VODOHOSPODÁŘSKÉ TECHNICKO-EKONOMICKÉ INFORMACE
(WATER MANAGEMENT TECHNICAL AND ECONOMIC INFORMATION)

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60 years ago in VTEI

VTEI No. 2 of 1966 featured an article entitled "Diving Station". Its author was L. Pojezdný of the Labe-Vltava organisation.

The Labe-Vltava organisation's diving station currently has six divers, a mechanic and a station manager. In the two years since it was established, its staff have already worked 1,830 hours underwater.
What does their work involve? Above all, they are called in to deal with problems arising during day-to-day operations. For example, the lower gates of a small navigation lock may fail to close completely, creating a risk of damage to the gates as vessels enter and leave. The lock staff are unable to resolve the problem. The divers discover that a 40 cm-long steel beam has become wedged in the gates after being thrown into the lock by a careless worker from a contracting company. There are also larger operations for which divers are absolutely indispensable. At the South Bohemian Paper Mills in Větřní, for example, they cut Larsen sheet-pile cofferdams at a depth of 60 cm; they took part in dismantling the intake valves at the Orlík Dam; and they assisted in inspecting the cables of the auxiliary towers of the Žďákov Bridge at a depth of 48 m, among other tasks.
Water management organisations requiring assistance with the removal of underwater obstacles, cutting work at depths of up to 40 m, or other installation work at depths of up to 60 m should contact:
Diving Station for Bohemia and Moravia, Labe-Vltava organisation, V Botanice 4, Prague 5.
The charge per hour, including travel to the site, is 494 Czechoslovak crowns.

From the TGM WRI archives

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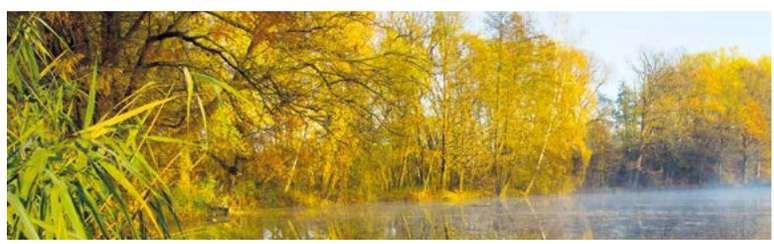

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Photo: T. Hrdinka

Dear Readers,

October offers several opportunities to reflect on topics closely linked to water and water management. World Habitat Day falls on 5 October 2026, while International Day for Disaster Risk Reduction is observed on 13 October. Both events draw attention to issues that are becoming increasingly relevant in the context of ongoing climate change – the resilience of landscapes and human settlements, our ability to prevent risks and our preparedness for extreme events.

Water plays a crucial role in this resilience. The ability of the landscape to retain water, the protection and restoration of water resources, mitigating the impacts of droughts and floods, preserving functioning aquatic ecosystems, and preparing water management infrastructure for future conditions are all interconnected issues. And it is precisely from several different perspectives that the October issue of VTEI explores these topics.

The first article, by our colleagues Pavel Eckhardt and Kamila Tichá, focuses on changes in spring areas following sudden, significant disturbances. The authors compare the development of sites affected by groundwater abstraction, failures of drainage systems, and a large-scale forest fire. The results show that spring areas vary in their sensitivity to different types of disturbance. While the abstraction of spring water for drinking-water supply can fundamentally affect the very existence of springs, in the case studied, even a large-scale forest fire had no significant impact on the quality or quantity of groundwater. Another interesting finding was the gradual emergence of secondary spring areas associated with the natural recovery of disturbed drainage systems.

Examples of situations in which nature itself plays a significant role in water retention are explored in a study by Adam Babuljak and his co-authors on the water-retention potential of beaver dams. Based on field data and GIS analyses, the authors quantified the amount of water accumulated in beaver impoundments and also used modelling to estimate the retention potential of the catchment assuming that European beavers had colonised it to the maximum extent. The study thus provides quantitative data on the hydrological significance of a species that, through its activities, can significantly alter the character of watercourses and their surroundings.

An article by Jana Bernsteinová and her co-authors explores the possibilities offered by modern modelling through the concept of a river basin digital twin. Using the Dyje River basin and a pilot basin in the upper Svratka catchment as study sites, the authors employ the integrated MIKE SHE modelling system to assess the effects of adaptation measures on the water balance under climate change conditions. The assessment incorporates a set of 26 climate scenarios and examines, among other things, the effects of a comprehensive package of measures referred to as "hydrologically optimal agriculture." The results demonstrate the potential of these measures to slow runoff from the landscape and support baseflow, while also documenting the potential of digital tools to support decision-making in catchment management.

In the next article, we move from the quantity of water to the ecological continuity of watercourses. Eduard Bouše, Miroslav Barankiewicz and their colleagues assessed the impact of restoring fish passage on the Rolava river on populations of rheophilic fish. Their results demonstrate the effects of river network fragmentation on the species composition of fish communities, while also confirming the importance of appropriately designed restoration measures. Radiotelemetry monitoring demonstrated the high effectiveness of the fish passes that had been constructed and the ability of fish to make use of the restored river continuum. The study also highlights the importance of the remaining migration barriers for the long-term status of the native fish fauna.

The fifth scientific article, by Aleš Havlík, Adam Vizina and Barbora Krijt, focuses on simulation of the thermal regime of a drinking-water reservoir under projected climate change conditions. Using the Vrchlice reservoir as a case study, the authors employ the two-dimensional CE-QUAL-W2 model to assess possible changes in the thermal regime for the 2050 and 2085 climate horizons. In addition to changes in climatic conditions, they also examine a scenario involving a substantial reduction in the reservoir's water level. The study thus addresses another important aspect of adaptation in water management – possible changes in conditions in reservoirs that serve as sources of drinking water.

The October issue concludes with an interview with associate professor RNDr. Jan Unucka, Ph.D., head of the Hydrology Department at the Ostrava branch of the Czech Hydrometeorological Institute. He has been a regular contributor to VTEI for several years, writing scientific articles, serving as a reviewer, and also as a photographer.

Looking at the issue as a whole, it is clear how broad a range of processes we now need to take into account when managing water resources. From small spring areas, through the effects of beavers and the ecological continuity of watercourses, to modelling entire river basins and the future thermal regime of drinking-water reservoirs, it ultimately comes down to the same question: how can we understand the changes taking place in the aquatic environment and respond to them appropriately?

Thank you to all the authors, reviewers and others who contributed to the preparation of this issue. To you, our readers, I would like to thank you for your continued support and wish you an enjoyable and inspiring read.

On behalf of the VTEI editorial team
Ing. Josef Nistler

Changes in spring areas following sudden major disturbances

PAVEL ECKHARDT, KAMILA TICHÁ

Keywords: groundwater — springs — water resources — drainage — restoration — forest fire

ABSTRACT

This article compares the condition of selected spring areas following sudden major disturbances with their previous condition, while also assessing long-term changes in drained and undrained spring areas. The impacts examined include major changes in groundwater abstraction for drinking-water supply, disturbances resulting from failures of drainage systems, and the effects of a large-scale forest fire. Three areas with contrasting hydrogeological characteristics were selected for the study. The results show that, while the abstraction of spring water for drinking-water supply has a fundamental effect on the very existence of springs, the large-scale forest fire did not significantly affect either the quality or quantity of groundwater. By contrast, gradual changes in agricultural management and the natural recovery of non-functioning drainage systems lead to the formation of secondary spring areas and a gradual improvement in the quality of the emerging water.

INTRODUCTION

A spring is a concentrated point of emergence of groundwater at the Earth's surface, representing a unique and highly vulnerable habitat at the interface between groundwater, surface water, and terrestrial ecosystems [1–3]. Springs are susceptible to a range of changes, including contamination of groundwater from the surface, changes in discharge resulting from damage to the underlying aquitard, and changes in the way springs are captured, as well as many other, mostly anthropogenic, factors. Particularly since the 19th century, with the development of agricultural needs and public water supply, spring areas throughout Europe have undergone widespread transformation [3]. In addition, the Czech Republic has been heavily affected, from lowlands to foothill areas, by systematic large-scale drainage, which peaked in the second half of the 20th century [4, 5].

These disrupted ecological processes are now manifested not only in a decline in local biodiversity but, in the context of ongoing climate change, also in a reduced ability of the landscape to cope with hydrological extremes such as floods and prolonged droughts. The conservation and restoration of natural spring areas are therefore crucial, as these sites function as reliable, thermally stable hydrological refugia [6]. This article focuses on changes in selected springs, particularly those resulting from spring capture and significant groundwater abstraction in their vicinity; the effects of a large-scale fire on selected springs were also examined, as were the effects of historical drainage and the current restoration of these springs. The springs investigated had been mapped and studied in previous research, e.g. [7–14]. The current research is part of the TA CR Environment for Life II project, No. SQ01010130.

METHODOLOGY

The main objective of this study is to assess and compare the impacts of sudden environmental disturbances (forest fire and intensive groundwater abstraction) and long-term landscape changes (large-scale drainage and subsequent natural recovery) on the hydrochemical status of springs and, where applicable, their discharge.

The springs selected for further study were primarily those for which we had documented the baseline conditions prior to significant changes. All available archival materials were reviewed and analysed and compared with the current conditions.

In 2026, a comprehensive standardised form was completed for all springs investigated. It included not only information on the location and extent of the spring areas and the results of field measurements of water parameters, but also a description and basic quantification of the biological components of the natural environment.

At the selected springs, discharge and the physical and chemical properties of the water were measured, and water samples were collected for chemical analysis. During repeated visits to the springs, their discharge was measured using a suitable measuring container, along with water parameters including electrical conductivity, temperature and, where applicable, pH and dissolved oxygen.

For the study, three areas with markedly different hydrogeological characteristics were selected. The study area around Hřensko in northern Bohemia forms part of the Czech Cretaceous Basin, with significant deep hydrogeological structures and a greater delay in the response of spring discharge to precipitation and is located within a national park. In the Hřensko area, eight springs with high discharge at different altitudes were monitored directly as part of the ongoing project. Other springs were inaccessible for monitoring and were therefore assessed using only archival data and supporting materials.

In the Hřensko area, the impact of the large-scale wildfire on springs was investigated. This involved comparing our own field measurements and the results of water analyses with archival sources of expert information, as well as data from the Raw Water Database and, last but not least, freely available data from the Czech Hydrometeorological Institute (CHMI).

Another selected spring area was the Aš region in western Bohemia, which is located in an area of crystalline rocks (underlain by low-grade metamorphic phyllites and schists), where springs are generally highly dependent on climatic conditions. In the recent past, major changes in agricultural management took place here, affecting the springs, and the area is also home to specially protected organisms associated with aquatic environments.

The third study area was the Blanice catchment in the Šumava foothills. From a hydrogeological perspective, it lies within the crystalline basement, in an area of highly metamorphosed rocks of the Moldanubian Zone (migmatites,

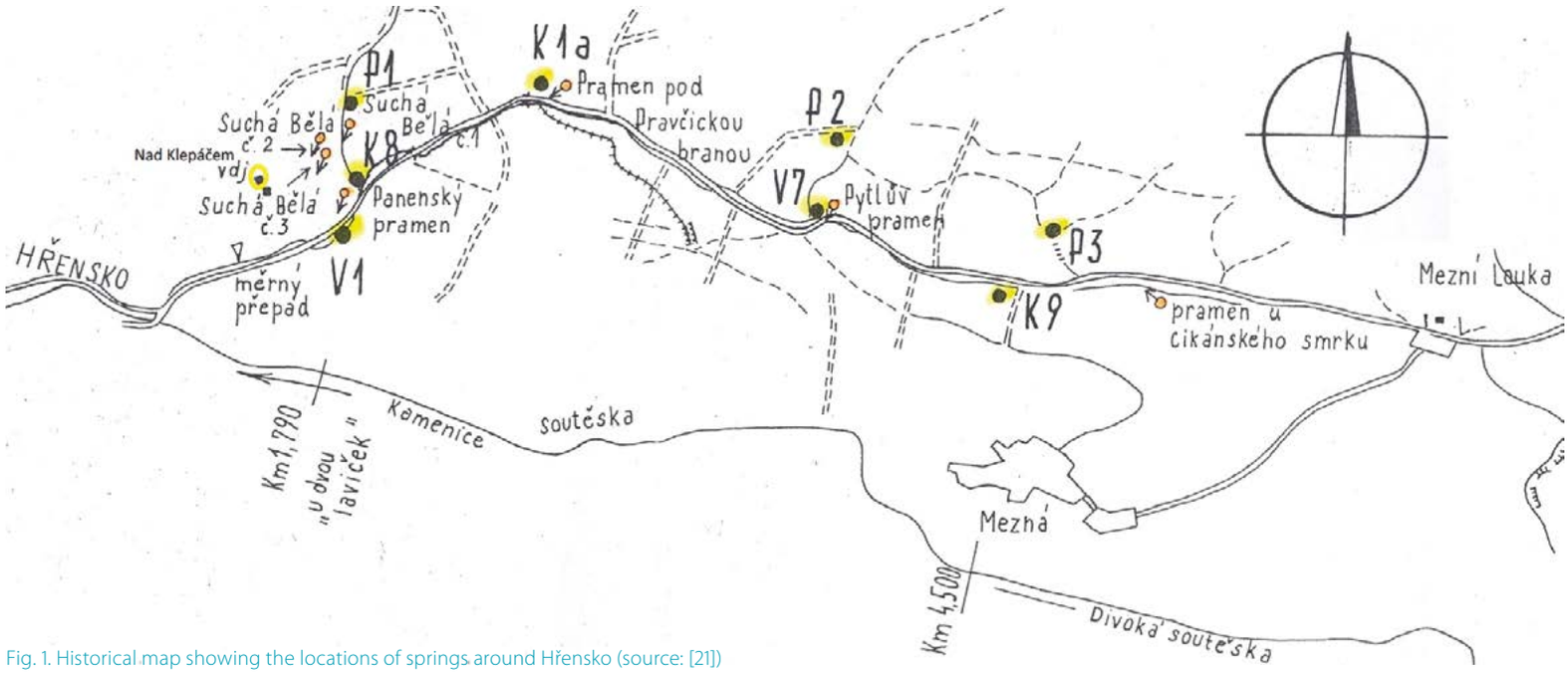

Fig. 1. Historical map showing the locations of springs around Hřensko (source: [21])

granulites, etc.). The area is situated at a higher altitude than the two previous areas and is therefore slightly wetter and cooler.

For comparison of water quality at spring areas affected and unaffected by drainage, data from two periods 16–20 years apart were obtained. The first period covers the beginning of monitoring between 2005 and 2009. The comparison dataset is current, covering 2025/2026. The data include individual spring areas from two study regions: the Aš region and the Blanice and Zlatý Stream catchments. The following water-quality parameters were selected: conductivity, nitrate, nitrite, ammonium-ion, phosphate and chloride concentrations. For the calculation of the resulting score, indicating an improvement or deterioration in the hydrochemical status of the spring area, only those parameters for which data from the first period were available were used (*Tab. 2*). Where data from multiple seasons were available for a given spring area within a particular period, the mean values were used. Individual parameters were assigned one or two positive or negative points depending on the magnitude of the improvement or deterioration. Where a parameter remained unchanged (or the change was negligible), it was assigned zero points. The theoretical score could therefore range from –12 (significant deterioration in all monitored parameters) to +12 (significant improvement in all monitored parameters).

The spring areas investigated were divided into two categories according to whether or not they were affected by drainage. In this context, drainage refers both to systematic subsurface drainage systems and to deepened surface ditches conveying water to a receiving watercourse. In addition to entirely natural spring areas, the unaffected category also included spring SP82/SC05 (U panenky Marie), which has been modified as a drinking-water spring, but is not affected by drainage in any way.

RESULTS FOR THE SELECTED SPRING AREAS

Study area around Hřensko

The study area east of the town of Hřensko is in the Ústí nad Labem Region, within Bohemian Switzerland National Park.

From a hydrological perspective, the springs investigated are located in the Dlouhá Bělá Stream catchment. The stream flows into the Hřenská Kamenice from the right at Hřensko, just over one kilometre upstream of its confluence with the Elbe river. The Suchá Bělá stream is a right-bank tributary of the Dlouhá Bělá, and its catchment contains five of the springs investigated. In total, eight high-discharge springs were monitored directly as part of the project. Some other historical springs were inaccessible for direct monitoring, particularly because they are used for groundwater abstraction for public drinking-water supply.

From a hydrogeological perspective, the study area is part of the Czech Cretaceous Basin and lies in the northern part of Hydrogeological Region 4660 – Lower Kamenice and Křinice Cretaceous Basin and Groundwater Body 46600 – Lower Kamenice and Křinice Cretaceous Basin [15]. The hydrogeologically significant aquifers in the study area occur in psammitic Cretaceous rocks, particularly sandstones, with intergranular and fracture permeability. The springs studied are associated with the locally most important aquifer (BC), hosted in the sandstones of the Jizera Formation and the upper part of the Bílá Hora Formation [16]. The high-discharge springs of interest occur at aquitard layers within the BC aquifer, as described, for example, in more detailed Saxon geological and hydrogeological studies [10]

Evolution of the springs east of Hřensko

The earliest available study of the springs [7] provides a clear picture of their condition more than 100 years ago. It describes the following situation in 1911–1912: the settlement of Hřensko already had a public water supply fed by a captured spring in the upper part of Malinový důl (the Nad Klepáčem spring; see *Fig. 4*). The author classifies it as a contact spring emerging at the outcrop of an overlying sandstone layer underlain by a clay layer.

One of the highest-discharge springs in the area was the Tři prameny spring area (Pod Pravčickou bránou spring), at an elevation of 200 m above sea level. Near the junction of the hiking trail to Pravčická brána and the Dlouhá Bělá stream, a powerful spring emerged from a rocky slope covered with scree, forming a small pond inhabited by trout and covered with aquatic vegetation. The original three outlets of the spring area had already been artificially combined. The spring discharge was at least 6 L/s, and the water temperature on 6 March 1912 was 8 °C. The author concludes that it is a contact spring emerging at the outcrop of a sandstone layer (Labiatus).

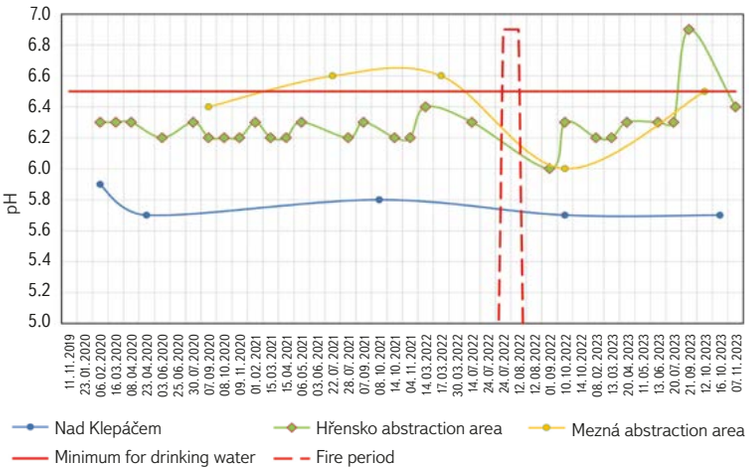

Fig. 2a. Changes in pH of abstracted groundwater sources near Hřensko before and after the fire (data source: [22])

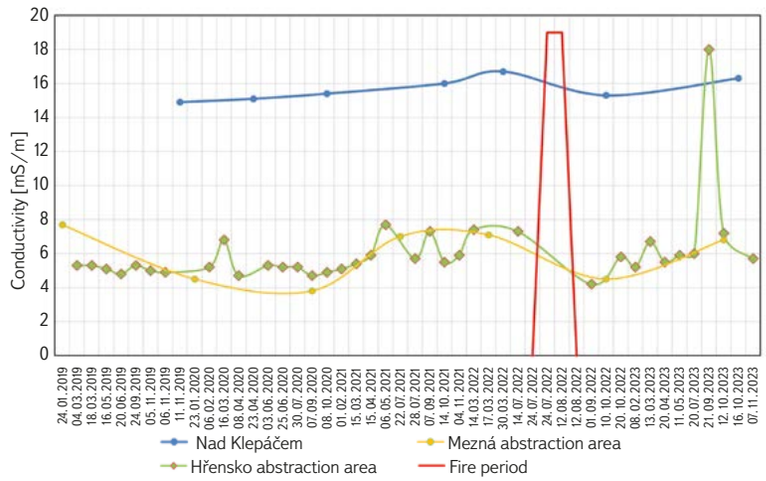

Fig. 2b. Changes in conductivity of water from abstracted groundwater sources near Hřensko before and after the fire (data source: [22])

One of the best-known springs in Saxon-Bohemian Switzerland was Panenský spring (elevation 185 m above sea level), which had already been modified at the time, with its banks artificially widened. Clear water emerged from the ground at several points, playing over white pebbles at the spring outlets. The spring discharge was similar to that of Tři prameny. On 3 February 1911, the water temperature at the strongest outlet of Panenský spring was measured at 9.05 °C. From this, the author concluded that it was an ascending spring, since under normal conditions its temperature would be expected to be only around 7.5 °C. In the Suchá Bělá valley, about 200 metres from its confluence with the Dlouhá Bělá, a spring (Suchá Bělá 3) emerged from scree, with a discharge of around 2 L/s [7].

In the late 1960s and early 1970s, a series of hydrogeological investigations were conducted in the study area, including monitoring of some of the major local springs (e.g. [9] and other studies [21]). Borehole drilling and other hydrogeological work led to the establishment of the extensive Hřensko groundwater abstraction area. Groundwater was, and continues to be, abstracted here from a system of hydrogeological boreholes in the Dlouhá Bělá valley. The high-discharge Pod Pravčickou bránou (Tři prameny) and Pytlův springs were subsequently incorporated into the system. Since the second half of the 20th century, the Hřensko abstraction area has supplied drinking water to the town of Děčín and the surrounding area.

Around the groundwater abstraction area, seven springs were monitored regularly once a week in the late 1960s and early 1970s (Panenský spring, Suchá Bělá 1–3, Pod Pravčickou bránou spring, Pytlův spring and U Cikánského smrku spring). Their former locations are shown on the historical map in *Fig. 1*. Panenský spring disappeared completely as a result of groundwater abstraction and was decommissioned in 1974 [20]. The monitored springs were gradually removed from the monitoring programme. Of these, only Suchá Bělá 3 continues to be monitored regularly by the CHMI.

The discharge of Suchá Bělá 2 spring gradually declined from 3.8 L/s in 1960 until surface discharge ceased completely in 1989. This was most likely due to a combination of increased groundwater abstraction from the Hřensko abstraction area (up to 135 L/s) and unfavourable climatic conditions [10]. Following a reduction in groundwater abstraction and the end of the dry period, the discharge of Suchá Bělá 2 spring increased slightly again.

The discharge of some other major springs responded similarly to high levels of groundwater abstraction and unfavourable climatic conditions. Pod Pravčickou bránou spring, which has the highest discharge in the area, had a discharge of approximately 20 L/s in the late 1970s and early 1980s, compared with only around 10.6 L/s in 2013. The discharge of U Cikánského smrku spring generally fluctuated between 0.5 and 3.3 L/s from 1957 to 1982, whereas in 2012–2014 the mean discharge was only 0.22 L/s.

Between 2012 and 2014, springs in the area were mapped and their discharge measured and assessed as part of the cross-border GRACE programme [8, 10].

In the early 2020s, the area was affected by a bark beetle outbreak. In July 2022, the resulting dry woody biomass was consumed by a large-scale wildfire covering more than 10 km^2 (e.g. [18]), which, with a few exceptions, affected the entire study area from the built-up area of Hřensko to that of Mezná village.

Current status of springs in the Hřensko area

Panenský spring has disappeared as a result of groundwater abstraction, and no traces of it remain at the site of its former outflow. Nad Klepáčem spring area in Malinový důl is used as a source of drinking water for the town of Hřensko. The main surface outflow from this spring area has disappeared (the spring intake is shown in *Fig. 4*). Groundwater outflows with substantially lower discharge occur within the spring area, but infiltrate back into the rock environment after several tens of metres. After abstraction, the overflow from the main spring is discharged unused through a pipe into the Dlouhá Bělá stream. Pod Pravčickou bránou spring (Tři prameny) and Pytlův spring are fenced off, covered by chambers and soil, and connected to the public water supply system; consequently, there are no longer any surface groundwater outflows at these sites (*Fig. 5*). U Cikánského smrku spring still exists in a degraded state (a concrete well ring; see *Fig. 6*) and has a markedly lower discharge than in the last century. The five high-discharge springs monitored in the Suchá Bělá valley flow freely onto the surface without any significant restrictions. The highest-discharge spring, Suchá Bělá 3, is regularly monitored by CHMI. Groundwater abstraction from the Hřensko abstraction area has decreased compared with the past and is currently around 80 l/s [17]. Even several years after the fire, much of the area remains covered with charred wood debris. Scorched tree trunks rise towards the sky, with vegetation gradually regenerating between them, particularly through self-seeding birch (*Figs. 5* and *6*).

Potential effects of the fire on spring water quality

The large-scale fire, which burned from 24 July to 12 August 2022, affected an area of more than 10 km^2 around the monitored springs east of the town of Hřensko [18]. It was the largest forest fire recorded in Czechia in modern times.

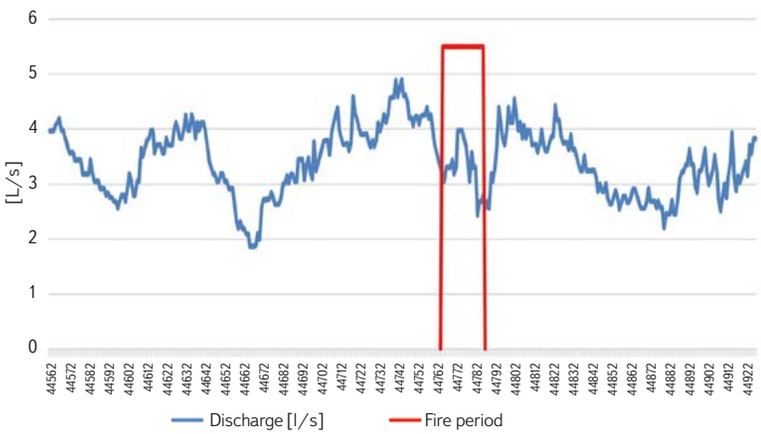

Fig. 3. Fluctuations in the discharge of the Suchá Bělá 3 spring in 2022 (data source: CHMI)

Fires can generally affect groundwater, particularly through contamination by substances contained in smoke and ash (toxic metals, polycyclic aromatic hydrocarbons, etc.). Infiltration of firefighting water and fire-suppressing agents may also play a role [19]. In this case, water from the Elbe river, Lake Milada and other sources was used to extinguish the fire.

Evaluation of data from the Raw Water Database

To assess changes in water chemistry, analytical data on abstracted groundwater from the Raw Water Database [22] were available for the captured springs. The database contains data for Nad Klepáčem spring (a drinking-water source for Hřensko) and the Hřensko abstraction area, into which the high-discharge Pod Pravčickou bránou and Pytlův springs are incorporated. Within the study area affected by the fire, the Mezná abstraction area is also monitored in this way; it abstracts groundwater from a hydrogeological borehole east of U Cikánského smrku spring. Results from the Mezná abstraction area were therefore also included for comparison in the assessment of the effects of the fire on groundwater (see, for example, the graphs in *Figs. 2a* and *2b*).

The three groundwater sources mentioned above abstract groundwater with low mineralisation and low pH. Groundwater from these sources was sampled both before the fire (analyses from 2019 to spring 2022 were considered) and after the fire (analyses from autumn 2022 and 2023).

Nad Klepáčem captured spring

The pH of water abstracted from Nad Klepáčem spring area was around 5.8 before the fire and decreased slightly to 5.7 after the fire (*Fig. 2a*). Water conductivity gradually increased slightly between autumn 2019 and spring 2022, reaching 16.7 mS/m before the fire. After the fire, it decreased to 15.3 mS/m before returning to around 16.3 mS/m in 2023 (*Fig. 2b*).

In 2022, following the fire, chloride concentrations increased slightly compared with pre-fire levels (from 4.47 to 5.35 mg/L), while sulphate concentrations decreased slightly (from 46.7 to 40.7 mg/L). Nitrate concentrations were identical before and after the fire (11.5 mg/L). Magnesium concentrations fluctuated around 3 mg/L both before and after the fire. Concentrations of ammonium ions, nitrites, aluminium and manganese were below the analytical detection limit both before and after the fire. No *Escherichia coli* or enterococci were detected either before or after the fire.

In autumn 2022, slight increases were recorded in the concentrations of iron (from < 0.02 to 0.07 mg/L), calcium (from 18.4 to 20.2 mg/L), the sum of Ca + Mg (from 0.58 to 0.63 mmol/L), and COD_{Mn} (from < 0.5 to 0.71 mg/L) in water

Fig. 4. Historical capture structure at Nad Klepáčem spring near Hřensko; condition in February 2026 (photo: P. Eckhardt)

Fig. 5. Pod Pravčickou bránou spring site near Hřensko, currently with no water emerging at the surface, status in May 2026 (photo: P. Eckhardt)

Fig. 6. Concrete well ring at U Cikánského smrku spring in the Hřensko study area, May 2026 (photo: P. Eckhardt)

abstracted from Nad Klepáčem spring. However, all these parameters returned to their previous typical levels in 2023.

In October 2022, a broader range of analyses was conducted, confirming the absence of significant concentrations of polycyclic aromatic hydrocarbons (PAHs), nickel, lead, zinc, phosphates, boron, copper, mercury, fluorides, selenium, chromium, cadmium, cyanides and beryllium in the abstracted water.

When compared with the requirements of Decree No. 252/2004 Coll. [20], the abstracted water failed to meet the same parameters both before and after the fire. These included, in particular, low pH and low magnesium concentrations, which were attributable to the natural background conditions.

Groundwater from the Hřensko abstraction area

In the Hřensko abstraction area, most groundwater is abstracted by pumping from hydrogeological boreholes. In 2022, the mean abstraction rate from this area was 75.7 L/s [17]. The discharge of the two captured springs (Pod Pravčickou bránou and Pytlův) is not measured but calculated, which our findings indicate is unreliable [8]. Based on expert estimates, spring water accounts for approximately one seventh of the total volume abstracted. Any contamination of the springs resulting from the fire could therefore be reflected in the results for the mixed abstracted groundwater, but only to a limited extent due to substantial dilution by groundwater pumped from the boreholes. In 2022, water analyses were conducted both before the fire (March and 14 July) and after the fire (September and October 2022).

The raw water from the Hřensko abstraction area was weakly mineralised and slightly acidic both before and after the fire. Comparison of the values before and after the fire showed a slight decrease in pH (from 6.3 to 6.0), followed by a return to the initial level (*Fig. 2a*). Similarly, the conductivity of the groundwater decreased after the fire and then returned relatively quickly to its previous level (*Fig. 2b*). The graphs also show an isolated sharp increase in both pH and conductivity in September 2023 (more than a year after the fire), which, in view of the preceding and subsequent measurements, we interpret as a probable measurement or database entry error.

For comparison, conductivity in the Mezná abstraction area decreased after the fire in a similar manner to that in the Hřensko abstraction area (*Fig. 2b*). By contrast, the decrease in pH after the fire was considerably greater in the Mezná abstraction area (from 6.6 to 6.0), falling well below the minimum limit for drinking water specified in Decree No. 252/2004 Coll. [20].

Both before and after the fire, groundwater from the Hřensko abstraction area had favourably low concentrations of nitrates, nitrites, ammonium ions, phosphates, sulphates, chlorides, iron, manganese, toxic metals and selected bacteria, as well as a wide range of other parameters analysed.

When compared with the requirements of Decree No. 252/2004 Coll. [20], the water from the Hřensko abstraction area failed to meet the same criteria both before and after the fire, including pH below the specified range and low calcium and magnesium concentrations, all of which are of natural origin. The raw water is treated before being supplied to the public water-supply system to ensure compliance with the requirements of the Decree [20]. Water analyses show that the fire did not cause any significant changes in the quality of water from the Hřensko abstraction area.

Overall, the differences in the quality of groundwater from the monitored sources incorporating captured springs before and after the fire near Hřensko were not significant, although some short-term adverse changes were observed. A marked decrease in groundwater pH after the fire was recorded in the Mezná abstraction area, which, however, does not abstract water from springs.

Suchá Bělá 3 spring

The high-discharge Suchá Bělá 3 spring (database number PP0552) has been monitored by CHMI over the long term. The spring has been modified for monitoring purposes, with both its discharge and water quality being monitored. Daily discharge data and the results of chemical and bacteriological analyses, generally conducted once or twice a year, are freely available for the study period (2019–2024) from the CHMI hydrological database (https://hydro.chmi.cz/hpps).

The discharge of Suchá Bělá 3 spring fluctuated slightly around a mean value of 4.3 L/s between 2013 and 2024. During some periods, discharge increased to more than 5 L/s, while at other times it fell to just above 3 L/s. The only period in which discharge fell below 3 L/s was during the study year 2022 (*Fig. 3*). Marked decreases in discharge had already occurred before the fire, falling to 2.5 L/s in February and subsequently to below 2 L/s, with the annual minimum occurring in mid-April. Discharge then gradually increased to an annual maximum of approximately 4.8 L/s around the end of June and beginning of July, followed by a decrease to around 3 L/s in mid-July. During the fire in late July, spring discharge increased from 3.18 L/s to almost 4 L/s before falling to 2.44 L/s in early August, including a very marked daily decrease of as much as 0.9 L/s. After the fire, discharge increased to the usual level of around 4 L/s in the second half of August, before declining to the second-lowest annual value in November and then returning to usual levels by the end of December. In our opinion, the daily discharge data recorded during the fire should be interpreted with caution, particularly given the possible sensitivity of the automatic measuring equipment to changes such as trees and branches falling into the measuring structure or firefighting activities (e.g. the use of water). Nevertheless, it is apparent that the more pronounced absolute changes in spring discharge in 2022 occurred not during the fire itself, but in the periods before and after it.

Water quality was compared primarily using analytical results from October 2021 (well before the fire), May 2022 (the last analysis before the fire), October 2022 (the first analysis after the fire) and May 2024 (the second analysis after the fire).

