POST-FIRE HYDROLOGICAL ANALYSIS; CZECH BOHEMIAN SWITZERLAND NATIONAL PARK

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Abstract

In 2022, Bohemian Switzerland National Park experienced the largest wildfire in the recent history of the Czech Republic, affecting over 1,000 hectares. The aim of this study was to perform a hydrological assessment of the post-fire conditions in the Sucha Bela sub-basin, located in the park, using the HEC-HMS software package. Rainfall–runoff relationship data and landscape classification data specific to the Sucha Bela sub-basin were categorized using Sentinel-2 imagery and local surveys. The results showed that the forest fire temporarily affected the soil infiltration capacity and therefore influenced runoff.

Keywords

Post-fire, Sentinel-2, Hydrology, Rainfall–Runoff, HEC-HMS

1 INTRODUCTION

Forest fires pose a significant risk to the sustainability of various plant ecosystems and the development of wildlife habitats. In addition, the assessment of the environmental impacts of forest fires is crucial in today's context, as they affect the runoff regime, the transport of various chemical elements, greenhouse gas emissions, and also have an impact on local communities [1]. The consequences of fires not only cause major stress on the water balance of ecosystems but also alter soil structure, mineral content, and soil acidity, thus affecting the hydraulic properties of the soil.

The 2022 wildfire in Bohemian Switzerland, the largest in recent Czech history, burned over 1,000 hectares and significantly altered the hydrology and vegetation of the region [2]. The loss of vegetation reduced canopy interception and soil stability, increasing the risk of surface runoff and soil erosion [3]. The fire likely affected the soil's hydrological properties, such as infiltration capacity, resulting in increased flood risk and changes in landscape water retention. Vegetation recovery is critical to stabilizing soils and restoring ecological and hydrological balance. However, this can take years, particularly in areas where intense heat has altered soil structure and nutrient availability.

In this study, a hydrological model of the Sucha Bela sub-basin (EPSG:32633) was created using the Hydrologic Modeling System (HEC-HMS) software package to assess the impacts of the fire on the runoff regime. The changes on the soil surface after the fire, including soil erosion rills and different vegetation patterns, were examined using Sentinel-2 imagery with a controlled classification approach. This helped us to better understand the impact of the post-fire changes in vegetation cover on runoff processes. The influence of these changes on the Curve Number (CN) values was assessed. The hydrological soil class for this study was determined using the Global Hydrologic Soil Groups (HYSOGs250m) with a 250-meter horizontal resolution [4]. In addition, physical soil samples were collected at the site for further comparative analysis. The hypothesis that post-fire changes in vegetation cover influence runoff was evaluated by analyzing how vegetation and runoff evolve, and whether the runoff regime shows a tendency to return to pre-fire conditions [5].

The objective of this study is to apply a CN classification model and evaluate the weighted outcomes to assess the impact of the wildfire on hydrological behavior.

Received 20/12/2024/Accepted 14/05/2025/Published 30/09/2025 DOI 10.13164/juniorstav.2025.25044

2 METHODOLOGY

To assess the changes in soil hydraulic properties across different land uses, saturated hydraulic conductivity (Ks) was measured immediately after the wildfire in September 2022, later in September 2023, and in November 2024, after vegetation and soil had partially recovered. The study focused on two typical vegetation stands: a beech forest that was affected by the wildfire but where the trees were resilient, and a spruce forest where the trees had already been killed by a bark beetle infestation before the fire. Undisturbed soil samples with a volume of 250 cm^3 were collected from the topsoil at each site, carefully packed to prevent disturbance, and transported to the laboratory. The saturated hydraulic conductivity was then measured using a KSAT device (METER Group, USA).

The hydrological analysis was performed using the HEC-HMS software package for a wildfire-affected area. The exact study area comprises a sub-basin of the Sucha Bela Stream, a tributary of the Kamenice River. A DEM (Digital Elevation Model) of the Czech Republic with a 2-meter horizontal resolution (DMR5G) was utilized for catchment delineation and further analysis [6]. The elevation map was processed using QGIS software. In addition, the DEM was compared with the DSM (Digital Surface Model) and DTM (Digital Terrain Model) reconstructed from UAV (Unmanned Aerial Vehicle) data (DJI M300). The DSM was constructed by photogrammetry, and the DTM was obtained by laser scanning. An illustrative elevation difference between the DSM and DTM is shown in Fig. 1.

