of rainfall fall in the study area, and approximately 88% of this volume was retained in the river basin. Immediately after the precipitation, approximately 2.1 million m<sup>3</sup> of water drained out of the basin in the form of surface runoff, which is an amount corresponding to about two-thirds of the operating volume of the Fryšták water reservoir, located in the central part of the Dřevnice river basin. The average value of water retention in the entire analysed river basin (on all types of land cover) is 36.71 mm m<sup>-2</sup>. In order to identify specific sites where surface runoff is primarily formed, areas from which more than 20% of a causal precipitation flowing downslope as surface runoff were selected from the runoff height model (Fig. 8). As can be seen from the map in Fig. 8, the sites understood as the “surface runoff source areas” include larger cities in the river basin (especially the city of Zlín), but there is also a relatively large area of arable land in the central part of the basin, east of the Fryšták water reservoir, with high potential for surface runoff formation.

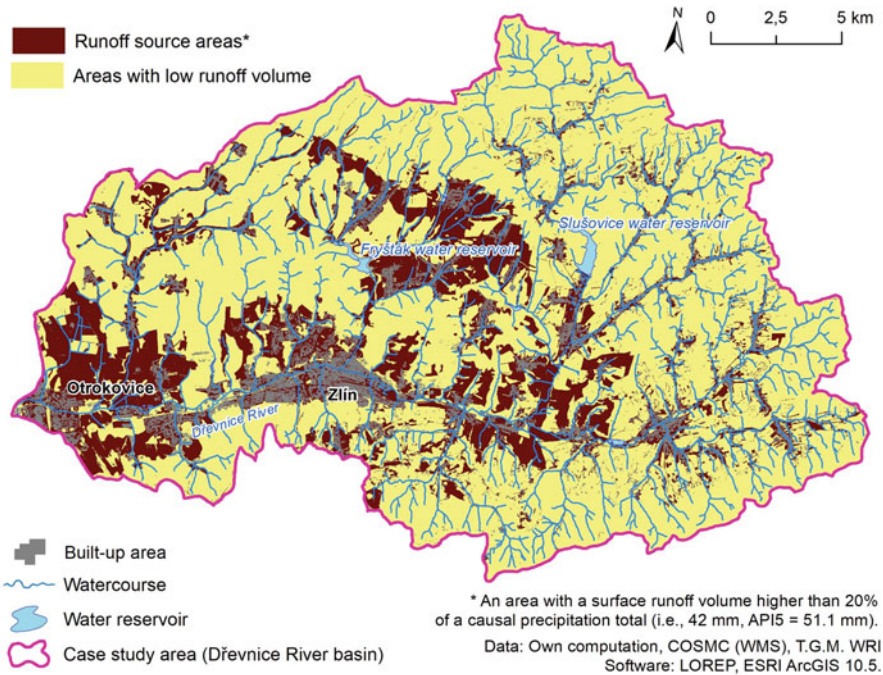
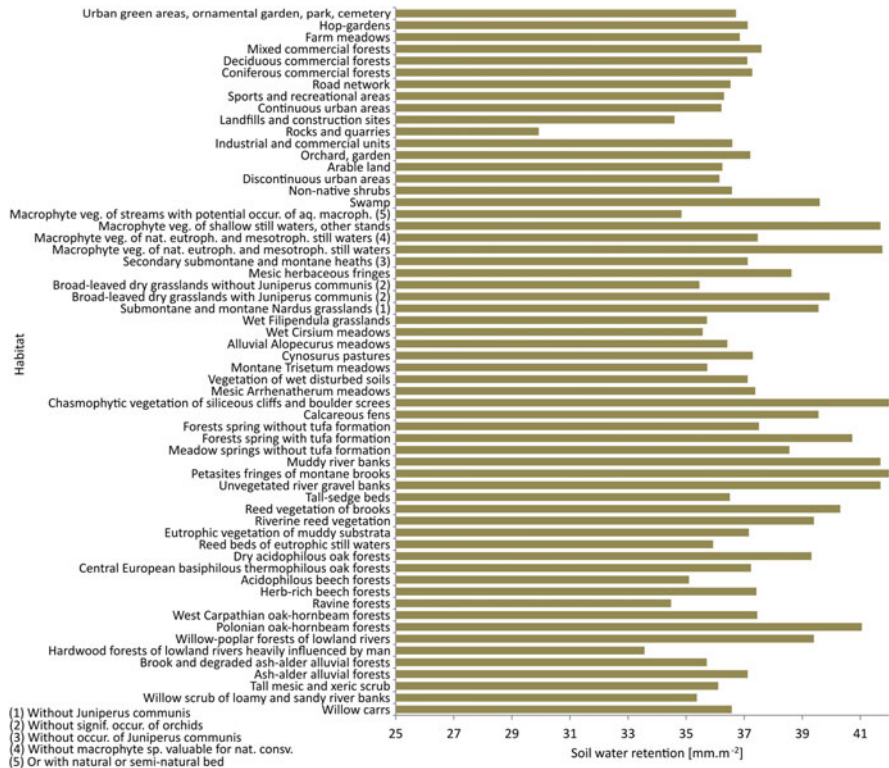


