Cent. Eur. For. J. 70 (2024) 176–186 sciendo DOI: 10.2478/forj-2024-0001

CENTRAL EUROPEAN Forestry Journal

ORIGINAL PAPER

Unseen consequences: tracking soil water potential in forests influenced by coal mining

Jaroslav Vido*, Paulína Nalevanková, Jiří Kučera

Technical University in Zvolen, Faculty of Forestry, T. G. Masaryka 24, SK-96001, Zvolen, Slovak Republic

Abstract

Over the past decades, anthropogenic disturbance of geological structures has been significantly documented in Slovakia, mainly driven by the national economy's demand for mining resources. Among these resources, brown coal, primarily mined in the Upper Nitra coal basin in the Prievidza district (Slovakia), has been essential. Mining activities around town of Handlová, and villages of Koš, Cígeľ and Sebedražie, particularly at the Cígeľ coal mine, have induced several geological defects. These defects, characterised by large cracks and local landslides, disrupt the hydrogeological conditions, significantly impacting the soil water regime stability of the forest ecosystems in these damaged areas. This study investigates the variability and dynamics of the soil water potential in a mining-affected site (Račkov laz) compared to an intact reference area (Čertove chodníky) between 2020 and 2022. Our findings suggest that mining activities could have substantial implications for the soil water regime and, consequently, the ecological stability of forest ecosystems.

Key words: soil water potential; anthropogenic disturbance; forest ecosystems; water regime; undermining; ecological stability

Editor: Bohdan Konôpka

1. Introduction

Anthropogenic disruption of geological structures has significantly occurred in Slovakia over the past decades (Halmo et al. 2010). The reason was the logical need for mining and obtaining mineral resources for the national economy. One of the essential resources was brown coal, mined mainly by underground and surface methods in the Upper Nitra coal basin in the Prievidza district. Brown coal was mined mainly by deep method in the vicinity of the town of Handlová, the village of Koš, and the villages of Cígeľ and Sebedražie (Drdoš et al. 1994; Machajová et al. 2000). Near the last mentioned village is the Cígeľ mine, the activity of which caused a lot of geological faults, which are characterized by extensive cracks, local landslides and collapses on the west part of the Vtáčnik Mts. and its foothills (Jakál 1998; Baliak & Stríček 2012). Mentioned mining activity disrupted the geological continuum and influenced the hydrogeological conditions of the area (Ivanička 1959; Jakál 1998; Machajová et al. 2000; David et al. 2013).

Geological faults in the area of interest were widely described, and their origin justified in the works (Machajová et al. 2000; Baliak & Stríček 2012). Aware of the extent and impacts of this activity, much effort was devoted mainly to research into the impacts of mining activity in the Upper Nitra coal basin in the area of the village of Koš, where rare anthropogenic lakes and wetlands were formed by sinking of the basin floor due to excavation of the coal seam (Jakál 1998). These rightly became the subject of research interest of the conservation as well as agricultural professional public (David et al. 2013).

However, the forest landscape in the foothills of the Vtáčnik mountain range, affected by undermining and damage to the substrate (Machajová et al. 2000; Baliak & Stríček 2012) with many recorded and described geological faults, was not the subject of this interest to a greater extent. Nevertheless, examples from deep mines abroad showed that disruption of the hydrogeological continuum impacts the surface and ground waters in foothills, slopes, and mountains (Goswami 2015; Tang et al. 2019; Kolapo et al. 2022). Also, historically, some indications of such processes in the area of our interest have been published (Ivanička 1959; Jakál 1998). A logical question arises whether such antropogenous activities could significantly impact forests (or forest

*Corresponding author. Jaroslav Vido, e-mail: vido@tuzvo.sk

environment) undermined by Upper Nitra coal mining activities. In addition, since the debate on the expected and expectable impacts of climate change on forest ecosystems is a serious interest of the scientific community, we consider as very interesting to examine the possible so-called "unseen consequences" of the mining activities resulting in a disturbed hydrogeological environment on the dynamics of soil water potential of forest soil in the considered locality.

Even though the physiological response of trees or other plants is not functionally dependent on the dynamics of soil water potential, it can, to some extent, indicate their reactions in conditions of extraordinary weather situations, especially drought (Vido et al. 2016; Stojanović et al. 2017). Notably, empirical evidence strongly supports the notion that drought stress primarily impacts the fine roots of forest trees, leading to rapid modifications in the rhizosphere (Konôpka & Lukac 2013). Subsequently, visible effects, including defoliation/discoloration at the crown level (e.g., Pajtík et al. 2022), and reduced growth (Wiklund et al. 1995), predominantly observed through stem increment studies (Bošeľa et al. 2013), become apparent.

Therefore, our article aims to try to indicate the impact of mining activity on the dynamics of soil water potential of the forest soil environment and implicitly open a discussion on the impact of abandoned or closed brownfields on the quality of forest ecosystems in the dynamic conditions of ongoing climate change.

2. Material and methods

2.1. Characteristics of the study area

The study areas are located in the northwestern part of the Vtáčnik Mts. within the Prievidza district. Two sites – a reference site and a mining-disturbed site – were selected for the study. The reference site, Čertove chodníky, is situated at an elevation of 590 m above sea level (a.s.l.) and is approximately 10.5 km southwest of the mining-disturbed site, Račkov laz, which is at an elevation of 619 m a.s.l. The locations and natural conditions of the sites are presented in Table 1.

From the geological point of view, both sites share the same formation, being composed of Neogene volcanics, and sediment layers from the Sarmatian to the Lower Pannonian periods (Biely et al. 2002). Extending the general literature descriptions by Šály & Šurina (2002), our in-depth investigation at both sites confirmed the presence of modal Cambisols, further classified as Haplic Cambisol through in-situ soil probes and detailed laboratory methods. These Cambisols are derived from medium to light skeletal weathering products of non-carbonate rocks, presenting identical soil properties across both sites.

The specific soil profile at Račkov Laz, ascertained through textural classification and soil particle size distribution analysis, excluded the B/C horizons due to their high content of coarse gravel and stones from volcanic parent material. This plot revealed a soil depth of approximately 45 cm with four horizons, featuring a shallow root zone concentrated within the upper 15 cm, below which there is a significant decrease in root density. Coarse fragments in the main root zone constituted less than 15% of the soil, increasing to 50% beneath and reaching 80% in the B/C horizon. Similarly, the Čertove chodníky site exhibited a soil depth of around 46 cm with five horizons, where root density peaked in the upper 11 cm, inclusive of less than 10% coarse fragments. The presence of roots dwindled a few centimeters below, coinciding with an abrupt increase in the proportion of coarse gravel and stones, thus defining the end of the root zone.

The surface of both research plots held a distinctive layer of leaf litter, measuring 2 cm at Račkov Laz and nearly 5 cm at Čertove chodníky, contributing to the nuanced character of the soil profiles. These specific attributes of the soil horizons, determined by our targeted field and laboratory analyses, resonate with the shared geological features of the sites and underline the similarity in soil properties, as detailed in the comprehensive characteristics (Table 2).

