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

VTEI / 2026 / 1

60 years ago in VTEI

In issue No. 2 of VTEI from 1966, an article entitled "Information Technology" was published, authored by J. Krupička, a graduate librarian from the Water Research Institute in Prague.

The greatest attraction for VTEI staff at the most recent trade fair in Brno was printing and office machinery and equipment. As a new product, the Czech electric typewriter CONSUL, model 1551 B, manufactured by the state enterprise Závody Jana Švermy, Brno, was exhibited. The delivery period was from the fourth quarter of 1965, and the price was approximately 6,000 Czechoslovak crowns (Kčs). The machine has dimensions of 360 × 435 × 258 mm and weighs 22 kg. It is powered by an AC electric motor operating at 220 V or 120 V, with a power input of 25 W and a permanently connected auxiliary capacitor. The operating speed of the machine is 1,200 keystrokes per minute.

Its main advantage is a regular and even keystroke that produces a bold Pica typeface, which is particularly appreciated when typing duplication stencils. When only a smaller number of copies is required, it can also serve as a substitute for an Ormig duplicator, as with good-quality carbon paper it is possible to obtain up to 20 copies, although only 14–15 of these are clearly legible.

Among foreign products on display was the Swiss electric typewriting and typesetting machine VARITYPER, model 660 F, manufactured by Robinco AG, Zurich. Its dimensions are 336 × 495 × 686 mm. It is particularly suitable for printing and reproduction purposes, as it offers characters of varying heights and widths, along with a comprehensive range of automatic auxiliary features.

Of key importance for libraries and VTEI departments was the West German electric typewriter FRIDEN FLEXOWRITER and JUSTOWRITER, manufactured by Friden GmbH in Nuremberg. The approximate price was around 28,000 Czechoslovak crowns (commercial parity). In addition to the above-mentioned advantages of an electric typewriter, it allows the user to type and visually check the document text while simultaneously punching a 5- or 8-track paper tape in the appropriate code. Using a reader, further copies of cataloguing and documentation records, bibliographies, translations and similar materials can then be produced automatically from the tape by means of electrical impulses transmitted to the keys.

Another advantage is the possibility of transferring data from punched tape to punched cards. The built-in reader, or certain types of auxiliary readers, may be equipped with devices for punching and reading edge-punched cards and standard punched cards.

Its greatest advantage, essential for large-scale mechanisation, is the ability to transfer documentation records with descriptors (headings) from punched tape to magnetic tape and to progressively store the information core in the memory of an automatic computer for subsequent retrieval of records according to the specified descriptors, particularly for more complex bibliographic or research queries.

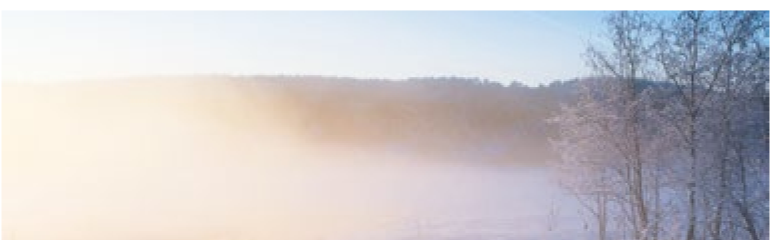
The Flexowriter system allows full programming via a program tape, into which all commands and functional characters required for further processing of the punched tape are entered.

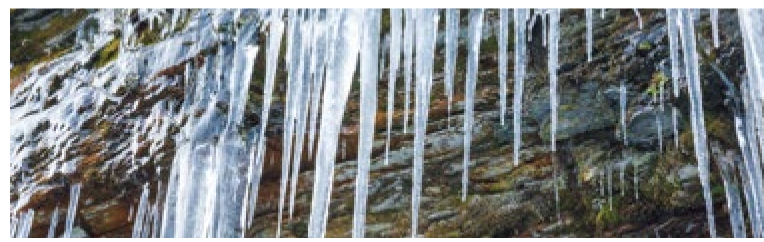
The auxiliary equipment is extensive, comprising 16 different readers and 9 punch units. In addition, the JUSTOWRITER trims the right-hand margin of the text by adjusting the spacing between characters on the line.