The spring water was weakly mineralised and slightly acidic (pH around 6) both before and after the fire. Concentrations of ammonium ions, nitrites, fluorides, dissolved organic carbon and phosphates, as well as acid neutralising capacity to pH 4.5 and base neutralising capacity to pH 8.3, remained consistently below the laboratory detection limits both before and after the fire. Similar levels before and after the fire were recorded for bicarbonates (around 5 mg/L), magnesium (approximately 1.7 mg/L), potassium (around 2.5 mg/L), sodium (approximately 2.8 mg/L), carbonates and total hardness (around 0.26 mval/L). Slight increases after the fire were recorded in nitrate concentrations (from 10 to 11 mg/L), calcium (from 6.75 to 7.75 and subsequently 8.11 mg/L), chlorides (to above 4 mg/L) and sulphates (from 17.9 to 18.5 mg/L). COD_{Mn} increased from approximately 0.5 mg/L before the fire to 0.62 mg/L in October after the fire, before decreasing to 0.54 mg/L in 2024.

No analysis of metals and other elements is available for the period shortly after the fire. However, both before the fire (October 2021 and May 2022) and in May 2024, concentrations of antimony, arsenic, boron, chromium, cadmium, cobalt, lithium, manganese, copper, molybdenum, nickel, lead, selenium, vanadium, zinc and iron were below the laboratory detection limits after filtration. Similarly, anionic surfactants, the pesticides analysed, chlorinated aliphatic hydrocarbons, simple aromatic hydrocarbons, chlorinated benzenes and other substances were below the detection limits.

Comparison with the drinking-water limits [20] showed no change in the assessment of the water quality of Suchá Bělá 3 spring before and after the fire. The water failed to meet the requirements primarily because of its low pH (below the specified range), magnesium concentrations below the minimum limit, and calcium and magnesium concentrations below the recommended ranges. These deviations are of natural origin.

Springs monitored in the Spring Areas project

During fieldwork in the first half of 2026, water parameters were measured at eight major freely accessible springs in the study area that had been monitored previously. Samples for chemical analysis were collected from six of these springs.

Recent analyses of groundwater from the five springs in the Suchá Bělá valley showed similar characteristics. The pH was slightly acidic, ranging from 5.8 to 6.0, and water conductivity was low (8.7–10.0 mS/m). Concentrations of ammonium ions and nitrites were below the analytical detection limit (< 0.05 mg/L), as were concentrations of phosphates and total phosphorus (< 0.025 mg/L) and aluminium (< 0.005 mg/L). Nitrate concentrations were only around 10 mg/L, while calcium concentrations were around 8 mg/L and magnesium around 1.6 mg/L. The groundwater at Nad Klepáčem spring originates from a higher level of the sandstone complex. Compared with the springs in the Suchá Bělá valley, water sampled from the smaller outlets of Nad Klepáčem spring area had higher conductivity (16.8 mS/m) and higher calcium and magnesium concentrations, consistent with the characteristics described above based on data from [22].

Comparison of the parameters of emerging groundwater measured in the field using the same method (in each case, the mean of at least three sets of spot measurements taken at different times) in 2012–2014 (well before the fire) and in 2026 (well after the fire) showed the following:

Measured discharge remained broadly similar between 2012–2014 and 2026 at four springs, including Suchá Bělá 3 spring (approximately 3.9 L/s) and U Cikánského smrku spring (approximately 0.22 L/s). At two of the monitored springs, measured discharge decreased markedly, including Suchá Bělá 2 spring (from 1.2 to 0.5 L/s). By contrast, discharge increased markedly at two other monitored springs.

Mean measured water conductivity increased slightly compared with 2012–2014. For example, at Suchá Bělá 2 spring, it increased from a mean of 7.75 to 9.0 mS/m. The higher-elevation springs in the area have higher water conductivity; for example, at U Cikánského smrku spring, the mean increased from 19.55 to 22.2 mS/m. The slight increase in conductivity is probably unrelated to the fire; data from more frequently monitored springs (e.g. Nad Klepáčem) suggest that it is more likely part of a longer-term trend.

Overall, the differences in groundwater quality at the monitored springs before and after the fire were not considered significant.

Aš study area

To compare changes in spring areas that are demonstrably occurring and measurable, but do not result from sudden disturbances, we selected two areas for which both older and more recent data are available. The first study area, around the town of Aš, is located in the Cheb District of the Karlovy Vary Region. The older, incomplete dataset available to us comes from spring-area mapping conducted in 2009 as part of a restoration study commissioned by the Nature Conservation Agency of the Czech Republic [11]. Some of these spring areas were monitored again under an Interreg project in 2020–2022. The most recent data come from the current Technology Agency of the Czech Republic project *Methods for the identification and stabilisation of existing spring areas and restoration of historical spring areas*.

From a hydrological perspective, the springs investigated lie within the catchments of the Lužní, Pekelský, Újezdský, Rokytnice and Bystřina streams. These watercourses flow across the border into Germany, where, via the Südliche Regnitz and Schwesnitz, they form part of the Saale catchment and, ultimately, the Elbe river basin.

Hydrogeologically, the area forms part of the crystalline basement of the Bohemian Massif, specifically Hydrogeological Region 6111 – Crystalline Basement of the Fichtel Mountains and the western part of the Ore Mountains, and Groundwater Body 61110 of the same name [15]. The area is characterised by fractured-rock aquifers, particularly in phyllites and schists, together with intergranular aquifers in the overlying deposits [12].

Fig. 7. No water flows at the surface from the captured Pekelský stream spring near Aš, which is enclosed in a chamber (photo: P. Eckhardt)

Fig. 8. Historical aerial photograph showing the construction of drainage systems around the village of Pastviny in the Aš area

Fig. 9. Luz 67 spring area formed by a drainage-system failure in a pasture; previously fenced off, the secondary spring outlet has since shifted, and the wetland area is now repeatedly damaged by livestock (Aš area)

Fig. 10. One of the upper spring outlets of the Lužní stream, dry in 2025; drainage channels located 20–50 m from the outlet convey water towards the Lužní stream, affecting the discharge and overall condition of the spring areas (Aš area)

Fig. 11. VMP08 spring area drained by a drainage channel (upper Blanice catchment area)

Development of the springs in the Aš area

Historically, water management in the Aš area was strongly associated with a dense network of springs and small streams that had been extensively modified by people for centuries. At the beginning of the 18th century, local watercourses powered around 20 mills, while by the end of the 19th century the landscape also contained networks of small retention ponds. In the floodplains of the Bílý Halštrov and Rokytnice, farmers constructed sophisticated irrigation and drainage systems. A distinctive chapter in the area's history began with the expansion of the textile industry in the late 19th century, when local factory owners had special underground water-collection galleries constructed, remains of which can still be found around the villages of Mokřiny, Štítary and Vernéřov [23].

Around 1900, some of the springs, including those in the Pekelský stream catchment, were captured to supply drinking water to the local population. This occurred mainly on the German side of the border, although Pekelský stream, located on the Czech side, was also connected to the system [12]. Today, this spring is captured in a concrete chamber with a cast-iron cover, with no water emerging at the surface (*Fig. 7*); all the water is conveyed by pipes to Germany. At the border section of the Pekelský stream, the channel contains wetland vegetation but is completely dry in the spring area, with only isolated areas of standing water farther downstream. On the German side of the border, springs in the headwaters of the Pekelský stream have been fenced off and fitted with chambers with rather more presentable stainless-steel covers. The effect on both the springs and the Pekelský stream is similar, however: capture has eliminated surface discharge from the springs, and no water from them now flows into the former border stream.

Another major intervention affecting the structure of springs in the study area was land drainage, introduced to increase agricultural yields, particularly on arable land. Subsurface and surface drainage systems in this area date from the 1960s and 1970s [23] (*Fig. 8*). Over the past 30 years in particular, arable land in this submontane area has increasingly been converted to meadows and pastures, and drainage has therefore largely lost its agricultural purpose. The landscape has undergone numerous changes since the drainage systems were constructed and now contains a mosaic of functional and degraded drainage systems [13]. On some level sites in the floodplains of small watercourses, particularly in the Rokytnice catchment, the old drainage systems are now completely non-functional. This has led to natural recovery and the return of these areas to near-natural wetlands or periodically flooded floodplains. At the same time, approximately one third of all spring areas mapped in the Aš area on both sides of the border in 2020–2022 occur on land drained by systematic subsurface drainage. These are therefore so-called 'secondary spring areas' formed where blocked or damaged pipes cause drainage water to emerge at the surface (*Fig. 9*). Perhaps surprisingly, these secondary spring areas can perform the same functions in the landscape as natural spring areas, although they may have certain disadvantages by comparison. These can include greater fluctuations in temperature over the course of the year, poorer and more variable water quality, or instability of the spring outlet itself. As blockages and other changes occur within damaged drainage pipes, the point at which water emerges may

Fig. 12. Natural forest spring area M01A (upper Blanice catchment area)

shift from place to place. This has been observed, for example, at the long-term monitored secondary spring area U stružky (Luz 67) (*Fig. 9*), where the manager of the Bystřina – Lužní stream National Nature Monument (Slavkovský les Protected Landscape Area) has confirmed that the subsurface drainage system has been blocked for many years. Nevertheless, in spring areas with a disturbed water regime, even these habitats are important components of the heterogeneous landscape structure. They provide refugia for temporary macrozoobenthic species and other animals and increase biodiversity within the study area. *Tab. 1* presents basic information on the nine monitored spring areas, including their principal characteristics and relationship to drainage.

By contrast, where parts of the subsurface drainage systems remain functional, they continue to accelerate water runoff, reducing the landscape's capacity to retain water and causing spring wetlands to dry out. In some cases, drainage systems continue to serve a useful purpose. For example, they are often retained around major linear infrastructure or infrastructure reconstructed in the recent past to prevent damage to these structures. In protected areas, or in catchments immediately adjacent to them, however, nature conservation interests should take precedence [24]. In spring areas, the quality of drinking water and the benefits of retaining water in the landscape likewise outweigh the benefits of maintaining agricultural land on sites that would otherwise be naturally waterlogged. Nevertheless, although the removal of systematic drainage is desirable in many places, it faces numerous administrative and practical obstacles, involves complex property ownership issues, is financially costly and requires not only project planning but also cooperation between several stakeholders.

In the forests of this area, surface drainage channels were constructed in the past to drain some spring areas and other wetlands locally (*Fig. 10*). They are most concentrated in the headwaters of the Lužní stream and in the Rokytnice catchment above Dolíška pond. These are generally simple excavated ditches leading from small forest spring areas to the nearest headwater stream, or sometimes into another ditch, forming a more or less functional drainage network. Some ditches carry water throughout the year, others only for part of the year, while some have now dried up completely. Straightened spring-fed channels lined with concrete slabs, such as those in the spring area of the Újezdský stream, also contribute to accelerated runoff and reduced infiltration. The present-day landscape of the Aš area is also changing as small historical ponds and pools, often situated in or along the edges of forests, gradually silt up and disappear naturally. These were constructed by the original German inhabitants of the area from the beginning of the modern period, but particularly during the 19th century. Interestingly, one reason for constructing these retention ponds was the seasonal fluctuation in streamflow during the summer months, which had already been observed in the Aš area at that time, and the need to maintain a reliable water supply for mills, sawmills and the first ironworks, and later for paper mills and the textile industry [23].

Drainage of agricultural and forest land, whether through subsurface systems or surface drains, rapidly conveys water from spring areas into watercourses. In years with below-average precipitation, this contributes to the drying out of spring wetlands and, subsequently, small watercourses. In years with average or above-average precipitation, by contrast, accelerated runoff can contribute to flash flooding or lead to the formation of gullies and other forms of erosion. Since the designation of small-scale protected areas in the Aš area from the 1990s onwards, numerous restoration projects of varying scales have been conducted and land management practices have improved [14]. The most recent example is the restoration of a straightened and incised

section of the Lužní stream near Pastviny [25]. Most restoration measures, however, have focused solely on watercourses, while spring areas and small headwater channels have been neglected for various reasons.

Blanice and Zlatý streams catchment study area

The upper catchments of the Blanice and Zlatý stream in the Šumava region are important headwater areas. In addition to well-known springs and wells that have historically been used by local people, hundreds of natural and near-natural spring areas have been mapped here in several phases associated with different projects from 2005 to the present. From a hydrogeological perspective, the study area lies within Hydrogeological Region 6310 – Crystalline Basement in the Upper Vltava and Úhlava Catchments, and Groundwater Body 63101 – Crystalline Basement in the Upper Vltava and Úhlava Catchments [15]. Hydrologically, some of these spring areas lie within the catchments of the Spálenecký, Sněženský and Tetřívčí streams and the upper Blanice itself, while others lie within the Luční and Zlatý stream catchments. The Zlatý stream is also a tributary of the Blanice downstream of Husinec Reservoir.

Development of springs in the Blanice study area

Historically, small watercourses flowing from springs in the Křišťanov, Arnoštov and Boletice areas were used for gold panning from as early as the 14th century, as was the Blanice itself. Later, under Schwarzenberg administration, timber harvesting expanded considerably in the catchment. Transporting the timber required modifications to the hydrographic network, including the construction of log-driving reservoirs (splash dams), which were used to increase water levels artificially. Most have since disappeared, although some still exist, including Pucháreński pond. Springtime timber floating continued until the beginning of the 20th century. As in other areas, water was also used to power mills and ironworks.

This area is unique within the Czech Republic in that, although agriculture and forestry were intensified here between 1970 and 1990, accompanied by efforts to drain land extensively for agricultural use, it was relatively little affected by drainage schemes [26, 27] (*Fig. 11*). This may have been because the area was not targeted until the late 1980s. Systematic subsurface drainage systems were constructed, for example, in the catchments of the Vyšenský, Zbytinský, Magdalenský and Kukaččí streams within the Blanice catchment, and in the Luční and Zlatý stream catchments in the neighbouring area. Some catchments remain unaffected by large-scale drainage, including those of the Hornosněženský, Tetřívčí and Spálenecký streams, as well as other small watercourses within the Boletice Military Training Area (*Fig. 12*). In these catchments, therefore, the capacity of natural spring areas to retain water in the landscape, maintain local biodiversity and potentially provide other ecosystem services can be readily compared, on a larger scale than in the Aš region, with the limited functionality of secondary spring areas. Although, after 1990, arable land in the Blanice National Nature Monument and the Prameniště Blanice National Nature Monument was converted to grassland and extensive management was introduced, significantly improving water quality [28], the historical large-scale drainage itself is still regarded as an irreversible adverse intervention, with the deteriorating drainage systems continuing to have a negative impact on the landscape water regime.

For comparison, we identified the basic characteristics of 14 spring areas in the Blanice and Zlatý stream catchments and their relationship to drainage. An overview is provided in *Tab. 1*.

Comparison of water quality in natural and restored spring areas in the Aš and Blanice study areas

The comparison of changes in water quality between natural and drained spring areas revealed several interesting patterns within this limited sample. While some natural spring areas showed slight improvements and others slight deterioration, the overall mean score for all undrained spring areas (0.42 points) indicated that water quality at these outlets was relatively stable. No differences were observed between the catchments (Aš versus Blanice/Zlatý stream). The scores for spring areas affected by drainage showed a different pattern. No deterioration was recorded; water quality at these outlets had either remained unchanged or improved since the initial sampling in 2005–2009 (mean score 2.22 points). Relatively marked improvements in two or three parameters were recorded, for example, at three spring areas in the Aš area. Two of these are secondary spring areas formed as a result of failures in drainage systems (Luz 67 – U stružky and Bys 04 – U hlásky), while the third is drained by a deepened ditch (Luz 23 – Bílý vývěr).

DISCUSSION

Of the three impacts investigated, spring capture for public drinking-water supply proved fatal to the very existence of surface spring outlets. This was the case both in the Hřensko study area (Pod Pravčickou bránou spring, Pytlův spring and the main outlet of Nad Klepáčem spring) and in the Aš area (e.g. Pekelský stream spring). Intensive groundwater abstraction near Hřensko also resulted in the disappearance of Panenský spring and a decline in the discharge of some of the surrounding springs.

By contrast, the large-scale fire around Hřensko did not result in significant long-term changes in either the quantity or chemical composition of water from the major springs monitored within this hydrogeological structure. Some short-term adverse changes were nevertheless observed. A marked decrease in groundwater pH after the fire was recorded in the Mezná abstraction area, although this area does not abstract water from springs. Following the deterioration of some groundwater parameters after the fire, individual hydrochemical parameters returned to their usual long-term levels within several months to one year. The forest fire therefore had only a minor effect on groundwater quality, unlike some fires at industrial sites [19].

Land drainage and the shortening and straightening of watercourses in the Aš area have accelerated runoff from the catchments. Together with the capture of some springs, particularly in the Pekelský stream area, this causes significant problems during periods of drought. Changes in the landscape water regime, combined with climate change, are resulting in more frequent hydrological extremes – floods and droughts – which increasingly disrupt the normal functioning of human society and also have a major impact on aquatic and water-dependent organisms in the area. In the Blanice and Zlatý stream catchments, the smaller extent of land drainage means that, although flooding and the drying out of some surface springs also occur, there are currently no records of watercourses drying out.

The comparison of water quality in the spring areas shows that water quality improved in those affected by drainage, particularly in terms of nitrogen compounds. In contrast to sudden disturbances, such as the fire around Hřensko, gradual changes can therefore have a positive effect on water quality in spring areas. The observed improvement was probably largely due to changes in land management between 2005 and 2025 and the gradual natural recovery of areas affected by systematic drainage. All the secondary spring areas investigated are located either within small-scale protected areas or in their immediate vicinity. In the late 1990s and after 2000, most of the formerly intensively managed land in this area was converted to meadows or pastures, including the sites containing the monitored non-forest spring areas. While the effects of intensive management probably persisted during the first sampling period, when concentrations of nitrogen compounds were still elevated, by the second monitoring period these substances were below the detection limit in the secondary spring outlets. A second factor is the natural recovery of drained areas. As unmaintained subsurface drainage systems gradually deteriorate, secondary

Tab. 1. Basic characteristics of spring areas affected and unaffected by drainage in the Aš area and the upper Blanice and Zlatý stream catchments

Area	Code	Name	Record	Coordinates	Elevation [a.s.l.]	Drainage
Ašsko	Luz08	Boční pramen Kyselého potoka	2008, 2020, 2026	50.2561000N, 12.1304000E	659	drainage ditch
Ašsko	Ryb01	Železný pramen	2008, 2020, 2026	50.2649000N, 12.1570667E	655	drainage ditch
Ašsko	Luz67	U stružky	2008, 2020, 2026	50.2713833N, 12.1548667E	642	systematic drainage
Ašsko	Str03	Střelecká louka	2008, 2021, 2026	50.3262572N, 12.1409178E	607	none
Ašsko	LesL03	Helokren u klád	2008, 2021, 2026	50.2570667N, 12.1510000E	642	none
Ašsko	Luz20	Terezčin pramen	2008, 2021, 2026	50.2509206N, 12.1440689E	643	none
Ašsko	Luz23	Bílý vývěr	2008, 2020, 2026	50.2475850N, 12.1453897E	675	drainage ditch
Ašsko	Bys04	U hlásky	2008, 2020, 2026	50.3133031N, 12.1361653E	593	systematic drainage
Ašsko	Luz07	Ptačí helokren	2008, 2021, 2026	50.2573500N, 12.1373667E	633	none
Bla/Zla	LV03	Nad pasekou	2005, 2026	48.9228889N, 14.0673889E	741	drainage ditch
Bla/Zla	TET52	(no name)	2023, 2026	48.9158231N, 13.9996119E	840	drainage ditch
Bla/Zla	M03	Skřípinná rozlivná louka	2005, 2026	48.9042419N, 13.9902008E	849	none
Bla/Zla	M01A	Olšové kaliště	2005, 2026	48.9033781N, 13.9927350E	860	none
Bla/Zla	VMP08	U čarověníku	2005, 2026	48.9085519N, 13.9924664E	864	systematic drainage
Bla/Zla	VMP05	Helokren pod klenem	2005, 2026	48.9083672N, 13.9893950E	850	systematic drainage
Bla/Zla	SN05	U borovic	2006, 2009, 2025	48.9144249N, 13.9673625E	870	none
Bla/Zla	SNB17B	Kukačka	2005, 2023, 2025	48.9134517N, 13.9625612E	865	none
Bla/Zla	SP82 / SC05	U panenky Marie	2005, 2006, 2009, 2023, 2025	48.9063987N, 13.9527977E	935	none
Bla/Zla	LAP02	Lapačka	2006, 2009, 2025	48.9190200N, 13.9674361E	812	none
Bla/Zla	ZL66	Pod sklípkem	2006, 2009, 2025	48.9476542N, 14.0176434E	824	systematic drainage
Bla/Zla	1P2	Nad dvěma zubatými koly	2006, 2009, 2025	48.9209885N, 14.0562187E	797	none
Bla/Zla	TA08	Studánka Tetřívčí	2005, 2023, 2025	48.9255836N, 14.0018190E	849	drainage ditch
Bla/Zla	Bla16	Bílý pramen	2006, 2009, 2025	48.9225082N, 13.9789619E	800	none

Tab. 2. Chemical water-quality parameters in selected spring areas during the two monitoring periods

WITHOUT DRAINAGE								
Code	**Conductivity [µS/cm]**	**NO_3 [mg/L]**	**NO_2 [mg/L]**	**NH_4 [mg/L]**	**PO_{4-} [mg/L]**	**Cl- [mg/L]**	**Parametrs**	**Change (score)**
1P2 – Nad dvěma zubatými koly								
2005–2009	68	6.57	< 0.005	< 0.01	0.111	1.75	6/6	–1
2020–2026	79	6.62	< 0.050	< 0.050	0.129	1.82		
Bla16 – Bílý pramen								
2005–2009	50	1.41	< 0.050	< 0.050	0.081	4.88	6/6	0
2020–2026	62	1.45	< 0.050	< 0.050	0.082	1.27		
LAP02 – Lapačka								
2005–2009	73.7	1.35	< 0.005	< 0.01	0.027	3.95	6/6	–3
2020–2026	80	5.26	< 0.050	< 0.050	0.113	2.05		
LesL03 – Helokren u klád								
2005–2009	79.2	3.2	1.2	0.9	N/A	N/A	4/6	0
2020–2026	135.0	6.3	< 0.050	< 0.050	< 0.077	2.99		
Luz07 – Ptačí helokren								
2005–2009	84.8	5.0	0.05	0.8	N/A	N/A	4/6	+2
2020–2026	135.8	< 0.500	< 0.050	< 0.050	< 0.077	2.18		
Luz20 – Terezčin pramen								
2005–2009	65.3	2.3	0.1	N/A	N/A	N/A	3/6	+2
2020–2026	85.0	0.555	< 0.050	< 0.050	< 0.077	2.69		
M01A – Olšové kaliště								
2005–2009	80	N/A	N/A	N/A	N/A	N/A	1/6	0
2020–2026	81	3.0	< 0.050	< 0.050	< 0.077	1.77		
M03 – Skřípinná rozlivná louka								
2005–2009	64	N/A	N/A	N/A	N/A	N/A	1/6	+2
2020–2026	39	< 0.500	< 0.050	< 0.050	0.102	1.11		
SN05 – U borovic								
2005–2009	60.5	2.07	< 0.005	< 0.01	0.085	3.44	6/6	0
2020–2026	56	2.21	< 0.050	< 0.050	0.11	1.64		
SNB17B – Kukačka								
2005–2009	111	N/A	N/A	N/A	N/A	N/A	1/6	+2
2020–2026	68.6	< 0.500	< 0.050	0.051	< 0.077	< 0.500		
SP82/SC05 – U panenky Marie								
2005–2009	41.3	2.63	< 0.005	< 0.01	0.113	1.21	6/6	+2
2020–2026	42.9	0.515	< 0.050	< 0.050	1.17	< 0.077		
Str03 – Střelecká louka								
2005–2009	122	N/A	N/A	N/A	N/A	N/A	1/6	–1
2020–2026	135	6.30	< 0.050	< 0.050	< 0.077	3.31		

WITH DRAINAGE								
Code	**Conductivity [µS/cm]**	**NO_3 [mg/L]**	**NO_2 [mg/L]**	**NH_4 [mg/L]**	**PO_{4-} [mg/L]**	**Cl- [mg/L]**	**Parametrs**	**Change (score)**
Bys04 – U hlásky								
2005–2009	123.5	2.3	1.7	0.15	N/A	N/A	4/6	+4
2020–2026	80.0	9.07	< 0.050	< 0.050	< 0.077	2.13		
Luz08 – Boční pramen Kyselého potoka								
2005–2009	125.6	3.0	0.05	1.3	N/A	N/A	4/6	+2
2020–2026	113	5.74	< 0.050	< 0.050	< 0.077	3.12		
Luz23 – Bílý vývěr								
2005–2009	79.0	2.2	0.6	0.4	N/A	N/A	4/6	+5
2020–2026	52.0	2.31	< 0.050	< 0.050	0.089	2.67		
Luz67 – U stružky								
2005–2009	89.59	2.1	0.15	0.3	N/A	N/A	4/6	+4
2020–2026	101.0	1.54	< 0.050	< 0.050	< 0.077	2.84		
LV03 – Nad pasekou								
2005–2009	74	N/A	N/A	N/A	N/A	N/A	1/6	0
2020–2026	76	1.18	< 0.050	< 0.050	< 0.077	1.18		
Ryb01 – Železný pramen								
2005–2009	112.3	N/A	N/A	N/A	N/A	N/A	1/6	+2
2020–2026	106	< 0.500	< 0.050	< 0.050	< 0.077	3.17		
TA08 – Studánka Tetřívčí								
2005–2009	99.6	N/A	N/A	N/A	N/A	N/A	1/6	0
2020–2026	98	6.23	< 0.050	< 0.050	< 0.077	2.93		
VMP05 – Helokren pod klenem								
2005–2009	70	N/A	N/A	N/A	N/A	N/A	1/6	+2
2020–2026	39	< 0.500	< 0.050	< 0.050	< 0.077	< 0.500		
ZL66 – Pod sklípkem								
2005–2009	77	4.53	< 0.005	0.01	0.085	4.86	6/6	+1
2020–2026	79	3.79	< 0.050	< 0.050	0.86	1.67		

springs increasingly acquire near-natural characteristics, while their water quality improves through natural self-purification processes.

The gradual improvement in water quality observed at secondary spring areas in the Aš area and Šumava closely corresponds with the growing need to protect these small aquatic habitats. Although these spring areas developed secondarily as a result of failures in drainage systems, studies from other countries show that, despite their secondary origin, they can provide key ecosystem services [29, 30]. Protecting and supporting these naturally recovering spring outlets is all the more important because ongoing climate change is likely to expose springs to increasing anthropogenic pressure from widespread abstraction of water resources, potentially leading to further irreversible degradation of these sensitive habitats [6]. Assessment of water chemistry alone, however, is only a first step and one of many criteria. A comprehensive assessment of the success of natural recovery in spring areas must also take into account biological indicators, typically benthic macroinvertebrate and bryophyte communities [31]. Previous research indicates that the ecological recovery of wetland habitats may not proceed entirely linearly: the diversity of sensitive communities may temporarily decline or remain unchanged immediately after changes in habitat conditions before a demonstrable increase occurs [32–34]. For this reason, as part of the ongoing project No. SQ01010130, the hydrochemical data presented here will be further evaluated in conjunction with the results of detailed biological monitoring.

Springs contribute to biodiversity and help maintain water availability near the surface during dry periods. Their at least partial restoration would therefore be desirable, not only within the study areas.

For example, in Bohemian Switzerland National Park, where enhancing biodiversity and nature conservation should be a priority, some historical springs

could be restored at suitable sites. Restoration could make use of overflow water from Nad Klepáčem spring and potentially some of the water from Pod Pravčickou bránou and Pytlův springs, provided that this water is not essential for the public water supply and that the work is carried out in accordance with the enhanced groundwater protection measures applying in the area. Carefully returning spring water to the surface would not only enhance biodiversity but could also reduce the risk of fire in this sensitive area of the national park. Finally, the heavily used hiking trail to Pravčická brána, which is currently dusty and runs alongside the road, could once again become a more pleasant environment for both nature and the many visitors to the area.

Similarly, returning at least some of the water from Pekelský stream spring in the Aš area to the surface could restore the border watercourse, improve natural conditions, enhance biodiversity, and provide some additional protection against fire on land on both sides of the border.

CONCLUSION

Springs are important landscape features that enhance local biodiversity and help maintain water availability in the landscape during dry periods. Research into spring areas in the three study areas showed that the most significant intervention is their direct technical capture for drinking-water supply, which results in the complete loss of surface spring outlets. Large-scale land drainage also has a significant impact, contributing to the drying out of small watercourses and wetlands during dry years and accelerating runoff from the landscape. By contrast, some sudden disturbances, such as the large-scale forest fire in the national park, have no significant long-term effect on either the hydrochemical status or the quantity of groundwater in deeper hydrogeological structures.

Longer-term monitoring confirmed that gradual changes have a positive effect on water quality, particularly by reducing concentrations of nitrogen compounds. Specifically, these changes include the transition to extensive land management and the natural recovery of areas resulting from the deterioration of old drainage systems, leading to the formation of more or less stable secondary spring areas. For future landscape management, the sensitive restoration of historical springs by returning surplus or overflow water to the surface would be desirable, for example in Bohemian Switzerland National Park and the Aš area. This would not only help enhance biodiversity but also provide more effective protection against fire in sensitive areas.

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Photo: P. Eckhardt

Retention potential of beaver dams for surface water storage in the Czech landscape

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Keywords: Eurasian beaver — ecosystem engineer — water retention — beaver dam — hydrological regime — GIS analysis — beaver dam capacity modelling — wetlands — landscape management

ABSTRACT

The Eurasian beaver (*Castor fiber*) is an important ecosystem engineer that alters the hydrological regime of the landscape through its activities. The aim of this study was to quantify the volume of surface water retained by beaver dams in the Czech landscape and to estimate the potential retention capacity of a selected catchment assuming the maximum predicted extent of beaver colonisation. The main focus of the research was to determine the volume of surface water accumulated behind 150 beaver dams at sites in the Plzeň Region (the Křemelná catchment and ten other selected wetlands) and the inundated area of the associated beaver ponds. GIS analyses based on a combination of precise geodetic data and a digital terrain model were used for the calculations. A beaver dam capacity model based on fuzzy logic principles and parameters such as stream slope, channel width, flow strength, and availability of riparian vegetation was also applied to the Chlístovický Stream catchment (fourth-order catchment, 13.8 km^2) to estimate the amount of water that could realistically be retained by beaver dams in the study area assuming full colonisation of the catchment by beavers.

Field measurements showed that the 150 surveyed dams retain a total of 31,321 m^3 of surface water, with 89 dams in the Křemelná catchment retaining 12,389 m^3 across an area of 169 km^2. The distribution of retained volumes exhibits pronounced right-skewness (median 41.0 m^3, mean 208.8 m^3), confirming that the vast majority of dams retain relatively small volumes, while a small number of large beaver ponds account for a substantial proportion of the total retained volume – the largest 3 % of ponds account for 54 % of the total volume. A similar distribution pattern was observed for the inundated areas of beaver ponds, with a total area of 98,586 m^2. The median inundated area of an individual beaver pond was only 168.9 m^2, compared with a mean of 657.2 m^2, and the four largest ponds accounted for 53 % of the total inundated area. Modelling in the 13.8 km^2 Chlístovický Stream catchment identified nearly 6 km of watercourses suitable for beaver colonisation. Under full colonisation, the model predicts the formation of 13–43 dams. Based on the volumes measured at the experimental sites, surface water accumulation in the Chlístovický Stream catchment can be expected to amount to hundreds or several thousand cubic metres. A significant proportion of retention, however, also occurs below ground, further increasing the overall hydrological benefit. The formation of beaver ponds covering a total area of several thousand to tens of thousands of square metres could also provide an important ecological benefit by creating opportunities for the development of wetland habitats. The study demonstrates that beaver dams represent an important component of nature-based water retention in the landscape; however, their importance extends far beyond surface water accumulation. Beaver dams also contribute to sediment deposition, stabilisation of runoff patterns, and increased ecological stability of the landscape, and should therefore be given adequate space in the landscape.

INTRODUCTION

The Eurasian beaver is native to the European landscape and historically occupied extensive areas from the British Isles to eastern Siberia. Intensive hunting, however, brought it close to extinction, and by the end of the 19th century the European population was estimated at only about 1,200 individuals in eight isolated populations [1]. Species protection and reintroduction programmes have enabled its gradual return since the 20th century, and by around 2020 the European population was estimated at approximately 1.5 million individuals [2]. A similar development occurred in the Czech Republic, where, following its complete extirpation, the beaver was recorded again in 1977 at the confluence of the Dyje and Kyjovka rivers, and its population has grown rapidly since the beginning of the 21st century [3, 4]. In 2020, the population in the Czech Republic was estimated at approximately 15,000 individuals [5, 6].

Beavers are often described as 'ecosystem engineers' because of their ability to modify their environment by building dams [7]. As populations grow rapidly, this can lead to conflicts with people, but also produces a range of positive effects. A beaver dam is a structure made of natural materials that impounds a watercourse. A beaver pond forms upstream of the dam, comprising accumulated water that changes the character of the watercourse from flowing to standing water. Dams and ponds often form cascades that cause water to spread across the surrounding floodplain. These complexes subsequently form what is known as a beaver wetland (*Figs. 1 and 2*) [6, 8]. Although dams and the ponds they create primarily provide protection from predators and access to food [9], they also have a major influence on the hydrological regime of the landscape. They slow water flow, promote sedimentation, enhance interactions between surface water and groundwater, and increase surface water and groundwater storage [10–12].

The benefits of beaver activity, however, extend beyond water retention alone. Dam building contributes to the restoration of near-natural river corridors and the natural structural diversity of floodplains, promotes the spontaneous renaturation of technically modified watercourses, and reduces the adverse effects of agricultural and forestry drainage systems [6, 13–15]. Newly created wetland habitats increase habitat diversity and biodiversity, aided by the fact that beaver activity increases the amount of ecologically valuable dead wood in watercourses [6, 13, 16, 17].