The mining-disturbed site, Račkov laz, is located in the zone of mining activities of the now-closed Cígeľ deep coal mine in the extraction area of the Handlová coal deposit (Fig. 1). The causes and reasons for the hydrogeological damages in this location can be defined as follows. The geological structure of the area (Fig. 2) shows that mechanically soft and plastic claystone, siltstones, and conglomerates underlie rigid andesite and tuff strata, resulting in the fracturing of the entire Vtáčnik mountain range into a system of block fields. The movement of these blocks was subsequently accelerated by subsurface mining of the Cígeľ mine in the Handlová coal deposit (Halmo et al. 2010; Baliak & Stríček 2012). The area of interest in the Račkov laz locality is thus disrupted by several tectonic faults of a subsidence nature, with a complex system of grabens and crevices.

Table 1. Characteristics of the research sites.

Site type	Locality name	Coordinations and elevation	Exposition and slope	Group of forest types and altitudinal stage
Mining-disturbed	Račkov laz	48.723N 18.664E 619 m a.s.l.	north; 12%	Fagetum typicum, 4th vegetation altitudinal stage
Reference	Čertove chodníky	48.664N 18.587E 590 m a.s.l.	north; 15%	Fagetum pauper, 4th vegetation altidutinal stage

Table 2. Detailed soil characteristics.

Site name	Soil horizon	Root density	Soil skeleton (>2 mm)	Estimated textural classification in situ	Textural classes			Textural classification
					sand	silt	clay	
Račkov laz	A (0–7 cm)	high	5%	sandy loam	23	49	28	clay loam
	A/B (7.1–15 cm)	high	15%	sandy clay loam	26	52	22	silt loam
	B (15.1–37 cm)	absent roots	50%	sandy clay loam	25	54	21	silt loam
	B/C (>37 cm)	absent roots	80%	loam	—	—	—	—
Čertove chodníky	A (0–5 cm)	high	2%	clay loam	13	66	21	silt loam
	A/B (5.1–11cm)	high	10%	sandy loam	11	66	23	silt loam
	B1 (11.1–27cm)	sharp decrease	25%	clay loam	13	80	7	silt loam
	B2 (27.1–38 cm)	absent roots	50%	loam	12.3	70	17.7	silt loam
	B/C (>38 cm)	absent roots	75%	loam	—	—	—	—

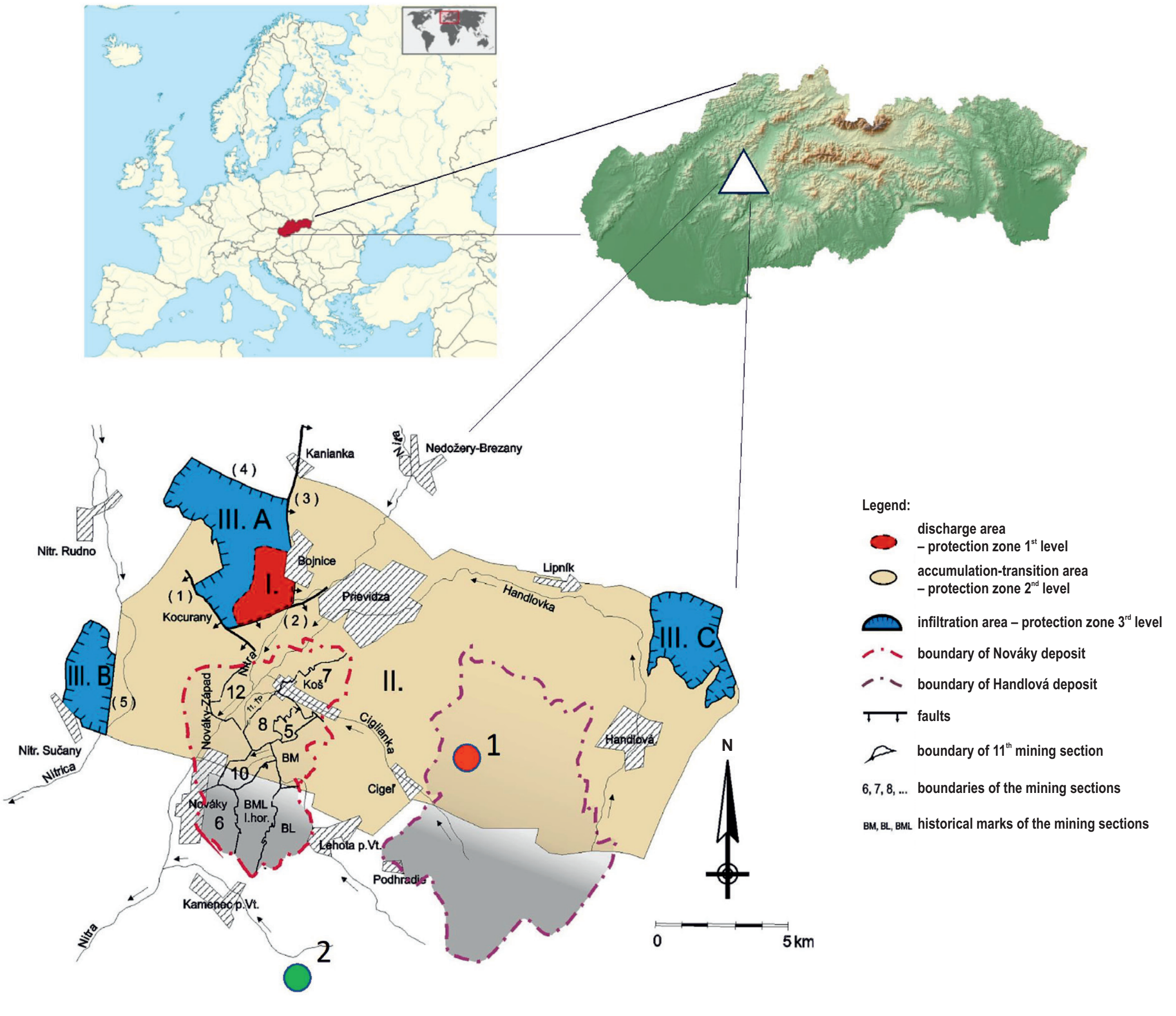

Fig. 1. Situational map of the Novácka and Handlovská coal basin area (Source of the coal basin map adopted by: Halmo et al. 2010). The red target "1" marks the location of the undermined research site Račkov laz, and the green target "2" marks the reference research site Čertove chodníky.