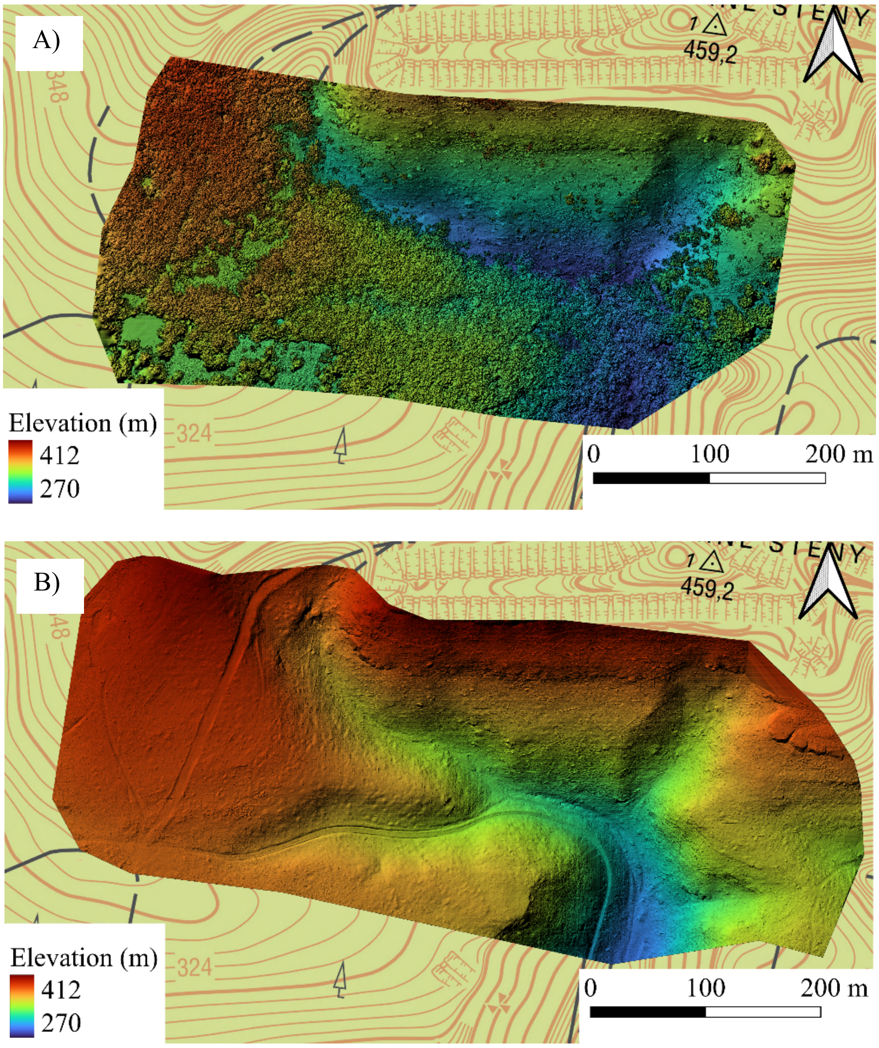

Fig. 1 A) Comparison of the photogrammetric DSM; B) LIDAR DTM shown in a detail of Sub-basin-4.

The hydrological analysis included the extraction of sub-basins and river channels. The sub-basin boundaries and river flow directions are shown in Fig. 2.

DOI 10.13164/juniorstav.2025.25044

Runoff in the HEC-HMS model was simulated using the CN method. The inputs for the CN method were determined using a hydrological soil group map and a land-use value map. The hydrological soil group map was obtained from the DAAC (Distributed Active Archive Center) database [4].