Fig. 8 Spatial distribution of surface runoff source areas within the Dřevnice River basin

### 3.2 Links between Soil Water Retention and Habitat Types

In order to obtain more detailed information about the water retention function of the landscape, the dependencies between individual habitats (natural, anthropogenically influenced and completely artificial habitats were taken into account) and their soil water retention capacity were analysed in addition to the relationship between land-use and soil water retention. A more detailed look at the soil water retention within the habitats occurring in the area of interest (see Fig. 9) shows a relatively large variability between individual types of habitats. High water retention values, similar to the amount of water fell during the analysed precipitation episode (i.e., 42.0 mm), have been reported in several habitats, but in many cases, vegetation in close proximity to watercourses (e.g., “*Petasites* fringes of montane brooks”, “muddy river banks”, and “reed vegetation of brooks”) occur on permanently wet soils or muddy substrates, and low values of surface runoff are therefore a completely natural phenomenon due to permanent waterlogging. Among the habitats in which a large water retention capacity was found, and at the same time in which the vegetation was not directly conditioned by the presence of watercourses, we can especially highlight “Pollonian oak-hornbeam forests” (with computed soil water retention of  $41.05 \text{ mm m}^{-2}$ ), “Broad-leaved dry grasslands without significant occurrence of orchids and with *Juniperus communis*” ( $39.94 \text{ mm m}^{-2}$ ) and “Dry



**Fig. 9** Soil water retention capacity computed for all habitat types observed in the Dřevnice River basin, following a causal precipitation of 42 mm

acidophilous oak forests“ (39.32 mm m<sup>-2</sup>). These habitats can therefore be considered to be very effective in terms of their ability to retain rainwater and improve the water retention function of the landscape. On the contrary, habitats that are significantly anthropogenically influenced are characterized by the most limited water retention function; e.g., “landfills and construction sites” (34.60 mm m<sup>-2</sup>) and “hardwood forests of lowland rivers heavily influenced by man” (33.57 mm m<sup>-2</sup>). Low values were also recorded in natural or near-to-nature habitats, but these were again cases in which soil water retention was not possible or was significantly limited for natural reasons, such as “vegetation of exposed fishpond bottoms” (31.29 mm m<sup>-2</sup>) or “ravine forests” (34.48 mm m<sup>-2</sup>). Overall, it can be stated that the “mixed commercial forests” (37.60 mm m<sup>-2</sup>) and “coniferous commercial forests” (37.28 mm m<sup>-2</sup>) have the highest water capacity from a set of unnatural habitats or habitats most significantly affected by humans.

All analysed habitats occurring on naturally very poorly permeable soils (i.e. a total of 28 habitats) were divided into three categories for easier interpretation, depending on their maximum water retention potential. The first category included habitats with the lowest ability to eliminate surface runoff and increase the water

**Table 5** Habitats classified into three categories according to their water retention potential on poorly permeable soils (hydrological group “D”)

Category	Max. soil water retention [mm]	Habitats
I	25.99	Willow scrub of loamy and sandy river banks Tall-sedge beds Vegetation of exposed fishpond bottoms
II	38.62	Hardwood forests of lowland rivers heavily influenced by man Ravine forests Eutrophic vegetation of muddy substrata Forests spring with tufa formation Forests spring without tufa formation Broad-leaved dry grasslands without significant occurrence of orchids and with <i>Juniperus communis</i> Macroph. Vegetation of natural eutrophic and mesotrophic still waters without macroph. Species valuable for nature conservation
III	41.09	Tall mesic and xeric scrub Ash-alder alluvial forests Brook and degraded ash-alder alluvial forests Polonian oak-hornbeam forests Carpathian oak-hornbeam forests Mesic Arrhenatherum meadows Herb-rich beech forests Acidophilous beech forests Central European basiphilous thermophilous oak forests Dry acidophilous oak forests Reed beds of eutrophic still waters Meadow springs without tufa formation Vegetation of wet disturbed soils Cynosurus pastures Wet Cirsium meadows Wet Filipendula grasslands Broad-leaved dry grasslands without significant occurrence of orchids and without <i>Juniperus communis</i> Mesic herbaceous fringes

retention function of the landscape (a maximum of 62% of the volume of causal precipitation was captured), but these were mostly relatively specific habitats (see Table 5) that were dependent on the presence of a watercourse, and their potential enlargement is possible only in isolated cases (e.g., during complex restorations of watercourses and their floodplains). The second category included more habitats (only examples of the most widespread habitats, covering the largest area are given in Table 5) that had a “moderate” ability to retain rainwater (up to 92% of the precipitation volume). The third category included habitats with the greatest potential to perform a water retention function (in exceptional cases, they can retain up to 98% of the precipitation volume). In the given overview, only the most represented habitats within the study area are mentioned. It should be noted that the stated

maximum values of soil water retention in individual habitats are valid for causal precipitation, taking into account the antecedent precipitation of 51.1 mm in 5 days.