From TGM WRI archives

Friden Flexowriter typewriter – model SPD
(source: VTEI 2/1966, modified using the Nano Banana Pro tool)

Content





Dear Readers,

You are opening the February issue of VTEI at a time when water – perhaps more than ever – reveals itself in its full breadth: as a technical, environmental, social, and human issue. Winter is traditionally a period of reflection and planning, but it is also a time when the need for a well-prepared water management system becomes particularly evident – not only for routine operation, but also for the unexpected challenges brought by variable weather and the impacts of long-term climate change.

In January and February, the framework of this year's key debates also began to take shape. These discussions naturally include the theme of World Water Day 2026, "Water and Gender Equality" – a topic that reminds us that access to water and sanitation is not only a matter of infrastructure, but also of justice and opportunity. It places particular emphasis on challenges that disproportionately affect women and girls in many parts of the world, while at the same time opening space for broader connections ranging from food security and climate to governance.

Linking disciplinary precision with a broader context is also the central idea of this month's issue. In the expert section, we present five peer-reviewed articles which together demonstrate the diversity of the field of water, ranging from municipal practice to highly specific environmental objectives.

The first article focuses on food waste from the perspective of municipalities and identifies the key issues currently faced by towns and cities: preventive measures, the economics of waste management, capacity for handling biowaste, pressure on staffing and administrative resources, as well as deeply rooted habits related to waste sorting that are difficult to change.

This is followed by a study on the assessment of flood hazard in confluence areas, which demonstrates in model regions why separate modelling of individual watercourses can lead to distortion and why a more integrated approach is warranted (including recommendations for the methodological development of flood hazard and risk maps).

The third scientific article addresses atmospheric deposition of polycyclic aromatic hydrocarbons (PAHs) as a significant source of surface water contamination and presents a comprehensive perspective on the issue, ranging from the monitored matrices to the use of fingerprinting techniques for source apportionment.

The fourth paper focuses on the tightening of environmental objectives for the stone crayfish, which is a critically endangered species in the Czech Republic, and provides an important methodological framework as well as detailed information on specific procedures for setting limits for key water quality parameters in order to ensure the maximum protection of the species at its sites of occurrence.

The fifth article presents the use of ground thermometry in the search for mineral springs and, using the differing examples of Mariánské Lázně and Karlovy Vary, clearly demonstrates when thermometry can be highly effective and when, by contrast, the methodology must be adapted to the specific conditions of a given site.

Alongside the expert articles, the issue also includes an informative section featuring an interview with Assoc. Prof. Ing. David Stránský, Ph.D. He is the Head of the Department of Municipal Water Management at the Faculty of Civil Engineering of CTU in Prague, and in the interview he reflects on his professional career while also considering how both the topics and the answers related to urban water management have evolved since his previous interview. The February issue concludes by returning to the 5th conference of the *Water Centre* project, held on 25 November 2025 at TGM WRI, which offered an evaluation of current research results as well as space for interdisciplinary dialogue on adapting water management to changing climatic conditions.

We believe that everyone will find "their" topic in this issue – whether your interests lie in municipal practice, flood management, water chemistry, the protection of endangered species, or hydrogeological applications. We wish you inspiring reading and look forward to any comments, suggestions, or valuable feedback you may wish to share.

Ing. Josef Nistler

Food waste from the perspective of municipalities – approaches and measures for reducing production and preventing its occurrence

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Keywords: food waste – municipalities – waste prevention

ABSTRACT

The presented article addresses current problems in food waste management and prevention at the municipal level in the Czech Republic. It summarises the authors' team's knowledge within the framework of long-term solutions to this issue, presents a diverse range of preventive measures, conducts an elementary economic analysis of municipal expenditures and revenues in waste management, and points out current problems and pitfalls for development in the coming years. The most important ones include the growing obligations of municipalities in preventing the creation and management of municipal waste and the associated increasing pressure on staffing the circular economy and waste management agenda, insufficient capacities for food waste management in the near future (with the planned fulfilment of national goals), an inadequate system of transmission and exchange of relevant information, and the ever-recurring indiscipline of citizens in primary waste sorting.