Anthropogenic geoecosystem (landscape) disruption in the Račkov laz locality occurred in a specific sequence and interconnection. Initially, part of the geological bedrock was mined (coal seam extraction). Subsequently, after the collapse, the overburden slid into the empty mined-out space, displacing its layers, changing its density, and disrupting its continuity(Jakál 1998). The effects of mining on the slope were significantly more pronounced than on flat terrain (Fig. 3). This was followed by changes in the surface water regime (changes in runoff ratios, river networks) and changes in the underground water environment. The area must be completely drained during mining, and the processes by which this is achieved can be temporary or permanent, potentially having broader impacts on surrounding ecosystems. Changes and disruptions to the geological environment of the overburden are

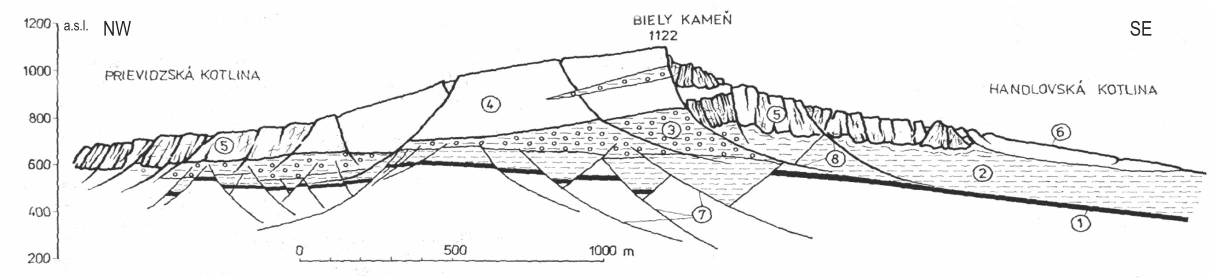

Fig. 2. Geological cross-section through the Vtáčnik mountain range (Source: Baliak & Stríček 2012). Explanations: (1) coal seams, (2) Baden age claystone and siltstones, (3) Sarmatian age gravels, (4) Sarmatian age andesites, agglomerate tuffs, (5) block rifts, block fields, (6) landslides.

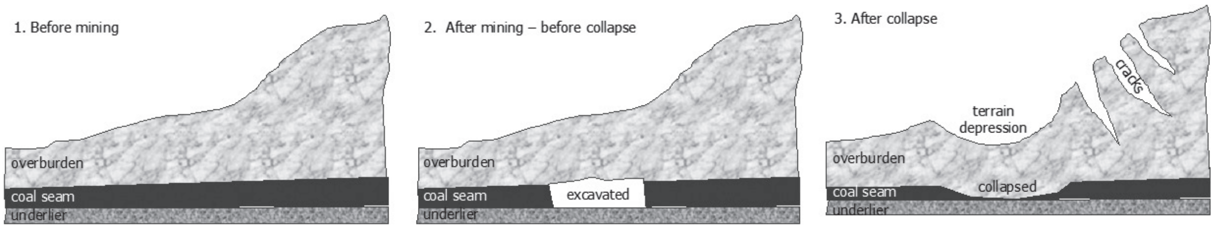

Fig. 3. Schematic cross-section of the terrain illustrating the effects of subsurface mining followed by overburden collapse resulting in disruptions in sloping terrain (Illustration: J. Vido based on information of Jakál 1998; Machajová et al. 2000).

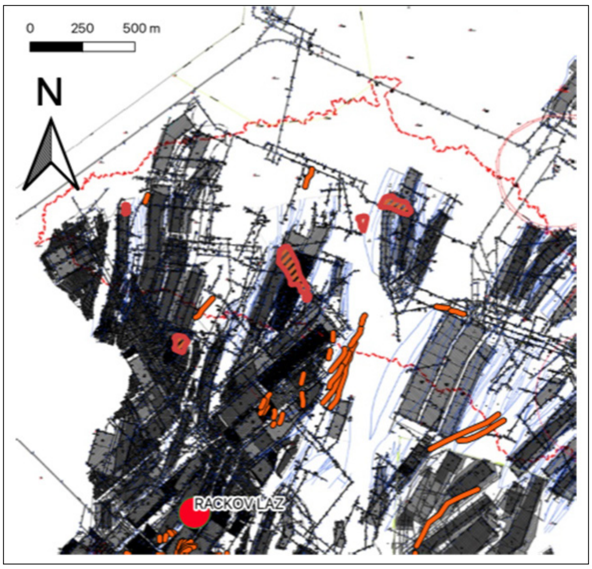

Fig. 4. Surface projection of the extracted brown coal deposits of the Cígeľ Mine, showing the location of the Račkov laz research area. The orange lines represent extensive surface cracks, while the hatched areas represent landslides activated by mining activity. The red target indicates the location with installed SP3 soil potential meters. The surface projection data was obtained from HBP Prievidza JSCo (Upper Nitra Coal Mining company in Prievidza), while other source data was acquired from ÚGKK SR (The Geodesy, Cartography and Cadastre Authority of the Slovak Republic).

indeed associated with possible and probable changes and disruptions to the underground water collectors, which can have consequences over a larger area (Sjölander-Lindqvist 2005; David et al. 2013; Goswami 2015).

An illustration of the plan projection of subsurface brown coal mining in the vicinity of the Račkov laz locality, superimposed on a map that shows the extensive cracks and landslides on the terrain surface, is shown in Figure 4. Our research area is located in a region that has been extraordinarily heavily impacted by mining, as evidenced by surface cracks and landslides.

2.2. Measurement techniques and data acquisition

The established experiment comprises continuous monitoring and recording of soil water potential at a depth of 30 cm. Based on preliminary soil surveying, the onset of the main root zone was identified at this depth. Soil water potential sensors manufactured by Delmhorst (U.S.A), designated as type GB 1, capable of measuring potential up to a maximum pressure of –15 bars, were deployed to this depth. These were connected to SP3 data loggers produced by Environmental Measuring Systems Ltd., which are also equipped with an integrated sensor for measuring ambient temperature. For this reason, the data logger was embedded into the soil to a depth of 5 cm, and, in addition to the continuous recording of soil water potential values, it also measured the temperature of the soil environment. The device is made from durable, corrosion-resistant materials with an overall IP 68 rating, ensuring reliable operation even under conditions of full burial in the soil environment. Each data logger is equipped with three GB 1 sensors, ensuring the repetition of measurements at three measuring points. The soil potential values were evaluated as the average data value measured by individual sensors connected to the data logger.

Atmospheric precipitation and air temperature were measured in an open area at the Púšť – Prievidza recreation centre, 2 km away from the Račkov laz site. These measurements were conducted using an automatic weather station with continuous data transmission via the IoT network (RainSet 02, Environmental Measuring Systems Ltd., Brno, Czech Republic).

Meteorological data and soil water potential values were processed and used as daily averages, except for atmospheric precipitation, which was evaluated as daily totals. The exception also applies to absolute temperature daily values. We analysed daily data from May 21st, 2020, to September 22nd, 2022.

3. Results

3.1. Meteorological conditions during the period of measurements

Environmental weather conditions were continuously monitored throughout the observation period from May 21, 2020, to September 22, 2022. During this period, the highest average air temperature was recorded on July 20, 2022, while the lowest average daily air temperature was recorded on February 12, 2021. The course of weather conditions, as measured by the RS Púšť – Prievidza meteorological station (350 m a.s.l.), is shown in Figure 5.