The land-use value map was based on Sentinel-2 images with atmospheric correction. A supervised classification was performed for the Sucha Bela sub-basin. During the classification process, only minor land-use changes were observed in parts of the watershed, while other areas– classified as forested or burned– showed temporal variability. Using the classification image, areas corresponding to hydrological soil groups were intersected using the Tobler interpolation method, and a new map of CN values was generated. The average CN values for the sub-basins were calculated using the zonal statistics method. The CN method was then applied to each sub-basin. For the burned areas, the initial abstraction was set to zero. The SCS Unit Hydrograph method was selected as the transformation method, and the lag time (Lag) and the time of concentration (Tc) were calculated using Equations (1), (2), and (3):

$$\mathrm{Tc} = \frac{\mathrm{l}^{0.8}(\mathrm{S}+1)^{0.7}}{1{,}140\mathrm{Y}^{0.5}} \tag{1}$$

$$\mathrm{Lag} = 0.6\mathrm{Tc} \tag{2}$$

$$\mathrm{S} = \frac{1000}{\mathrm{CN}} - 10 \tag{3}$$

Where *Tc* is the time of concentration in hours (h), *Lag* is the lag time of concentration in hours (h), *l* is the flow length in feet (ft), *Y* is the average sub-basin slope in percent (%), *S* is the maximum potential retention in inches (in), and CN is the average sub-basin curve number.

The Muskingum method was applied to the stream channel and its tributaries down to the outflow of the sub-basin. Regarding the Muskingum parameters, both K and X values were set to 0.5. The values calculated in Equations (1), (2), and (3) are shown in Tab. 1. Water discharge, average water temperature, and daily total precipitation data for the Kamenice River near the Sucha Bela outlet were obtained from on-site monitoring provided by the Czech Hydrometeorological Institute. The Specified Hyetograph was used to input precipitation into the HEC-HMS meteorological model to perform and evaluate the hydrological analysis [7], [8].

Tab. 1 Values used in the model.

	CN	**S (in)**	**l (ft)**	**Y (%)**	**Tc (h)**	**Lag (h)**
Sub-basin-1	75.9	3.2	1537.1	53.7	0.115	0.069
Sub-basin-2	90.1	1.1	1146.7	107.9	0.039	0.023
Sub-basin-3	87.4	1.4	1108.5	92.0	0.046	0.027
Sub-basin-4	81.9	2.2	2233.5	25.8	0.186	0.111
Sub-basin-5	88.2	1.3	1866.8	77.2	0.075	0.045
Sub-basin-6	90.1	1.1	1731.8	81.5	0.063	0.038
Sub-basin-7	76.0	3.2	1780.6	49.5	0.134	0.080