INTRODUCTION

Food waste generation represents a significant environmental, economic and socio-ethical challenge. At both international and national levels, this issue has received increasing attention, as it is closely linked to the efficient use of natural resources as well as to the principles of the circular economy and food security. On the one hand, these include wastes that, through appropriate separation, can provide a valuable raw material source, for example for composting or biogas production (instead of ending up in landfills), and, on the other hand, food products that are still fit for consumption but, for various reasons, are not used and become waste. Food waste is generated at all stages of the complex food supply chain – starting with primary production, where losses occur due to weather conditions, pest infestations, or failure to meet market standards for shape and size, through the processing industry, distribution and retail, and finally to end consumers (including households, restaurants, school canteens, and other public catering facilities) where the share of waste generation is often the highest [1]. From the perspective of the agri-food sector, the issue of food waste therefore affects a wide range of different areas and represents an interdisciplinary matter involving the competencies of several ministries of the Czech Republic.

In the European Union, households are identified as the largest producers of this type of waste, accounting, according to estimates, for more than 50 % of the total volume of food waste [2] (*Fig. 1*). This is mainly due to poor shopping planning, improper food storage, misunderstanding of the labelling "best before" and "use by", inappropriate portion sizes during cooking, and other factors such as, for example, reluctance to make use of leftover food. Another significant share of food waste is generated in public catering facilities. A substantial proportion of this waste consists of food that would still be edible and usable. Such food is often discarded for reasons of convenience, lack of time, low awareness of environmental impacts, or due to organisational and operational constraints.

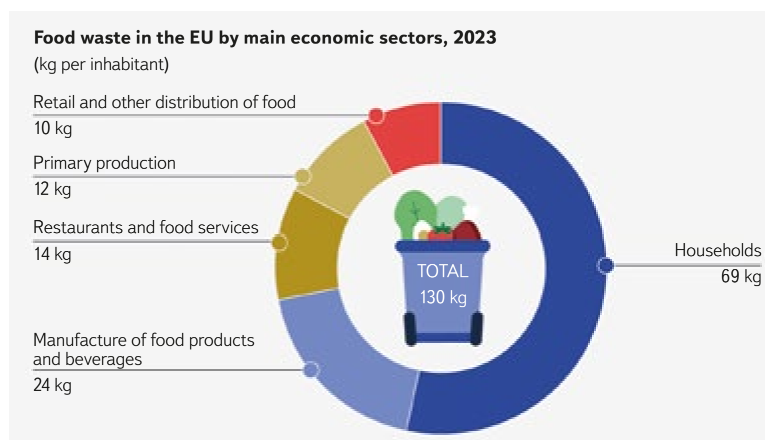

Fig. 1. Food waste production in the European Union at each stage of the food chain in 2023 [2]

Household food waste burdens not only household budgets but also the environment. The impacts are significant:

- **Environmental** – natural resources (water, energy, land, and human labour) are consumed unnecessarily. It is estimated that the global carbon footprint of food waste accounts for approximately 8–10 % of worldwide greenhouse gas emissions [3]. In addition, food waste disposed of in landfills generates methane, a gas with a significantly higher global warming potential than carbon dioxide.

— **Economic** – for households, discarded food represents a direct financial loss. At the macroeconomic level, it constitutes a loss of value across the entire supply chain and increased costs for municipalities related to waste management.
— **Socio-ethical** – in a global context, where hundreds of millions of people suffer from undernutrition and food insecurity, massive waste represents a serious ethical paradox: while some of the population experiences food insecurity, a substantial amount of food prepared for consumption goes unused.

For the sustainable and circular-economy-compliant management of already generated food waste, as well as the practical implementation of measures to prevent its generation, it is necessary to provide expert support to municipalities in the Czech Republic. Increasing responsibilities in the areas of circular economy and waste management are being transferred to them, and for many, navigating this environment is becoming complex and, in the long term, unmanageable. The provision of methodological, data-driven and technical support to cities and municipalities in the Czech Republic is essential to achieving national and European targets for reducing food waste and to enabling a successful transition to a more sustainable model of resource management [4].

METHODOLOGICAL PROCEDURE

The methodological approach to addressing preventive measures for reducing food waste at the municipal level was based on current strategic documents in the fields of circular economy and waste management, on the results of previous research projects conducted by the authors' team, and on a review of relevant outputs from research projects carried out by other organisations, as well as practical experience.

Strategic documents

At the international level, the key document is the UN 2030 Agenda for Sustainable Development, specifically Sustainable Development Goal (SDG) 12.3, which aims to halve per capita global food waste by 2030. To support its implementation, the Champions 12.3 initiative was established, bringing together governments, businesses, and non-profit organisations.