Fig. 1. Drone image of a beaver wetland on the Litohlavský stream, showing two beaver dams and associated ponds forming a cascade, and a wetland that developed on the right bank of the stream (photo: T. Laburda)

The principal focus of this study is to determine the volume of surface water retained by beaver dams. The vast majority of studies addressing this topic come from North America and show that beaver dams substantially increase the volume of water stored in watercourses and wetlands [18–20]. Beedle [18], for example, found that beaver ponds in Alaska retained up to 37 times more water than natural stream reaches, with individual pond volumes ranging from tens of cubic metres to more than 11,000 m^3. Karran et al. [19] determined pond volumes of 1–9,001 m^3 at four sites in North and South America. The few European studies available also confirm a substantial retention effect of beaver dams; for example, the total volume of water retained by 22 beaver dams in the Krzemianka catchment in Poland was estimated at 15,000 m^3 [21].

In addition to retained volumes, this study also quantifies the inundated area of beaver ponds. This is important not only hydrologically but also ecologically, as larger beaver wetlands are associated with greater bird species richness and abundance and also increase the availability of lentic and littoral habitats within the floodplain [22, 23].

Although beaver behaviour and the development of their territories cannot be predicted reliably, certain parameters can be used to assess the suitability of an area for potential beaver colonisation [24]. Research has demonstrated relationships between beaver occurrence and watercourse characteristics such as slope, channel width, and the availability of riparian vegetation [25]. These findings have been used to develop spatial models that predict the capacity of the environment to support dam building [26]. Such models are also used to estimate potential water retention in the landscape. For example, a study in the Sierra Nevada, California, estimated that beaver dams could store up to 120 million m^3 of surface water while also helping to increase landscape resilience to fire [27].

In this study, precise geodetic methods were used to determine the volume of surface water retained by 150 beaver dams in the Křemelná catchment and at ten other selected wetlands in the Plzeň Region, predominantly in the Šumava Mountains, with the aim of contributing quantitative evidence to assessments of the importance of beavers in the Czech landscape. The inundated area of the beaver ponds was also evaluated. At the same time, we modelled the potential number of dams that could develop in a selected fourth-order catchment following beaver colonisation, assuming minimal human restriction of beaver activity. These results were then used to quantify the amount of water that beavers could retain in the catchment through their activities.

The aim of the study was therefore to improve understanding of the positive effects of beaver colonisation by quantifying surface water retention in the landscape, which is one of the prerequisites for effective management of the Eurasian beaver and objective assessment of conflicts associated with its occurrence. Surface water retention is only one benefit of beaver dams and is linked to a range of other hydrological and ecological processes. In addition to retaining water and sediment, beaver structures can, for example, help sustain flows during dry periods, improve the microclimate, create valuable wetland habitats, and increase the amount of dead wood in watercourses [11, 18, 28].

Fig. 2. Beaver wetland on the Litohlavský stream, viewed upstream; the main beaver dam (right, among the trees) has caused water to spread beyond the stream channel, creating a wetland (left and centre) (photo: A. Babuljak)

METHODOLOGY

In the Křemelná catchment in the Šumava Mountains, a geographically and hydrologically coherent area containing 89 beaver dams at the time of the survey in spring 2023, and at ten selected beaver wetlands in the Plzeň Region, precise field surveying was used to determine the volumes of surface water retained by the dams and the inundated areas of the beaver ponds. In the Chlístovický Stream catchment, the potential occurrence of beaver dams was also modelled according to the suitability of individual watercourse reaches for dam construction.

Study areas

The study covered three areas, shown in *Fig. 3*. Field measurements and determination of the actual volumes of water retained by beaver dams and the inundated areas of their ponds were carried out at 89 beaver dams in the Křemelná catchment and at ten beaver wetlands in the Železná Ruda area, on the Úslava river, and on the Voldušský stream.

The Křemelná catchment was selected in cooperation with Šumava National Park for the study *Field measurement and mapping of beaver dams in the Křemelná catchment* [29] as an example of a landscape in which the presence of beavers is subject to only minimal human restriction. All known beaver dams in the catchment were examined, from small ponds within watercourse channels to extensive ponds forming wetlands on stream floodplains. The research in the Křemelná catchment therefore provided a comprehensive picture of the characteristics of beaver dams and ponds at the regional scale.

The ten selected wetlands in the Plzeň Region were chosen in cooperation with the Nature Conservation Agency of the Czech Republic (NCA CR) for the study *Effects of beavers on river-landscape ecosystems* [30] as examples of areas representing the target state of development of a watercourse and its immediate surroundings following beaver colonisation. The wetlands contain varying numbers, types, and sizes of beaver dams and associated ponds, although on average the ponds are generally larger than those in the Křemelná catchment.

The third area, the Chlístovický Stream catchment, was used to model beaver dam capacity. This work was carried out as part of the project *Water systems and water management in the Czech Republic under climate change*, in which the Chlístovický Stream catchment was already being used for other modelling of landscape water retention and rainfall–runoff relationships and was therefore also selected for modelling potential beaver dam capacity.

Křemelná catchment

Surveying and determination of the actual volume of water retained by beaver dams and the inundated areas of beaver ponds were carried out in the Křemelná River catchment in Šumava National Park. The study area, whose principal watercourse is the Křemelná river, more than 30 km long, lies in the north-western part of the park, predominantly within the Czech Republic but extending marginally into Germany. The catchment has a total area of approximately 169 km^2, corresponding to about one quarter of the area of Šumava National Park.

Orographic conditions result in long-term above-average precipitation totals in the catchment (the Prášily rain-gauge station recorded mean annual precipitation of 1,413.7 mm in 1991–2020 period), resulting in abundant water and a dense hydrographic network. This includes both torrential reaches in incised mountain valleys and small meandering watercourses on upland plateaus.

Thanks to the high level of protection and historically limited human activity, the watercourses and their floodplains have retained a relatively natural character. These conditions provide suitable habitat for the Eurasian beaver,

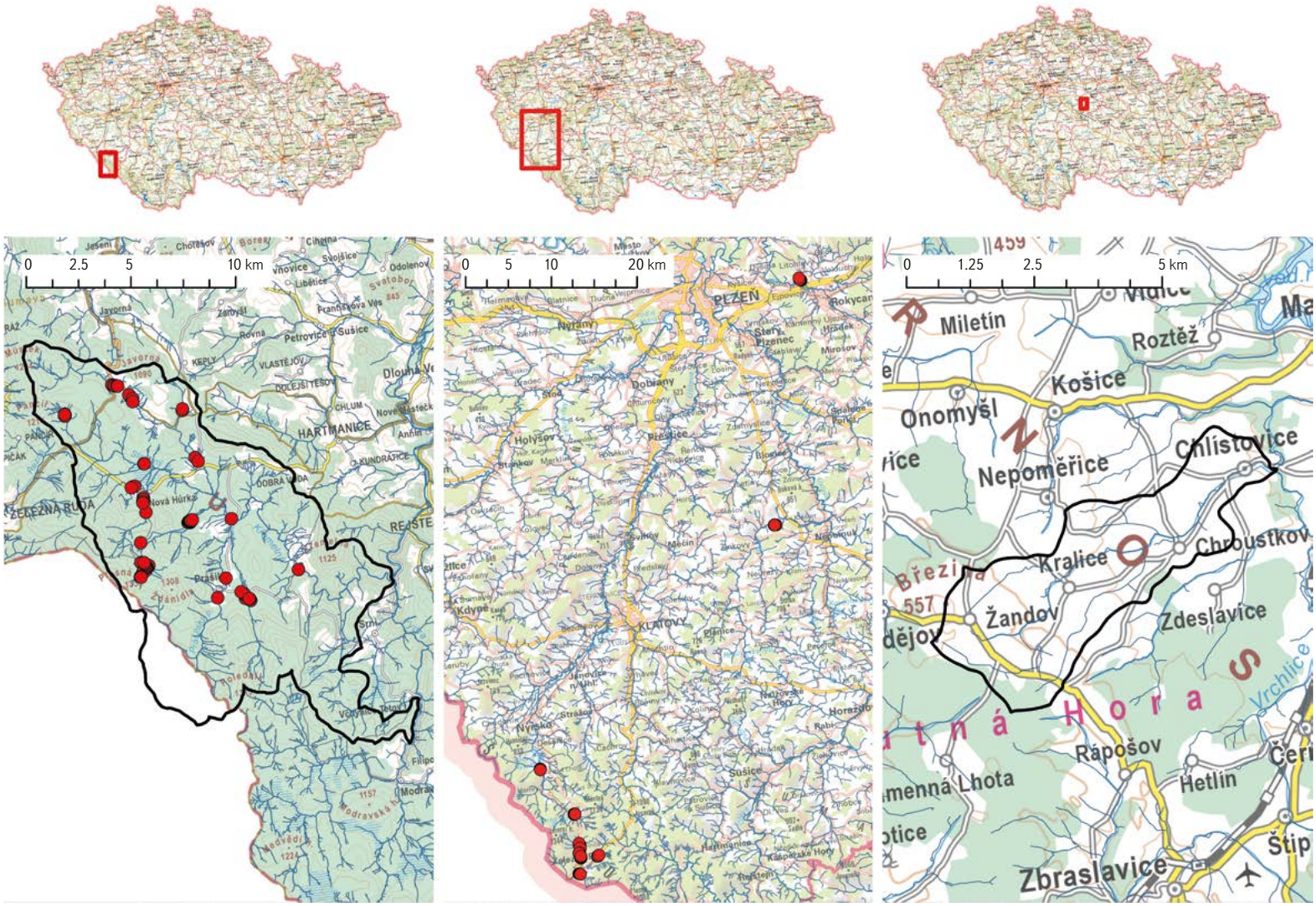

Fig. 3. Study areas – left: Křemelná catchment; centre: ten selected beaver wetlands in the Plzeň Region; right: Chlístovický catchment (basemap: Basic Topographic Map of the Czech Republic, Czech Office for Surveying, Mapping and Cadastre; ČÚZK)

Fig. 4. One of the largest beaver dams and associated ponds in the Křemelná catchment, forming part of the wetland near the settlement of Mechov (photo: A. Babuljak)

whose population is thriving and whose activities further increase the water-retention capacity of the landscape.

The Šumava National Park Administration has conducted long-term monitoring of Eurasian beaver activity in the area. Data from this monitoring were used to identify sites containing beaver dams, which were subsequently surveyed in the field.

One of the beaver dams in the Křemelná catchment near the settlement of Mechov is shown in *Fig. 4*.

Ten beaver wetlands in the Plzeň Region

Actual volumes of water retained by beaver ponds were also determined at ten selected beaver wetlands in the Plzeň Region. Eight were selected around Železná Ruda, in the Řezná and Úhlava catchments, the latter adjoining the Křemelná catchment. These wetlands lie outside the national park and are more affected by human activity than sites in the Křemelná catchment, although nature conservation is strengthened by their location within the Šumava Protected Landscape Area.

Fig. 5. One of the four dams that make up the beaver wetland on the Úslava river near the village of Prádlo (photo: A. Babuljak)

The remaining two wetlands studied were on the Úslava River near the village of Prádlo and on the Voldušský stream near Litohlavy. Both sites lie outside protected areas in a typical Czech agricultural landscape. While the wetland on the Úslava developed in open countryside, the wetland on the Voldušský stream is partly within woodland. The ten wetlands studied contained a total of 61 individual beaver ponds, often directly adjoining one another.

One of the four dams forming the beaver wetland on the Úslava river is shown in *Fig. 5*.

Chlístovický Stream catchment

Potential beaver dam occurrence was modelled in the Chlístovický Stream catchment. This is a fourth-order catchment covering 13.8 km^2 and is predominantly agricultural in character. It is located in the Central Bohemian Region near the village of Malešov. The principal watercourse is the Chlístovický stream, a left-bank tributary of the Vrchlice river, which it joins near Malešov approximately 3 km upstream of the upstream boundary of the Vrchlice Reservoir.

Evaluation of retained volumes and inundated areas

The volume of water retained by existing dams at the experimental sites and the inundated area of the beaver ponds were determined by analysing the geodetic survey outputs using GIS tools.

Surveying

Geodetic surveying of beaver dams and ponds in the Křemelná catchment was carried out in spring 2023, while the beaver wetlands in the Železná Ruda area, on the Úslava river, and on the Voldušský stream were surveyed in spring 2024 and 2025. Three high-precision GPS instruments were used. Emlid Reach RS+ and Emlid Reach RS2 GPS receivers were used at all sites, with a CHC X91 GPS receiver additionally used in the Křemelná catchment.

A total of 89 beaver dams and their inundated areas were surveyed in the Křemelná catchment. For the great majority of dams, three points on the dam were surveyed (left abutment, right abutment, and centre of the crest), together with the channel bed downstream of the dam, the pond depth upstream of the dam, and the upstream boundary of inundation. Several dams with complex pond shapes or dam alignments were surveyed in greater detail.

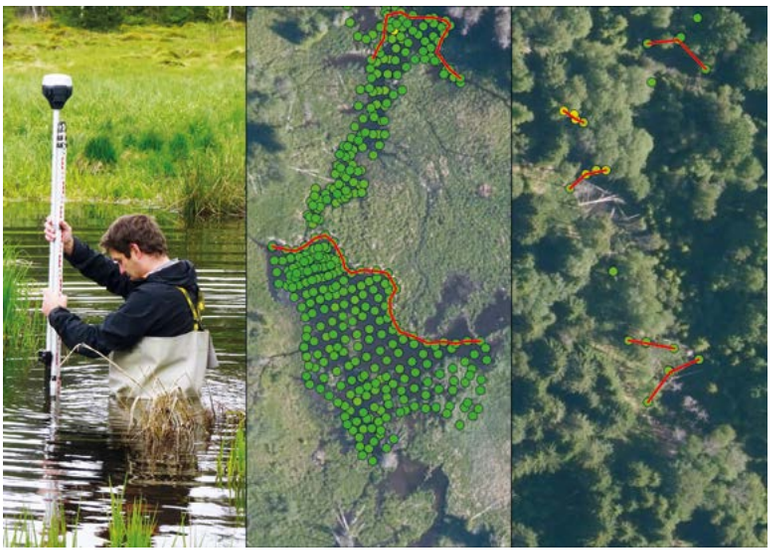

Fig. 6. Surveying of beaver ponds and dams – left: GPS-based surveying and water-depth measurement; centre: detailed survey of a beaver pond; right: simplified survey of beaver dams and inundation boundaries (photo: J. Uhlíková; basemap: Orthophoto of the Czech Republic, Czech Office for Surveying, Mapping and Cadastre; ČÚZK)

For five selected dams, the ponds, including water depths, were also surveyed in detail to validate the GIS method used to determine retained volumes (*Fig. 6*). A total of 1,445 points were surveyed in the Křemelná catchment.

At the ten selected wetlands in the Železná Ruda area, on the Voldušský stream, and on the Úslava river, a total of 61 beaver dams and their inundated areas were surveyed. Dam polylines, inundation boundaries, and water depths in the ponds were measured. Owing to the morphological conditions, these were generally larger ponds than those in the Křemelná catchment. A total of 3,716 points were surveyed at these sites.

GIS tools

Based on the field GPS measurements described in the previous section, GIS analyses were applied at the two experimental study areas to determine the volume of water retained by beaver dams. The approaches used share the principle of combining precise geodetic data with a digital terrain model (DTM), while their specific implementation was adapted to the characteristics of the individual sites and the data available.

For the 89 dams surveyed in the Křemelná catchment in spring 2023, a GIS-based volume-determination method was used that combined beaver dam lines surveyed by high-precision GPS with a detailed digital terrain model representing conditions before the ponds formed. Dam lines were derived from the geodetic survey, and a high-accuracy, fine-resolution DTM capturing pond-bed morphology was used (a 50 × 50 cm LiDAR DTM from 2017, produced for Šumava National Park by German partners as part of a joint cross-border project).

In the GIS environment, the dam lines were converted to raster format and used to determine the water level in each inundated area as the highest terrain elevation along the beaver dam line (usually at the left or right dam abutment). The contributing catchments were then delineated so that individual ponds could be assessed separately even where they immediately adjoined one another in cascades. The extent of each inundated area was subsequently defined as the intersection between the contributing catchment and areas with terrain elevations below the specified water level.

Volume was calculated by comparing the water-surface elevation with the digital terrain model within the delineated inundated area, from which

the spatial distribution of water depths was derived. Total water volume was then calculated as the sum of the partial volumes corresponding to individual raster cells. The procedure was implemented as a Python script in ArcGIS Pro, enabling efficient processing of a large number of dams and generation of accompanying raster outputs.

The method was validated using detailed geodetic surveys of five dams. For these dams, water depths within the inundated area and the perimeter and crest of the dam were surveyed in detail. Volume was calculated using the Thiessen polygon method and compared with the value obtained from GIS analysis of the dam lines and terrain model. The comparison confirmed that the method was suitable for determining the volume of surface water retained by beaver dams.

The method was modified slightly to determine the volume retained by the 61 dams within beaver wetlands in the Železná Ruda area, on the Úslava river, and on the Voldušský stream, for two reasons. First, at some of these sites the dams had created extensive wetlands with several water-surface levels across the wetland floodplain, which the original method could not represent. Second, the inundation boundaries and water depths had been surveyed in greater detail, and the aim was to incorporate these values into a more accurate calculation. To make optimal use of the survey outputs and account for variable water levels, a modified method was applied combining point measurements of water depth with the 1 × 1 m DMR 5G digital terrain model.

Water-surface elevation at individual points was derived from the measured depths and corresponding elevations in the digital terrain model and was then interpolated into a continuous water-surface raster. Comparing this surface with the terrain model yielded the spatial distribution of water depths and subsequently the water volume and inundated area of individual ponds. The method thus maintains high accuracy where direct measurements are available while minimising uncertainties in sparsely surveyed areas where terrain is difficult to access or water is too deep for the survey team to work safely.

Modelling potential beaver dam occurrence

Based on models developed abroad, a beaver dam capacity model adapted to Czech data sources was created in ArcGIS Pro. The model classifies individual watercourse reaches according to the potential number of beaver dams that could develop following colonisation. Each reach is assigned a category together with an estimate of the minimum and maximum expected number of dams.

The beaver dam capacity model used for the Chlístovický Stream catchment is based on a British model derived from the American BRAT (Beaver Restoration Assessment Tool) model. The American model was developed by a research team led by William W. Macfarlane [26], subsequently validated repeatedly at several sites in North America [14, 31], and used in numerous studies [27, 32, 33]. For European conditions, the model was adapted by a team led by Hugh A. Graham of the University of Exeter [24], and the model applied to the Chlístovický Stream catchment is based on this adaptation.

Graham et al. [24] present the BFI (Beaver Foraging Index) and BDC (Beaver Dam Capacity) models, which were developed, validated, and applied in the British catchments of the Tay, Otter, and Coombeshead. The BFI model classifies the availability of vegetation for food and dam construction in two key zones: immediately adjacent to the bank (10 m) and within a wider riparian zone (40 m). BFI outputs are subsequently used as one of the inputs to the BDC model, which also analyses longitudinal channel slope and stream power at both low (Q80% – 80% quantile) and high (Q2% – 2% quantile) flows, thereby assessing the ability of beavers to build dams and the dams' potential resistance to floods. The model integrates these variables using a fuzzy inference system (FIS). The principal BDC output is a classification of reaches into theoretical maximum-capacity categories expressed as ranges in the number of dams per kilometre of watercourse.

Graham et al. [24] validated the model by comparing its predictions with field-survey data covering 258 km of watercourses and 89 identified beaver dams.

The model used for the Chlístovický Stream catchment retains the same parameters and fuzzy-logic principles as the British model but differs in its input data, some of which in the original version were specific to Great Britain. A further modification was the introduction of two threshold values: maximum watercourse width and minimum Q80% flow. According to Hartman et al. [34], beavers build dams almost exclusively on watercourses less than 6 m wide. Although watercourses of this width do not occur in the Chlístovický Stream catchment, the threshold serves to exclude small ponds and reservoirs. The second threshold was minimum flow, reflecting the fact that beavers build

Tab. 1. Input parameters for the beaver dam capacity model

Parameter	Input data	Derivation / Notes
Watercourse network	Detailed watercourses – DIBAVOD	Watercourses were taken from the DIBAVOD database. Reaches longer than 100 m were repeatedly divided in half until all individual reaches were shorter than 100 m.
Watercourse slope	DMR 5G	Derived using zonal statistics from the terrain model for each individual watercourse reach.
Stream power Q2% and Q80%	DMR 5G; daily data from CHMI limnigraphic stations	Stream power for low flow Q80% and high flow Q2% was derived from terrain slope and estimated Q80% and Q2% discharges. Discharge estimates were obtained by analysing CHMI daily discharge series. Q2% and Q80% values were determined for seven regional stations with catchment areas of up to 100 km^2, and regional regression equations relating both Q2% and Q80% to catchment area were then derived. The contributing catchment area was determined for each watercourse reach and the regression equations were applied to estimate Q2% and Q80% discharges.
Vegetation	Copernicus Tree Cover Density	Based on TCD, mean tree-cover density was determined for the immediate vicinity of the watercourse (within 10 m – for dam construction) and the wider riparian zone (within 40 m – for food), and then classified into categories according to Graham et al. [24]. Although TCD does not reflect tree-species composition, which can produce misleading results in coniferous forests, the dataset is suitable for the Chlístovický Stream catchment, which contains deciduous and mixed forests.
Watercourse width	ZABAGED	Small watercourses were assumed to be less than 6 m wide. For wider watercourses and reaches intersecting small ponds and reservoirs, width was determined by GIS analysis of the polygon layer of water areas.
Minimum flow	Daily data from CHMI limnigraphic stations	The Q80% threshold, set at 10 L · s^{-1}, was compared with the Q80% values determined when calculating stream power (see above).

dams only on perennial watercourses, whereas intermittent watercourses are unsuitable. Watercourse reaches that failed to meet either threshold were automatically classified by the model as 'none', i.e. with zero capacity for beaver dam construction. The individual parameters and input data used are summarised in *Tab. 1*.

Application of the beaver dam capacity model divided individual watercourse reaches in the Chlístovický Stream catchment into four categories according to the potential density of beaver dams following colonisation of the catchment. Each category represents a range between the minimum and maximum number of beaver dams per kilometre that can be expected following beaver colonisation of a watercourse. The resulting categories and ranges of expected beaver dam density were adopted from Graham et al. [24] and MacFarlane et al. [26]:

- Frequent – capacity of 5–15 beaver dams per kilometre of watercourse;
- Occasional – capacity of 1–4 beaver dams per kilometre of watercourse;
- Rare – capacity of 0–1 beaver dam per kilometre of watercourse;
- None – capacity of 0 beaver dams per kilometre of watercourse.

RESULTS

Actual volume retained by beaver dams at the experimental sites

The 150 beaver dams at the experimental sites retain a total of 31,321 m^3 of water. Measurements of the volumes of surface water retained by the dams show a strongly right-skewed distribution with high variability. Mean volume is 208.8 m^3, median volume 41.0 m^3, and the standard deviation 681.5 m^3, demonstrating considerable variation in beaver pond size. Recorded volumes range from 0.02 to 6,583 m^3. High skewness (6.83) and kurtosis (53.78) confirm the pronounced asymmetry of the distribution and the presence of extreme values, while a normality test showed a statistically significant departure from a normal distribution ($p < 0.001$).

The largest pond forms part of the beaver wetland on the Úslava river and retains 6,583 m^3 of water. The entire wetland, formed by four dams, stores a total of 9,991 m^3 of water. The distribution of water depths within this wetland is shown in *Fig. 7*.

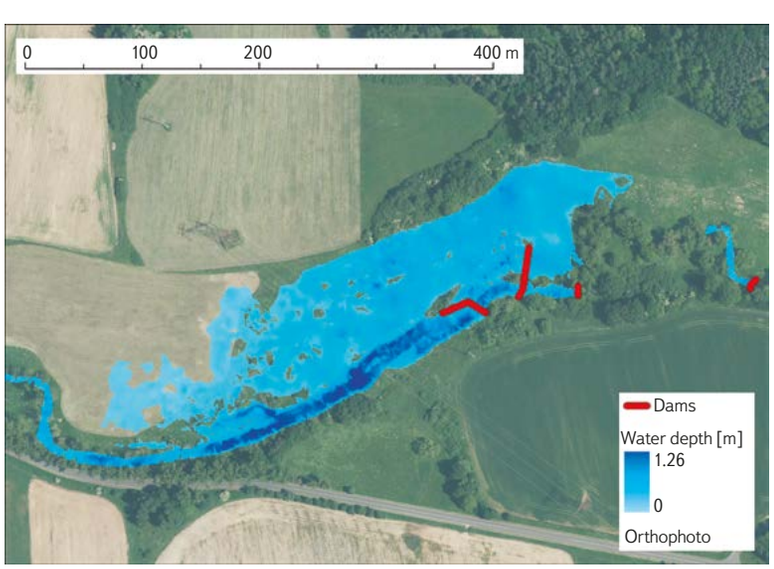

Fig. 7. Water depths in a beaver wetland on the Úslava river formed by four dams and their associated ponds (basemap: Orthophoto of the Czech Republic, Czech Office for Surveying, Mapping and Cadastre; ČÚZK)

The data show that most beaver dams retain relatively small volumes of water, while only a small number of sites accumulate substantially larger volumes and have a major influence on the overall distribution of the data.

Figs. 8 and *9* show that the five largest ponds, representing 3 % of the total number, stored 54 % of the total water volume. Conversely, the smallest 80 % of ponds, each with a capacity of up to 200 m^3, retained only 15 % of the total volume.

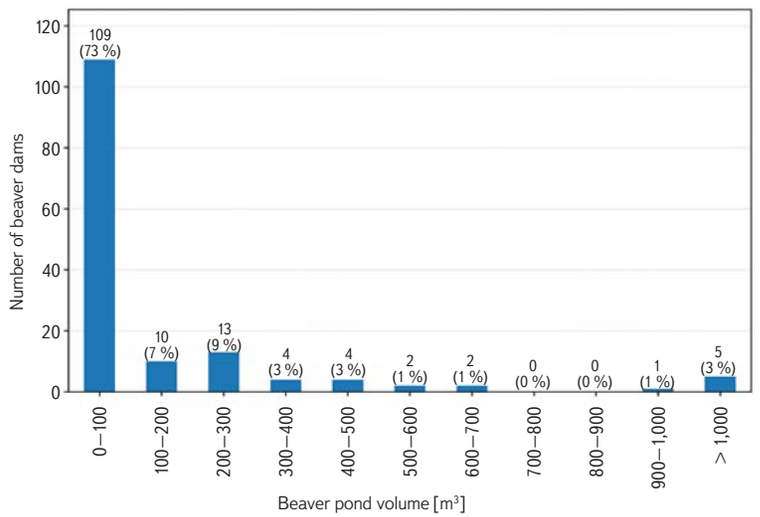

Fig. 8. Water volumes retained by beaver dams at the experimental sites

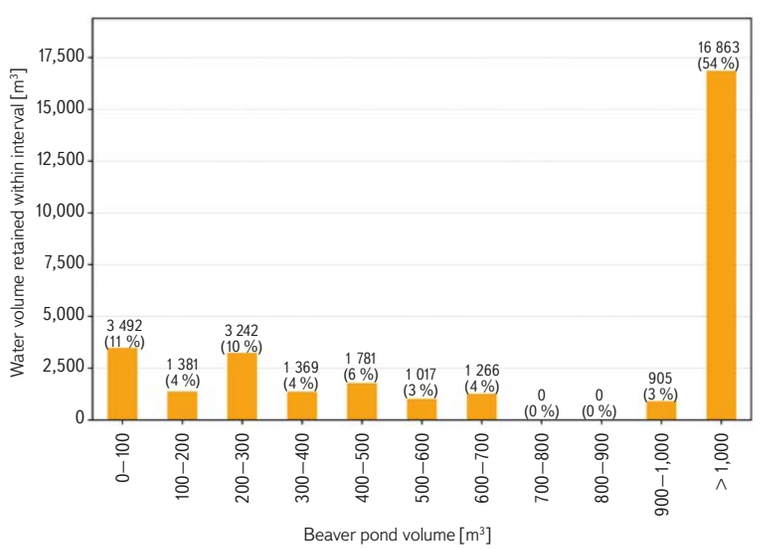

Fig. 9. Contribution of different pond size classes to the total retained volume

This pattern is accentuated by the inclusion of several extensive beaver wetlands, particularly the wetland on the Úslava river. It nevertheless remains pronounced when the dataset is restricted to the Křemelná catchment, a geographically and hydrologically coherent area in which retained volumes were determined for all known beaver dams. Here too, the dataset of 89 dams shows a strongly right-skewed, non-normal distribution. Mean volume is 139.2 m^3, median volume 33.9 m^3, and the standard deviation 404.9 m^3. Skewness (6.14) and kurtosis (41.27) again confirm the strong asymmetry of the data and the influence of several extreme values.

In the Křemelná catchment, the largest pond accounts for 26 % of the total retained volume, specifically 3,274 m^3 out of 12,389 m^3. The largest 10 % of dams retain approximately two thirds of the total water volume. On average, beaver

dams in the Křemelná catchment retain 73.3 m^3 of water per square kilometre of catchment area.

The results show that the great majority of dams at the experimental sites retain only small volumes of water: 73 % of dams had pond volumes of 0–100 m^3. These volumes are not substantial in terms of the overall total. Instead, a small proportion of extensive ponds that store thousands of cubic metres of water plays the decisive role. Although small ponds make only a limited contribution to total retained volume, they may be highly important for biodiversity and the other related aspects discussed above.

Inundated area of beaver ponds at the experimental sites

The 150 beaver dams at the experimental sites create a total inundated area of 98,586 m^2. As with retained water volumes, the inundated areas of the beaver ponds show a strongly right-skewed distribution, dominated by smaller ponds with a small number of extremely extensive ponds. Mean inundated area is 657.2 m^2, whereas the median is only 168.9 m^2, with recorded values ranging from 0.5 to 27,941 m^2. High skewness (8.84) and kurtosis (85.73) confirm the strong influence of extreme values on the distribution; compared with retained water volumes, the higher values of these statistics indicate an even greater dominance by a few very extensive beaver ponds. The distribution of inundated beaver pond areas is clearly shown in *Fig. 10*.

The largest inundated area was recorded for the same pond on the Úslava river that also had the greatest retained water volume, reaching 27,941 m^2. The entire beaver wetland, formed by four beaver dams, has a total inundated area of 41,740 m^2, representing more than 40 % of the total inundated area in the dataset (the Úslava river wetland shown in *Fig. 11*).

The results show that, as with retained water volumes, the total inundated area is strongly influenced by a few of the largest ponds. The four largest ponds, each with an inundated area exceeding 4,000 m^2 and representing only 2.7 % of the sites studied, account for 53 % of the total inundated area.

This pattern remains evident when the dataset is restricted to the Křemelná catchment. As in the full dataset, the 89 beaver ponds show a strongly right-skewed, non-normal distribution. However, skewness (5.69) and kurtosis (39.40) are lower than in the full dataset, reflecting the absence of several extremely extensive sites, particularly the beaver wetland on the Úslava river. Mean inundated area is 379.6 m^2, the median 137.8 m^2, and the total inundated area of all surveyed ponds in the Křemelná catchment is 33,785 m^2.

The largest pond in the Křemelná catchment has an inundated area of 6,639 m^2 and accounts for approximately 20 % of the total inundated area of beaver ponds in the catchment. The nine largest ponds, representing 10 % of sites in the Křemelná catchment, account for 54 % of the total inundated area. In the full dataset, a similar proportion is accounted for by only the four largest ponds. The mean inundated area of beaver ponds in the Křemelná catchment is approximately 200 m^2 per square kilometre of catchment area.

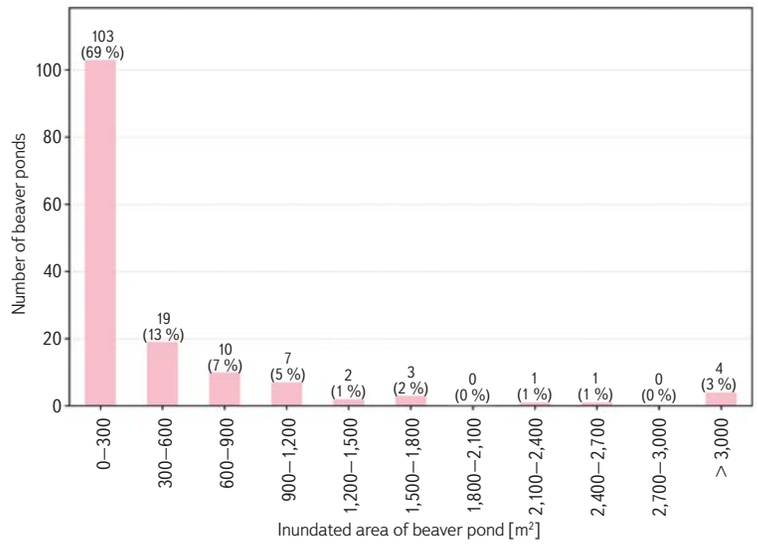

Fig. 10. Inundated areas of beaver ponds at the experimental sites

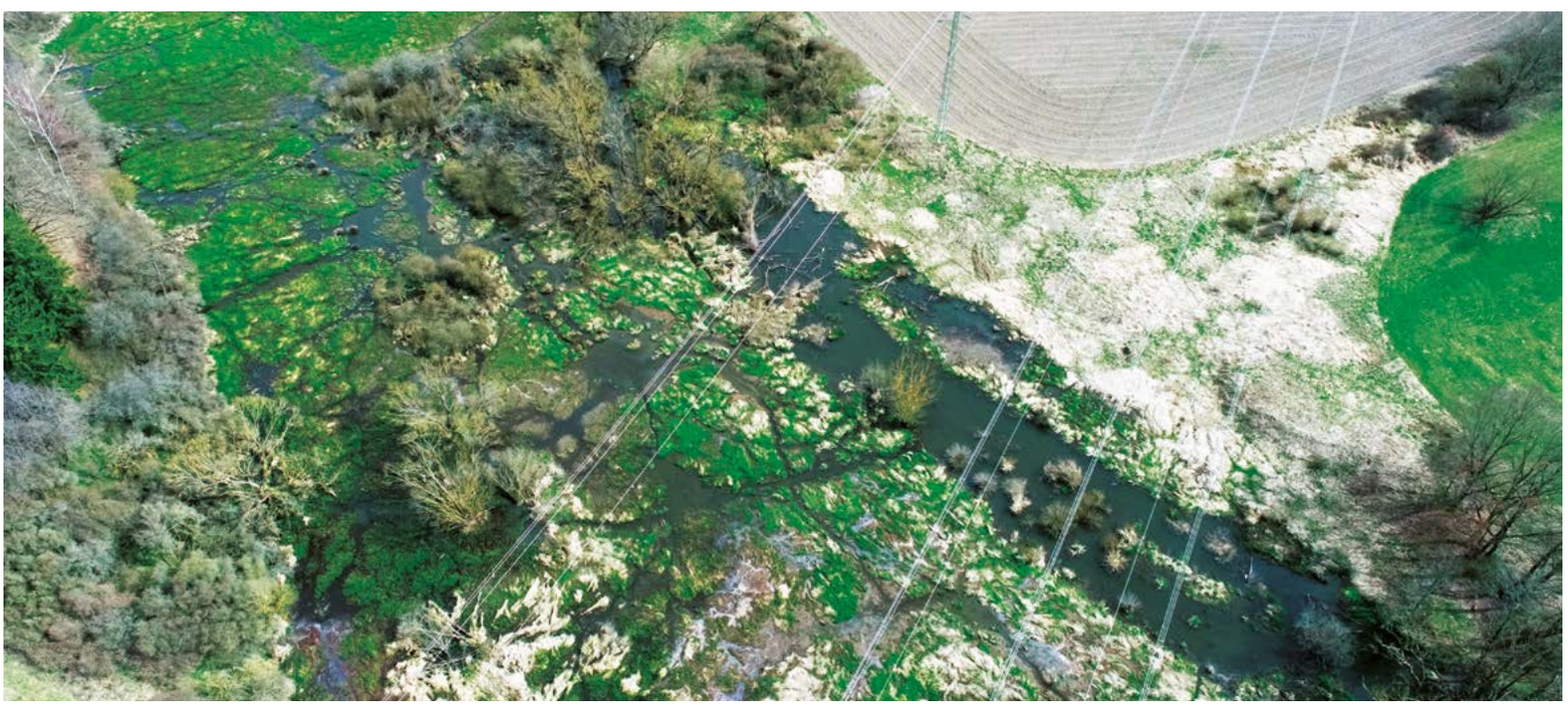

Fig. 11. Beaver wetland on the Úslava river, which accounts for more than 40 % of the total area of all 150 beaver ponds (photo: T. Laburda)

Modelling potential beaver dam capacity on watercourses in the Chlístovický Stream catchment

All watercourse reaches in the Chlístovický Stream catchment were classified into four categories according to the potential number of beaver dams per kilometre of watercourse. The resulting classification of individual reaches is shown in *Fig. 12*.