In 2020, the highest daily rainfall was measured on October 4, 2020 (51.2 mm). The second-highest daily total was recorded on October 14, 2020 (36.2 mm) and the third highest on October 13, 2020 (36 mm). It can be stated that the most precipitous period was recorded in 2020 from October 10 to October 19, with a total of 135.2 mm, while for almost the entire growing season from June 1 to September 30, the total was 269.4 mm. The most prolonged continuous dry period was from September 8 to September 23, 2020 (15 days). However, the period from November 12, 2020, to December 21, 2020, was also very dry, with these forty days interrupted by only three days of precipitation ranging from 1 to 3.2 mm. Concerning temperature, the growing season of 2020 was the coldest on average of all the studied years. It should be noted that the coldest months (January and February) were not observed, as the measuring equipment was only installed on May 21, 2020. The average daily temperature from June 1 to September 30, 2020, was 17.9 °C, with the absolute maximum recorded on August 7, 2020 (28.7 °C) and the absolute minimum on December 27, 2020 (–7.8 °C).

The year 2021 is characterized by two prominent periods of precipitation in the spring (May 8–21) with a total of 96.8 mm and in summer (July 21–August 5) with a total of 109.4 mm and two drought episodes. The first was in the pre-spring period from February 16 to April 30 (79 days with a total of 52.6 mm) and a dry autumn episode lasting 70 days (from September 15 to November 20) with a total of 31.8 mm. The period from June 1, 2021, to September 30, 2021, was better supplied with precipitation (280.8 mm) than in 2020 (269.4 mm).

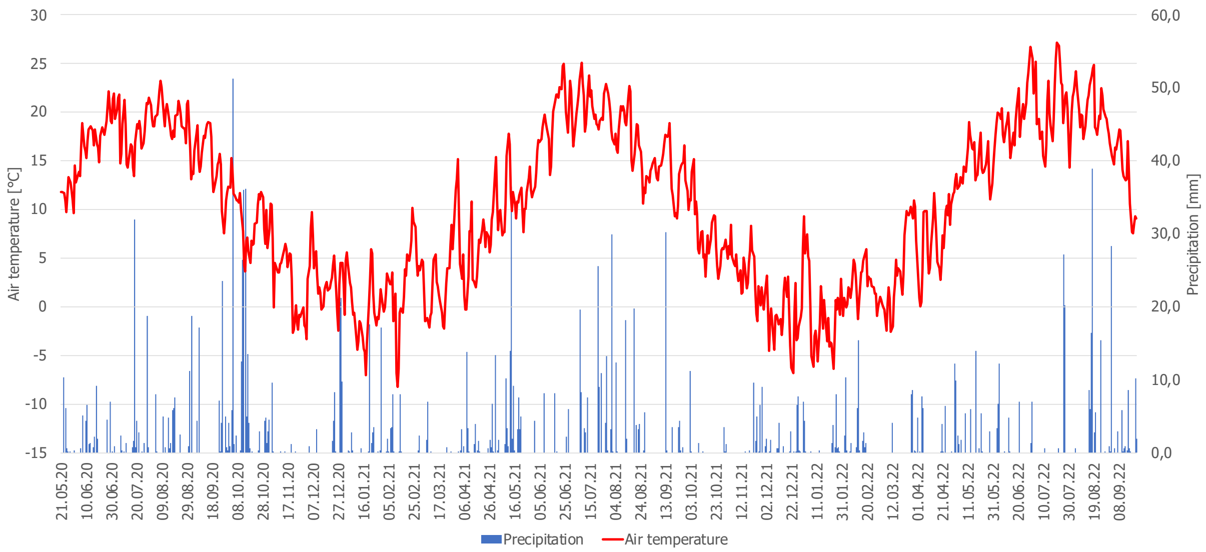

Fig. 5. Daily average air temperature dynamics and daily precipitation totals at the RS – Púšť Prievidza meteorological station, from May 21, 2020, to September 22, 2022.

Table 3. Selected indicators of meteorological conditions based on measurements from the meteorological station RS – Púšť Prievidza in the years 2020 to 2022.

2020					
Precipitation		(mm)	Air temperature		(°C)
Total in period	1.6.–30.9.2020	269.4	Absolute min.*	27.12.2020	–7.8
Daily maximum	4.10.2020	51.2	Absolute max.	7.8.2020	28.7
Longest episode with no rain	8.9.–22.9.2020	15 days	Mean air temperature	1.6.–30.9.2020	17.9
2021					
Precipitation		(mm)	Air temperature		(°C)
Total in period	1.6.–30.9.2021	280.8	Absolute min.	23.12.2021	–9.6
Daily maximum	13.5.2021	36.4	Absolute max.	24.6.2021	35.0
Longest episode with no rain	13.10.–28.10.2021	16 days	Mean air temperature	1.6.–30.9.2021	18.2
2022					
Precipitation		(mm)	Air temperature		(°C)
Total in period	1.6.–30.9.2022	295.5	Absolute min.	24.1.2022	–11.7
Daily maximum	18.8.2022	39.0	Absolute max.	21.7.2022	36.5
Longest episode with no rain	20.2.–11.3.2020	20 days	Mean air temperature	1.6.–30.9.2022	18.4

Note:*in 2020 measurements started from 21.5.2020.

However, it is important to emphasize the poorer temporal distribution concerning the drought episodes in spring and autumn, as mentioned earlier.

From a temperature perspective, 2021 was warmer than the previous year, with the average daily air temperature from June 1 to September 30 being 18.2 °C (+0.4 °C compared to 2020). That was also reflected in the significantly higher absolute air temperature recorded (35 °C – June 24, 2021). The absolute minimum was recorded on December 23, 2021 (–9.6 °C).

The period from June 1 to September 30, 2022, was the best supplied with precipitation among the years evaluated (295.5 mm). However, several factors need to be noted in this context. Firstly, there was the occurrence of a very long summer drought spell (55 days) from June 1 to July 25, with a meagre precipitation total (44.2 mm). Secondly, it needs to highlight that this meagre rainfall total occurred during periods with the highest air temperatures (two heatwaves peaking with average daily temperatures of 26.7 °C on June 30 and 26.8 °C on July 22 and the absolute highest recorded temperature of 36.5 °C on July 21). The above-mentioned minimum rainfall total could not saturate the evaporative demands of the atmosphere during practically half the summer period. Significant relief from the drought did not occur until August 16, when a period of rainfall began (lasting until the end of the evaluated period, September 30), which replenished the meteorological deficit and paradoxically placed the evaluation of 2022 from a precipitation perspective at the best level among the years evaluated, when adopting only precipitation totals. However, we can state that, from a comprehensive perspective, 2022 was, in fact, the driest if we evaluate the cumulative effect of air temperature and rainfall. That was also reflected in the course and the soil water potential dynamics, which will be presented in the next chapter. Table 3 presents a summary assessment of weather dynamics in the monitored years.

3.2. Soil water potential dynamics

The variation and nature of weather conditions over the observed years have been markedly differently manifested in different regimes and dynamics of soil water potential at the site affected by mining activity compared to the reference site. Figure 6 provides a vivid view of the variability in the course of the water potential during the whole studying period.