At the European level, the issue has become a priority within the Circular Economy Action Plan. The key legislative framework is provided by the revised Directive (EU) 2018/851 of the European Parliament and of the Council [5], which amends the Waste Framework Directive (2008/98/EC). This amendment requires Member States to adopt specific food waste prevention programmes and sets a target to reduce food waste by 50 % by 2030, in line with SDG 12.3 of the UN 2030 Agenda for Sustainable Development. To ensure comparable data across the EU, Commission Implementing Regulation (EU) 2019/1597 [6] was adopted, defining a uniform methodology for measuring food waste. Scientific knowledge on food waste has been further advanced through projects such as FUSIONS and REFRESH, funded under the Horizon 2020 programme [7, 8]. Both projects delivered methodologies for measuring food waste, prevention scenarios, and policy recommendations. Current European initiatives build on these findings, including support for food redistribution and waste taxation.

The Czech Republic has implemented the European requirements on food waste into its national legislation and strategic documents. A key instrument is the Czech Waste Management Plan for 2025–2035, which in Chapter 3.4 includes the Food Waste Prevention Programme [4]. This programme defines three specific national targets:

A. Prevent the generation of food waste and reduce its production in primary production, food processing, distribution, and consumption.

B. By the end of 2030, reduce food waste generated during processing and production by 10 % compared with the amount produced in 2020.

C. By the end of 2030, reduce per capita food waste in retail and other food distribution channels, in restaurants and catering services, and in households by 30 % compared with the amount produced in 2020.

In summary, the legislative and strategic framework at the EU level is now relatively robust. The Czech Republic transposes these requirements into national policy and research activities; however, a comprehensive and detailed strategy is still lacking – one that would more effectively integrate the various actors across the food supply chain and provide municipalities with concrete, data-driven tools to achieve the established targets. In the future, it will therefore be essential to strengthen inter-ministerial cooperation, expand targeted measures at the level of municipalities, schools, and food facilities, and establish a reliable system for data sharing and monitoring.

Research results and experience from practice

For the development of concrete and practically applicable proposals for preventive measures, key inputs were the empirical findings, results, and knowledge obtained through research projects conducted by the authors' team as well as by other organisations.

Within the activities of the Centre for Environmental Research: Waste and Circular Economy and Environmental Safety (CEVOOH; SS02030008), the TGM WRI team has long addressed the issue of food waste in Section 1.C on Biodegradable Waste. In previous years, the aim has been to develop a national methodology to meet reporting obligations for food waste generation in the Czech Republic at the national level for the European Union authorities [9]. The methodology covers all stages of the food supply chain (primary production, processing and manufacturing, retail and other food distribution channels, restaurants and catering services, households) and is based on a calculation approach strictly aligned with EU requirements and the waste catalogue. The methodology has become the main stimulus for an interdisciplinary, independent approach to precise reporting and documentation of waste generation in the primary production and food processing segments.

The main indicator for the municipal sector is the generation of household food waste, determined based on data from the Waste Management Information System (ISOH). The calculation includes waste from selected catalogue items (20 01 08, 20 01 25, 20 02 01, 20 03 01) with handling codes A00, AN60, and BN30. The resulting value represents the annual quantity of food waste generated by households participating in the municipal system. The purpose of monitoring this indicator is to assess whether food waste generation is decreasing. Trend analysis enables municipalities to evaluate the effectiveness of measures related to collection optimisation, food redistribution, and public awareness campaigns.

The supplementary indicator I.KO expresses the quantity of avoidable food waste, i.e., waste that could have been consumed but was discarded. It uses data from ISOH and conversion factors established for individual components of municipal waste – mixed municipal solid waste (MSW), biodegradable waste, and market waste. The combination of both indicators provides municipalities with a comprehensive tool for planning, evaluating the effectiveness of measures, and monitoring progress in food waste prevention.