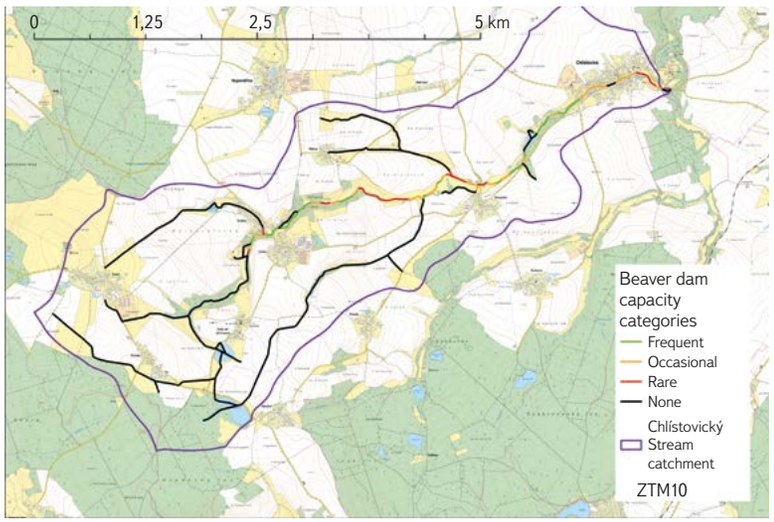

Fig. 12. Classification of watercourses according to beaver dam capacity in the Chlístovický Stream catchment (basemap: Basic Topographic Map of the Czech Republic, Czech Office for Surveying, Mapping and Cadastre; ČÚZK)

After all watercourses in the catchment (the Chlístovický stream and all its tributaries) had been divided into reaches with a maximum length of 100 m, 274 watercourse reaches with a total length of 23.1 km were identified. The catchment contained:

- 28 watercourse reaches classified as **frequent**, with a total length of 2,200 m and a capacity of 11–33 beaver dams;
- 27 watercourse reaches classified as **occasional**, with a total length of 2,225 m and a capacity of 2–9 beaver dams;
- 17 watercourse reaches classified as **rare**, with a total length of 1,540 m and a capacity of 0–2 beaver dams;
- The remaining 202 watercourse reaches, with a total length of 17.1 km, were classified as **none**. These reaches are unsuitable for beaver dams.

Overall, the model identified almost 6 km of watercourses in the catchment as suitable for beaver colonisation and dam construction. Under full colonisation of the catchment, beavers could build 13–43 dams.

Our evaluation of the surface water volumes retained by 150 beaver dams at the experimental sites in the Křemelná catchment and wetlands in the Plzeň Region can be used to estimate how much water potential beaver dams in the Chlístovický Stream catchment might retain and the extent of inundation they might create. It should be emphasised, however, that these estimates are based on the characteristics of beaver ponds in areas different from the catchment for which the estimates are being made.

Using the median retained volume, rounded to 40 m^3, 13 beaver dams would retain approximately 520 m^3 of water, while 43 dams would retain 1,720 m^3. Using the mean retained volume, rounded to 200 m^3, and assuming that several larger beaver ponds develop in the catchment, 13 dams would retain 2,600 m^3 of water and 43 dams as much as 8,600 m^3.

Similarly, using the median value from the Křemelná catchment and the ten wetlands in the Plzeň Region, it can be estimated that 13–43 beaver ponds in the Chlístovický Stream catchment would create a total inundated area of approximately 2,200–7,200 m^2. Assuming the development of several larger ponds and using the mean inundated area, the total could reach 8,500–28,000 m^2.

The broad ranges between the limiting values of expected volumes result from the nature of the beaver dam capacity model used, but also reflect the variability and irregularity characteristic of beaver ponds. The estimates could probably be refined by geomorphological analysis of the area, but the outcome of beaver activity at any particular site is always unique and cannot be predicted precisely. Beaver colonisation of the Chlístovický Stream catchment can therefore be expected to result in several tens of beaver dams, creating surface water storage of several thousand cubic metres and inundating several thousand to several tens of thousands of square metres. Given the catchment area of 13.8 km^2, this would correspond to several hundred cubic metres and several hundred to a few thousand square metres per square kilometre of catchment area.

DISCUSSION

We investigated the volume of surface water retained by beaver dams in the Czech landscape. The 150 dams studied in the Plzeň Region retained 31,321 m^3 of surface water, with a mean pond volume of 208.8 m^3 and a median of 41.0 m^3. Compared with published studies from North American sites, the beaver ponds in this study had substantially lower volumes: only 3 % of the dams studied retained more than 1,000 m^3 of water and most ponds had volumes of up to 200 m^3, whereas pond volumes in North American studies are generally in the order of several thousand cubic metres. Much higher values were reported, for example, by Burns and McDonnell [35], who quantified the volume of one beaver pond at 7,500 m^3, and Westbrook et al. [20], who determined a total volume of 18,992 m^3 for four ponds at Sibbald fen. In a survey of 44 dams in Alaska, Beedle [18] found a mean pond volume of 1,020 m^3, with values ranging from 10 to 11,400 m^3. Although mean volumes were higher than in our dataset, the distribution was consistent with our results: retained volumes were strongly right-skewed, with several extremely large ponds. European studies, by contrast, provide values more comparable with our results. Puttock et al. [36] determined a total volume of approximately 1,000 m^3 for 13 dams in south-east England, while Grygoruk et al. [21] estimated a retention volume of 15,000 m^3 for 22 dams in Poland's Krzemianka catchment; after beaver activity declined and the number of dams fell to 19, pond volume decreased to 7,000 m^3. This also illustrates that retained volumes change over time as beaver wetlands develop, with the duration of colonisation and with increases or decreases in beaver activity at a site.

The inundated areas of beaver ponds showed a pattern similar to that of retained water volumes. A total area of 98,586 m^2, with a mean of 657 m^2 and a median of 169 m^2, shows that most beaver ponds create only relatively small inundated areas, while a few extensive ponds have a major influence on the overall total. This effect was even more pronounced for inundated area than for retained water volume: the four largest ponds, representing 2.7 % of all sites, accounted for more than half of the total inundated area.

Modelling in the Chlístovický Stream catchment showed that beavers could potentially build 13–43 dams. Based on the volumes determined in this study in the Křemelná catchment and at the ten other beaver wetlands in the Plzeň Region, these dams could be expected to store approximately 520–1,720 m^3 of water using the median pond volume, or as much as 2,600–8,600 m^3 using mean values that allow for the development of several larger ponds. These values represent only surface water storage, whereas a substantial proportion of retention also occurs within the soil. Dittbrenner et al. [37] and Hafen et al. [38] estimate that an additional 2–2.4 times the volume of surface water

retained by beaver dams is stored below ground. In the Chlístovický Stream catchment, groundwater storage could therefore increase by up to approximately 20,000 m^3.

In addition to the volume of water retained, beaver dams would also enhance the ecological value of the area by increasing the extent of open water [22, 23]. Using the values determined in this study, the total inundated area of beaver ponds in the Chlístovický Stream catchment can be estimated at approximately 2,200–7,200 m^2 using median values and up to 8,500–28,000 m^2 using mean values and assuming the development of several larger ponds.

Beaver dams also have a significant effect on sediment transport. Dams slow water flow and create conditions for sediment deposition, with published sedimentation rates varying greatly according to site characteristics – from 0.4 cm · $year^{-1}$ according to Polvi et al. [12] in the Rocky Mountains to 28 cm · $year^{-1}$ in Montana [39]. Assuming a total pond area of 2,200–28,000 m^2 in the Chlístovický Stream catchment, this could very approximately result in the deposition of tens to, under an extreme scenario, a few thousand cubic metres of sediment per year. The magnitude of this process, however, depends strongly on catchment characteristics, sediment production, and hydrological conditions.

Although this study focused on quantifying the volume of surface water retained by beaver dams, their retention effect represents only one aspect of their influence. As published studies have shown, beaver activity has a substantial effect on a range of hydrological and ecological processes, including the renaturation of watercourses and floodplains, reduction of the effects of historical drainage systems, increased habitat diversity and amounts of wood in watercourses, and enhanced biodiversity [6, 13–15, 17].

CONCLUSION

Our study quantified the volume of surface water retained by 150 beaver dams at experimental sites in the Czech landscape and assessed the potential occurrence of beaver dams in the Chlístovický Stream catchment as a model catchment in a conventionally managed agricultural landscape in Central Bohemia.

The total volume of surface water retained by beaver dams at the experimental sites exceeded 31,000 m^3. The distribution of volumes was highly uneven: the median was 41.0 m^3, whereas the mean reached 208.8 m^3. More than half of the total water volume (54 %) was retained by only the five largest ponds, while the smallest 80 % of ponds together stored just 15 % of the total volume. In the Křemelná catchment, beaver dams retained 73.3 m^3 of surface water per square kilometre.

Comparison with studies from other countries showed that beaver pond volumes under Czech conditions are generally lower than at North American sites, although their distribution is similar. This comparison suggests that the retention capacity of beaver dams depends not only on local geomorphological and hydrological conditions but also on other factors, such as the duration of beaver colonisation and the amount of space people allow beavers in the landscape.

Like retained water volumes, the inundated areas of beaver ponds were also highly unevenly distributed. The total inundated area exceeded 98,000 m^2, but 53 % of this was accounted for by only the four largest ponds. Median inundated area was just 168.9 m^2 compared with a mean of 657.2 m^2, indicating, as with retained water volumes, the high heterogeneity of beaver ponds, driven primarily by differences in local site conditions.

Modelling potential colonisation of the Chlístovický Stream catchment showed that its 13.8 km^2 area contains approximately 6 km of watercourses suitable for beaver dam construction. Under full colonisation, 13–43 beaver dams could develop. Based on the volumes determined at the experimental sites, surface water storage of hundreds to several thousand cubic metres can be expected. Available evidence also suggests that the overall retention effect may be greater because of groundwater storage, which represents an important component of water retention in beaver wetlands. Based on the inundated areas of beaver ponds, it can additionally be estimated that the dams would inundate several thousand to several tens of thousands of square metres, thereby enhancing the ecological value of the area. Beaver dams are also associated with other benefits, particularly sediment deposition, support for wetland habitats, stabilisation of runoff patterns, and increased ecological stability of the landscape.

The results confirm the important role of the Eurasian beaver as an ecosystem engineer capable of substantially altering the hydrological regime of the landscape at the local scale. Although most individual dams retain relatively small volumes of water, systems of multiple dams and the development of larger wetlands can represent an important component of nature-based water retention in the landscape. As with other nature-based measures for addressing the impacts of climate change, they may be less effective than targeted engineering measures in some individual functions – a few small reservoirs can store a greater volume of water than a much larger number of beaver dams. At the same time, however, the scientific literature clearly shows that dam building by beavers produces a wide range of additional positive effects that contribute to the hydrological and ecological stability of the landscape, of which beavers are a natural and historically integral part. It is therefore important that they are given adequate space in the landscape.

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River basin digital twin: A tool for modelling adaptation measures for water retention in a landscape affected by climate change

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Keywords: river basin digital twin — MIKE SHE — climate change — adaptation measures — water balance — baseflow

ABSTRACT

River basin digital twin technology is an advanced tool for assessing the effects of complex adaptation measures on the water balance in the context of ongoing climate change. The integrated, fully distributed, physically based MIKE SHE modelling system forms the basis of the digital twin developed for detailed simulation of the hydrological cycle. Using the Dyje River basin and the pilot upper Svratka catchment as case studies, specific measures to promote natural infiltration and enhance baseflow were tested, designed and quantified. The effects of climate change were assessed using an ensemble of 26 independent climate scenarios based on global climate models (CMIP6) for a 30-year period centred on 2050, compared with the historical reference period 1981–2010. Simulations without adaptation measures predict a decline in mean and low flows. Model tests showed that implementing a complex set of measures termed "hydrologically optimal agriculture", involving modifications to the hydropedological properties of the soil and changes in vegetation cover, does not increase total runoff volume but has demonstrable potential to slow runoff from the affected areas and enhance baseflow. The simulation tool developed provides support for decision-making in river basin management.

INTRODUCTION

Rational water resources management currently faces unprecedented challenges arising from ongoing climate change and the resulting risks to the water balance. In this context, maintaining functioning ecosystems requires comprehensive support for natural infiltration through water retention in the landscape. The principal strategic aims of modern adaptation measures are to enhance baseflow, increase groundwater recharge and attenuate flood waves. These measures directly contribute to improving the overall security of both surface water and groundwater resources. Reliable assessment of the effects of climate change and the design of effective adaptation strategies require advanced simulation tools incorporating a comprehensive ensemble of climate scenarios that adequately cover the range of projection uncertainty.

Traditional static models are no longer sufficient to address these complex interdisciplinary questions.

An innovative response is the development of technology known as a digital twin, originally developed for industrial applications and increasingly established in environmental sciences in recent years [1]. Although there is no single precise definition of the term [2], digital twins in water management and hydrology offer a promising tool for integrated river basin management, flood forecasting and the optimisation of water supply systems [3–5]. Most definitions agree that a digital twin is a virtual replica of the physical environment that combines advanced data analysis with process-based modelling and incorporates real-time assimilation of measured data, including two-way feedback interaction. Developing such a complex system is a gradual process; however, the computational architecture of the Dyje River basin digital twin presented here enables real-time operation to address operational issues such as adaptive management of water abstractions and drought early-warning systems.

The aim of this article is to present the core component of the Dyje River basin digital twin: an advanced scenario model developed for quantitative and qualitative assessment of a river basin with a tight water balance. The principal advantage of a physically based process model, which requires a detailed understanding of hydrological processes in the landscape, is the ability to test areal and linear changes virtually without risking adverse effects on the real environment. The tool is based on the integrated MIKE SHE hydrological modelling system and is applied to the Dyje River basin as a regional-scale case study and the upper Svratka catchment at pilot scale. The methodology presented demonstrates the tool's readiness for detailed assessment of the effects of complex adaptation measures on the water balance, integrates an ensemble of climate scenarios and evaluates the potential for mitigating climate-change impacts on baseflow through systematic landscape adaptation.

METHODOLOGY

Climate change scenarios

Climate projections from CMIP6-generation global circulation models (GCMs) were used for a detailed assessment of changes in the hydrological balance towards 2050. The selected dataset covers four Shared Socioeconomic Pathway (SSP) scenarios: SSP1–2.6 (Sustainability), SSP2–4.5 (Middle of the Road), SSP3–7.0 (Regional Rivalry) and SSP5–8.5 (Fossil-fuelled Development). From an original set of approximately 30 models, validation for the Czech Republic [6] was used to select a representative subset of the seven best-performing models that captures the uncertainty of the full ensemble (CMCC-ESM2, EC-EARTH3, GFDL-ESM4, MPI-ESM1-2-HR, MRI-ESM2-0, CNRM-CM6-1-HR and TaiESM1).

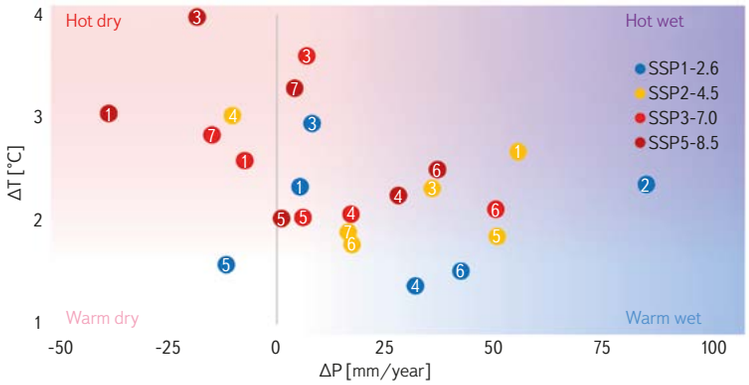

Fig. 1. Differences in the mean climatic characteristics of seven GCMs under four SSP scenarios for the 2050 projection period (2035–2064), relative to the reference period (1981–2010), aggregated for the Dyje River basin. SSP scenarios are distinguished by colour [7]. The GCMs used in this study are numbered as follows: (1) CMCC-ESM2, (2) CNRM-CM6-1-HR, (3) EC-EARTH3, (4) GFDL-ESM4, (5) MPI-ESM1-2-HR, (6) MRI-ESM2-0, and (7) TaiESM1

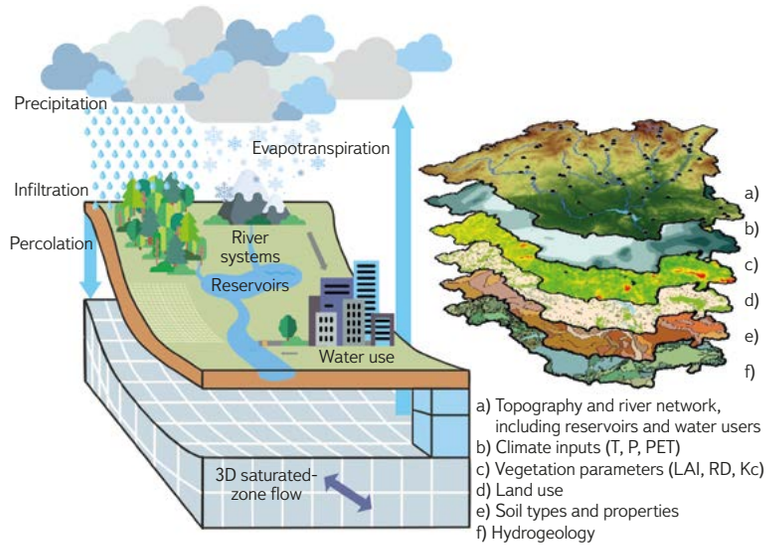

Fig. 2. MIKE SHE model structure, showing the processes represented in the model (left) and spatially distributed input-parameter layers (right)

The complete projection ensemble comprised 26 independent CMIP6 model runs (*Fig. 1*), evaluated against the reference conditions (the 1981–2010 climate normal) for the 2050 projection period (2034–2064).

The model ensemble shows a high degree of variability and no consistent spatial pattern of precipitation change, even within individual SSP scenarios. Although SSP1–2.6 is generally associated with relatively moderate warming and smaller changes in precipitation regimes, whereas SSP5–8.5 represents very strong warming accompanied by major changes in precipitation, no consistent spatial pattern of change can be identified across the models within the individual SSP scenarios. Moreover, inter-model variability in long-term means differs substantially between decades of the future period. To understand and objectively quantify the uncertainty associated with climate change reliably, it is therefore essential to evaluate the entire climate projection ensemble rather than identify a single central scenario.

Because of the coarse spatial resolution and systematic biases of the global models, their outputs were transformed using the Advanced Delta Change (ADC) method, employing observed time series representing locally specific climatic conditions during the 1981–2010 reference period. This approach incorporates changes in both means and variability into the transformation process, thereby accounting for shifts in extremes that differ from shifts in mean values and compensating for systematic biases in precipitation simulations [8]. Mean daily temperature and precipitation totals entered the modelling process directly as boundary conditions, while reference evapotranspiration (ETo) was calculated using the standard Penman–Monteith equation.

River basin digital twin

The Dyje River basin digital twin is based on the fully distributed, physically based MIKE SHE modelling system (*Fig. 2*), designed to simulate complex hydrological processes across water-management components [9, 10]. At regional scale, spatial discretisation uses an orthogonal grid with 500 × 500 m cells.

Data are exchanged between modules at a daily time step, although the simulation engines operate at finer temporal resolutions according to their internal dynamics. Surface runoff is represented using a two-dimensional diffusive-wave approximation dynamically coupled with channel flow. Processes in the unsaturated zone are described by the one-dimensional Richards equation, including the effects of macropores, while the saturated zone is represented by a three-dimensional approximation of the Boussinesq equation. This close coupling allows two-way interaction between the aquifer and river network to be modelled, including baseflow and bank infiltration. Evapotranspiration is also included, combining evaporation from interception and bare soil with transpiration. Vegetation parameters, such as leaf area index, were derived at a daily time step from MODIS sensor data from the Terra satellite [11]. The model also includes 17 reservoirs, whose fully dynamic simulation is based on the applicable reservoir operating rules. Finally, water-use data derived from historical records in water-use registers are incorporated.

The reliability of the tool is underpinned by measured data from 52 stream-gauging stations. The model was calibrated for the hydrologically normal period 2000–2010 and successfully validated for the subsequent decade, 2011–2020, which included the extreme drought of 2015–2018, confirming its robustness even under extreme conditions. Calibration targeted the parameters with the greatest uncertainty and sensitivity (saturated-zone transmissivity, runoff characteristics, vegetation and snowmelt), while soil parameters were set using the authors' own measurements of hydropedological properties, including laboratory determination of retention curves from soil pits at representative sites in the Dyje River basin. Agreement between simulated and observed discharge was assessed using the Nash–Sutcliffe efficiency coefficient (NSE), while groundwater levels (GWL) in 70 boreholes were assessed using root mean square error (RMSE). The final run, which optimised NSE and RMSE (*Fig. 3*), achieved NSE > 0.5 at 78 % of stations. Calibration emphasised agreement across the full flow-duration curve, with particular attention to low flows. Lower calibration efficiency in the Svitava catchment resulted from the limitations of spatial schematisation in representing highly complex hydrogeological conditions.

Conceptualisation of adaptation measures

The design of the adaptation measure comprised several successive phases (*Fig. 4*) and was based on an official methodology [12]. The first step was to define and conceptualise the effect of the adaptation measure in the physical reality of the catchment and identify the processes directly affected by it. Suitable locations for targeting the proposed measure then had to be identified objectively. The next step was the so-called "translation" of the physical effects of the measure into the MIKE SHE model-parameter framework, while ensuring that the measure remained functional and logically consistent with the nonlinear feedback relationships among parameters in the four-dimensional

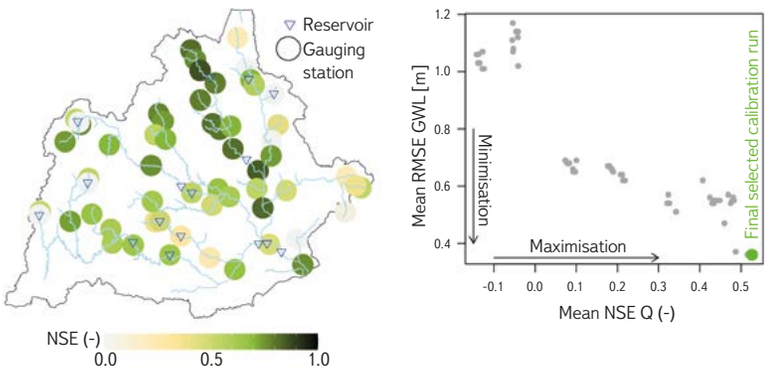

Fig. 3. Calibration results for mean daily discharge: spatial distribution of NSE values (left) and multicriteria selection of the final model run based on minimising RMSE for simulated and observed groundwater levels (GWL) and maximising NSE for mean daily discharge (right)

simulation environment (3D space and time) of the digital twin. These phases tend to be time-consuming and involve an iterative process of testing the effects of the proposed measure and reconciling them with expectations based on expert judgement, measured data or a literature review. In the next phase, the model incorporating the measure is run under 26 climate scenarios, and the results of the individual runs are compared with the reference-state model and with future projections without adaptation measures.

The aim of the measure termed "hydrologically optimal agriculture" was to enhance natural infiltration, soil-water retention and baseflow. Its spatial targeting was based on an analysis of ecosystem vulnerability, which identified the greatest risk of declining runoff in highland areas [10]. As the modelling results demonstrated the low effectiveness of isolated measures – increasing soil-water retention where it was constrained by a moisture deficit primarily increased evapotranspiration – a complex set of measures termed "hydrologically optimal agriculture" was designed. The concept is theoretically grounded in the available literature and the interdisciplinary expert judgement of the CzechGlobe team, and integrates synergistic measures including no-till farming [13], biochar application [14], surface mulching [15], year-round soil cover using cover crops [16], targeted support for soil biota to restore macropores [17], and modifications to land-drainage systems to slow episodic runoff [18]. The design also prioritises crops with lower transpiration requirements [19]; under Czech conditions, millet may be one such crop. Translating these modifications into the logic of the simulation tool involved defining a new shape for soil-water retention curves, increasing saturated hydraulic conductivity and enhancing vertical flow through the macropore system. Rapid runoff was slowed in the model by increasing Manning's roughness and enhancing macropore flow. Changes in vegetation cover were represented by modifying leaf area index (LAI) and rooting depth, enabling the digital twin to simulate the hydrological response of the catchment in detail.

RESULTS

The modelling results indicate that, by around 2050, climate change can be expected to reduce mean and low flows throughout the Dyje River basin relative to the reference period. Analysis of flow-duration curves for mean daily discharges, evaluated over the P25–P75 percentile range (*Fig. 5*), provides a comprehensive view of future development. A substantial decline is expected across the full flow range (up to 20 % in highland areas and 40 % in lowland areas), except at the highest flows, where optimistic climate scenarios (predominantly SSP1–2.6) instead simulate a slight increase. Variability in the decline in discharge is greater in the lowland catchment.

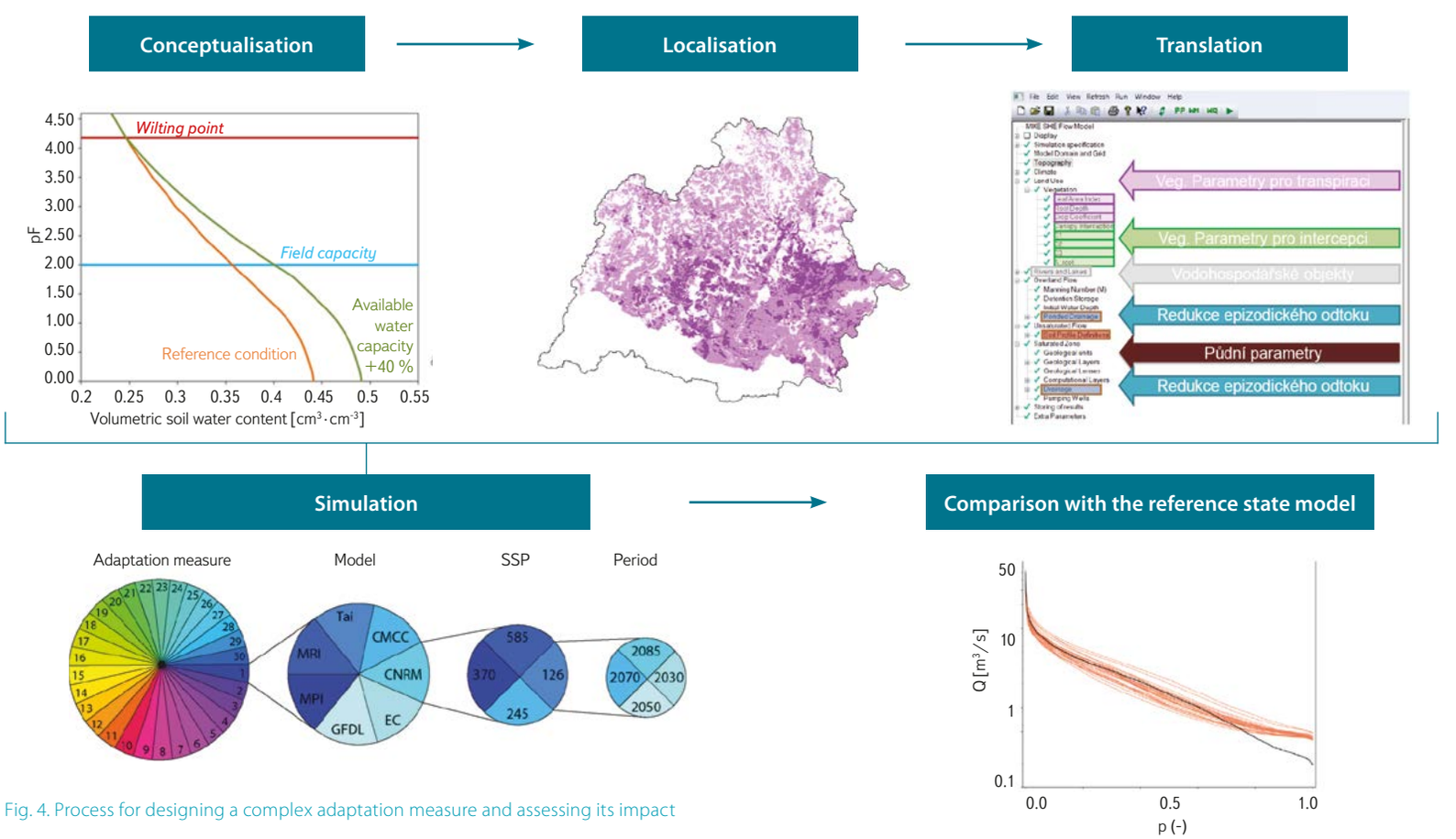

Fig. 4. Process for designing a complex adaptation measure and assessing its impact

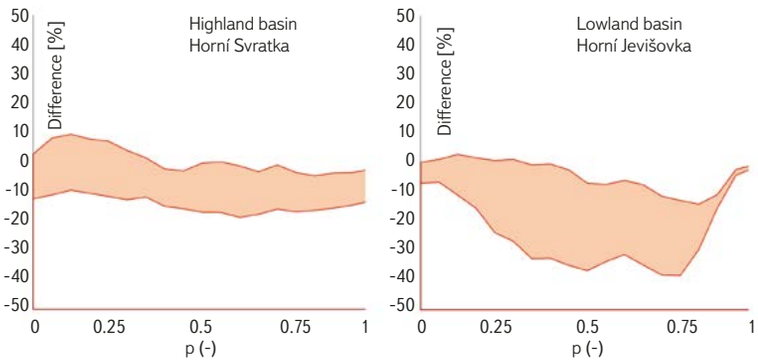

Fig. 5. Effects of climate change by 2050 on flow duration curves for mean daily discharge, including the P25–P75 uncertainty interval of the climate scenarios, in the highland catchment (left) and lowland catchment (right)

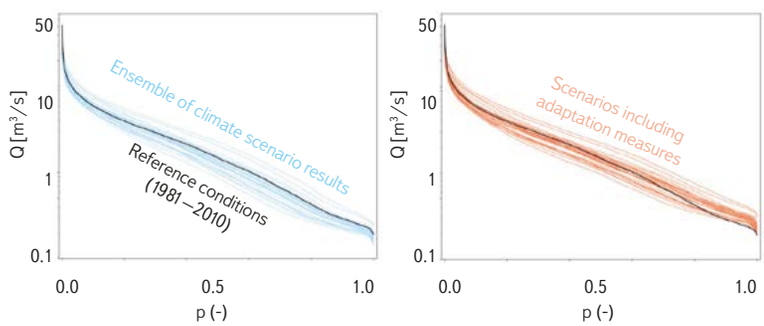

Fig. 6. Effects of climate change by 2050 on flow duration curves for mean daily discharge in the upper Svratka catchment (station 4420 – Dalečín): direct effects of climate change (left) and effects following implementation of the complex adaptation measure "hydrologically optimal agriculture" (right). The curves are based on daily modelled discharge. Individual coloured lines represent the 26 model scenarios

Model tests confirmed that the adaptation measures considered have a meaningful effect only when applied as a complex package, combining modification of hydropedological properties, suitable vegetation and management practices that prevent soil compaction and rapid episodic runoff. Although by around 2050 these complex agricultural measures do not increase long-term mean discharge (Qa) – and therefore do not provide a greater absolute volume of water leaving the catchment in the long-term water balance – they improve the distribution of water across hydrological conditions, promote water retention in the landscape and enhance baseflow by several to tens of per cent (*Fig. 6*).

DISCUSSION

Assessment of climate-change impacts and the design of adaptation strategies are inherently associated with a cascade of uncertainties. These arise not only from the climate scenarios themselves, but also from the modelling and calibration processes and from expert judgement used to parameterise the proposed measures [20]. Because the individual climate projections are independent, no single universally applicable scenario can simply be identified. A comprehensive ensemble of appropriately selected climate models is therefore required to capture future development more reliably [7, 21]. The resulting projections should consequently be presented not as isolated deterministic values but as probabilistic developments with a clearly defined uncertainty interval. In the context of this study, which assesses the effect of the proposed measure across the entire catchment, the benefits of a detailed physically based approach become particularly apparent.