In 2020, the dynamics of soil water potential were primarily influenced by short-term rainfall-free episodes. The course of the water potential dynamics in 2020 is detailed in Figure 7. The figure documents a notably different course of water potential in the mining-damaged area and the reference area. During short-term drought episodes, such as in the first and second decades of July 2020, only a slight decrease in water potential to values of –1.4 bar on the reference area (15.7.) and –4.4 bar on the damaged site (17.7.) occurred. The reference area also documented a higher soil water content or retention capacity, even after very light rainfall on 16.7. (0.8 mm) and 17.7. (1.6 mm), the soil potential value increased to –0.3 bar, while at that time, the value of –4.4 bar was recorded on the damaged site. This value on the undermined site only reached –0.25 bar on 20.7, after rainfall totals of 32 mm occurred on 18.7, followed by 4.4 mm total on 20.7.2020.

Later, in the first decade to mid-August, there was a several-day period without rain, to which the reference area responded only with a slight potential decrease to values of –3.9 bar. In comparison, during the same period, water potential dropped on the undermined area to the minimum measurable value of –15 bar (16.8.). After the rains from 16.8, the potential began to rise in both areas, but with an evident time delay in the case of the damaged area. A significant difference occurs from 8.9 to 22.9 when the more prolonged drought episode mentioned in the meteorological analysis for this year occurs. This

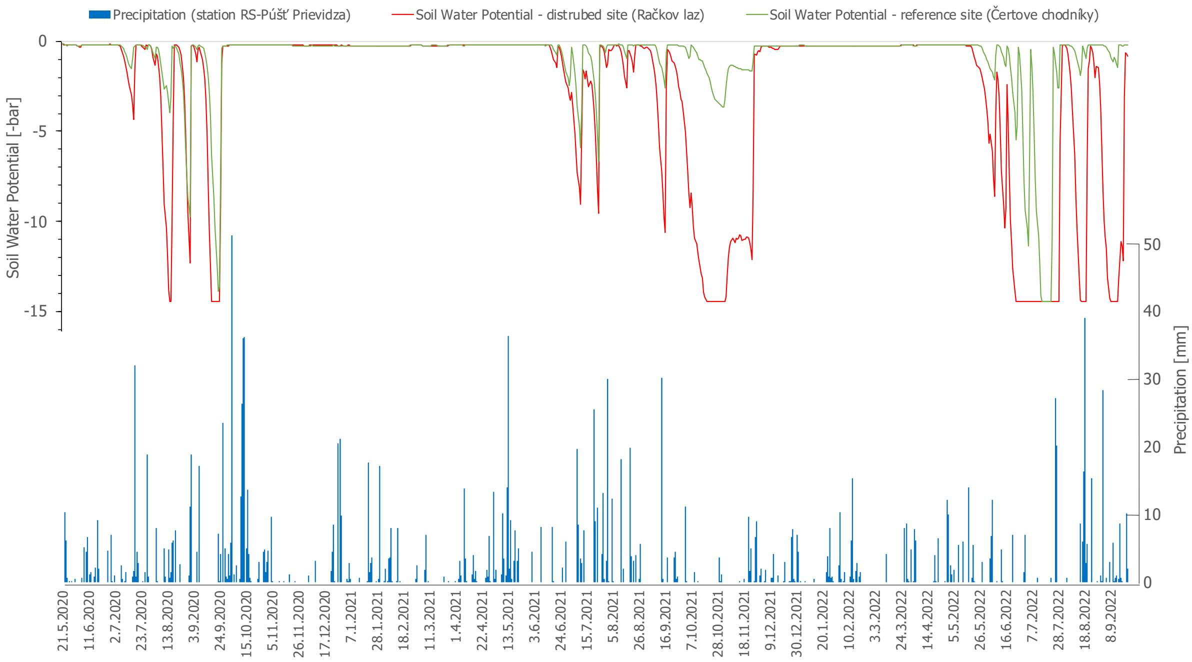

Fig. 6. Different dynamics of the soil water potential during the observed years (2020 to 2022) on the undermined (Račkov laz) and reference sites (Čertove chodníky).

more significant drought episode manifested with a rapid and sudden drop in water potential in the damaged area over ten days (9.9–19.9) from –0.25 bar to –15 bar, while the reference area recorded its lowest values on 23.9 at –13.9 bar. The water potential drop is also dated to 9.9., but it decreased to its minimum over 14 days (four days longer than the damaged area). The return to near-zero values occurred shortly after heavy rains from 23.9. In this case, the return to normal occurred on the same dates, as the rainfall period that started on 23.9 was heavy and fully saturated the water deficit, as shown by the common sharp increase in soil water potential in both areas.

The year 2021 was characterized by a relatively cool and well-supplied spring in terms of rainfall. That was also reflected in the course of the water potential, which remained very high until 16.6.2021. Soil water supplies from the first and second decades of May, together with a very slowly emerging spring phenology, caused the water potential to start dropping only to values of –9 bar (Račkov laz) and –5.8 bar (reference area Čertove chod-

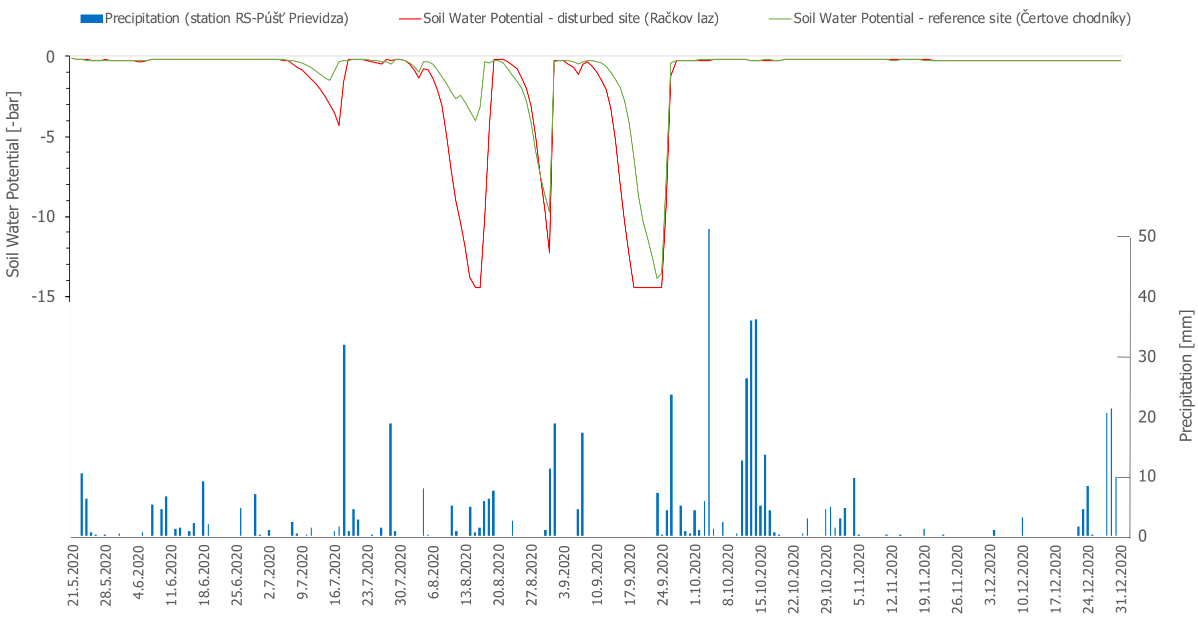

Fig. 7. Soil water potential in 2020. Due to the later installation, the evaluation of the year 2020 only starts on 21st May.