For a detailed understanding of the quantity and composition of the biodegradable fraction of mixed municipal waste, and for the subsequent development of realistic proposals for measures, insights from MSW analyses are essential. These analyses were carried out in several projects: first, within the research project *Waste and Prevention of Its Generation – Practical Procedures and Activities for Implementing the Obligations of the Regional Waste Management Plan of the Capital City of Prague* (Growth Pole programme; CZ.07.1.02/0.0/0.0/16_040/0000379, *Fig. 2*), and currently within the ongoing project *Effective and Sustainable Management of Food Waste in Municipalities* (acronym NAPO, Environment for Life 2 programme, TA CR, No. SS07010095, 2024–2026). The main aim of the second project is to establish a previously unrealised systematic approach and to develop a comprehensive tool for the sustainable management of food waste for municipal authorities and their associations in the Czech Republic. Dozens of MSW analyses, with a particular focus on food waste, have provided detailed information on the composition of these wastes and have identified the fractions with the greatest potential for waste prevention. Equally important is the highly active involvement of representatives from selected cooperating cities and municipalities, with whom proposals for preventive measures were consulted in connection with the ongoing results of MSW analyses and the operational experience of officials responsible for waste management. The preliminary results of these MSW analyses clearly confirm that there is a sufficient quantity of food waste in municipal waste with potential for utilisation and waste prevention (*Fig. 3*); the complete results of the MSW analyses will be published in 2026.

Fig. 2. One of the key activities in identifying food waste and obtaining the necessary data is the analysis of MSW in municipalities (photo: authors' archive)

Fig. 3. After being sorted from the MSW, food waste is photo-documented and provided with a description of its condition, expired warranty period, etc. (photo: authors' archive)

In research and awareness-raising, the initiative *Save Food (Zachraň jídlo)* plays an important role, highlighting the extent of food waste through campaigns and collaboration with retailers, schools, and producers, while providing concrete recommendations on how to prevent it [10]. In 2022, an extensive study by the Food Bank Prague and Mendel University in Brno quantified the scale of food surpluses in retail and proposed improvements to the food donation system [11]. In collaboration with the Faculty of Education at Charles University and the Faculty of Business and Economics at MENDELU, the project *Smart with Food (Chytře s jídlem)* was launched, focusing on food waste and aiming to raise awareness and change the behaviour of children, schools, and households [12]. Household shopping and cooking practices are further supported by the platform *Buy What You Eat (Kup, co sníš)*, which offers advice, tips, guides, recipes, and inspiration on how to use ingredients as efficiently as possible, minimising unnecessary losses [13].

Experience has also been gained through the project and platform *I Sort Gastro (Třídím gastro)*, which provides comprehensive services by the company Energy Financial Group (EFG) focused on the separation, collection, and energy recovery of biodegradable kitchen (catering) waste [14, 15]. In the management of already generated food waste, the results of research activities related to composting and biogas plants were also utilised [16–18].

Other relevant sources that supported the development of preventive measures include expert materials from the Ministry of the Environment of the Czech Republic, ISOH statistics, EKO-KOM outputs (MSW analyses), and reports from municipalities that conducted their own MSW analyses. These materials enable comparisons across different regions, municipality sizes, and types of municipalities, help identify key determinants of food waste, and allow the design of measures that are practically implementable under the conditions of various municipalities [19–21].

RESULTS

Systemic measures at the national or municipal level targeting food waste must lead to a reduction in the production of mixed municipal waste. This reduction can be achieved through two mutually complementary approaches:

- through consistent and well-planned waste prevention (including not only food waste itself but also the wastes that are sometimes inevitably generated during food production, such as plastic packaging in which food is discarded),
- through a significant increase in the efficiency of separation and subsequent utilisation of food waste that has already arisen within cities and municipalities.

Proposed measures can be applied individually within a municipality. However, it is more effective to integrate these solutions into a coherent system and exploit potential synergies (for example, combining awareness-raising with technical interventions, or infrastructure with incentive tools). The goal is to design the most comprehensive solutions possible, enabling the development of efficient, adaptable models that can function in diverse local conditions.

When implementing the proposed measures in practice, it is necessary to comply with current legislation and also take into account regulations concerning other specific areas (particularly public health protection, hygiene standards, and technical norms). Technical solutions (such as bin sizes, collection logistics, and composting or biogas capacities) should be dimensioned appropriately to local conditions.