Once the model setup has been properly verified, the nonlinear nature of interconnected hydrological processes repeatedly challenges simplified hypotheses about catchment behaviour, meaning that the modelled effects of the proposed measures differ from initial expert expectations. As noted, for example, by O'Connell et al. [22] and Collentine and Futter [23], spatial redistribution of water and nonlinear interactions between retention and evapotranspiration often produce counter-intuitive results that can be captured accurately only using physically based distributed models. With simpler empirical or conceptual models, these a priori and simplified assumptions could themselves become a primary source of substantial bias in the results. Fully distributed physical models, by contrast, can capture these nonlinear feedback mechanisms in detail, thereby reducing the risk of overestimating or underestimating the overall effect of the measures.

Fully distributed models also make it possible to quantify accurately the so-called green–blue water paradox. The widespread expert assumption that promoting vegetation and increasing infiltration automatically enhance baseflow often proves misleading. As Jackson et al. [24] demonstrate, denser vegetation cover increases total evapotranspiration. In managed landscapes, infiltrated water may therefore either be consumed entirely by crops with high transpiration requirements or be rapidly drained by historical subsurface drainage systems. The combined effects of increased evapotranspiration and functioning shallow drainage can then paradoxically lead to an overall decline in river-network flows – a loss of so-called blue water – causing the proposed retention measure to lose its primary purpose.

CONCLUSION

River basin digital twin technology (Digital Twin) is a key tool for rigorous assessment of climate-change impacts and the design of adaptation strategies. Application of the fully distributed, physically based MIKE SHE model to the Dyje River basin and the pilot upper Svratka catchment confirmed its ability to represent complex, nonlinear hydrological processes in the landscape in detail. Evaluation of an ensemble of 26 independent climate scenarios showed that, without timely implementation of measures, a substantial decline in mean and low flows can be expected by 2050. Isolated interventions are insufficient to mitigate these adverse effects reliably; instead, a complex package of measures is required, for example in the form of hydrologically optimal agriculture. Although this spatially extensive, synergistic modification of soil hydropedological properties and vegetation cover does not increase the absolute volume of long-term runoff, it improves the distribution of water within the catchment and enhances baseflow during dry periods. The simulation tool, rigorously calibrated using historical data, thus provides robust and fully operational support for strategic decision-making in river basin management.

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Assessment of fish passage in the Rolava river and estimated effects of its restoration on fish communities

EDUARD BOUŠE, MIROSLAV BARANKIEWICZ, PETR VLAŠÁNEK, HANA NOVÁKOVÁ, TOMÁŠ DANĚK

Keywords: restoration — fragmentation — ichthyofauna — biodiversity — Ohře River basin — fish passes

ABSTRACT

The study examines the effects of river network fragmentation on populations of rheophilic fish species in the Rolava and Ohře river basins, with particular emphasis on assessing fish passage and the effectiveness of restoration measures. An analysis of the river inventory indicates a high degree of anthropogenic disturbance in the Rolava; of the 41 transverse structures identified, more than half constitute critical barriers over 0.6 m high that most native fish species are unable to overcome. Ichthyological surveys conducted between 2022 and 2025 showed that, while the section below the key barrier in Rybáře supports a species-rich community, including specially protected species such as the European bullhead (*Cottus gobio*) and European brook lamprey (*Lampetra planeri*), isolated sections above the weir exhibit lower diversity and a higher proportion of non-native species. Radiotelemetry monitoring of brown trout (*Salmo trutta*) migrating across restored weirs in Nová Role confirmed the high effectiveness of the fish passes (88–100 % success rate) and the ability of fish to use the restored river continuum. This was accompanied by an increased occurrence of brown trout fry, although the specific conditions in the year concerned may also have played a role. The findings indicate that restoring fish passage at the remaining critical barriers in Karlovy Vary is essential for the recolonisation of the river by native ichthyofauna and the long-term sustainability of populations that cannot currently be effectively stabilised even through intensive artificial stocking.

INTRODUCTION

River environments were historically dynamic systems characterised by natural meandering and highly diverse channel morphology. However, increasing anthropogenic pressure has resulted in up to 95 % of aquatic ecosystems worldwide being directly affected or intensively used by humans [1], making them some of the most degraded habitats in existence [2, 3]. This transformation – including channel straightening, culverting, and the construction of weirs and sills – has in many cases turned formerly diverse watercourses into uniform channels disconnected from their floodplains. At the same time, the structure and functioning of aquatic ecosystems, and hence their ecological status, have deteriorated. According to the European Environment Agency, more than half of Europe's rivers are in poor ecological condition [4]. The situation is similar in the Czech Republic, where engineering modifications have impaired the ecological status of tens of thousands of kilometres of watercourses [3].

Fragmentation is a major problem affecting the river network in the Czech Republic. Thousands of transverse structures are currently registered, more than 6,000 of which exceed 1 m in height and have no fish pass [5, 6]. These barriers fundamentally affect native ecosystems and have considerable impacts on fish communities, among other biota [5, 7]. The loss of suitable spawning grounds and refuges, together with habitat fragmentation, has particularly severe effects on rheophilic fish species, resulting in reduced abundance and biomass as well as lower species diversity [8–10]. However, populations of diadromous fish species, such as Atlantic salmon (*Salmo salar*) and European eel (*Anguilla anguilla*), are affected most severely, as their life cycles involve reproductive migrations between freshwater rivers and the marine environment. In the Czech Republic, these species are currently entirely dependent on artificial stocking.

Both the Rolava and Ohře underwent extensive channel modifications in the past, closely associated with the industrial development of the Ore Mountains. The earliest wooden and stone sills were constructed as far back as the 16th century to serve hammer mills and other mills, particularly around Nejdek. The work of naturalist Antonín Frič, who conducted an extensive survey of the Ohře River basin, provides important evidence of the condition of the river in the 19th century. His findings indicate that, although various weirs already existed on the Ohře at that time, the river remained passable to migrating salmon except for structures on its lower reaches at Terezín and Doksany [11].

Both rivers underwent major transformation during the 1880s, at the height of industrialisation, when the Ohře and its tributary, the Rolava, began to be systematically exploited for modern urban infrastructure and industry. In Karlovy Vary, the city purchased a mill at Tuhnice on the Ohře in 1880, commissioning its first waterworks there two years later and constructing the Tuhnice weir. On the Rolava, an industrial complex was established at Rybáře in 1885 to serve the Knoll porcelain factory, which entailed the construction of further engineered sills within the channel. These interventions significantly reduced fish passage in both rivers.

The number, type and height of individual transverse barriers are key factors when assessing fish passage. Brown trout (*Salmo trutta*) are capable of negotiating obstacles approximately 60 cm high, and under ideal conditions even up to 100 cm, whereas a sill just 50 cm high represents a virtually impassable barrier to most other native fish species [7, 12]. Smaller or benthic species, such as Eurasian minnow (*Phoxinus phoxinus*) and European bullhead (*Cottus gobio*), are even more sensitive in this respect. For these species, even very low transverse structures of approximately 5–10 cm can restrict passage [7, 12].

Existing transverse barriers can be made passable in several ways, with fish passes among the most commonly used solutions. Fish passes have a long

history in the Czech lands: they were constructed on the Ohře near Terezín as early as 1885, during the time of Antonín Frič [13]. Their effectiveness depends on numerous factors, including how readily fish can locate the entrance, flow velocity within the pass, the overall gradient, water depth and the dimensions of the internal chambers [7]. If these characteristics do not correspond to the biological requirements and swimming abilities of particular species, the result is selective passage, whereby the structure remains a barrier to some of the fish community [7, 12]. Ensuring free fish migration should therefore be a priority, not least in order to meet the objectives of the Water Framework Directive [14].

This study aims to assess fish passage along the Rolava and compare commonly used methodological approaches. A further objective is to predict the ecological effects of restoration measures, specifically the effects of restoring river continuity in the Rolava and Ohře on species composition and biodiversity.

MATERIALS AND METHODS

Study area

The study area is located in the northern part of the Karlovy Vary Region and comprises the Rolava River and the adjoining section of the Ohře. The Rolava (36.7 km long; catchment area 137.3 km^2) rises in the Ore Mountains at an elevation of 920.8 m above sea level. Its average gradient is approximately 1.5 %, although it exceeds 2 % in the middle reaches. To provide flood protection for built-up areas in Nejdek, Nová Role and Karlovy Vary, the channel was engineered and stabilised with retaining walls and embankments during the 1960s and 1970s. The steep gradient and anthropogenic modifications to the river necessitated the construction of transverse structures (weirs and sills). These barriers reduce the overall gradient but also fragment the river network and impede longitudinal fish migration. In Karlovy Vary, the Rolava flows into the Ohře at river km 171.6; the historical significance of the latter is reflected in its Celtic name, *Agara*, meaning 'salmon river'.

According to the classification of A. Frič [15, 16], the Rolava belongs to the trout-to-grayling zone owing to its steep gradient, rapid flow and cold, highly oxygenated water. By contrast, the Ohře represents the barbel zone, characterised by a gentler gradient, slower flow and higher water temperatures with naturally lower oxygen concentrations. While the Rolava provides habitat for cold-water salmonids, the Ohře is characterised by fish species that prefer deeper, warmer and more nutrient-rich environments, such as Barbus–Chondrostoma communities.

Fish community composition

To determine changes in the fish community of the Rolava and the adjoining section of the Ohře, the available scientific literature and publications were reviewed. Given the limited amount of published information, fisheries statistics from the Czech Anglers Union (catch records and stocking records) for the Rolava 1A, Rolava 1B, Rolava 2, Ohře 13 and Ohře 14 fishing grounds were also included in the assessment. Although these data have certain limitations, they can provide an important basis for interpreting long-term changes in the fish community.

As historical sources and statistics generally lack precise data on population abundance or size structure, these records were evaluated qualitatively in terms of species presence or absence. This provided a basic comparative framework for assessing long-term changes in species diversity within the study area.

The current status of the fish community was determined by field monitoring focused on the lower reaches of the Rolava, from Nová Role to its confluence with the Ohře in Karlovy Vary. Monitoring also covered the immediate

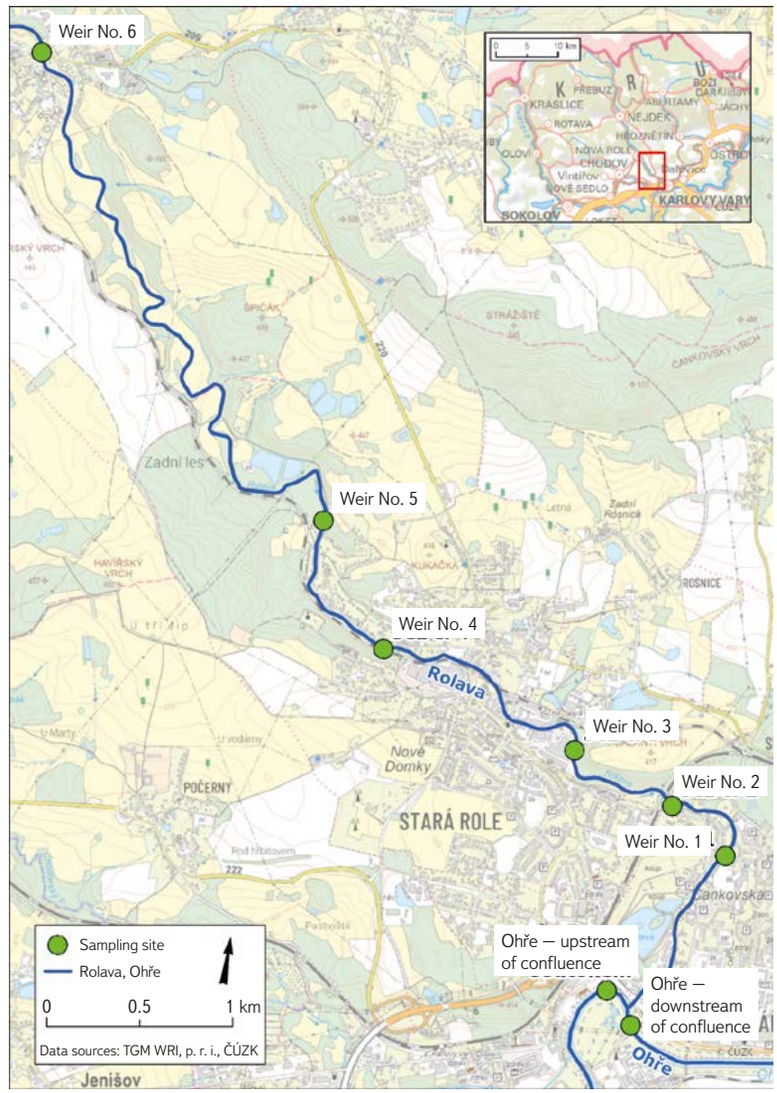

Fig. 1. Geographical distribution of eight monitored sites on the lower reaches of the Rolava river and the adjacent reach of the Ohře river

vicinity of the confluence, which is particularly important in terms of fish migration. Surveys were conducted at eight sites on 18–19 May 2022, 27 June 2023, 17–18 April 2024 and 20 May 2025. Six sites were located on the Rolava (a 100 m section downstream of each transverse barrier), with a further two 100 m sites on the Ohře in the vicinity of the confluence (*Fig. 1*).

Fish were sampled by electrofishing in accordance with applicable Czech legislation. Continuous wading electrofishing, as described in detail in [2], was used for sampling. Fish were captured using an ELT 60-IIH petrol-powered backpack electrofishing unit (300–500 V, pulsed DC; Hans Grassl GmbH, Schönau am Königssee), equipped with a 2 m pole with a circular anode 30 cm in diameter and a mesh size of 4 mm. Each section was fished twice consecutively, with the transverse structure in the watercourse serving as the boundary at which sampling ended. All captured fish were subsequently identified to species. Standard length (SL) and total length (TL) were measured for each individual to the nearest 1 mm.

Assessment of fish passage

Several methodological approaches were used to provide a comprehensive assessment of fish passage along the Rolava. The initial assessment was

based on data from the Passportization of watercourses, followed by biological monitoring using radiotelemetry. Finally, data from fish sampling conducted downstream of each barrier were used as an additional basis for assessing fish passage.

The first stage of the analysis used data from the mapping of watercourses and wetlands contained in the Passportization of watercourses [17], which records the height of each barrier and whether a fish pass is present or absent. The barriers between the confluence with the Ohře and Nová Role were subsequently also assessed directly by the assessors.

In the next stage, biological monitoring of fish migration using radiotelemetry was conducted from 30 September 2021 to 11 October 2022 at two restored sills on the Rolava (river km 8.8 and 9.2) in Nová Role. A total of 56 brown trout were tagged. Guidelines for assessing fish passes [18] recommend monitoring one or two indicator species by telemetry in small watercourses within the trout zone. However, previous findings [19] showed that brown trout was the only species occurring in sufficient numbers and of a suitable size in the section concerned. Adult fish (n = 40) were fitted with NTF-6-2 transmitters (Lotek, Newmarket, Canada), while juveniles (n = 16) were fitted with NTF-5-2 transmitters (Lotek, Newmarket, Canada). The transmitters were programmed to frequencies of 138.30 MHz and 138.42 MHz, with pulse intervals of 5.0–5.5 s. Fish were collected by electrofishing directly within the study area on 29 September 2021. To stimulate upstream migration, some tagged individuals were translocated to a different sector. This enabled their ability to negotiate barriers to be tested by exploiting the homing effect, i.e. their tendency to return to their original home range (see *Fig. 2* for further details).

Fish movements and successful passage of the barriers were monitored using a combination of two radiotelemetry methods. Mobile telemetry using an SRX 800 receiver (Lotek, Newmarket, Canada) and a 60CSx GPS receiver (Garmin, Kansas, USA) was conducted at regular monthly intervals to determine the current positions of individuals in the sections upstream and downstream of the monitored sills. This enabled detailed mapping of fish movements throughout the study reach. Continuous recording of migration through the restored sections was provided by automatic stationary ATS telemetry using Lotek SRX 800D and SRX DL receivers (Lotek, Newmarket, Canada). These stations were equipped with two antennas directed upstream and downstream of the sills, enabling fish passage through the monitored structures to be accurately detected.

Two parameters were monitored when assessing fish-pass performance: passage efficiency (the proportion of fish that successfully traversed the entire fish pass relative to those that merely entered it) and overall migration success (the proportion of successful migrants relative to all tagged fish). The number of tagged fish was adjusted using an overall coefficient of K = 0.17, which accounts for transmitter loss, fish mortality and the detection accuracy of the ATS systems [18]. All individuals detected downstream of the barrier were included in the analysis of migration success, comprising both released fish and individuals that had migrated naturally to the site from upstream or downstream. The direction and timing of migratory behaviour were also recorded during monitoring.

The resulting data were subsequently analysed statistically. Differences in successful passage of the lower and upper sills were compared using Fisher's exact test [20]. Differences in movement rates between seasons were assessed using repeated-measures analysis of variance (repeated-measures ANOVA) [20] or a linear mixed-effects model (LMM) [21]. Subsequent pairwise comparisons between individual seasons (post-hoc analysis) were performed using paired t-tests with Bonferroni correction of the significance level [20].

The final key approach to assessing fish passage used data on the current structure of the fish community, evaluated on the basis of species composition by comparing sections upstream and downstream of individual barriers. The input data comprised standardised abundances (CPUE; individuals/100 m)

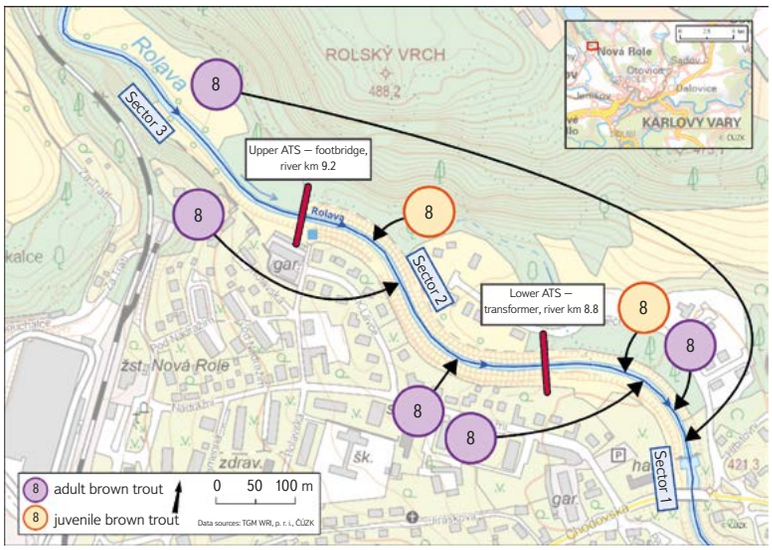

Fig. 2. Division of the study area into sectors and the release of fish within individual sectors of the Rolava river; arrows indicate whether fish were released into the same sector in which they were captured or translocated to a different sector to encourage upstream migration of tagged individuals across migration barriers (homing effect)

for 23 fish species from 32 sampling events at eight sites between 2022 and 2025. To reduce the influence of highly dominant species, the data were square-root transformed prior to analysis. Similarities in community composition among individual sampling events and sectors were visualised using non-metric multidimensional scaling (NMDS) ordination based on Bray–Curtis dissimilarity [22]. The ordination plot included 95% confidence ellipses for individual sectors and the positions of key species.

The statistical significance of differences in species composition among sites and sectors was tested using permutational multivariate analysis of variance (PERMANOVA) with 999 permutations. SIMPER (similarity percentages) analysis was used to identify the species contributing most to the observed differences between sections [23]. All statistical analyses were performed using R [24].

RESULTS

Fish community composition

Historical records from the 19th century report the occurrence of 20 fish species in the study area [25], or 28 species according to [26]. These earliest surveys comprise almost exclusively native fish species, although 19th-century records make no mention of rainbow trout (*Oncorhynchus mykiss*), despite evidence that the species was already being stocked in the Rolava in 1887 [27]. Studies dating from the late 20th century [28] recorded a total of 37 species in the catchment. Among native species, pike-perch (*Sander lucioperca*) and ide (*Leuciscus idus*) appear for the first time, although the newly recorded taxa are predominantly non-native species, including brook trout (*Salvelinus fontinalis*), brown bullhead (*Ameiurus nebulosus*), largemouth black bass (*Micropterus salmoides*), silver carp (*Hypophthalmichthys molitrix*), bighead carp (*Hypophthalmichthys nobilis*) and common nase (*Chondrostoma nasus*), which is non-native to the Ohře catchment.

The highest species diversity in the area was reported by Matějů a Holub [29], who recorded as many as 43 fish species. Newly recorded species included non-native Siberian sturgeon (*Acipenser baerii*) and invasive pumpkinseed (*Lepomis gibbosus*), as well as the native crucian carp (*Carassius carassius*) and sunbleak (*Leucaspius delineatus*). However, a more detailed description

Tab. 1. Occurrence of fish species in the Ohře River basin in the Karlovy Vary area

	English name	Scientific name	Glückselig [25]	Howorka [26]	Flasar and Flasarová [28]	Matějů and Hulub [29]	ČRS (2010–2024)	TGM WRI (2022–2025)	Protection, status
Trout and grayling zone	European grayling	*Thymallus thymallus*	x	x	x	x	x	x	EVL, VU
	Atlantic salmon	*Salmo salar*		x	x*				EVL, CR
	European brook lamprey	*Lampetra planeri*	x	x	x	x		x	KO, EVL, VU
	Burbot	*Lota lota*	x	x	x	x	x	x	O, NT
	Stone loach	*Barbatula barbatula*	x	x	x	x		x	
	Spirlin	*Alburnoides bipunctatus*		x	x				SO, VU
	Rainbow trout	*Oncorhynchus mykiss*			x	x	x	x	BL
	Brown trout	*Salmo trutta*	x	x	x	x	x	x	
	European eel	*Anguilla anguilla*	x	x	x	x	x		EW
	Brook trout	*Salvelinus fontinalis*			x	x	x		BL
	Eurasian minnow	*Phoxinus phoxinus*		x	x	x		x	O, VU
	European bullhead	*Cottus gobio*	x	x	x	x		x	O, EVL, NT
Barbel zone	Asp	*Aspius aspius*		x	x	x	x		EVL
	Freshwater bream	*Abramis brama*	x	x	x	x	x		
	White bream	*Blicca bjoerkna*		x	x	x			
	Gudgeon	*Gobio gobio*		x	x	x		x	
	Ide	*Leuciscus idus*	x		x	x	x	x	O, NT
	Common dace	*Leuciscus leuciscus*		x	x	x		x	
	Chub	*Squalius cephalus*		x	x	x	x	x	
	Ruff	*Gymnocephalus cernuus*		x	x	x			
	Common carp	*Cyprinus carpio*	x	x	x	x	x	x	
	European perch	*Perca fluviatilis*	x	x	x	x	x	x	
	Common nase	*Chondrostoma nasus*			x	x	x		VU
	Bleak	*Alburnus alburnus*	x	x	x	x		x	
	Common barbel	*Barbus barbus*	x	x	x	x	x	x	EVL, NT
	Rudd	*Scardinius erythrophthalmus*	x	x	x	x			
	Roach	*Rutilus rutilus*	x	x	x	x		x	
	Vimba bream	*Vimba vimba*		x	x	x	x		VU
	Northern pike	*Esox lucius*	x	x	x	x	x	x	

	English name	Scientific name	Glückselig [25]	Howorka [26]	Flasar and Flasarová [28]	Matějů and Hulub [29]	ČRS (2010–2024)	TGM WRI (2022–2025)	Protection, status
	Grass carp	*Ctenopharyngodon idella*				x	x		BL
	Pike-perch	*Sander luciopeca*	x		x	x	x	x	
	Siberian sturgeon	*Acipenser baerii*				x			WL
	Crucian carp	*Carassius carassius*	x	x	x	x			CR
	Prussian carp	*Carassius gibelio*				x	x	x	BL+
	Three-spined stickleback	*Gasterosteus aculeatus*				x		x	WL
	Tench	*Tinca tinca*	x	x	x	x	x	x	
Bream zone	Largemouth black bass	*Micropterus salmoides*			x				BL
	Weatherfish	*Misgurnus fossilis*	x	x		x			O, EVL, EN
	Whitefish	*Coregonus* sp.				x	x		WL
	Pumpkinseed	*Lepomis gibbosus*				x			IN, BL+
	Sunbleak	*Leucaspius delineatus*			x	x			CR
	Topmouth gudgeon	*Pseudorasbora parva*				x		x	IN, BL+
	Wels catfish	*Silurus glanis*				x	x		
	Brown bullhead	*Ameiurus nebulosus*			x	x			GL
	Bighead carp	*Hypophthalmichthys nobilis*			x	x			BL
	Silver carp	*Hypophthalmichthys molitrix*			x	x	x		BL

Legend: **ČRS** – data provided by the Czech Anglers Union; **VÚV TGM** – fish sampling conducted in 2022–2025; * – historical record; **EVL** – Species of Community interest (Natura 2000 species); **O/SO/KO** – threatened / highly threatened / critically threatened species (pursuant to Decree No. 395/1992 Coll.); **EW/CR/EN/VU/VU+/NT** – Red List of the Czech Republic (extinct in the wild / critically endangered / endangered / vulnerable / vulnerable, non-native to the basin / near threatened); **IN** – invasive species (included on the Union list); **BL/BL+/GL/WL** – classification of non-native species (black list – human-dispersed / black list+ – spontaneously spreading / **grey list** – non-native, tolerated / **watch list** – monitored, potential occurrence).

of the authors' local records shows that most occurrences of these newly reported species were in private ponds or isolated pools, and that their occurrence in the Rolava and Ohře is very rare. Anglers' records provide valuable information on the occurrence of certain species. Analysis of catch and stocking records from the Czech Anglers Union shows that 23 fish species are regularly caught in the Ohře and Rolava. However, these statistics primarily cover species of commercial or recreational importance and contain no data on smaller species such as European bullhead (*Cottus gobio*), stone loach (*Barbatula barbatula*) and Eurasian minnow (*Phoxinus phoxinus*).

Our monitoring conducted between 2022 and 2025 recorded the presence of 23 fish species. A detailed overview of species occurrence in the individual studies is provided in *Tab. 1*.

Assessment of fish passage

Analysis of the Pasportization of watercourses [17], followed by our own field assessment of the study reach (from the confluence with the Ohře to Nová Role), showed a high degree of anthropogenic fragmentation of the Rolava river network. A total of 41 transverse structures (weirs, sills, ramps, etc.) were identified along the Rolava, disrupting its longitudinal continuity. Detailed analysis showed that 25 of these barriers have a head difference of more than 0.6 m. At present, only eight of these structures (32 %) are equipped with a fish pass.

The main barriers to fish migration within the study reach are two large weirs in Karlovy Vary that lack fish passes. The first is Weir No. 1 – Rybáře (river km 1.1), which represents the most problematic point in terms of river continuity, as it

Fig. 3. Current condition of the fixed weir with a movable gate in Rybáře at river km 1.1 (photo: E. Bouše)

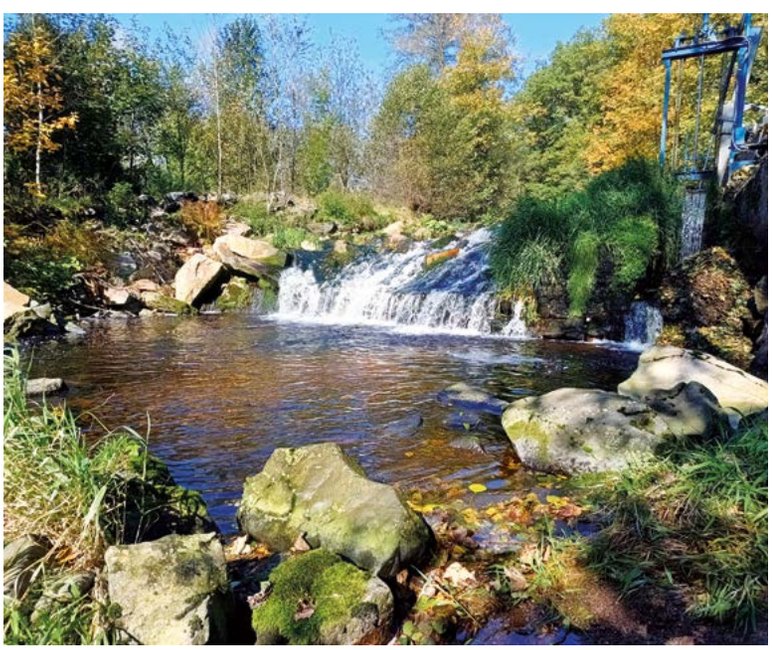

Fig. 4. Weir in Stará Role at river km 4.6, constructed of boulders embedded in concrete (photo: E. Bouše)

Fig. 5. Weir in Karlovy Vary at river km 1.5 – an example of a migration barrier with a damaged structure (photo: E. Bouše)

isolates the entire Rolava from the Ohře. It is a fixed weir fitted with a movable gate, with a total height exceeding 1.5 m (see *Fig. 3* for further details).

The second migration barrier is the weir at Stará Role (river km 4.6). This vertical structure, more than 1.5 m high, consists of large boulders set in concrete (*Fig. 4*).

In addition to these two main barriers, there are three smaller transverse structures within Karlovy Vary, with head differences of 0.2–0.3 m. The structural condition of these three structures is currently partly degraded due to localised erosion of the structure or missing concrete infill (*Fig. 5*).

Upstream of the weir at Stará Role (river km 4.6) lies a section where two sills in Nová Role were restored in 2020. These works restored fish passage at the structures at river km 8.8 and 9.2 and were subsequently followed by restoration of the structure at river km 8.4. The original impassable migration barriers, which exceeded 1.5 m in height, were converted into ramp-type fish passes (*Fig. 6*).

Fig. 6. Restored weir in Nová Role at river km 9.2 (photo: E. Bouše)

Restoration of these three structures in Nová Role opened approximately 10 km of the river to fish passage. Subsequent radiotelemetry monitoring confirmed successful fish passage through this reach. Passage efficiency through the fish passes themselves ranged from 88 to 100 %, while overall migration success ranged from 66 to 90 % (*Tab. 2*).

Tab. 2. Quantitative assessment of fish-pass efficiency on the Rolava river

Fish pass profile	Fish-pass passage efficiency	Overall migration success		
		Juvenile fish	Adult fish	Total
Lower fish pass – transformer	100%	67%	95%	90%
Upper fish pass – footbridge	88%	10%	82%	66%

Of the 40 tagged adult brown trout, 16 were confirmed to have passed the lower weir and 14 the upper weir. Among the 16 juvenile trout, five individuals migrated across the lower weir, one of which also successfully passed the upper weir. Statistical analysis, however, found no difference in the passability of the two monitored weirs for either adult or juvenile fish ($p = 0.4669$).

Fish activity was highest during the first 14 days after release in both age groups ($t = 13.531$, $p < 0.001$), with movement during this period predominantly upstream. In adults, this direction of movement was closely associated with a pronounced homing effect, i.e. an attempt to return to their original territory. This proved to be a key motivating factor, with adult trout translocated downstream of the barriers showing overall return success of 75–100 %. Success was directly affected by translocation distance: fish moved two sectors downstream achieved 75% return success, whereas those moved one sector achieved 100%. By contrast, fish released at their capture site remained within their sector.

In terms of seasonality, movement was greatest in autumn and activity lowest in summer. Autumn migration differed significantly from spring ($t = 4.405$, $p < 0.001$), summer ($t = 5.375$, $p < 0.001$) and winter activity ($t = -4.126$, $p < 0.001$). The high return success and the ability of juvenile fish to negotiate both barriers confirm that both weirs are passable. Movement within this reach therefore depends primarily on the fishes' current motivation.

Fish passage was also assessed by sampling fish below individual barriers. This ichthyological survey enabled detailed assessment of the species and size structure of fish communities at sites immediately downstream of each barrier. Comparison of species composition and ichthyofaunal abundance among these sites revealed statistically significant differences ($F = 8.7939$; $p < 0.001$). These marked differences in community distribution were evident both between the main stem of the Ohře and among the reaches isolated by weirs. SIMPER analysis showed that five fish species accounted for more than 81 % of the overall variability in the data. Brown trout made the largest contribution to differences among communities (35.0 %), followed by chub (16.9 %), European bullhead (15.2 %), stone loach (8.2 %) and gudgeon (6.3 %). The mean relative abundance of individual species (%) (± standard deviation) is summarised in detail in *Tab. 3*.

The Ohře sites (below/above the confluence) exhibited high species diversity. Chub (*Squalius cephalus*) dominated (30.3 ± 16.3 % and 38.9 ± 6.2 %, respectively), together with European bullhead (*Cottus gobio*) (24.9 ± 16.5 % and 18.3 ± 5.0 %, respectively) and common dace (*Leuciscus leuciscus*). These were the only two sites in the entire study reach where common barbel (*Barbus barbus*) occurred, while the Ohře site above the confluence also contained an isolated occurrence of the critically endangered European brook lamprey (*Lampetra planeri*) (0.2 ± 0.3 %).

Upstream along the Rolava, the diversity of rheophilic cyprinid species declined, accompanied by an increasing prevalence of salmonids. Weir No. 1 – Rybáře represented a transition zone where European bullhead remained dominant (39.1 ± 12.7 %), but brown trout (27.9 ± 11.2 %) and stone loach (12.7 ± 6.8 %) already accounted for substantial proportions of the community. Eurasian minnow was recorded only at this site (0.3 ± 0.6 %). At Weirs Nos. 2–6, the community was completely dominated by brown trout, whose mean relative abundance progressively increased from 56.2 ± 9.6 % (Weir No. 2) to a maximum of 81.1 ± 10.7 % (Weir No. 6). Stone loach formed a consistent component of the community, reaching its highest relative abundance at Weir No. 2 (20.3 ± 4.0 %). European grayling (*Thymallus thymallus*) was also well represented, particularly at Weirs Nos. 2 and 3, although its relative abundance declined sharply at the uppermost structures.