níky) on 10.7. and respectively 25.7. (Fig. 8). This proves that the difference between the damaged and the reference area is relatively negligible if rainfall is balanced in time and quantity. However, suppose a prolonged lack of atmospheric rainfall occurs (from 7.9. to 22.11.) with relatively weak and occasional rainfall. In that case, the difference in dynamics of water potential between the disrupted and reference site becomes very pronounced. That is true even considering the ending growing season and lower water needs for the transpiration of forest stands. During the aforementioned period of autumn meteorological drought, the drop in soil water potential on the reference site was recorded at a minimum level of –3.6 bar on 2.11., while on the damaged site, the soil potential reached almost minimum values of –14.4 bar from 21.10 to –12 bar on 25.11.2021. The above shows that the dynamics of soil water potential in the damaged area are most influenced by previous rainfall, the course of potential evapotranspiration (air temperatures) and rainfall distribution over time. If these conditions are met, the differences between the reference area and the damaged one are almost negligible.

The dynamics of the soil water potential in 2022 were mainly influenced by the very poorly rain-supplied months of February to July in terms of precipitation (Fig. 9). During this part of the year, only 157 mm of rainfall fell over 156 days (from 20.2. to 25.7.). However, the expected drop in water potential due to such low total precipitation began relatively late (19.5. – damaged area, 26.5. – reference area). The reason for this unusually delayed onset of the soil potential's reaction to the lack of atmospheric precipitation is the relatively cold progression of March (average temperature 3.78 °C), April (average temperature 7.00 °C), and May (14.53 °C). These, when compared to the long-term normals (1981–2010) for the meteorological station of the Slovak Hydrometeorological Institute in Prievidza, were lower by 0.42 °C in March, –2.9 °C in April, and 0.47 °C in May. This relatively cold period resulted in delayed spring phenophases and slowed down the forest stand's transpiration need. However, the precipitation deficit led to a drastic drop in soil water potential. In the area affected by mining activity, it remained practically at the minimum level of –15 bar, except for a few days-long exceptions after occasional heavy rains at the end of July (23–24.7., and 15.8.).

The most prolonged period during which the soil water potential remained at –15 bar was the drought episode from 23.6. to 27.7. Interestingly, this critical soil potential progression is characteristic only at the mining-affected location of Račkov laz. Even on the reference plot, the potential course was dynamic and dropped to the minimum level of –15 bar, but this period lasted only from 14.7. to 20.7. It is, therefore, evident and confirms the claim that when the precipitation supply is unfavourable in terms of time distribution and quantity, drought or low water potential values are more pronounced on the damaged plot than on the reference one. A general increase of the soil water potential occurred at the end of the observed period (September) exclusively on the reference plot, while on the plot damaged by mining activity, the situation did not improve even in connection with heavy rains from the end of August and the beginning of September.

The character of soil water potential dynamics on the reference site (Čertove chodníky) and the damaged site (Račkov laz) can also be observed in the significantly different variability (Fig. 10). The figure shows that the dynamics of soil water potential on the damaged site are markedly higher. That allows us to assert that damage to the geological substrate, and hence the worsened soil water regime, intensifies the effects of drought and exposes forest ecosystems to increased drought stress. Based on this evidence, we conclude that damage to the

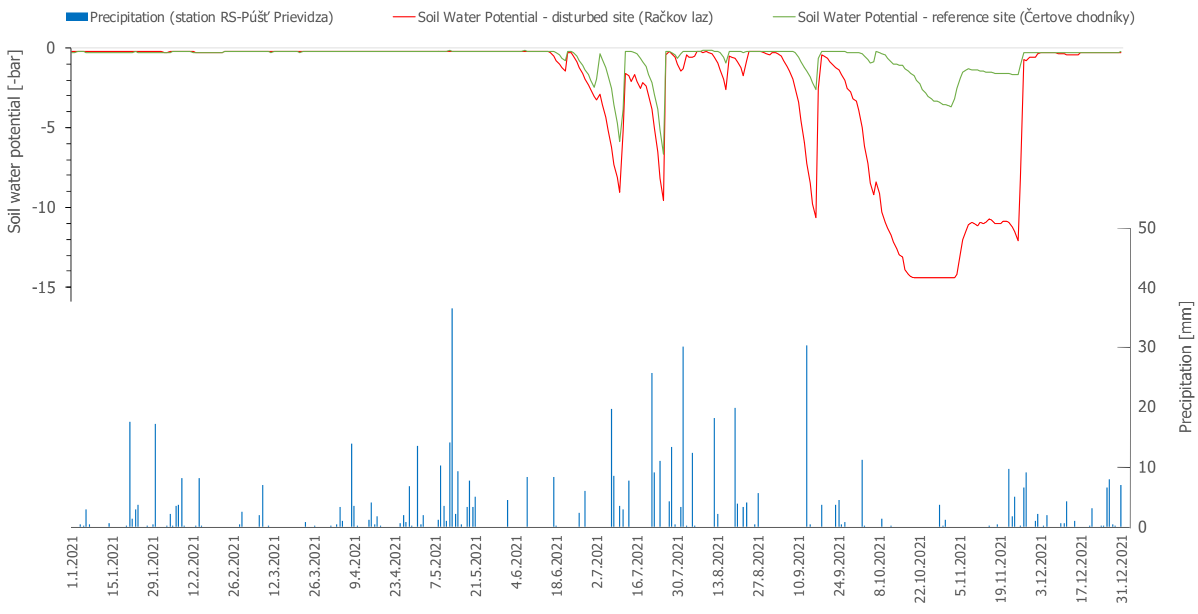

Fig. 8. Soil water potential dynamics on study sites in 2021.