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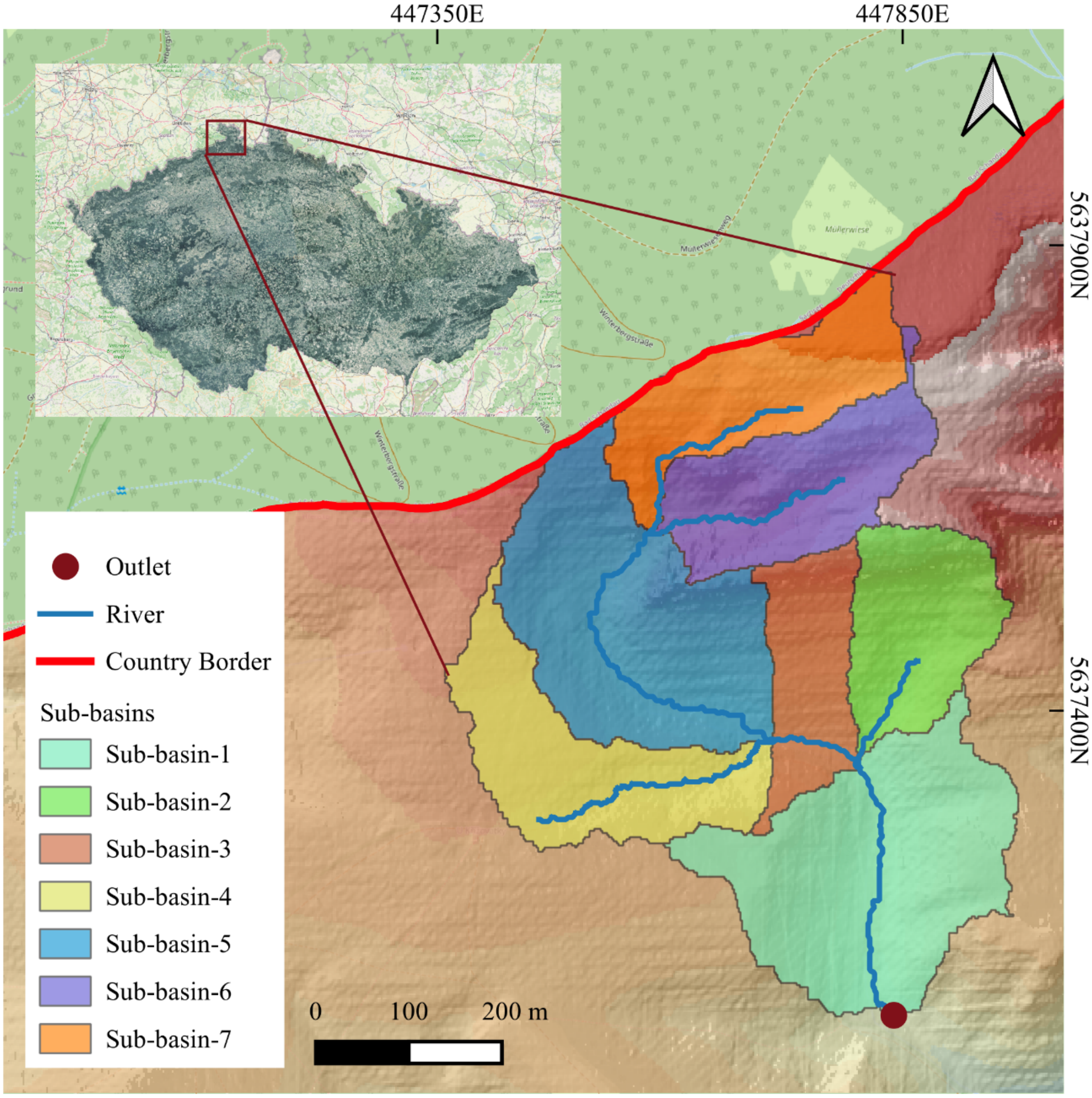

Fig. 2 The Sucha Bela study area in the Czech Bohemian Switzerland National Park (EPSG-32633).

3 RESULTS

The results indicate distinct differences in Ks values between the beech and spruce forests (Fig. 3), as well as temporal changes in the spruce forest following the wildfire. The beech forest exhibits consistently higher Ks values compared to the spruce site across the measurement periods, with no apparent change over the first two years and a significant decrease in 2024. However, there is significant spatial variability in Ks values within the beech forest, as shown by the large error bars. In contrast, the spruce forest shows a substantial temporal change in Ks values. Immediately after the fire, the Ks values in the spruce forest were very low, with an average of 12.2 cm/d, likely due to the combined effects of soil degradation and fire-induced hydrophobicity. In September 2023, Ks values increased to 53 cm/d, and in November 2024 to an average of 90 cm/d, reflecting soil recovery and potential improvements in soil structure as vegetation began to regenerate.

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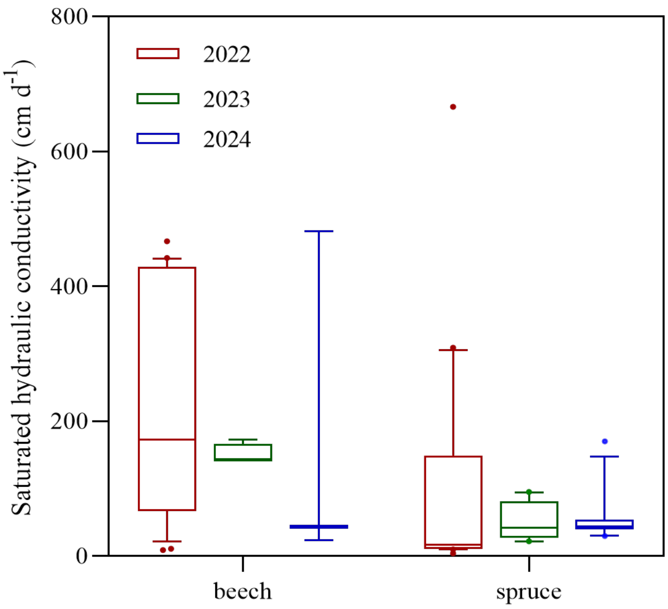