## 4 Discussion and Conclusions

The results of the analysis of soil water retention and related surface runoff source areas are consistent with the established hypotheses, concerning the potential influence of the habitat type on the volume of surface runoff, if we neglect the influence of terrain properties. Although the main variables shaping runoff conditions are mainly the soil properties (infiltration capacity), terrain roughness (steepness of slopes), and prevailing land-use category, it has been proven that individual habitat types also have a verifiable effect on the hydrological regime of the landscape. Based on data from the forest-agricultural river basin of a medium-sized watercourse located in the Czech Republic, it was verified that the natural and near-to-natural habitats are characterized by a higher ability to accumulate water and can thus make a positive contribution to mitigating the effects of climate change, manifested in Europe by more frequent flash floods [52].

However, it must be taken into account that the spatial distribution of individual habitat types is also the result of local conditions, including soil properties; thus, the primary variables determining the character of runoff processes in the basin remain the relief and soil. At the same time, it is important to mention that the modelling technique used do not take into account the rainfall interception by vegetation canopy or the effect of evapotranspiration, and so the reported final values of water retention and surface runoff for different habitats will actually be lower, especially in forest habitats. The interception loss can be relatively high for certain types of habitats [53]. Kermavnar and Vilhar [54] state, based on a case study from Slovenia, that the highest values of interception are reached by a mixed forest (18.0% of causal precipitation) and the intermediate level of interception rate (7.1% of causal precipitation) was found for the floodplain hardwood forest. Černý et al. [55] state that, in the Czech Republic, the interception loss of the spruce forests canopy can be up to 30% of the causal precipitation (the exact interception loss depends on the total precipitation – e.g., interception of 30% can be valid for gross precipitation up to 15 mm).

The results from our study, therefore, relate exclusively to the influence of the character of individual habitats on the formation of surface runoff (in terms of their species composition, representation of herbaceous, shrub and tree vegetation floor, and average surface cover due to vegetation).

Data on the potential impact of individual habitats on surface runoff coefficient, and thus the water retention capacity of the given habitats, can represent a relatively important source of information when designing restoration projects for terrestrial parts of river landscapes, but also in other localities outside the river landscape, aimed at mitigating the frequency of hydrological extremes.

Within the study area, localities with an increased potential to generate surface runoff (i.e., performing as runoff source areas) were identified, which were located mainly in the built-up area. The highest runoff values (more than 38% of the initial precipitation), and thus the minimum water capacity, were identified in continuous urban areas located on sloping land; i.e., especially larger settlements and the outskirts of cities. Therefore, it can be stated that the source areas of surface runoff in the Dřevnice River basin are located out of the headwater areas of the main watercourses, which drain larger parts of the river basin. This fact is relatively favourable in terms of groundwater quality and quantity, as in the spring areas in the eastern part of the river basin there is a significant infiltration of rainwater, which positively contributes to groundwater replenishment and the overall balance of discharges in local watercourses. The higher water retention capacity of the landscape in the headwater areas of local watercourses also has a positive impact on reducing the level of flood risk in municipalities located in narrow valleys where these streams flow. The retention of higher amounts of water and its subsequent release reduces the likelihood of potential flash floods, because these occur after intense rainfall in an environment that is unable to retain rainwater and to distribute water runoff over a longer time interval.

For more effective flood protection of larger towns in the lower part of the river basin, it is appropriate to implement certain measures in the floodplains along the middle part of the watercourses and its headwater areas, which would increase the water retention capacity of the landscape under the conditions of ongoing climate and environmental change. Based on our results that identified the runoff source areas located especially in the central part of the river basin, mainly occupied by agricultural areas, selected structural measures can have potential for reducing surface runoff volume – e.g. the creation of retention ponds, flood polders and fills, changes in sowing practices or grassing of river banks. In the headwater area, non-structural measures such as change in infrastructure policy or land-use management by planning tools become important factors, because there is no immediate surface runoff in these localities, but a higher ability of the landscape to retain rainwater can have a positive effect on ensuring a balanced discharge in watercourses and eliminating the occurrence of possible extreme hydrological situations. As the model outputs confirmed that the water retention capacity is significantly higher in several selected habitat types (e.g., ash-alder alluvial forests or Polonian oak-hornbeam forests), it is appropriate to support the expansion of these habitats where conditions allow for river and floodplain restoration plans. The vast majority of the above-mentioned measures can be classified as nature-based solutions, which are characterized by lower financial demands of implementation and at the same time these measures increase the ecological stability and support the quality of ecosystem services provided. In general, we can summarize that in the current intensively utilized agricultural landscapes the surface runoff source areas are very often concentrated in the middle and lower part of the Dřevnice River basin, within wider floodplains whose naturally higher water retention capacity is degraded by the presence of artificial and impermeable surfaces. Therefore, the measures that are feasible especially in the middle river basin zone (e.g. the construction of flood

polders or changes in sowing practices in the case of an agricultural landscape) should be implemented in order to eliminate the risks associated with the formation of surface runoff (soil erosion and possible occurrence of flash floods in particular).

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