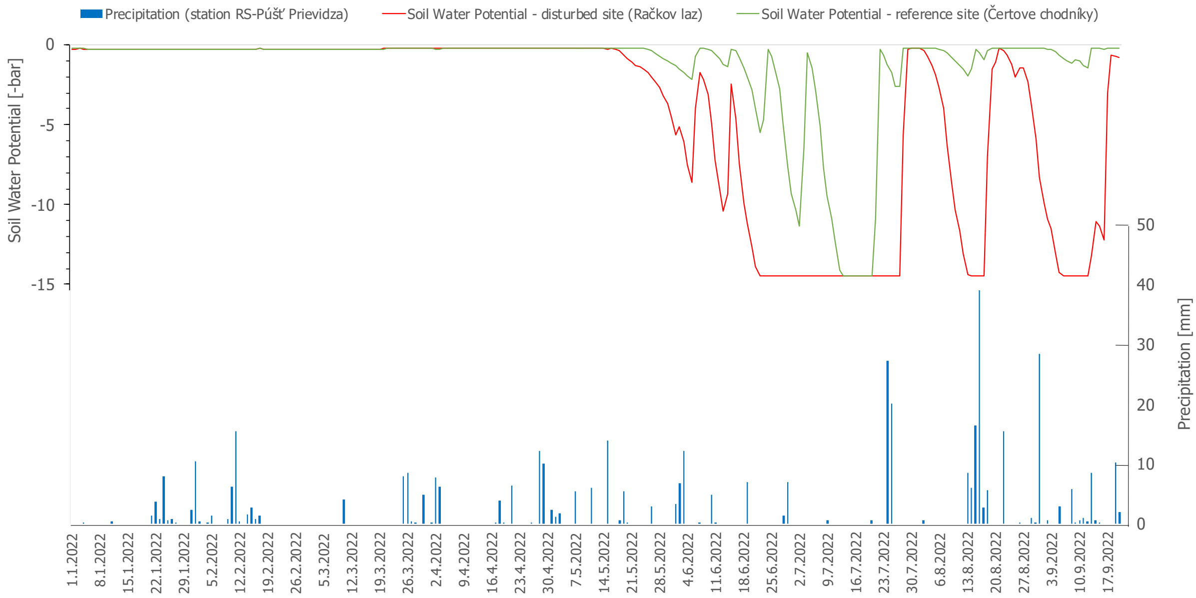

Fig. 9. Soil water potential dynamics on study sites in 2022.

hydrogeological continuum and the drainage of surface and subsurface waters leads to severe manifestations of drought on the damaged site compared to the intact reference area.

Due to the need to highlight the same thermal regime at both sites, we provide a graph of the soil temperature variation at a depth of 5 cm from 21 May 2020 to 22 September 2022 (Fig. 11). The graph clearly shows that the thermal regime in the surface soil layer, which is the contact zone for the transformation of shortwave radiation into infrared, is relatively consistent at both sites, ruling out any significant impact of a differing energy balance on the soil's water regime. That is also confirmed by Figure 12, in which no distinct variability in soil temperature values at both locations is apparent, supporting our conclusions.

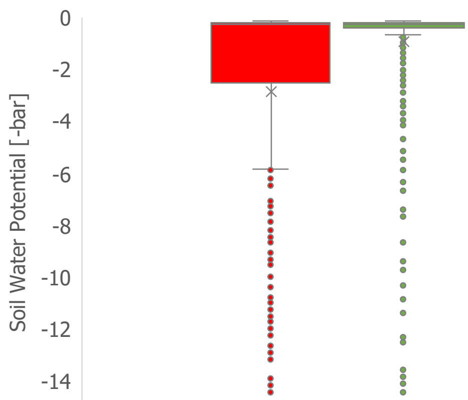

Fig. 10. Variability of soil water potential values at the damaged site Račkov laz (red colour) and the intact reference area Čertove chodníky (green colour).

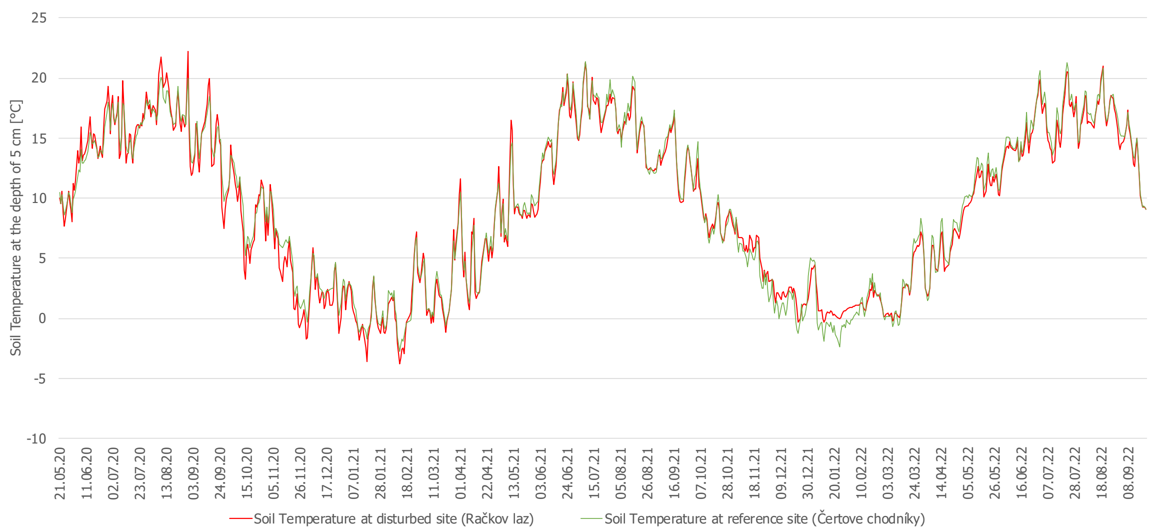

Fig. 11. Dynamics of soil temperature at a depth of 5 cm at the Račkov laz and Čertove chodníky sites from 21 May 2020 to 22 September 2022.

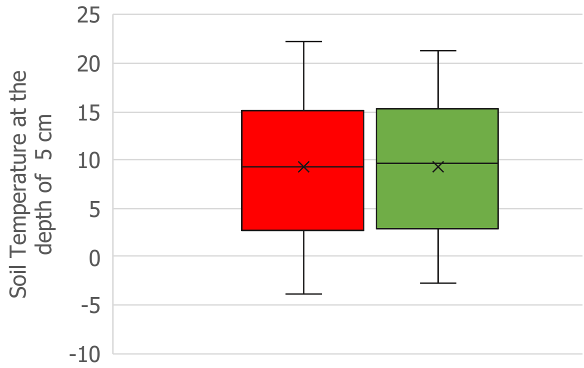

Fig. 12. Variability of soil temperature values at a depth of 5 cm at the disturbed – Račkov laz (red colour) and reference – Čertove chodníky (green colour) sites.

4. Discussion

Mining activity often risks damaging natural structures, especially hydrological and hydrogeological environments (Sjölander-Lindqvist 2005; Kolapo et al. 2022). Similar to our case, works (Goswami 2015; Tang et al. 2019) also highlight the negatives of undermining territories. The extraction of mineral resources and the construction of underground infrastructure signifies an interference in the geological continuum, which is almost always associated with damage, or at least a change, in the hydrological regime of underground waters (Goswami 2015). As in the example of our area of interest, numerous geological disturbances related to mining activities appear globally (Sjölander-Lindqvist 2005; Goswami 2015; Tang et al. 2019; Kolapo et al. 2022). Regarding the scale of impacts, or the extent of mining activity, the lignite brownfield of Upper Nitra is a relatively minor example (Tang et al. 2019). However, from a Slovak perspective, it is significant and deserves more attention. It is because the forests in the area of our interest have been significantly weakened in the past by industrial loads (Šimonovičová et al. 2004) and currently by significant changes in the hydrological regime due to ongoing climate changes (Hrvoľ et al. 2009). These are fundamental factors that, together with the impacts of mining activities, can have a cumulative adverse effect on the forests in the Vtáčnik mountain range area.

Our results prove that the interaction between weather conditions and damaged geological structures profoundly influences the dynamics of soil water potential. The findings show that changes in weather conditions significantly impact soil water potential at a damaged site compared to an undamaged reference site. Although a few comments and notes on this topic have been historically mentioned by (Ivanička 1959; Jakál 1998), exact results have not been published. Our contribution is, therefore, the first attempt to fill this gap in the area of interest. Our results suggest that damage to the geological bedrock can intensify drought impacts, thereby increasing stress in forest ecosystems during extreme drought episodes.