Fig. 3 Saturated hydraulic conductivity measured under beech and spruce burned sites in 2022, 2023, and 2024. The boxes show the interquartile range (25th–75th percentiles) with the median line inside. Whiskers represent the 10th and 90th percentiles; dots indicate outliers.

The results of the hydrological model, illustrating the runoff dynamics within the Sucha Bela sub-basins, are presented in Tab. 2. The hydrographs reflect the flashy response of the catchment (Fig. 4). The discharge in the Sucha Bela Stream exhibits an intermittent pattern, with sharp peaks occurring immediately after significant rainfall events, followed by a rapid recession. Extended periods of minimal or no flow are common, particularly during the summer and autumn months. This flashy behavior is likely influenced by the steep slopes, highly permeable shallow sandy soils, a complex network of fractures in the sandstone bedrock, and the presence of several disconnected aquifers. Discharge data for the stream are limited, as the monitoring station was only established in September 2024. However, preliminary comparisons suggest that the HEC-HMS model tends to overpredict discharge, with no-flow conditions occurring more frequently in reality than the model indicates.

Tab. 2 Simulated peak discharge and flood volume for the event on 26 September 2022.

	Drainage Area (km^2)	**Peak Discharge (m^3/s)**	**Volume (1,000 m^3)**
Outlet	0.303	0.072	100.528
Sub-basin-1	0.069	0.016	21.046
Sub-basin-2	0.031	0.008	10.203
Sub-basin-3	0.024	0.006	7.665
Sub-basin-4	0.042	0.010	13.123
Sub-basin-5	0.066	0.016	21.502
Sub-basin-6	0.037	0.009	12.171
Sub-basin-7	0.035	0.008	10.644

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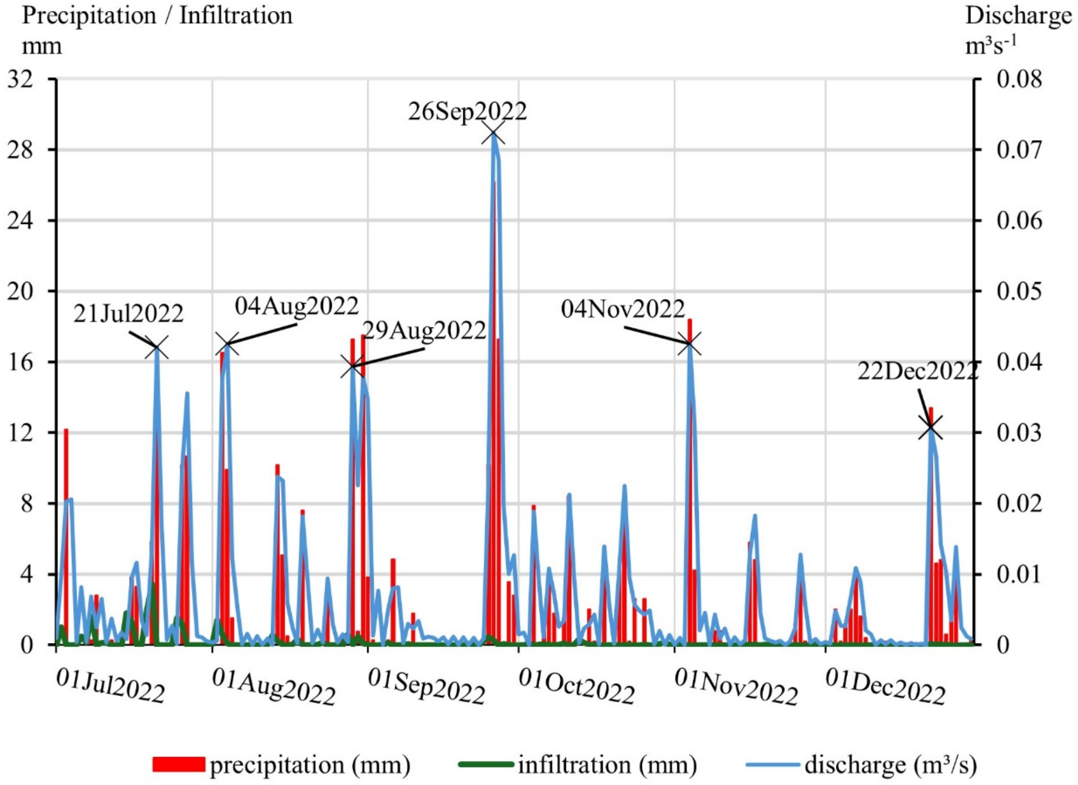