Isolated occurrences of eurytopic species were recorded at selected weir sites, specifically pike-perch (Weirs Nos. 3 and 5), Prussian carp (Weirs Nos. 4 and 6) and tench (*Tinca tinca*) (most weir sites). Their mean relative abundance, however, did not exceed 1.4 % in any case and was accompanied by a high standard deviation, indicating sporadic occurrence in these reaches. Northern pike (*Esox lucius*) was recorded exclusively at Weir No. 3. The observed distribution and overall structure of fish communities at the individual sites were further evaluated using multivariate statistical analysis. The resulting NMDS ordination (*Fig. 7*) had a stress value of 0.127, indicating a very good representation of the data in two-dimensional space and allowing reliable interpretation.

The ordination plot confirms a clear separation of Sector 1 (downstream of Weir No. 1 in the Rybáře area of Karlovy Vary) from the reaches upstream

Tab. 3. Relative abundance of ichthyofauna in individual river sections over a 4-year period, expressed in % ± standard deviation

English name	Scientific name	Ohře – downstream of confluence	Ohře – upstream of confluence	Weir No. 1	Weir No. 2	Weir No. 3	Weir No. 4	Weir No. 5	Weir No. 6
Pike-perch	*Sander lucioperca*					0.2 ± 0.4		0.2 ± 0.4	
Gudgeon	*Gobio gobio*	9 ± 11.4	10 ± 3.5	2.5 ± 2.4	7.8 ± 10.8	5 ± 4.6		2.1 ± 2.4	0.3 ± 0.4
Ide	*Leuciscus idus*	2 ± 1.5	5.3 ± 5						
Common dace	*Leuciscus leuciscus*	11.9 ± 16	9.1 ± 9.1	1.4 ± 2.4		0.2 ± 0.4			
Chub	*Squalius cephalus*	30.3 ± 16.3	38.9 ± 6.2	7.3 ± 8.3					
Common carp	*Cyprinus carpio*		0.1 ± 0.1						
Prussian carp	*Carassius gibelio*						0.4 ± 0.7		0.2 ± 0.3
Three-spined stickleback	*Gasterosteus aculeatus*		1.1 ± 1.1						
Tench	*Tinca tinca*			0.4 ± 0.7	1.4 ± 2.4	0.6 ± 1		1.2 ± 1	1 ± 0.4
European grayling	*Thymallus thymallus*	0.7 ± 0.8	0.1 ± 0.1	5.9 ± 6.8	13.6 ± 13.4	12 ± 9.1	9.5 ± 12.6	0.6 ± 0.6	2.3 ± 3.3
European brook lamprey	*Lampetra planeri*		0.2 ± 0.3						
Burbot	*Lota lota*				0.4 ± 0.7				0.1 ± 0.2
Stone loach	*Barbatula barbatula*	2.8 ± 2	7 ± 1.3	12.7 ± 6.8	20.3 ± 4	12.3 ± 2.3	18.6 ± 14.4	16.1 ± 7.2	14 ± 10.5
European perch	*Perca fluviatilis*	0.2 ± 0.3	0.6 ± 0.9	1 ± 1.2		6 ± 4.2			0.8 ± 0.5
Bleak	*Alburnus alburnus*	0.8 ± 1.1	0.1 ± 0.1						
Common barbel	*Barbus barbus*	5.3 ± 2.1	2.2 ± 1.1						
Roach	*Rutilus rutilus*	0.9 ± 1.1	3 ± 2.5		0.3 ± 0.5	0.6 ± 0.7			0.3 ± 0.4
Rainbow trout	*Oncorhynchus mykiss*	0.6 ± 0.9		0.4 ± 0.6					
Brown trout	*Salmo trutta*	4.9 ± 5.7	0.9 ± 0.8	27.9 ± 11.2	56.2 ± 9.6	62.4 ± 2.6	71.5 ± 12.2	79.8 ± 8.5	81.1 ± 10.7
Eurasian minnow	*Phoxinus phoxinus*			0.3 ± 0.6					
Topmouth gudgeon	*Pseudorasbora parva*	5.5 ± 5.5	3 ± 2.2	1 ± 1.1		0.6 ± 1			
Northern pike	*Esox lucius*					0.2 ± 0.3			
European bullhead	*Cottus gobio*	24.9 ± 16.5	18.3 ± 5	39.1 ± 12.7					

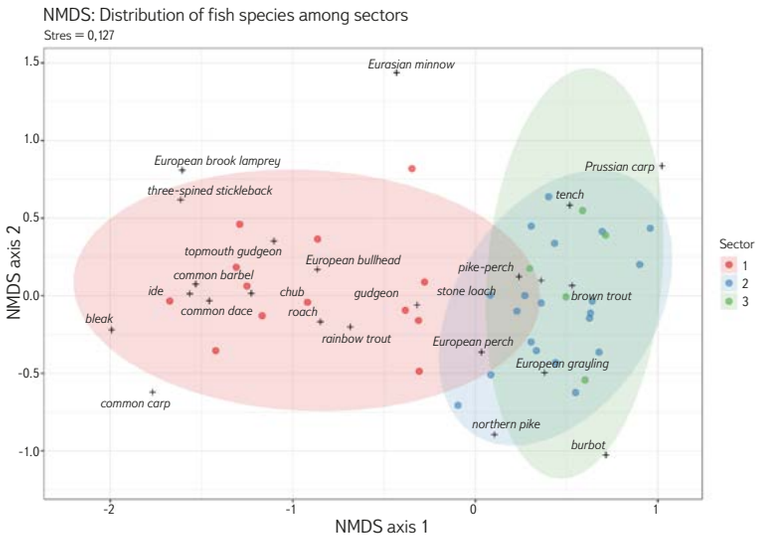

Fig. 7. NMDS ordination plot showing similarity in the species composition of ichthyofauna at the monitored sites (Sectors 1–3); stress = 0.127

of this barrier. The red ellipse clearly delineates the distinctive Sector 1 community (Ohře sites below/above the confluence and Weir No. 1), characterised by protected rheophilic species such as European brook lamprey, European bullhead and ide. Sectors 2 (Weirs Nos. 2–5) and 3 (Weir No. 6), by contrast, show high similarity in species composition and considerable spatial overlap. On the right-hand side of the plot are species indicative of wash-in from surrounding standing waters (e.g. tench and Prussian carp), which supplement the otherwise less species-rich rheophilic fish community upstream of the barriers.

DISCUSSION

Fish community composition

When interpreting long-term changes in the ichthyofauna, it is necessary to consider the methodological limitations and specific characteristics of the individual information sources, which directly account for differences in the total numbers of species recorded. The relatively low number of 20 species recorded in the first half of the 19th century [25] was undoubtedly influenced by the state of taxonomy at the time, when some closely related taxa, such as freshwater bream (*Abramis brama*) and white bream (*Blicca bjoerkna*), were not routinely distinguished in the literature [28]. Overall species richness in the past was therefore very likely higher than contemporary sources suggest.

Lower species richness is also apparent in the statistics of the Czech Anglers Union (ČRS). Angling records are primarily biased towards species of commercial and recreational interest, which explains the complete absence of data on small species such as European bullhead, stone loach and Eurasian minnow. Despite this bias, however, angling statistics represent a highly valuable data source that effectively complements electrofishing, which itself is selective. This selectivity is particularly evident for more mobile species such as common carp (*Cyprinus carpio*), silver carp and asp (*Leuciscus aspius*), as well as species inhabiting deeper parts of rivers, such as Wels catfish (*Silurus glanis*), whose abundance tends to be substantially underestimated. This is also confirmed by our monitoring results: these species are absent from our records despite their documented occurrence in the study area. In such cases, recreational anglers' catch records and ČRS fish-stocking statistics provide an invaluable indication of the actual presence of these taxa in the river and important context for distinguishing naturally reproducing populations from those dependent on artificial stocking.

The lower species diversity recorded in our study is probably attributable to a combination of its smaller spatial extent and the methodology used. Unlike study [29], which combined field surveys with records from the Nature Conservation Agency of the Czech Republic (NCA CR) database covering long periods, our study relied solely on our own electrofishing surveys. Study [29] also included specific isolated habitats such as private fishponds and pools. Species such as Siberian sturgeon (*Acipenser baerii*) and sunbleak (*Leucaspius delineatus*) are associated with these habitats and only rarely enter the flowing channels of the Ohře or Rolava, for example during fishpond harvesting.

Long-term changes in the community are closely associated with the increasing occurrence of non-native fish species, a trend that has been clearly apparent in the study area since the 20th century. Whereas non-native species were virtually absent from 19th-century historical surveys and the river community consisted exclusively of native species, non-native taxa are now considerably more frequent and have become a permanent component of species richness in the catchment. This upward trend was initially driven by deliberate introductions of species valued for commercial or recreational purposes, such as grass carp, silver and bighead carp, brook trout and rainbow trout, whose populations in the river continue to be maintained by ČRS stocking. In addition to these management interventions, however, recent data also show an increasing occurrence of spontaneously spreading invasive taxa included on the so-called blacklist, such as Prussian carp, topmouth gudgeon and pumpkinseed. The gradual shift in species composition from an entirely native community towards a system in which non-native species are increasingly common thus clearly reflects long-term anthropogenic pressure and changes in the character of the river habitat as a whole.

Assessment of fish passage

The high degree of fragmentation of the Rolava represents a major constraint on the functioning of the river ecosystem. A total of 41 barriers currently occur along a river only 37 km long. A head difference exceeding 0.6 m is generally considered a critical threshold that most native fish species are unable to negotiate. On the Rolava, 25 of these barriers exceed 0.6 m, representing a critical degree of obstruction for most migrating fish. This unfavourable situation is further compounded by the fact that only eight of these high barriers are currently equipped with fish passes.

Despite the clear need to address this fragmentation, socioeconomic constraints must be taken into account when designing specific restoration measures. Weirs No. 1 – Rybáře (river km 1.1) and No. 5 – Stará Role (river km 4.6) must therefore be regarded as barriers whose complete removal is not currently feasible. Both structures stabilise the river gradient and maintain the impounded water levels required for the operation of small hydropower plants, while the Rybáře weir also provides an important source of non-potable water for the local swimming pool. Complete restoration of river continuity through removal of these structures is therefore not realistic. Longitudinal fish passage in the lower Rolava can, however, be restored through engineering measures that are planned for both sites in the near future.

At Weir No. 1 in Rybáře, a pool-type fish pass with boulder obstacles is planned on the right bank in the immediate vicinity of the small hydropower plant. This location is optimal because migrating fish will be naturally attracted towards the pass by the strong attraction flow discharged from the power plant turbines. Weir No. 5 in Stará Role is expected to undergo major modification this year. The planned conversion of the vertical concrete structure into a boulder ramp will create a rough bed with sufficient water depth, enabling safe passage for a wide range of aquatic organisms.

By contrast, given their height (< 0.3 m), the remaining three smaller barriers located between the two large structures do not represent a constraint for

rheophilic species with good jumping and swimming abilities, such as brown trout and European grayling. Moreover, their partly degraded structural condition has created areas of reduced flow, local cavities and zones of lower water velocity within the structures. It can therefore be assumed that, under normal flow conditions, these sills are also passable to fish species with limited swimming ability, such as European bullhead and Eurasian minnow. However, the actual degree of fish passage at these smaller, damaged structures will need to be confirmed by further study. In terms of prioritising remedial measures on the Rolava, it therefore makes sense to focus primarily on restoring fish passage at the two major Karlovy Vary weirs (Nos. 1 and 5), which currently constitute complete migration barriers.

Comparison of methods — radiotelemetry vs. fish sampling at barriers

Assessment of fish passage in rivers is fundamental to understanding the effects of river-network fragmentation on fish communities and their biodiversity. This principle is closely linked to the requirements of the Water Framework Directive [14], which does not require active monitoring of passage at individual barriers but does require assessment of the longitudinal continuity of the water body as a whole. River-network continuity is a key supporting element in determining the ecological status of water bodies. Selecting an appropriate method for assessing fish passage is therefore essential for obtaining valid data that can support the effective design of remedial measures or functional fish passes in accordance with European standards. The following analysis compares telemetry and ichthyological sampling as two approaches that differ in their level of detail, practical requirements and potential for interpretative bias.

Telemetry is a highly precise tool for detailed analysis of individual behaviour. It can identify the specific barriers at which fish are stopped, document relatively precisely the time required to negotiate a migration barrier, and relate this activity to prevailing environmental conditions such as temperature and discharge. In terms of habitat connectivity, telemetry provides unique data on the dynamics of movement between key habitats. In our study, telemetry confirmed fish passage at the two restored barriers at river km 8.8 and 9.2, clearly demonstrating that both adult and juvenile brown trout were able to negotiate these fish passes successfully. Telemetry also allowed us to determine the speed of these movements and showed that fish generally returned to their home territory immediately after release or within a few days (*Fig. 8*). It also enabled detailed monitoring of migratory behaviour over the broader temporal context of an entire year. Although movement frequency was highest shortly after release, continuous year-round monitoring provided essential information on whether trout also actively used other parts of the river throughout the year. This confirmed that fish actively use different parts of the river according to their seasonal requirements, something that could not have been detected without continuous monitoring.

In addition to monitoring these larger-scale movements, telemetry allows detailed mapping of local movements by individual fish, helping to identify particular parts of the river that are attractive to them. Continuous monitoring of fish presence at a given location makes it possible to identify the microhabitats they preferentially use. Such information is highly valuable for future management and remedial measures, providing an important basis for the optimal design of river restoration, particularly in heavily modified urban reaches where appropriate channel configuration and the availability of refuges are essential for maintaining fish communities.

The disadvantages of telemetry, however, include its high cost, the need for surgical implantation and, above all, constraints on transmitter weight. Ideally, transmitter mass should not exceed 2 % of the fish's body mass. Although the smallest commercially available transmitters weigh approximately 0.24 g,

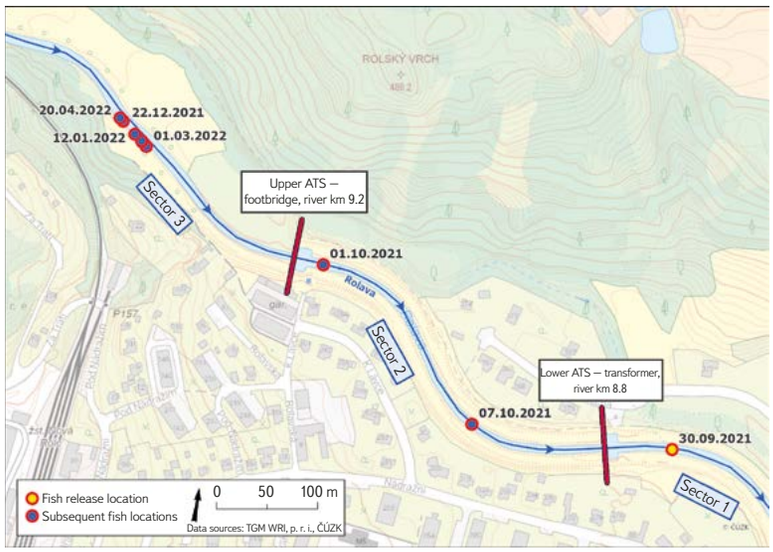

Fig. 8. Movement of adult brown trout ID 17 following translocation from Sector 3 to Sector 1 and subsequent homing: released in Sector 1 in September, detected in Sector 2 in October, and returned to its original home range in Sector 3 by November

theoretically allowing individuals weighing as little as 12 g to be tagged, their battery life is then only a few days. Such a short period is entirely inadequate for long-term monitoring, particularly of species that are not highly mobile. Telemetry is therefore inherently unable to reliably establish whether a reach is passable to smaller fish species such as European bullhead, Eurasian minnow and stone loach, for which long-term monitoring using this method is impractical. Other monitoring methods capable of assessing whether barriers can be negotiated are therefore necessary when evaluating connectivity for smaller species. Regular ichthyological sampling upstream and downstream of a barrier can play a key role, with the presence or absence of these small species providing important evidence as to whether they are actually able to pass the barrier.

By contrast, ichthyological sampling upstream and downstream of barriers provides broader ecological insight at lower cost. It can identify barriers from the presence or absence of particular taxa, detect invasive species, and reveal the age or size structure of populations. Using this method, our monitoring identified a total of 23 fish and lamprey species. These included protected and ecologically valuable species (European bullhead, Eurasian minnow, burbot, ide and European brook lamprey), as well as non-native or invasive taxa (Prussian carp, three-spined stickleback, rainbow trout and topmouth gudgeon). These records provide valuable information for designing future remedial measures to protect threatened species while also allowing the risk of non-native species spreading through the catchment to be assessed.

Detailed assessment of size structure also enabled us to determine the current status of individual populations and establish whether they were reproducing naturally within the study area. Successful natural reproduction in the Rolava was confirmed for brown trout, stone loach and European bullhead. In the Ohře, natural reproduction was demonstrated for, among others, all three *Leuciscus/Squalius* species – chub, ide and common dace – as well as common barbel, roach, three-spined stickleback and topmouth gudgeon.

The main limitations of fish sampling include more frequent direct disturbance of the river environment and the risk of injury to fish during capture and handling, particularly larger individuals; in rare cases, mortality may also occur. The efficiency and selectivity of electrofishing are also strongly influenced by numerous environmental factors, including water conductivity, channel width and depth, channel complexity, flow velocity and the nature of the bed substrate. Sampling provides no continuous record of the movements of individual

fish over time and therefore offers only a snapshot at the time of sampling; it cannot establish whether a fish previously negotiated a particular barrier and subsequently returned to its original home range. Finally, the interpretation of sampling results may be substantially confounded in fisheries subject to artificial stocking, where the presence of stocked individuals can mask the true passability or otherwise of the river for a particular species.

The two methods used to assess fish migration therefore have their own specific strengths and limitations. Combining ichthyological sampling with radiotelemetry, however, provides a comprehensive and robust tool for objectively assessing river connectivity and the functioning of aquatic ecosystems, with telemetry supplying the individual and temporal detail that sampling lacks. Data on the distribution and abundance of individual species provide direct indications of which barriers act as selective filters and which are completely impassable to particular taxa or size classes. Field sampling therefore provides an essential complement to telemetry data, revealing the actual long-term effects of barriers on the natural structure of fish populations in the affected reaches of the Rolava.

Predicted future development of the fish community in the Rolava

Restoring longitudinal river continuity and reconnecting the Rolava with the Ohře will represent a major ecological change that is likely to influence the future composition of the local fish community. It will also be important to determine how natural reproduction of salmonids responds to this restored connection, as successful natural reproduction is a key prerequisite for reversing the negative trend in their populations [5].

The first part of the prediction is based on planned engineering works on the Rolava, specifically the restoration of fish passage at two key migration barriers. At Stará Role, the existing Weir No. 5 will be replaced by a boulder ramp, but the crucial step will be the construction of a fish pass at Weir No. 1 in Rybáře [30]. This weir currently constitutes an impassable barrier to fish. Restoring passage will reopen the migration route from the Ohře and should lead to recolonisation of the Rolava by native species such as European bullhead, Eurasian minnow and European brook lamprey. These ecologically demanding species require high-quality, clean water and commonly occur as far upstream as the upper parts of the trout zone; they can therefore be expected gradually to recolonise the Rolava upstream as far as the next impassable barrier. The spread of European brook lamprey, however, will be limited by the availability of low-flow areas with fine muddy sediments, where its larvae (ammocoetes) spend the first years of their lives. Burbot (*Lota lota*) could also return to the Rolava. It is another characteristic species of the trout zone and is regularly stocked by the Czech Anglers Union in the Ohře in Karlovy Vary. Once fish passage has been restored, the Rolava should again provide suitable and characteristic habitat for the species.

Gudgeon (*Gobio gobio*) and rheophilic cyprinids such as common dace and chub can initially be expected to occur mainly in the lower Rolava. However, ongoing climate change, resulting in warmer river water and lower precipitation, could gradually shift this ecological boundary upstream, potentially allowing these species to colonise the currently cooler submontane reaches in the future. By contrast, a substantial expansion of non-native fish species such as three-spined stickleback (*Gasterosteus aculeatus*), Prussian carp and topmouth gudgeon (*Pseudorasbora parva*) is not expected. Given the biological requirements of these limnophilic taxa, restoration of passage at the lower barriers is likely to allow them to penetrate only the lowermost, anthropogenically modified urban reach of the Rolava in Karlovy Vary.

The second part of the prediction concerns the development of salmonid populations and is based on our ichthyological surveys conducted in the Rolava between 2022 and 2025. These surveys were carried out mainly in late spring and early summer, with a total of 32 sampling surveys conducted in the Rolava and Ohře. In the final year of the project, we recorded a marked increase in the abundance of brown trout fry in the upper part of the study reach near Weirs Nos. 5 and 6, reaching tens to hundreds of individuals per 100 m of river. The captured individuals were approximately 30 mm long. According to the stocking plan, the Czech Anglers Union (ČRS) routinely stocks the Rolava 1 A fishery with one-year-old trout or larger stocking fish at least 100 mm in length. Given this pronounced size difference, it is clear that the individuals recorded in our survey originated from natural spawning. This contrasts markedly with previous years, when fry were either entirely absent or recorded only in very low numbers [19].

Given the isolated nature of this finding, it is not yet clear whether the high abundance of fry was primarily attributable to restored fish passage at the structures at river km 8.8 and 9.2 or to the particular conditions prevailing that year. Further monitoring of the ichthyofauna at the site will be necessary to confirm any lasting benefits of restoring fish passage. Nevertheless, the finding is an important indication of the river's potential for natural reproduction. Supporting natural reproduction appears to be a key means of achieving stable populations with a balanced age structure. Czech Anglers Union data (*Fig. 9*) show a long-term decline in catches of both brown trout and European grayling despite intensive artificial stocking, which has been unable to compensate effectively for this decline. Although precise stocking records are available only from 2017 onwards, according to information provided by Ing. H. Dort, a fisheries officer of the regional association, stocking also took place in earlier years at approximately 1,500 grayling and 2,000 trout per year. The causes of this negative trend are complex and include predation pressure, illegal fishing and general habitat degradation, a phenomenon observed in most trout fisheries in the Czech Republic. Restoring fish passage is therefore one of the prerequisites for conserving local populations, but it must go hand in hand with measures addressing other environmental pressures.

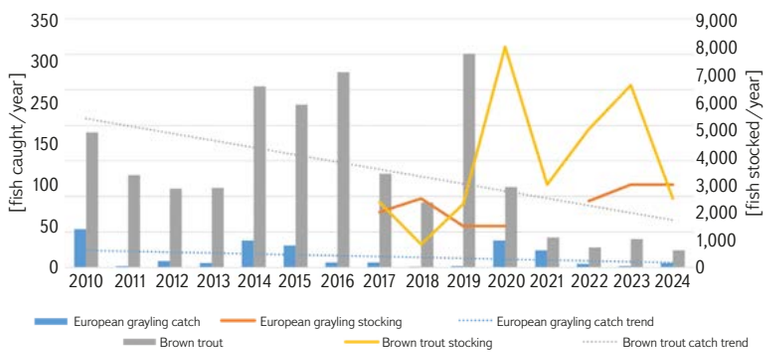

Fig. 9. Annual catch and stocking data for brown trout (*Salmo trutta m. fario*) and grayling (*Thymallus thymallus*) in Rolava 1A angling district (data source: West Bohemian Territorial Union of the Czech Anglers Union [ČRS])

CONCLUSION

In recent years, the Rolava has become a key focus of efforts to restore river continuity in the Karlovy Vary Region. The principal aim is to restore fish passage, which is essential for maintaining stable populations of rheophilic fish species. River restoration builds directly on the historical legacy of naturalist Antonín Frič, who recognised the need for unobstructed migration routes in Czech river basins as early as the second half of the 19th century.

The combination of impassable structures in the lower and upper reaches divides the Rolava into a series of isolated sections, substantially reducing

the ecological potential of the entire catchment, preventing fish from using their natural migration routes and hindering compliance with legislative requirements for the biological integrity of aquatic ecosystems. Removing barriers on the Rolava therefore opens the way to restoration of the entire river ecosystem, the return of many threatened and rare species, and the development of near-natural communities of fish and other aquatic organisms.

Analysis of changes in the ichthyofauna reveals an interesting trend: the total number of species recorded during our monitoring (23 species) remains very similar to that reported in 19th-century historical records (20–28 species). However, the composition of the community has changed substantially. Extreme fragmentation of the river by 41 transverse barriers has resulted in the disappearance of some sensitive native species from the Rolava. Over time, these have been replaced by non-native or invasive species that are more tolerant of environmental degradation.

The successful restoration of three structures in Nová Role in 2020 demonstrated that restoring fish passage is both technically and biologically feasible. Radiotelemetry clearly showed that the fish passes constructed are fully functional, at least for brown trout, and allow natural movement of fish along the river. The high passage success at the restored structures therefore provides encouraging evidence for the planned restoration of fish passage at the critical barriers in Rybáře and Stará Role, an essential prerequisite for the long-term sustainability of the local fish community.

Monitoring conducted between 2022 and 2025, particularly in the final year, indicates substantial natural reproduction in the Rolava. Whereas brown trout fry were scarce in previous years, the most recent data confirm that the river is capable of providing suitable conditions for successful natural spawning.

These findings are particularly significant in the context of the general decline in the abundance of rheophilic fish species in recent years, which even intensive artificial stocking has been unable to compensate for effectively. This trend is also reflected in declining catches of brown trout and European grayling in the Rolava 1A fishery. The results indicate that where fish are provided with adequate connectivity, natural reproduction is not only possible but can become one of the principal means of maintaining stable populations with a balanced age structure.

Acknowledgements

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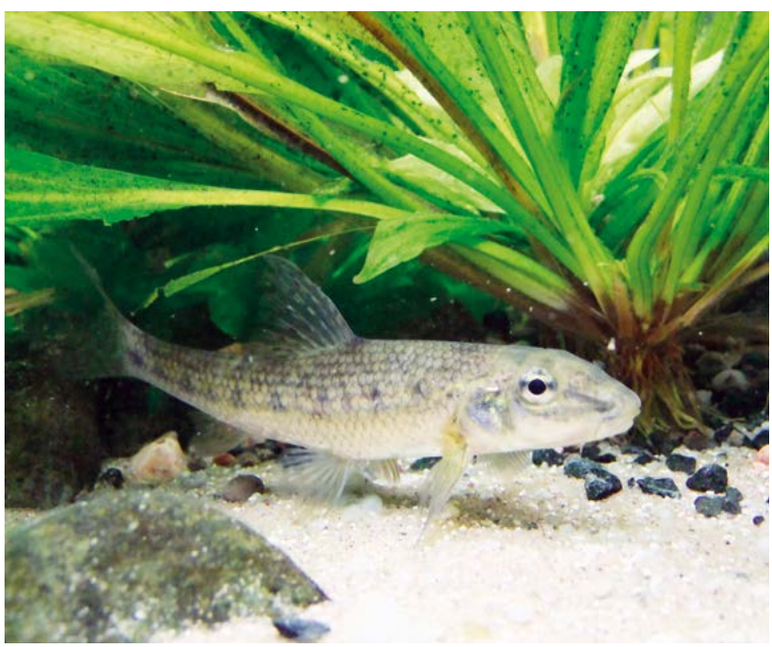
Stone loach (*Barbatula barbatula*), an inconspicuous yet significant bottom-dweller of our trout and grayling streams (photo: E. Bouše)



Gudgeon (*Gobio gobio*), a typical representative of fish from fast-flowing sections with sandy or gravelly bottoms (photo: M. Barankiewicz)

Measurement of a captured brown trout (*Salmo trutta m. fario*) during a field fish stock survey (photo: E. Bouše)

Brown trout (*Salmo trutta m. fario*) – an iconic species of clean, cold, and well-oxygenated waters (photo: M. Barankiewicz)

Brook lamprey (*Lampetra planeri*) – a rare and strictly protected species that is a sensitive indicator of water purity and the natural state of the river (photo: M. Barankiewicz)

Simulation of the thermal regime of a drinking water reservoir under projected climate change conditions

ALEŠ HAVLÍK, ADAM VIZINA, BARBORA KRIJT

Keywords: temperature profile — water temperature — climate change — water quality — drinking water reservoir

ABSTRACT

This paper examines the potential impact of projected climate change on the thermal regime of a drinking-water reservoir.

The methodology was based on simulating temperature changes in the reservoir using the two-dimensional (2D) CE-QUAL-W2 software, which incorporates a mathematical model for the hydrodynamic simulation of two-dimensional flow and water quality processes in reservoirs. Its hydrodynamic component is based on the laterally averaged three-dimensional equations of motion. Simulations of the thermal regime and water quality are performed by numerically solving the turbulent advection–diffusion equation. The total heat exchange between the water body and the atmosphere is quantified based on air temperature, dew point temperature, absolute humidity, wind speed, cloud cover and the geographical location of the reservoir surface.

The potential impact on the thermal regime was assessed using Vrchlice Reservoir as a case study. The model was calibrated for 2023 using detailed measurements of vertical water temperature profiles at selected monitoring sites provided by the Elbe River Water Authority; subsequent verification was carried out for 2022. To compare the affected thermal regime with the current state, 2018 was selected as the reference year. The observed daily air temperature series for 2018 was transformed using the Advanced Delta Change (ADC) method to reflect changes derived from climate models for the 2050 and 2085 horizons. The scenario calculations presented in this article isolate the effect of changes in air temperature, while other meteorological and hydrological-operational inputs are kept at their 2018 reference levels.

The results provide a comparison of mean water temperatures in characteristic vertical profiles for the selected climate change scenarios for 2050 and 2085 with the corresponding values for 2018, as well as a similar comparison of surface water temperatures.

INTRODUCTION

The issue of the potential impact on the thermal regime of a drinking-water reservoir was addressed as part of the TA CR project *Water Systems and Water Management in the Czech Republic under Climate Change Conditions* at the Faculty of Civil Engineering of the Czech Technical University in Prague from 2020 to 2026. At the beginning of the project, the Vrchlice River basin was selected as the pilot basin; the eponymous drinking-water reservoir is also located there. The potential impact on the thermal regime of the drinking-water reservoir was therefore assessed using this reservoir as a case study.

Globally, lakes and reservoirs respond to climate change through rising water temperatures, changes in the duration and intensity of thermal stratification, changes in mixing regimes and, in some cases, deterioration of oxygen conditions. Model projections of the thermal structure of reservoirs therefore provide an important basis not only for assessing their physical regime, but also for subsequent assessments of water quality and biogeochemical processes.

The aim of the study is to quantify how the thermal regime of Vrchlice Reservoir may change near the dam and at the surface under climatic conditions representing the 2050 and 2085 horizons and the SSP2-4.5 and SSP5-8.5 scenarios, and to compare these changes with the reference year 2018. The study addresses three questions: (i) how mean and surface water temperatures change, (ii) how the response differs between climate scenarios and time horizons, and (iii) what limitations need to be considered when interpreting the results for water management practice. Vrchlice was selected as the project's pilot site and, at the same time, as a drinking-water reservoir with available vertical-profile measurements and operational data. The practical benefit is the provision of a basis for assessing possible future changes in thermal conditions in the area of drinking-water intakes and for subsequent assessment of reservoir operation and water quality; the methodological benefit is the application of a laterally averaged 2D model to a specific Czech drinking-water reservoir using a set of climate scenarios.

METHODOLOGY

Theoretical analysis

A comprehensive comparison of reservoir models shows that CE-QUAL-W2 can simultaneously simulate water-surface elevation, flow, water temperature and selected water-quality parameters, while the choice of model must correspond to the geometry of the reservoir and the dominant physical processes [1]. Changes in the thermal regime of reservoirs under climate change conditions have been addressed, for example, in study [2]. Golub et al. [3] explicitly link projections of lake temperature and thermal structure with future modelling of oxygen, water quality, biogeochemical processes and algal blooms. Ferreira and Fernandes [4] addressed integrated modelling of river–reservoir systems and the importance of linking hydrodynamics, water quality and reservoir operation. Higher temperatures and changes in hydrological extremes may also affect nutrient mobilisation, turbidity, concentrations of dissolved substances and other water-quality parameters [5]. Similarly, earlier case studies of proposed reservoirs show that combining

monitoring, modelling of pollutant loads and modelling of reservoir response can be used to forecast future trophic status and support decision-making [6].

CE-QUAL-W2 was selected to simulate changes in the thermal regime of drinking-water reservoirs under projected climate change conditions. It consists of a model for the hydrodynamic simulation of two-dimensional flow and water quality processes in reservoirs, developed by the Department of Civil and Environmental Engineering at Portland State University. The model is available as free software for unrestricted use [7, 8]. Talebbeydokhti et al. [1] reviewed the monitoring and modelling of water quality in reservoirs, including the capabilities and limitations of CE-QUAL-W2.

In the Czech context, hydrodynamic and water-quality modelling of drinking-water reservoirs has also long been carried out by the research team at the Institute of Hydrobiology of the Biology Centre of the Czech Academy of Sciences, with the involvement of J. Hejzlar. For the Římov Reservoir, the CE-QUAL-W2 model was used for two-dimensional modelling of hydrodynamics and water quality [9]. Subsequent work also examined the potential impacts of climate change on water quality in the reservoir [10].

The thermal regime of deeper drinking-water reservoirs has a pronounced seasonal character: during the warm part of the year, stable stratification may develop, with a warmer surface layer and a cooler hypolimnion, while during periods of mixing, temperature differences within the water column decrease. For water management practice, the temperature at the intake level is particularly important because, together with stratification and oxygen conditions, it influences the choice of intake level and may be related to raw water quality. For ecological assessment, the thermal regime is also important because of its relationship with the rates of biological and biogeochemical processes [3, 9, 10].

The preparation of climate inputs was based on the Advanced Delta Change (ADC) incremental method, which transforms observed series so that the difference between the reference and future series corresponds to changes derived from climate models [11]. At a daily time step, it is important that the transformation captures not only changes in the mean but also changes in variability. This is particularly important for precipitation and extreme values, for which changes may not correspond to a simple shift in the mean value. For air temperature, the transformation is performed linearly, meaning that systematic bias in the climate model does not have the same significance for the resulting temperature change as it does for precipitation [11]. The output consists of daily series of mean air temperature and other hydroclimatological variables that can be used for subsequent hydrological and water management modelling. For the air temperature used in this study, the transformation preserves the temporal structure of the reference year and applies the change in mean and variability derived for the given climate model, scenario and time horizon. Fošumpaur and Kováčová [12] addressed adaptive reservoir management during hydrological drought.