The analysis of the influence of precipitation and temperature on the dynamics of soil water potential also revealed fascinating patterns. If the precipitation supply is balanced in timing and quantity, the differences between the damaged and reference areas are almost negligible. However, drought is markedly evident with a long-lasting lack of atmospheric precipitation, and the water potential values at the damaged site are low. These results point out the need to consider these dynamics in developing strategies to restore and manage damaged sites.

Although our results pointed to clearly different dynamics of soil water potential in the mining-damaged area compared to the intact reference site, it is essential to emphasize that these results require an expansion of the research in terms of area and methodological range. That is especially concerning the physiological manifestation of the observed forest tree species, which are the edificators of the examined forest ecosystems.

5. Conclusions

The study has revealed the crucial role of disturbed geological structures combined with weather patterns on the dynamics of soil water potential. These results demonstrate that changes in weather conditions can have a different impact on the soil water potential of undermined and intact locations. The study indicates that geological damage can exacerbate the effects of drought, thereby increasing stress in forest ecosystems.

The need for a comprehensive strategy to restore and manage damaged sites is evident, especially considering the potential impacts of changing climatic conditions. These strategies or measures must consider the unique response of site conditions to weather dynamics based on their specific geological condition. Because of that, further research is needed to broaden the scope of this study, both in terms of the area extent and the methodologies employed. Particular attention should be given to understanding the physiological responses of the earlier mentioned aspects on the dominant tree species in these forest ecosystems, as they are critical contributors to the ecosystem's stability. Also, the need for regional study on climate change assessment arises. Especially spatiotemporal changes in precipitation distribution and snow regime changes should be of research interest in the area.

The findings emphasize the importance of understanding "unseen" interactions between geological structures and weather conditions influencing hydrological regimes in the area of interest to protect and manage valuable forest ecosystems effectively in conditions of ongoing climate change.

Acknowledgements

This work was supported by the research grants of the Slovak Research and Development Agency No.: APVV-21-0224, APVV-18-0347 and APVV-19-0340; grant of the Science Grant Agency of the Ministry of Education, Science, Research and Sport of the Slovak Republic No.: 1/0392/22 and Cultural and Educational Grant Agency of the Ministry of Education, Science, Research and Sport of the Slovak Republic No.: 011TU Z-4/2021.

References

Baliak, F., Stríček, I., 2012: 50 rokov od katastrofálneho zosuvu v Handlovej, Mineralia Slovaca, 44:119–130. (In Slovak).

Biely, A., Bezák, V., Elečko, M., Gross, P., Kaličiak, M., Konečný, V. et al., 2002: Geological Structure, Landscape atlas of the Slovak Republic. Bratislava, p. 74–75.

Bošeľa, M., Pajtík, J., Konôpka, B., Šebeň, V., Vida, T., 2013: Modelling effects of weather condition on seasonal dynamics of the stem circumference increment in a mixed stand of Norway spruce and European beech. Forestry Journal, 59:180–188.

David, S., Mojses, M., Petrovič, F., Ambros, M., Baláž, I., Bugár, G. et al. 2013: Vplyv ťažby uhlia na krajinu a biodiverzitu Košských mokradí (Hornonitrianska kotlina), Ústav krajinnej ekológie SAV, Bratislava & Fakulta prírodných vied, Univerzita Konštantína Filozofa v Nitre. Bratislava, Nitra, p. 7–14. (In Slovak).

Drdoš, J., Ira, V., Jakál, J., Kollár, D., Krajčír, A., Székely, V. et al., 1994: The Upper Nitra region: Man and his environment. Geografický časopis, 46:131–148.

Goswami, S., 2015: Impact of Coal Mining on Environment, European Researcher, 3:185–196.

Halmo, J., Šarkan, J., Gurský, S., Toma, S., Lalúch, I., Bogdan, P., 2010: 11. ťažobný úsek Bane Nováky, nová ťažobná kapacita na Hornej Nitre, Mineralia Slovaca, 42:133–140. (In Slovak).

Hrvoľ, J., Horecká, V., Škvarenina, J., Střelcová, K., Škvareninová, J., 2009: Long-term results of evaporation rate in xerothermic Oak altitudinal vegetation stage in Southern Slovakia. Biologia (Bratislava), 64:605–609.

Ivanička, K., 1959: Príspevok k niektorým zmenám geografického prostredia na hornej Nitre, Geografický časopis, 11:207–221. (In Slovak).

Jakál, J., 1998: Antropická transformácia reliefu a jej odraz v krajine Hornej Nitry. Geografický časopis, 50:3–20. (In Slovak).

Kolapo, P., Oniyide, G. O., Said, K. O., Lawal, A. I., Onifade, M., Munemo, P., 2022: An overview of slope failure in mining operations. Mining, 2:350–384.

Konôpka, B., Lukac, M., 2013: Moderate drought alters biomass and depth distribution of fine roots in Norway spruce. Forest Pathology, 43:115–123.

Machajová, Z., Verbich, F., Sýkorová, I., 2000: Geologická a petrografická charakteristika ložiska Handlová. Acta Montanistica Slovaca, 261–264. (In Slovak).

Pajtík, J., Sitková, Z., Marčiš, P., Bošeľa, M., Pavlenda, P., Konôpka, B., 2022: Radial increment and defoliation of *Pinus sylvestris* (L.) on sandy soils relate to summer temperatures and ground water level. Central European Forestry Journal, 68:78–90.

Sjölander-Lindqvist, A., 2005: Conflicting perspectives on water in a Swedish railway tunnel project. Environmental Values, 14:221–239.

Stojanović, M., Szatniewska, J., Kyselová, I., Pokorný, R., Čater, M., 2017: Transpiration and water potential of young *Quercus petraea* [M.] Liebl. coppice sprouts and seedlings during favourable and drought conditions. Journal of Forest Science, 63:313–323.

Šály, R., Šurina, B., 2002: Soils, Landscape atlas of the Slovak Republic. Bratislava, p. 106–107.

Šimonovičová, A., Krnáčová, Z., Pavličková, K., Beňová, A., 2004: Microbial characterization of the soil influenced by the negative anthropization, Ekológia, 23:55–63.

Tang, J., Dai, Z., Wang, Y., Zhang, L., 2019: Fracture failure of consequent bedding rock slopes after underground mining in mountainous area. Rock Mechanics and Rock Engineering, 52:2853–2870.

Vido, J., Střelcová, K., Nalevanková, P., Leštianska, A., Kandrík, R., Pástorová, A. et al., 2016: Identifying the relationships of climate and physiological responses of a beech forest using the Standardised Precipitation Index: A case study for Slovakia. Journal of Hydrology and Hydromechanics, 64:246–251.

Wiklund, K., Konôpka, B., Nilsson, L. O., 1995: Stem form and growth in *Picea abies* [L.] Karst. in response to water and mineral nutrient availability. Scandinavian Journal of Forest Research, 10:326–332.