Fig. 4 Simulated discharge at the outlet in response to precipitation events.

4 DISCUSSION

The wildfire that occurred in 2022 had a significant impact on both topsoil hydraulic properties and surface vegetation density. The results of the saturated hydraulic conductivity measurements reveal notable differences in soil recovery dynamics between the two vegetation types studied. In the beech forest, the Ks values remained relatively stable between September 2022 (immediately after the wildfire) and November 2024 (two years after the wildfire), suggesting resilience in soil structure even after the fire. The large range of Ks values observed in both measurement periods indicates high spatial variability, likely influenced by the heterogeneity of soil properties and the capacity of beech trees to mitigate fire impacts through root system stability and organic matter retention. In contrast, the burned spruce forest exhibited a substantial increase in Ks values over the two years. The recovery of soil structure is driven by vegetation regeneration, the decomposition of organic debris, and the gradual restoration of soil porosity, as previously reported in the literature [9]. This marked change highlights the potential for soil recovery even in severely impacted areas. These results demonstrate that vegetation type and post-fire conditions strongly influence soil hydraulic recovery processes.

This alteration significantly affected the potential runoff model, influencing runoff dynamics and potentially increasing flood risk. The wildfire reduced the water infiltration capacity of the soil, particularly in severely burned spruce forests. From a land-use perspective, the distinction between undisturbed forest and burned land is essential for accurate spatial assessment. The calculated time of concentration reflected the response of sub-basins to precipitation events. Post-fire landscape changes suggest a shortened runoff response time, potentially resulting in more rapid flow and, consequently, more intense flood events. Moreover, the assumption of zero initial water retention at the start of the simulation may lead to results that do not fully capture the true hydrological dynamics of the area, especially as vegetation begins to recover.

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5 CONCLUSION

The application of the HEC-HMS model to the fire-affected region integrates various data sources, including UAV imagery, satellite imagery, precipitation and discharge records, temporal changes in saturated hydraulic conductivity, and land-use classifications, to assess hydrological changes within the affected area. The results show changes in runoff behavior, primarily driven by the loss of vegetation cover and changes in soil infiltration capacity. The Muskingum and Curve Number (CN) methods provide critical insights into the dynamics of surface runoff and river discharge, enhancing the understanding of flood risk in the study area. Although this preliminary study provides valuable insights, the accuracy of the results may be affected by the use of generalized meteorological and soil data, which have certain limitations. To improve the robustness of future models, it is essential to incorporate more precise, site-specific meteorological datasets and detailed laboratory soil characterization. Such improvements would allow a more accurate representation of hydrological processes and bring the model closer to real-world conditions. In summary, this study contributes to a deeper understanding of runoff dynamics in fire-impacted regions and highlights the importance of hydrological modeling in assessing environmental change. It also demonstrates the impact of model-based predictions on flood risk management and environmental mitigation strategies.

Acknowledgements

This research was supported by the Technology Agency of the Czech Republic, grant no. SS07010308, and by the Grant Agency of the CTU in Prague, grant no. SGS23/155/OHK1/3T/11.

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