CE-QUAL-W2 software

The solution is based on the governing equations. The hydrodynamic component consists of the laterally averaged longitudinal momentum equation, the hydrostatic equation in the vertical direction, and the continuity equation. The CE-QUAL-W2 model uses the hydrostatic approximation: because the longitudinal dimension of the reservoir is considerably greater than its vertical dimension, vertical accelerations and shear stresses are neglected in the vertical momentum equation. The vertical velocity component is not zero, however; it is included in the advection term of the longitudinal momentum equation and in the continuity equation. Lateral averaging assumes that lateral variations in velocity, temperature and other water-quality parameters are negligible. It should be borne in mind that this assumption may be inappropriate for large water bodies exhibiting significant lateral variations in water quality.

For a horizontal longitudinal axis and neglecting the longitudinal atmospheric pressure gradient, the longitudinal momentum equation (1) and the hydrostatic equation in the vertical direction (2) take the following form:

$$\frac{\partial \overline{u_x}}{\partial t} + \frac{\partial \overline{u_x}\,\overline{u_x}}{\partial x} + \frac{\partial \overline{u_x}\,\overline{u_z}}{\partial x} = g\frac{\partial H}{\partial x} - \frac{g}{\rho}\cdot\int_h^z \frac{\partial \rho}{\partial x}\,dz + \frac{1}{\rho}\cdot\frac{\partial \tau_{xx}}{\partial x} + \frac{1}{\rho}\cdot\frac{\partial \tau_{xz}}{\partial z} \qquad (1)$$

$$g - \frac{1}{\rho}\cdot\frac{\partial \rho}{\partial z} = 0 \qquad (2)$$

where:

x, z	are	the coordinates in the longitudinal and vertical directions [m]
$\overline{u_x}$		the laterally averaged longitudinal velocity component [m · s^{-1}]
$\overline{u_z}$		the laterally averaged vertical velocity component [m · s^{-1}]
t	is	time [s]
g		gravitational acceleration [m · s^{-2}]
r		density [kg · m^{-3}]
p		pressure
H		water-surface elevation [m]
t_{xx}, t_{xz}	are	turbulent shear stresses acting in the longitudinal direction [Pa]

The integration limits extend from the elevation z to the water surface at z = h. A condition for using the governing equations formulated in this way is that the transverse velocity components are negligible compared with the longitudinal and vertical components. They are therefore recommended for narrow and deep reservoirs, preferably with a predominantly straight longitudinal alignment.

The choice of a 2D laterally averaged model for Vrchlice Reservoir was based on the longitudinal character of the reservoir. The length of the reservoir at maximum flows is approximately 4.8 km, while the average bottom width in the model is approximately 200 m and the maximum bottom width is 476 m; the height of the dam above the surrounding terrain is almost 34 m. Given the scale of the reservoir, it can therefore be expected that gradients along the longitudinal axis and in the vertical direction are dominant when assessing the longitudinal–vertical temperature structure. This assumption does not, however, mean that lateral inhomogeneities are negligible under all conditions. Uncertainty may be increased particularly by the local effects of side bays and tributaries, spatially variable wind effects, and conditions in the immediate vicinity of the intake structures. The results therefore represent a laterally averaged picture of the thermal regime and should not be interpreted as a substitute for a fully three-dimensional description of local flow and temperature structures [7, 8].

The continuity equation (3) is given by:

$$\frac{\partial \overline{u_x}}{\partial t} + \frac{\partial \overline{u_z}}{\partial z} = 0 \qquad (3)$$

The governing diffusion equation for modelling temperature and water quality is [13]:

$$\frac{\partial \varphi}{\partial t} + \frac{\partial \overline{u_x}\varphi}{\partial x} + \frac{\partial \overline{u_z}\varphi}{\partial z} - \frac{\partial}{\partial x}\cdot\left[D_x\frac{\partial \varphi}{\partial x}\right] - \frac{\partial}{\partial z}\cdot\left[D_z\frac{\partial \varphi}{\partial z}\right] = 0 \qquad (4)$$

where:

Φ is the water temperature [°C]

D_x, D_z are the longitudinal and vertical dispersion coefficients [$m^2 \cdot s^{-1}$]

From the perspective of external influences, the thermal regime of the reservoir is predominantly affected by heat exchange between the water surface and the atmosphere. This consists of a number of components; the total heat flux is given by equation (5):

$$q_H = q_1 + q_2 + q_3 - q_4 - q_5 \quad (5)$$

where:

q_H is the total heat flux between the water surface and the atmosphere [$W \cdot m^{-2}$]

q_1 the heat flux received from shortwave solar radiation [$W \cdot m^{-2}$]

q_2 the heat flux received from longwave radiation [$W \cdot m^{-2}$]

q_3 the heat flux by convection [$W \cdot m^{-2}$]

q_4 the heat loss through longwave radiation from the water surface [$W \cdot m^{-2}$]

q_5 the heat flux due to heat loss through evaporation [$W \cdot m^{-2}$]

While the quantities q_1 and q_2 are independent of temperature, the remaining terms are functions of the water temperature at the surface and the air temperature. A number of well-established empirical equations are available for determining them.

Data for the model

The model solution is based on dividing the reservoir longitudinally into interconnected segments. Each segment is defined by its length along the reservoir axis, and its widths at selected elevations are then derived from a digital terrain model of the reservoir bottom. To determine the individual terms of equation (5), the model requires the geographical location of the reservoir and the time series of air temperature, dew point temperature, wind speed and direction, and cloud cover during the period being modelled [7, 8].

In the scenario calculations presented, climate change was applied only to air temperature. Dew point temperature, wind speed and direction, and cloud cover were kept unchanged in the scenario runs, using the 2018 reference meteorological series. This deliberately isolates the effect of changes in air temperature; at the same time, it represents a simplification, as future changes in other meteorological variables are not included in this study.

The boundary conditions are the time series of water inflow and outflow and the water temperature at the inflow, while the initial conditions are the initial water-surface elevation and water temperature in the reservoir.

Water-quality simulations in reservoirs using the CE-QUAL-W2 model have been presented, for example, in studies [9, 11, 14], while the thermal regime under projected climate change conditions has been addressed in studies [2, 10].

The model and its calibration

The basis of the model developed for Vrchlice Reservoir was the Bathymetry file, which defines the geometric model of the reservoir. It consisted of a total of 41 segments of varying length along the reservoir axis, with the longitudinal dimension of the segments being approximately 100 m. The varying widths of the individual layers were derived at 1 m elevation intervals throughout the water column in the Baltic height system after adjustment. An example of the location of the computational segment axes is shown in red against the background of the national map from ČÚZK [15] in *Fig. 1*. The maximum bottom widths ranged from 55 m in segment 1 to 476 m in segment 39, with an average of 200 m for the reservoir as a whole.

The calibration of the 2D model was carried out for 2023, when numerical simulations of the development of the thermal regime of Vrchlice Reservoir were performed using meteorological data from the Czech Hydrometeorological Institute (CHMI) stations at Chotusice and Vavřinec and their mean values (mean daily values). The Chotusice station is located 12 km east of Vrchlice Reservoir near Čáslav military airfield, while the Vavřinec station is 14 km west, near the village of Uhlířské Janovice. The time series of water inflow into the reservoir was calculated from the time series of water outflow and reservoir water-surface elevation. For the unknown water temperature at the inflow, a typical annual profile was estimated using water temperature measurements at vertical profile 1 at the beginning of the reservoir impoundment.

The hydrological input in the application presented was expressed as the total inflow calculated from the water balance between outflow and the change in the water storage volume in the reservoir. The individual inflows are therefore not assessed separately in this article, and their potential spatial temperature heterogeneity represents one of the limitations of the model simplification. The outflow condition was based on operational data; in the years assessed, the uppermost of the three intake levels was used according to the reservoir operator, and this was taken into account in the model. The effect of selecting an alternative intake level was not included in the scenarios presented here.

The calibration step was carried out for 2023. The meteorological input variants from the Chotusice and Vavřinec stations and their average were compared; agreement was assessed based on the vertical temperature profiles at verticals 8 and 9 and the difference between their mean temperatures. The best agreement was achieved using data from the Chotusice station. *Figs. 2* to *5* show representative comparisons for 17 April 2023, when summer stratification had already developed, and 28 August 2023, when summer stratification was fully developed.

For parameters for which separate site-specific calibration data were not available, the default settings based on the example CE-QUAL-W2 configurations were retained. As part of this study, no comprehensive multi-criteria optimisation of all model parameters or separate sensitivity analysis of wind sheltering, terrain shading of solar radiation, or evaporation parameterisation was performed. These factors are therefore taken into account below as sources of uncertainty in the results.

Subsequent verification was carried out for 2022 using the same model settings. The agreement between the vertical temperature profiles was comparable to that achieved for the 2023 calibration year. However, standard quantitative metrics such as RMSE or MAE were not calculated as part of the available assessment; the calibration and verification results must therefore be understood as a qualitative to semi-quantitative assessment of profile agreement.

Measurements from 2024 were available to the researchers as part of a broader project but were not included in the calibration and verification dataset presented here. Their use together with measurements from additional dates would provide a suitable basis for subsequent independent validation and quantitative assessment of the model.

Numerical experiments and scenarios

The aim of the numerical experiments was to assess the potential impact of the projected climate changes on the thermal regime of the drinking-water reservoir. For this purpose, future periods centred on 2050 (2036–2065) and

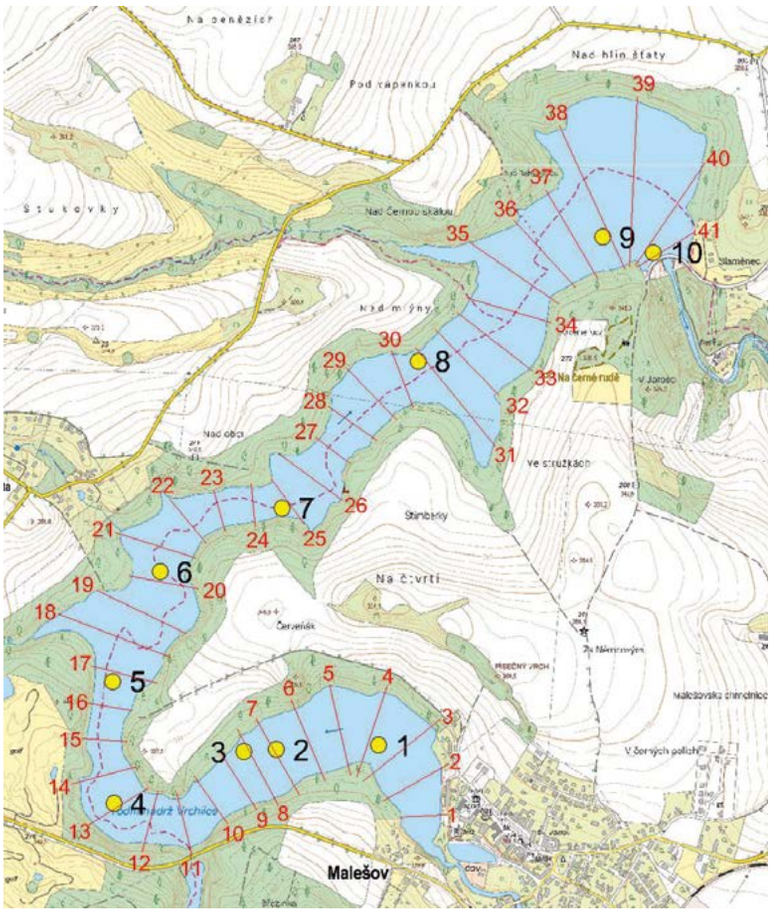


Fig. 1. Vrchlice Reservoir on the Vrchlice river, southwest of Kutná Hora, showing the vertical profiles used for measuring water temperature and other water-quality parameters and the axes of the computational segments

2085 (2071–2100) were selected. The year 2018 was used as the reference meteorological and hydrological period against which the results were compared. The year 2018 was not selected as a representative average year for the current climate period, but deliberately as a reference year representing a stress condition. It was characterised by a combination of above-average temperatures and dry conditions, which may be regarded as analogous to more frequent episodes in the future. Its use therefore makes it possible to assess further changes in the thermal regime of the reservoir under the climate scenarios against an already relatively unfavourable baseline condition. At the same time, continuous input series required for setting up and evaluating the model simulations were available for 2018. The designation of the years 2050 and 2085 refers to the midpoints of the 30-year periods 2036–2065 and 2071–2100, respectively. The transformation of the 2018 time series using the Advanced Delta Change method is described in the section Projected climate changes. The aim of the first set of calculations was to assess the potential impact on the thermal regime resulting solely from the assumed changes in air temperature. Water inflows and withdrawals for both 2050 and 2085 were assumed to be the same as in 2018, when the water level in the reservoir remained close to the storage level for almost the entire year.

As part of the wider project, a second set of calculations was also carried out, building on the outputs of Fošumpaur [12], in which the water level was assumed to follow the DG3 operating curve under minimum water withdrawals. As the results of this variant are neither presented nor discussed in this article, this scenario is not included in the set evaluated below and will be reported separately in the final TA CR project report.

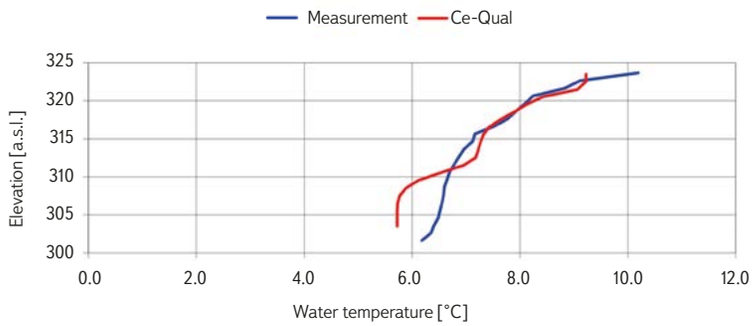


Fig. 2. Comparison of measured and simulated water temperature profiles at vertical profile 8 on 17 April 2023, based on measurements provided by the Elbe River Water Authority and simulations using the CE-QUAL-W2 model

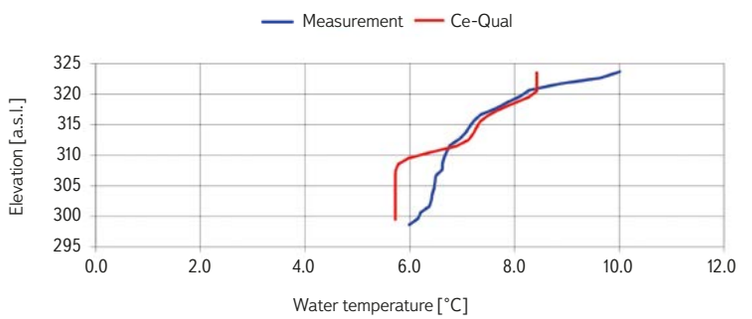


Fig. 3. Comparison of measured and simulated water temperature profiles at vertical profile 9 on 17 April 2023, based on measurements provided by the Elbe River Water Authority and simulations using the CE-QUAL-W2 model

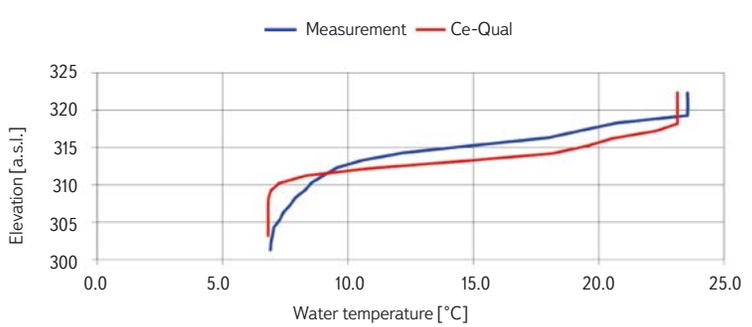


Fig. 4. Comparison of measured and simulated water temperature profiles at vertical profile 8 on 28 August 2023, based on measurements provided by the Elbe River Water Authority and simulations using the CE-QUAL-W2 model

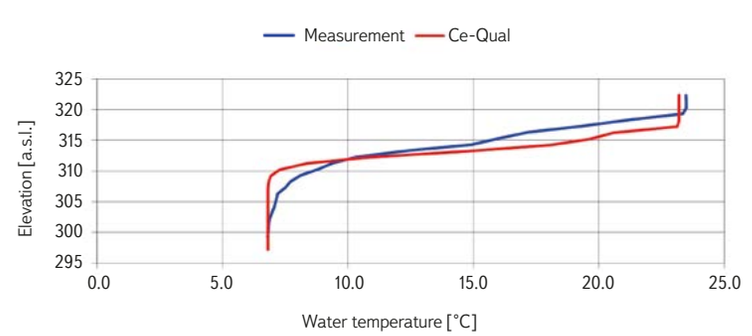


Fig. 5. Comparison of measured and simulated water temperature profiles at vertical profile 9 on 28 August 2023, based on measurements provided by the Elbe River Water Authority and simulations using the CE-QUAL-W2 model

Description of the location

Vrchlice Reservoir was selected for modelling the impact of projected climate changes on its thermal regime. It is located on the eponymous watercourse southwest of Kutná Hora and is impounded by a concrete dam. The dam crest is at an elevation of 325.80 m a.s.l., while the spillway crest is at 323.80 m a.s.l., which is also the elevation of the storage level. The height of the dam above the surrounding terrain is almost 34 m. The reservoir length at maximum flows is 4.8 km, the flooded area at the storage level is 0.935 km^2, and the storage volume is 7.89 million m^3. The location of the reservoir is shown in *Fig. 1*. The dam is equipped with a three-level intake structure. In the years assessed, only the upper intake was used, according to the reservoir operator, and this was taken into account in the model.

The reservoir is operated by the Labe River Water Authority, which has recently been carrying out detailed vertical-profile measurements of a range of water-quality parameters several times a year on a regular basis, including water temperature and dissolved oxygen concentration. Measurements are routinely carried out at 10 vertical profiles, the locations of which are shown in *Fig. 1*. As part of the collaboration, the researchers were provided with the results of vertical-profile measurements carried out in 2022, 2023 and 2024. Daily data on reservoir outflow, water level and air temperature measured at 7 a.m. were also available for 2018, 2022, 2023, and 2024.

Projected climate changes

The projected climatic conditions used to simulate the thermal regime of the reservoir were derived from the methodology and data outputs of Work Package WP 1, Partial Objective DC 1.2 of the Water Centre project, which focuses on identifying areas with water resource deficits and modelling water availability under current and future conditions [11, 16]. The CE-QUAL-W2 model was not supplied directly with raw outputs from climate models, but with adjusted meteorological series based on the observed reference climate and changes in climate variables derived for the selected future time horizons. The projected climate was derived primarily from simulations by global climate models from the Coupled Model Intercomparison Project Phase 6 (CMIP6), supplemented by the regional ALADIN-CLIMATE/CZ model. The dataset comprises six global models (CMCC-ESM2, EC-EARTH3, GFDL-ESM4, MPI-ESM1-2-HR, MRI-ESM2-0 and TAIESM1) and the regional ALADIN-CLIMATE/CZ model; the individual models differ in their spatial resolution and in the availability of Shared Socioeconomic Pathways (SSP) scenarios [11]. For the purposes of this study, the SSP2-4.5 and SSP5-8.5 scenarios were used, representing an intermediate future development pathway and a more emissions-intensive pathway based on high reliance on fossil fuels, respectively. These two scenarios make it possible to compare a more moderate and a more pronounced response of the reservoir's thermal regime to climate change.

The preparation of climate inputs was based on the incremental Advanced Delta Change (ADC) method, which transforms observed meteorological series so that the change between the reference and future series corresponds to changes derived from climate models [11]. The method allows not only changes in mean values but

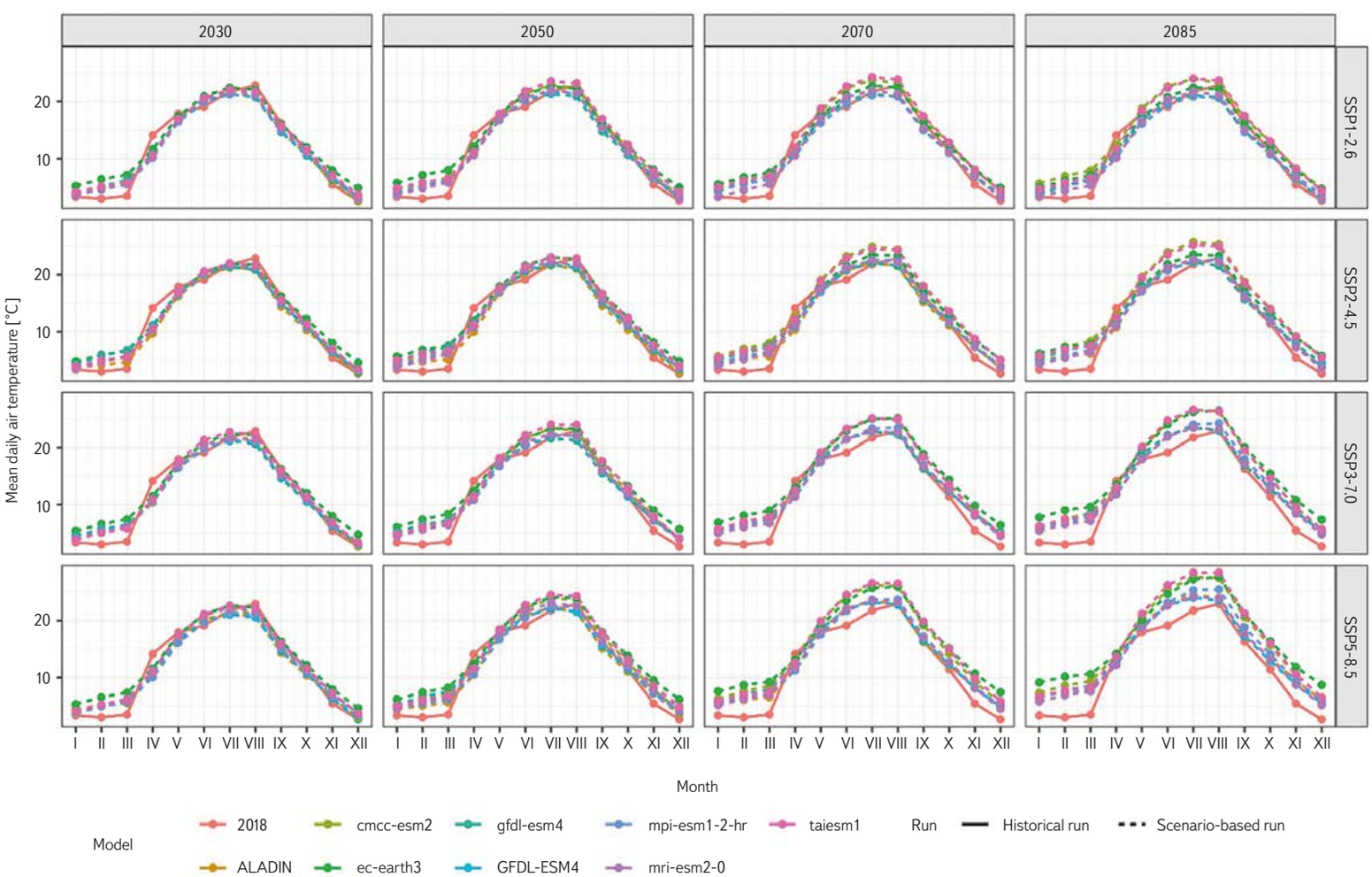


Fig. 6. Monthly mean daily air temperatures for the available climate models, scenarios and time horizons; 2018 represents the reference series

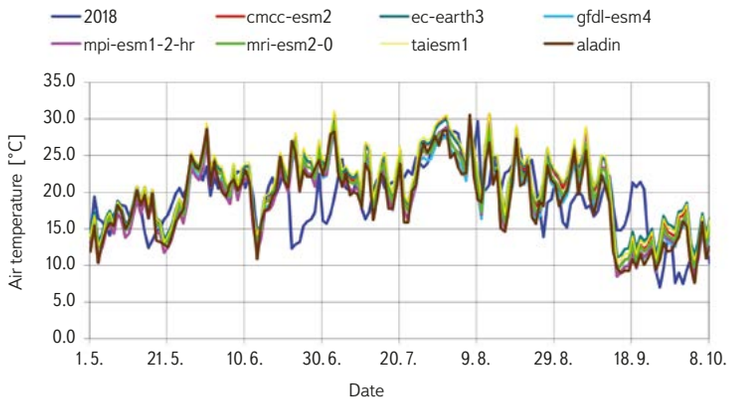


Fig. 7. Comparison of simulated mean air temperature time series from May to early October 2050 under the SSP5-8.5 scenario for all models listed above with 2018 as the reference year

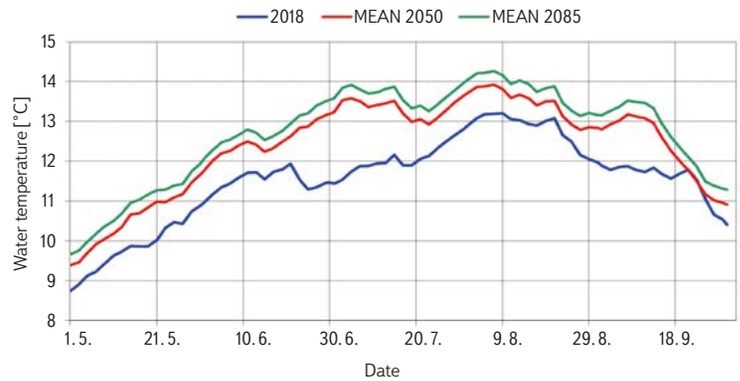


Fig. 8. Comparison of mean water temperatures at the profile 200 m upstream of Vrchlice Reservoir dam, based on the average results of simulations using individual climate models for the 2050 and 2085 horizons under the SSP2-4.5 scenario, with 2018 as the reference year

also changes in variability to be taken into account. This is particularly important for precipitation and extreme values, for which future changes may not correspond to a simple shift in the mean. In the case of air temperature, the transformation is performed linearly, thereby limiting the influence of systematic climate-model bias on the resulting change in temperature.

The reference climate period was 1991–2020, with 2018 selected as the specific baseline year for the simulations. The future time horizons do not represent simulations of individual calendar years, but 30-year periods, 2036–2065 and 2071–2100, which are referred to in the following text, for simplicity, as the 2050 and 2085 horizons. For each climate model and scenario, the ADC method was used to determine the changes between the reference period 1991–2020 and the respective future period. These changes were subsequently applied to the observed meteorological series for 2018. The resulting scenario series thus retain the temporal sequence and characteristic pattern of the baseline year, while their level and variability are adjusted to correspond to the climatic conditions projected for the 2050 and 2085 horizons.

The climate series used for the Vrchlice Reservoir simulations are based on the HYMOD-KZ database [16], which provides selected hydrological and climatic variables for different SSP scenarios, climate models and time horizons. For the scenario simulations, mean daily air temperature series for the 2050 (2036–2065) and 2085 (2071–2100) horizons were used as inputs to the calculation of heat exchange between the water surface and the atmosphere. The aim was to assess the potential impact of climate change on the thermal regime of the reservoir. The SSP2-4.5 and SSP5-8.5 scenarios and the climate models CMCC-ESM2, EC-EARTH3, GFDL-ESM4, MPI-ESM1-2-HR, MRI-ESM2-0, TAIESM1 and ALADIN-CLIMATE/CZ were selected for the analysis (mean daily air temperatures are shown in *Fig. 6*). The year 2018 was selected as the reference year, against which the adjusted temperature series for the future horizons were subsequently compared. A comparison of mean daily air temperatures for the 2050 horizon under the SSP5-8.5 scenario for all the models listed above with the reference year 2018 is shown in *Fig. 7*..

As shown in *Fig. 7*, the individual climate models provide relatively similar projected mean daily air temperature patterns for the 2050 horizon, although these differ from the pattern observed in 2018, which included, for example, a relatively cold second half of June and, conversely, high temperatures around 20 September.

Results of simulations of the potential impact on the thermal regime

Because the projected mean daily air temperatures for the selected horizons and scenarios showed a similar seasonal pattern across the climate models, the averages of the results from the seven-model ensemble are presented

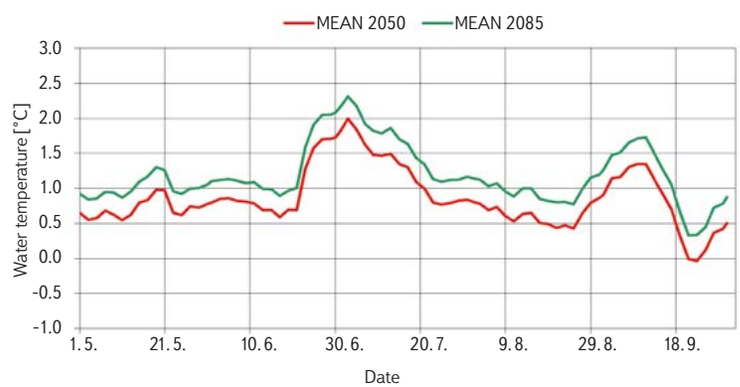


Fig. 9. Increase in mean water temperatures at the profile 200 m upstream of the Vrchlice Reservoir dam, based on the average results of simulations using individual climate models for the 2050 and 2085 horizons under the SSP2-4.5 scenario, compared with 2018

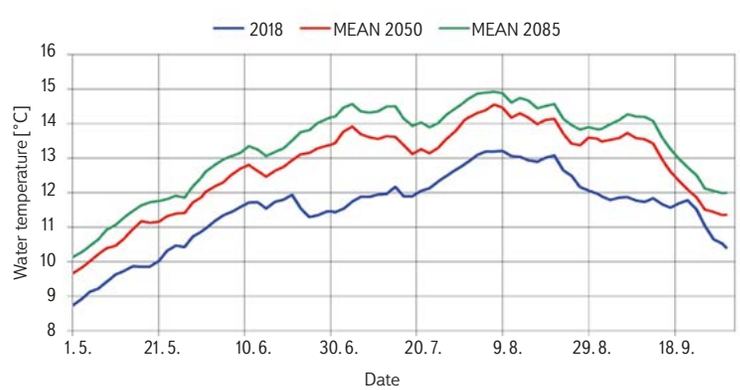


Fig. 10. Comparison of mean water temperatures at the profile 200 m upstream of Vrchlice Reservoir dam, based on the average results of simulations using individual climate models for the 2050 and 2085 horizons under the SSP5-8.5 scenario, with 2018 as the reference year

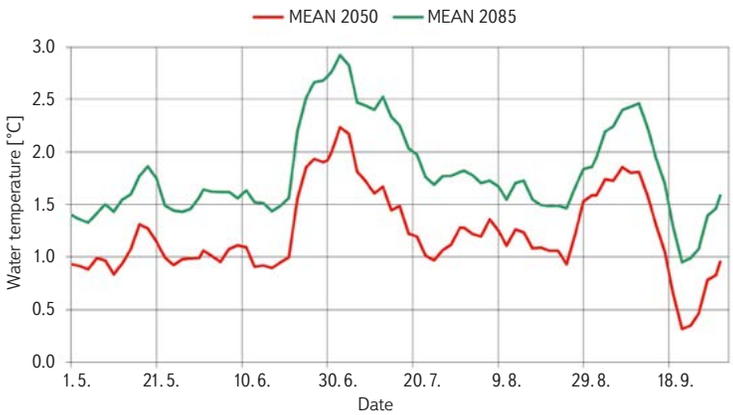


Fig. 11. Increase in mean water temperatures at the profile 200 m upstream of the Vrchlice Reservoir dam, based on the average results of simulations using individual climate models for the 2050 and 2085 horizons under the SSP5-8.5 scenario, compared with 2018

below for clarity. For the subsequent presentation, results for the segment located 200 m upstream of the Vrchlice Reservoir dam were selected, i.e. close to the drinking-water intakes located within the dam structure. The model calibration results showed sufficient agreement between the measurements and the simulated temperature profile produced by the CE-QUAL-W2 model.

Fig. 8 shows the mean water temperature profile 200 m upstream of the dam for 2018 and the mean values obtained by averaging the water temperature results from simulations using the individual global models for the 2050 (MEAN 2050) and 2085 (MEAN 2085) horizons under the SSP2-4.5 scenario. *Fig. 9* shows the increases in mean daily water temperature at this profile for the 2050 and 2085 horizons compared with 2018.

Figs. 10 and *11* were prepared in the same way, this time using the results of simulations for the SSP5-8.5 scenario.

Another interesting output is a comparison of the mean maximum water temperatures occurring from the beginning of May to the end of September at the water surface in the profile 200 m upstream of the dam, based on CE-QUAL-W2 simulations for 2018 and for the 2050 and 2085 horizons under the SSP5-8.5 scenario, using the seven climate models and their ensemble mean (MEAN), as shown in *Tab. 1*.

Tab. 1. Average surface water temperatures from the beginning of May to the end of September at the profile 200 m upstream of Vrchlice Reservoir dam, based on simulations using the CE-QUAL-W2 model for the reference year 2018 and the 2050 and 2085 horizons under the SSP5-8.5 scenario, using seven climate models and their ensemble mean

Year 2018	**21,6***	
Global model	**2050**	**2085**
CMCC-ESM2	23.2	25.2
EC-EARTH3	23.5	25.0
GFDL-ESM4	22.0	22.9
MPI-ESM1-2-HR	22.1	23.6
MRI-ESM2-0	22.6	22.9
TAIESM1	23.7	25.8
ALADIN	22.1	23.2
MEAN	22.8	24.1

* average surface water temperature from May to September 2018

Assessment of the results and discussion

The results of the simulations performed using the two-dimensional mathematical CE-QUAL-W2 model to assess potential changes in thermal conditions in drinking-water reservoirs confirmed the expected patterns.

For the SSP2-4.5 scenario, *Fig. 8* indicates that, for the model year corresponding to the 2050 climate horizon, an increase in mean water temperature of approximately 0.5 °C can be expected in the area near the dam, where the maximum depths occur, with increases of up to 1.5 °C compared with the reference year 2018. For the model year corresponding to the 2085 climate horizon, the mean water temperature is expected to increase by at least 1 °C throughout the profile, and locally by more than 2 °C.

If the SSP5-8.5 scenario were to prove realistic, much more pronounced changes would occur. According to *Fig. 10*, for the model year corresponding to the 2050 climate horizon, the increase in mean water temperature would range from 1.0 to 2.0 °C, while for the model year corresponding to the 2085 climate horizon, it would range from 1.5 to 2.5 °C.

In addition to a sustained increase in mean water temperature in the reservoir, a significant increase in surface water temperature can also be expected, as shown in *Tab. 1*. Surface water temperatures may increase by more than 1 °C on average by the 2050 horizon compared with 2018, and by as much as 2.5 °C by the 2085 horizon.

The observed increase in water temperature may also have implications for the oxygen regime of the reservoir. A long-term analysis of temperate lakes, in which J. Hejzlar was also involved, demonstrated a widespread decline in dissolved oxygen concentrations; in deeper layers, this decline was associated primarily with increasing thermal stratification and declining water transparency. The issue of oxygen deficits has also been addressed under Czech conditions, for example in Římov Reservoir. In Vrchlice Reservoir, warming and a possible extension of the stratification period can therefore be expected to increase the risk of oxygen deficiency in the hypolimnion, with the specific response also depending on the trophic status of the reservoir, organic matter inputs and the hydrological regime.

In terms of the direction of change, the results are consistent with published studies that project increasing water temperatures and changes in thermal stratification in reservoirs and lakes under a warming climate [2, 3, 10]. Direct quantitative comparison with other reservoirs is, however, limited because the response depends on geometry, hydrological regime, water abstraction operations, meteorological forcing and the way climate scenarios are constructed. The values reported for Vrchlice Reservoir therefore cannot be directly extrapolated to other drinking-water reservoirs.

The differences in water-temperature increases between the 2050 and 2085 horizons cannot be interpreted as a simple linear translation of changes in air temperature into changes in water temperature. CE-QUAL-W2 calculates the overall heat balance at the water surface and the longitudinal–vertical distribution of heat; the resulting mean or maximum temperature is therefore also influenced by the seasonal pattern of the reference year, stratification, mixing, depth and outflow conditions. Moreover, the scenario series retain the temporal structure of 2018 and modify only air temperature. Non-linear differences between the selected summary indicators are therefore possible, but their physical interpretation must take these limitations into account.

The uncertainty in the results arises from several sources: the spread among climate models, the choice of the exceptionally warm and dry year 2018 as the stress-condition reference year, keeping the other meteorological variables and hydrological-operational conditions at their 2018 levels, the lateral averaging inherent in the 2D model, the aggregated representation of inflows, and the limited calibration and verification assessment without standard quantitative metrics. The results should therefore be understood as scenario-based estimates of the sensitivity of the thermal regime to changes in air temperature, rather than as a deterministic prediction of future conditions.

CONCLUSION

Numerical simulations showed that, with the hydrological-operational conditions of the 2018 reference year kept unchanged, increases in air temperature under the climate scenarios considered would lead to warming of the water both in the area 200 m upstream of Vrchlice Reservoir dam and at the water surface. Under SSP2-4.5, an increase in mean water temperature of approximately 0.5 °C was simulated for the 2050 horizon, with local increases of up to around 1.5 °C, while for the 2085 horizon, the increase was generally at least around 1 °C and locally exceeded 2 °C. Under SSP5-8.5, the changes were more pronounced, ranging from approximately 1.0 to 2.0 °C for the 2050 horizon and from 1.5 to 2.5 °C for the 2085 horizon. The average maximum surface water temperature from May to September increased from 21.6 °C in the reference year to 22.8 °C for the 2050 horizon and 24.1 °C for the 2085 horizon and the global model ensemble mean under the SSP2-8.5 scenario.

The practical significance of the study lies in highlighting that warming may alter temperature conditions in the area of the drinking-water intakes and increase the risk of unfavourable oxygen conditions during the stratified period. The results can serve as a screening-level basis for the reservoir operator and for further analyses of operational options, particularly in relation to the choice of intake level and the assessment of water quality.

Interpretation is limited by the fact that the scenarios isolate the effect of changes in air temperature while other meteorological and hydrological-operational inputs are kept at their 2018 levels, the model uses lateral averaging, and the calibration and verification results were not quantified using standard error metrics. Further work should use a broader set of measurements, including those from 2024, carry out quantitative validation and sensitivity analysis of model parameters, incorporate changes in other meteorological and hydrological variables, and separately assess scenarios involving changes in water level and intake levels.

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Interview with Assoc. Prof. RNDr. Jan Unucka, Ph.D., Head of the Hydrology Department at the Czech Hydrometeorological Institute in Ostrava

He regularly contributes both scientific and informative articles to VTEI, reviews other submissions, and for two years had his own column on the back cover. He loves nature and animals and is an accomplished photographer. When he first contacted me in spring 2023 to offer a scientific article, which was published that summer, he sent me a photograph for his author profile that was strikingly different from the usual ones: a man in camouflage, kneeling on the ground in a forest, surrounded by his three enormous dogs. "Nature is still the stronger player," says Assoc. Prof. RNDr. Jan Unucka, Ph.D., who is now sitting across the table from me.

Associate Professor, do you still remember that photograph?

Of course I do *(he looks up at my noticeboard, where the photograph in question has been hanging for the past three years)*.

I must admit, even then I had an idea about how I might get that photograph into VTEI. It was obvious that we weren't going to squeeze it into a scientific article, and certainly not into an author profile, so I decided that one day I would simply have to interview you... So, welcome to Prague.

(Laughs.) Thank you for inviting me.

I also really liked something you wrote to me right at the beginning of our correspondence in May 2023: "Above all, don't call me Associate Professor!" May I ask how someone manages, almost "in passing", to acquire four university degrees and yet describes himself as a labourer? Isn't that being just a little too modest?

I don't think so, and I hope it doesn't come across as false modesty either. If I go right back to the beginning, I was fascinated by nature from childhood, and I also loved trains. So as a boy I never went through the usual astronaut–firefighter–policeman–soldier phases. For me it was always quite clearly either train driver or naturalist. What's more, while I was studying, I actually earned money doing various manual jobs – laying paving, bricklaying, carpentry, and working at a sawmill. Even now I occasionally help out with some carpentry or drive a lorry for a friend. It's a form of relaxation for me, although I don't have much time for it these days. But I have a great deal of respect for manual work, especially skilled manual work.

So what ultimately decided it?

I still love trains; I enjoy travelling by train, and I have plenty of friends who are train drivers, but in the end, becoming a naturalist won out. Perhaps that was partly because there were far more books about nature, and I was always an avid reader. At home, I tried to read as many books as I could, and my parents and grandparents often bought them for me too. At the same time, though, my father worked at the Czech Hydrometeorological Institute (CHMI) in Ostrava as a surface-water technician, so I had no ambition to go into hydrology because I didn't want to follow in his footsteps. And that brings me back to the idea of being a manual worker – I deliberately chose to attend a secondary technical school specialising in electrical engineering and computer technology, quite simply so that I wouldn't have to go to a grammar school and then on to university.

That certainly sounds like someone with two doctorates and a habilitation. :-)

(*Laughs.*) Well, that's how it turned out in the end anyway – I completed my Master's degree, followed by my first and then my higher doctorate. By that time, I was already teaching natural sciences at the University of Ostrava and at the Faculty of Mining and Geology at VSB – Technical University of Ostrava. Without it ever featuring in any kind of "personal development plan", it eventually led to my habilitation and appointment as Associate Professor at VSB – Technical University of Ostrava, with a focus on the use of geographic information systems and mathematical models in environmental sciences.

How long did you teach?

If I remember correctly, I started straight after my first state examination, in 2003. At the Faculty of Science, I taught hydrology and landscape science, while at the Faculty of Mining and Geology I taught practical classes under Associate Professor Grmela, historically one of the leading hydrogeologists in the country and, moreover, someone with extensive practical experience. So it was a tremendous learning experience for me too, and you could say that I learnt by teaching.

My regular, timetabled teaching at both faculties continued until around 2019. In the meantime, however, I joined the CHMI in 2014 and gradually began cutting back on my teaching – I mostly taught while on leave or after work well into the evening. Eventually, I realised that you simply can't do everything, and I quietly drifted away from university life.

Don't you miss having students and young people around you now?

I'm fortunate enough to have them on my team. We have quite a few recent graduates working with us, so I don't miss that "breath of fresh air", as they say. I also still teach occasional intensive blocks at the Mathematical Institute of the Silesian University and at the Faculty of Science of Palacký University, so I'm still in contact with students. But I should stress that I only teach in blocks, always on a specific topic, so that I can keep up with all the operational and development work associated with the CHMI, because that is now my priority.

Your work also occasionally takes you to the Faculty of Science in Prague. May I ask why, after your studies, your career took you to Ostrava in particular?

Although I've lived near Opava for years now, I was born in Ostrava. And since my studies weren't really planned or heading in any particular direction at first, I simply took the opportunities that came my way. At the time, Professor Kříž was working in the Geography Department at the University of Ostrava. He had been the first director of the CHMI's Ostrava branch and could, in a sense, be regarded as its founder. He had been my father's boss, and for a while my mother's too, so those connections eventually led me to study physical geography at the Faculty of Science there.

Fig. 1. Assoc. Prof. RNDr. Jan Unucka, Ph.D., with his dogs – from left: Leonberger, Pyrenean Mastiff, Spanish Mastiff

I know you have a farm. So did you choose to live in the countryside?

Yes, I live in a village not far from Opava. I'm not really a city person; I like being close to nature. Even as a boy, I loved going off on hiking trips into the woods. It was my main hobby, and one that combined nicely with travelling by train along local railway lines, many of which have since been abandoned. I'm still drawn to nature today. That's why I wanted to live somewhere outside the city, where I could be close to nature but still within a reasonable drive of work.

Could that desire to head into the woods, take the dogs and get out into nature be a kind of escape from a reality that isn't always entirely positive, particularly when it comes to climate change and projections for the future?

Definitely. It unquestionably gives me a sense of peace. When my wife and I take the dogs into the woods, we often hear people commenting on how miserable the weather is or that it's raining and we still have to go out. And I would add: yes, we have to, but we also want to. What's more, the gloomier and less appealing the weather, the fewer people there are in the woods and the better the chances of seeing more wildlife, so it clears your head all the more. Above all, though, there's something refreshing about being with dogs, which are always completely absorbed in the present moment, whatever the circumstances and whatever the time of day or night. For me, it's the best form of relaxation I know – both mentally and physically.

I know you're also a keen nature photographer. After all, you regularly send me a steady supply of wonderful photographs for VTEI, for which I'd like to thank you once again. How did you first get into photography?

I got my first digital single-lens reflex camera around 2016. Before that I had a Panasonic Lumix, which even today is capable of taking perfectly decent photographs for amateurs and semi-professionals. At first, I went through a phase when I wanted to document absolutely everything, to understand nature and

get to the bottom of it all, but I've given up on that now. Nature is such a complex, multilayered system that this is essentially a futile ambition. It is enough to begin to recognise and understand the connections within it, so that you can do your own work better or pass on new knowledge to your students, professional colleagues, or the wider scientific community.

At first, you have such an appetite for photographs that if you come back from the woods or the river without a perfect shot, you feel the day has been wasted. Fortunately, that phase didn't last long for me. After that, my own ethical principle took precedence: if taking a photograph might endanger a clutch of eggs or young animals, for example, or even cause an animal to abandon them or result in injury, then no photograph is worth it. These days, I quite often find myself putting the camera aside and simply trying to enjoy the moment.

Did you first get into photography through Kozmice Bird Meadows, where you also help with maintenance and feeding?

Exactly. Kozmice was where I first started taking photographs to specific briefs, focusing on particular animal species or on the wild horses there. The horses are particularly difficult to handle, and it is often very difficult to get close enough to photograph specific identifying marks, their colouring and so on. But that makes the results all the more valuable, and I particularly treasure the photographs that have turned out well.

Who introduced you to Kozmice Bird Meadows?

It happened entirely by chance, which brings me to my belief that all the important things in life happen by chance. We were there walking the dogs, as it isn't very far from where I live, and the site manager, Petr Bláha, who has since become a very good friend, spontaneously struck up a conversation with me about dogs, nature and so on, and we discovered that we had a great deal in common. I told him that I was particularly interested in Kozmice from a hydrological perspective, because the CHMI has a monitoring well nearby. Since then, our conversations and shared views on nature have developed into a strong friendship, and whenever I can, I enjoy helping Petr with the wild horses, as well as with the Highland cattle that now live there.

How do these wild animals cope outdoors with the heatwaves we experience nowadays? And which is actually worse for them – heat and drought, or freezing conditions when everything is covered in snow and they don't have enough food?

Definitely drought and heat. To a large extent, Kozmice Bird Meadows can be seen as a kind of laboratory, because a whole range of habitats and ecosystems are developing across its 71 ha. It is essentially a former fishpond landscape that was subsequently used for agriculture and has now been returned to nature, although succession has not yet reached a state of equilibrium everywhere. Water management is the top priority there because not only various species of waterbirds, such as waders, but also the wild horses and Highland cattle depend on it. Quite simply, we cannot do without water, so dry years and periods of hot weather aren't good for them either.

Another issue is open grassland versus forest. It is very clear there that, in hot weather, not only the birds but also all the ungulates, including the roe deer that live there, actively seek out shade and areas with higher moisture levels. So the traditional and much-valued mosaic character of the Czech landscape remains an ideal model for today's cultural landscape for wild animals that are able to move freely in search of water.

By contrast, the winter conditions you also asked about do not pose a serious threat to them. The main problem is freezing rain and ice, when they are unable to reach the vegetation beneath it.

Fig. 2. Exmoor pony in winter, Kozmice Bird Meadows

There have recently been reports in the media suggesting that some parts of the Czech Republic, such as South Moravia and Polabí, are already experiencing conditions more typical of a subtropical climate zone, with hot summers being compared to the climate of Mediterranean islands such as Hvar. What might this mean for us in the future? Is this trend expected to worsen, and according to CHMI projections, will temperatures continue to rise?

As you know, CHMI and your T. G. Masaryk Water Research Institute both collaborated on the PERUN Competence Centre, where global scenarios were tested and downscaled for Central Europe and the Czech Republic. There are also various other scenarios that start with socioeconomic factors, technology and population growth, which in turn determine emission levels and so on. I think it is clear even from the official conclusions presented, for example, by my colleague Radim Tolasz, that we are not in for an idyllic time in the years ahead. If one of the intermediate scenarios comes to pass, rather than the worst-case one, we can count ourselves relatively fortunate.

If I put the computer simulations to one side and look at it simply by taking a walk through the landscape, the aridification is obvious. Not only are xerothermic communities expanding, but every gardener today knows that if you cut the grass too short, the lawn gets scorched and, without watering, nothing green is going to grow there, let alone flowers or herbs. And if I look at it from my professional perspective as a hydrologist, two things are clear. The first is that extremes are increasing. You could say that total annual precipitation has not changed dramatically, but the types of precipitation and their distribution throughout the year are changing. Winter precipitation is decreasing, markedly so at middle and lower elevations, which means that the Oder-type flooding once used as a textbook example, where spring snowmelt causes spring floods, has now virtually disappeared. The second is that the frequency of thunderstorms and convective precipitation is increasing at the same time. Rain falls on the landscape and often runs off outside the watercourses; infiltration and percolation effectively do not take place. As a result, it may take only a few hours, or a few days at most, to go from a devastating flood to drought. To give you an example from the practical experience of field technicians: when my father and his colleagues used to measure some of these river profiles, they naturally had to take their measurements from a bridge, whereas today we can walk across them in wellington boots. Flows have been declining over the long term.

In this context, what impact do the views of those who criticise or reject climate change have, particularly when they are given a platform in the media? How do experts such as yourself view this?

To be honest, I have always tried to keep politics out of both my private and professional life. What's more, things taken out of context can be extremely dangerous. In any case, whatever has been said on this subject, and however it was intended, it is not particularly helpful. This is precisely where the fundamental problem lies. Experts generally acknowledge a certain degree of uncertainty in all data, scenarios and projections. To the casual observer – someone sitting in a pub watching television, for example – that can make an expert look like a bit of a "fool" who doesn't really know what they are talking about. By contrast, categorical political pronouncements, delivered with confidence and certainty, reinforce the impression that the person making them knows exactly what is what. To me, that is probably the most dangerous aspect of debates like these. I believe that people in all professions, politicians included, should recognise that we share a common goal: the sensible functioning of civilisation and the survival of *Homo sapiens* on this planet. Personal passions or attempts at self-promotion should take second place to that.

Two years ago, you and your colleagues measured discharges and carried out geodetic surveys of the high-water marks left by the September 2024 floods in the Jeseník area. Looking back, what has changed most in this field compared with the past? In other words, what are we now able to measure, what conclusions can we draw from these measurements, and how do mathematical models help us?

In this context, I'm reminded of a saying which I think also appeared in one of Václav Cílek's books: "In times of drought, think of floods, and vice versa." In other words, drought and floods are the two hydrological extremes, but they are essentially two sides of the same coin, interconnected phenomena.

I think new technologies are helping us enormously, both to speed up and improve the quality of primary data collection in the field, including measurements taken during floods. This is also limited by whether we can actually reach a particular river and whether we can take the measurements without putting the health and lives of field staff at risk. Sometimes that is the most difficult part. And I'm not even talking about individual gauging stations or monitoring profiles – some stations in the area covered by our branch literally disappeared from the map of the Czech Republic during those floods.

If I compare today's measurements using sonar, which can process acoustic data, with the current meters that used to be lowered from a bridge on a suspension cable, we are now in a completely different league, both qualitatively and quantitatively. Sonar has its limitations too, but under good conditions it can immediately plot the cross-section and velocity field and calculate the discharge, so if local mayors have any questions, we already have the information to hand there and then, on the riverbank or bridge. A second major benefit is the ability to process and convert the data digitally using mathematical models and geographic information systems.

The flood report produced at the time, which is available for download from the Ministry of the Environment website, shows, among other things, that without the aid of mathematical models it would have been impossible to determine the magnitude of the flood at some river profiles and along some reaches. Hydrology textbooks generally give flow velocities during natural floods of between four and four and a half metres per second; my colleagues and I routinely measured six metres per second.

After the horrors of 2024, is it possible to find anything positive in what happened – perhaps lessons for the future?

I always try to find something positive. For example, we have begun making much greater use of remote sensing data, which, together with our field measurements, have been used to calibrate hydraulic models for evaluating peak discharges and the extent of flooding. If I compare this with the last similarly catastrophic flood in Moravia and Silesia, in 1997, these technologies were still in their infancy and adequate data were not available either. Nevertheless, nature is still the stronger player in this game we are playing.

Fig. 3. Taking measurements on Kobylí stream near Karlovice with former fellow student and colleague Dr Martin Adamec

Do you ever worry that current trends towards rejecting or denying climate change could lead to real dangers, for example by underestimating the severity of a flood and the risks it poses?

Of course. Unfortunately, that is something I have experienced myself. Before the 2024 floods, the hydrological and meteorological models were in very close agreement, so there was growing confidence that a truly catastrophic flood was approaching, with a magnitude and characteristics comparable to the 1997 flood. Despite this, I heard a dismissive response from around 30–40% of people: "Surely something like that can't happen again." I found that utterly incomprehensible. After the floods, I spoke to firefighters and officers from the Police of the Czech Republic, who described how they had had to rescue by helicopter people who had refused to leave their homes when the evacuation order was issued, plucking them from trees and rooftops. It had been a matter of seconds and quite literally a matter of life and death. It was a deeply disturbing thing to hear. So I would once again urge everyone never to take the risks indicated by flood forecasts lightly. What's more, I would venture to say that flood extremes are more likely to increase than decrease.

Would you say that public awareness has improved since the floods of 1997 and 2002? Do models also help you with forecasting?

Definitely. The systems are more sophisticated and, above all, warning information is now distributed much more quickly and effectively. I understand that there can sometimes be too much information for the general public and that non-specialists can occasionally become lost in all the communication noise. In any case, in terms of the availability of information, the speed of calculations and the production of forecasts – whether rainfall-runoff models used to estimate peak discharges or meteorological models used to determine where the heaviest concentration of rainfall will occur – we are at the technological forefront, and anyone has the opportunity to access this information.

Let me now touch on a favourite Czech topic: would dams and large reservoirs help in our situation?

I'll start by taking a slightly broader view. The fundamental point, as I see it, is that we live in a cultural landscape. This means that, whether we like it or not, apart from the occasional hiking trip or holiday, we are accustomed to enjoying the benefits of modern technology. Manufacturing cars, computers or mobile phones obviously consumes water, while our everyday needs in terms of food and hygiene also entail a certain level of water consumption, whether we live in a town or in the countryside. So when someone calls categorically for the removal of technical flood-protection or water-management measures and advocates a return to nature, I think that is simply no longer achievable. What I mean is that nowadays we cannot do without reservoirs, whether for flood protection, energy generation, supplying water to households and industry, or other purposes. The demand for water and for a certain level of comfort is considerable.

In any case, if reservoirs are going to be built, they should be designed to be as efficient as possible, both in terms of their design and capacity and their operating parameters – in other words, what their priorities are. For example, whether their primary function is power generation, as at Dlouhé Stráně, or whether they are multipurpose hydraulic structures that provide water supplies as well as flood protection.

When Professor Pavel Pech from the Faculty of Environmental Sciences at the Czech University of Life Sciences Prague was sitting in this chair about three years ago, one of the things I asked him about was the construction of large reservoirs and dams in the Czech Republic, including Nové Heřminovy, and why – to put it in layman's terms – everything takes such an incredibly long time here. Apparently, the Nové Heřminovy dam was first planned after the floods of 1997.

It is certainly a protracted process, partly because governments keep changing in this country, and with them their priorities and stated objectives. But if I may, I'd like to correct you on one point – although there was really no way you could have known this. Do you remember when we were putting together our team's article reconstructing the historic 1903 flood in the Opava catchment…

… Of course, that was only recently *(the paper by Associate Professor Unucka et al. was published in VTEI in June this year; author's note).*

… Well, while working on it, I began collaborating closely with Dr Irena Moravcová from the Silesian Museum in Opava, and we discovered that the first proposals to build a dam at Nové Heřminovy actually date from around that time.

So in reality, it has already been more than 120 years?

Yes *(laughs)*. After the catastrophic flood of 1903, a joint Prussian and Austro-Hungarian commission identified a site in the Opava valley as suitable for the construction of a hydraulic structure. Cross-sections and a longitudinal profile were surveyed, and initial proposals were even made for the basic parameters of the dam itself. So the 1997 flood really only revived an idea that had been forgotten in the meantime.

Another important aspect from my perspective is how the issue is presented. Every flood-protection measure has its limitations, whether it is biotechnical and nature-based or a conventional water-management measure. And it is only fair to acknowledge that every hydraulic structure has a finite capacity and an initial water level. It is precisely this limitation on storage capacity that has been the main sticking point in the protracted debate between supporters and opponents of the dam.

Let's return to the other extreme, drought. Is there a real risk that we could face water shortages – or, more specifically, a shortage of drinking water for the population as a whole?

I think it has already happened several times. Indeed, that is one of the reasons why regional Drought Management Plans were drawn up at national level. However, their implementation in practice is still in its infancy, and local and regional authorities do not yet have sufficient practical experience of implementing them. Nevertheless, the plans do exist and are available to the regional authorities. In my view, nature has so far been fairly kind to us here in Central Europe, and we have not yet reached an extreme where the most stringent measures would have had to be introduced. But some restrictions were already in place here between 2017 and 2019.

Of course, looking at the rest of the world, it would be foolish to dismiss the possibility of drinking-water shortages on the grounds that the problem does not concern us. Water and drinking are physiological necessities, and we cannot survive without them. After all, history has been showing us since ancient times that shortages of water and food can even lead to the collapse of civilisations.

Speaking of history, you've just given me a lead-in to my next question. Could we say that if a meteorologist, a hydrologist and, for example, a historian from an archive were sitting around the same table, they would have plenty to talk about and would find some common ground in their work? You also mentioned the police and firefighters in connection with floods, so is it really about all these people working together?

Definitely. There is a willingness to work together, and we even have friendly ties and relationships with one another, so the collaboration works very well. In fact, that is what I like most about hydrology – it lies at the interface between the natural and engineering sciences, while historical floods also give it a connection with the social sciences and history, offering a rather romantic glimpse of the landscapes of Bohemia, Moravia, and Silesia in the past.

And we then put that into practice. For example, CHMI regularly takes part in the *Water Mills* event organised by the Ústí nad Orlicí Museum and its director, Dr Radim Urbánek. Several times during our presentations there, I've asked

Fig. 4. Taking measurements in Slučí stream experimental catchment below Rejvíz, operated by the Forestry and Game Management Research Institute and CHMI

Radim whether our participation in the event isn't becoming a little stale, but his response is always that we bring a different perspective that historians don't have. And conversely, to return to Dr Moravcová, I would have been completely overwhelmed in the archive by piles of files on the table and, without her insight, I wouldn't have had the slightest idea where to begin or what to photocopy first. They have thoroughly mastered their own craft, and it is precisely this interaction with us natural scientists and hydrologists that creates added value: on the one hand, the historical experience and knowledge of the landscape of our ancestors, to use a familiar phrase, and on the other, lessons for the present – for example, how we can manage water in today's landscape more effectively. I don't think hydrologists alone could piece all that together without historians and archivists.

Do you have a favourite place? Given how often your work takes you out into the field, I'm sure there must be quite a few in Bohemia, Moravia, and Silesia…

People probably expect a hydrologist to say…

"I love water…"

Exactly (*laughs*). I really do love rivers, and I try to spend time by them in my private life too, when I can put my professional work to one side and simply appreciate them as beautiful places. I have three favourite catchments in the Czech Republic. One is definitely the Křinice in Bohemian Switzerland, another is the Březná around Štíty and Hoštejn – for me, the Březná valley is one of the most beautiful I know – and then there is the Černá Opava, or more broadly the Opava catchment and its tributaries, around Rejvíz and the boundary between the Hrubý Jeseník and Nízký Jeseník mountains.

And speaking purely for myself, one of my favourite places is Jakartovice, where I used to go hiking even as a boy. It is a wonderfully romantic landscape of former slate mines and flooded mine workings, a place that holds many memories for me, and it is also fascinating in terms of its wildlife. The Eurasian eagle-owl, for example, is quite common there, although it is otherwise almost absent from the Nízký Jeseník, as is our smallest owl, the Eurasian pygmy owl, which I have even managed to photograph a few times. Fortunately, it isn't particularly shy – rather cheeky, in fact. :-) These are the places closest to my heart, the ones I'm always happy to return to.

Does your work leave you enough time for that?

Sometimes more, sometimes less. Unfortunately, mostly less. But whenever I can, I try to spend all my free time in nature. I have to admit that, despite being from Ostrava, I've never even been to the Karolina shopping centre.

Fig. 5. Common crane after arriving at Kozmice Bird Meadows

I understand. So it's more about escaping into the woods and spending time with your dogs…

Yes. Animals are always a reminder to me that, in our arrogance, we humans still tend to think of ourselves as the masters of creation, simply because animals do not possess articulate speech. But that does not mean they cannot do some things better than we can. Often it is a matter of subtle vibrations that lie beyond the limits of human perception. I know that certain types of dogs, cats and birds, as well as other animals I have had the opportunity to get to know better, are far more attuned to these things than humans are.

What I love most about dogs in general is their straightforwardness and the way they express their emotions so openly. We should enjoy moments like that more and appreciate every day we have with them. After moving to the countryside, I ended up – again, entirely by chance – breeding livestock guardian dogs. I always say that I didn't teach them; they taught me, because they are a completely different type of dog. You cannot drill them into obedience – with them, it really is all about partnership. And that makes the relationship all the more rewarding and, for me, all the more beautiful.

Associate Professor, I wish you not only good health and every success in your work, but also many wonderful moments in nature with your canine companions. Thank you for taking the time to travel to Prague and give me this interview for VTEI. I would also like to thank you once again for all your photographs of nature and for our excellent collaboration, which I hope will continue for many years to come.

Mgr. Zuzana Řehořová

Assoc. Prof. RNDr. Jan Unucka, Ph.D.

Assoc. Prof. RNDr. Jan Unucka, Ph.D., was born in Ostrava on 20 January 1977. After completing secondary school studies in electrical engineering and computer science, he studied Physical Geography and Geoecology and Environmental Geography at the Faculty of Science, University of Ostrava, first at master's and subsequently at doctoral level. He then completed his habilitation in Geoinformatics at VSB – Technical University of Ostrava (VSB-TUO). After graduating, he joined the Regional Forecasting Office of CHMI in Ostrava as a hydrologist and forecaster, while also beginning to teach at VSB-TUO, the Faculty of Science of the University of Ostrava, and other institutions. Following a period of teaching at universities in the Czech Republic and abroad, and working at the IT4Innovations research centre, he returned to CHMI, where he is now Head of the Hydrology Department. His professional interests include hydrology, environmental modelling, forest hydrology, and the significance of historical and disappeared hydraulic structures in both past and present-day landscapes. He is a member of several specialist committees and the author of scientific publications and studies, as well as software supporting hydrological and environmental modelling. He has been participating in research projects and in the operation of experimental catchments in the Beskids, Jeseníky, and Orlické Mountains in cooperation with the Forestry and Game Management Research Institute. His main hobbies include nature and nature photography, music, and livestock guardian dog breeds.

Photo: J. Unucka

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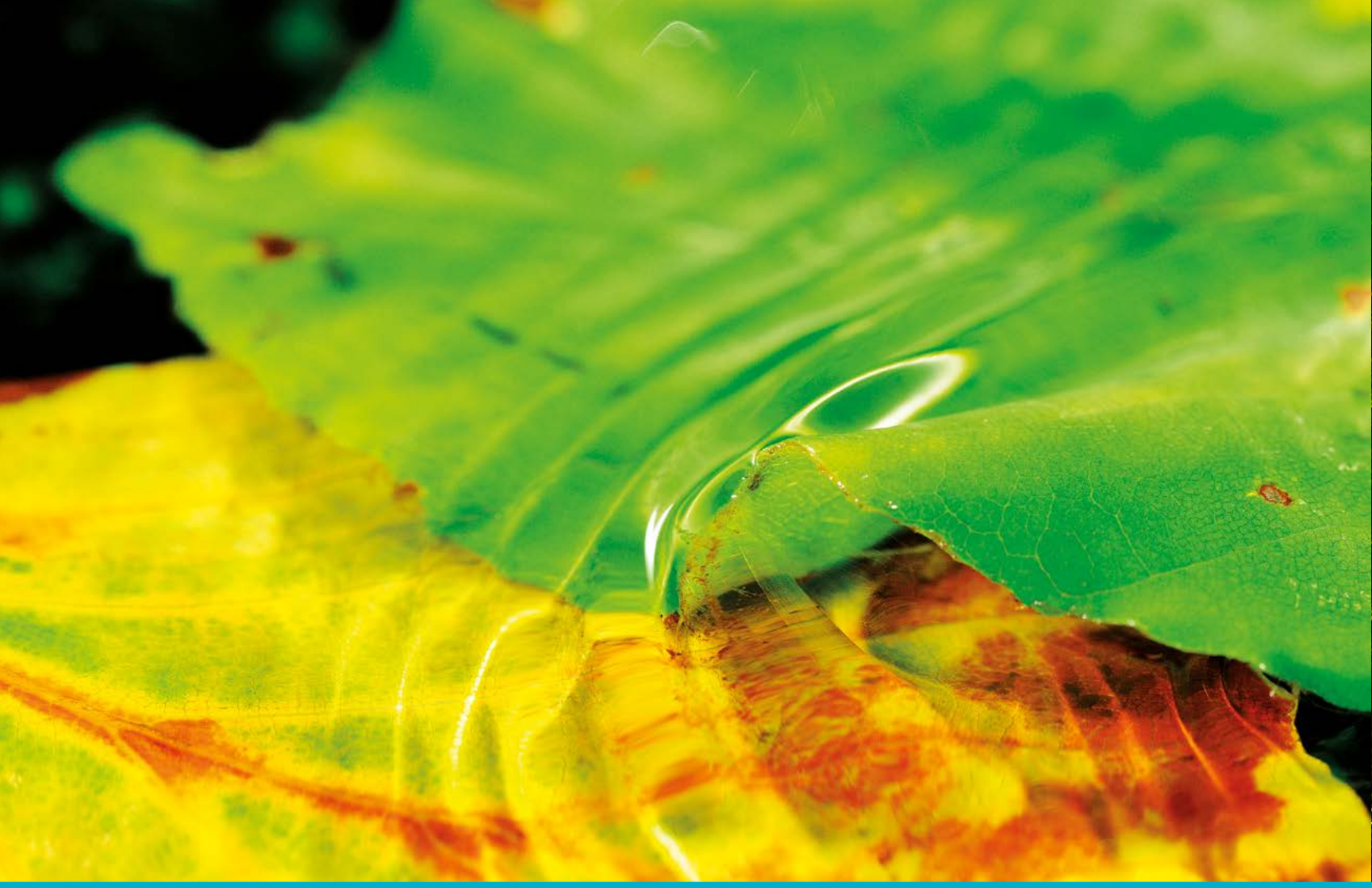

SECRET POCKET (KRKONOŠE, 2015)

I am very fond of the Krkonoše and Jizera Mountains and often travel there to take photographs. Despite the crowds of visitors, some parts of these mountains remain inaccessible in a sense, and thus somewhat protected – places where you can find peace and unspoilt nature. And it is probably here that my fascination with water finds its fullest expression. It is quite rare for me to be able to set aside almost a whole day for photography, wandering through hard-to-reach places and simply exploring freely and taking photographs, but that was exactly what I managed to do that day. The route along the Kamenický stream in Harrachov, particularly its upper, less accessible section, is a showcase of beautiful waterfalls, meanders and small rapids. At times, the stream runs hidden from view; elsewhere, it reveals picturesque spots that are difficult for tourists to reach. For me, it is a true photographer's paradise. At the water's surface, viewed from the right angle, amazing shapes and surprises lay hidden, while the autumn season offered me a far wider range of colours than at other times of the year. I explored the way submerged leaves and ferns seemed to float just beneath the surface, while tiny ripples played a game of hide-and-seek with them. The adventure was not just about getting the lens close enough to the water's surface and setting the polarising filter at the right angle to reduce the glare, but also about playing a game with the ripples to find just the right moment to press the shutter. And with this tiny little pocket of water, I managed to capture that perfect moment.

Text and photo by Milan Blšťák, www.macro4you.cz

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