From the perspective of the municipal waste producer (i.e., the municipality) prevention is absolutely key, as it significantly reduces waste management costs (for both residual and separated waste). However, waste prevention measures cannot be strictly enforced, or only to a very limited extent – for example, through differentiated waste fees, incentives for households producing low amounts of waste, or participation in awareness programmes. Voluntary motivation therefore plays a crucial role in preventing waste generation, and this can be strongly influenced by properly targeted awareness-raising. The second dimension involves creating an environment that enables motivated citizens to live a "zero-waste" lifestyle, supporting urban composting, establishing platforms for food redistribution, and similar initiatives.

Proposals of preventive measures

Biodegradable municipal waste and support for composting

Biodegradable municipal waste (BMW), a substantial part of which consists of discarded food, accounts for approximately 40 % of municipal waste. At the same time, it is the only type of waste that citizens can fully and legally utilise in the home environment, even in large quantities (*Fig. 4*). Landfilling of biowaste is also restricted by legislation, and waste producers are obliged to implement measures leading to separate collection and further utilisation of BMW.

There are several methods for ensuring the utilisation of biodegradable waste, but they differ considerably in terms of efficiency, financial costs, and environmental burden. Given the complexity of the issue, all methods have a place within waste management. However, it is advisable that their implementation and support follow a hierarchy similar to that applied to waste management in general: measures with the lowest environmental (and often financial) costs should be prioritised, with other solutions considered only once the more favourable options have been exhausted.

Fig. 4. Today, we can see composters not only in family houses, but they are also increasingly used by residents of panel houses in housing estates (photo: authors' archive)

Domestic and garden composting

According to the experience of municipalities, grant support for the purchase of garden composters for residents with gardens, users of inner courtyards, and similar settings has proven effective. Grant schemes can also be targeted at the acquisition of indoor vermicomposters intended for domestic composting of kitchen waste. A starter culture of earthworms must be placed in the vermicomposter, preferably a selectively bred, highly efficient species of so-called Californian earthworms (*Eisenia andrei*), which prefer higher temperatures, reproduce rapidly, and process kitchen waste very effectively. However, they require care comparable to that of a specific "domestic animal", namely the provision of sufficient food (biowaste), appropriate temperature, and adequate moisture. Users of vermicomposters therefore need to be familiar with the requirements of the earthworms and the rules of their care to ensure that the composter functions properly and that the earthworms do not die.

Community composting

Community composting refers to the shared composting of organic waste by multiple households, typically neighbours (residents of a single apartment building or entrance, or users of suitable shared spaces). Composting may take place in closed or open composters, or on compost heaps (*Fig. 5*). A composter located in a publicly accessible area must be enclosed and lockable, with keys held only by authorised users. The composter should be sited so that it does not cause nuisance through potential odour or insects and is reasonably accessible to all users. It is essential that at least one administrator is designated within the user group; this person oversees cleanliness, ensures proper compost management, and organises the use of the produced compost (or delegates necessary tasks to other users). Each group should establish internal operating rules (definition of acceptable compostable waste, user responsibilities, responsibility for equipment, etc.). Composters should preferably be insulated (to allow year-round use), lockable, and multi-chambered, with one chamber used for collecting fresh waste and the others for compost maturation.

Fig. 5. The disadvantage of community composting is the lower possibility of checking the deposited waste from a larger number of citizens, when waste in plastic bags or even waste that is not related to composting at all may appear at the collection point (photo: authors' archive)

Composting and the treatment of biowaste in schools

Schools and other institutions may compost biowaste provided that several rules are observed. Composting should involve plant residues only, not food leftovers. The composting process must not pose a risk to the environment or to human health; it therefore has to be carried out properly, with no leakage of leachate into watercourses or similar pathways. The resulting compost is ideally used on school grounds.

To ensure high-quality composting, biowaste must be consistently sorted at the point of generation; that is, during food preparation and in classrooms. Collection should take place in special ventilated bins placed in each classroom (or at each waste collection point within the school). Ventilated bins, into which compostable bags are inserted, ensure that the waste dries out rather than rotting. The bins must be closable to prevent pests, particularly fruit flies, from accessing the biowaste. The removal of bags containing biowaste should take place at least once or twice a week, or more frequently if necessary. The compost must be turned (aerated) at least twice a year, and it is necessary to ensure the mixing of residues with a high nitrogen content (fruit, food preparation residues) with carbon-rich materials (grass, wood chips). The resulting stabilised compost (after approximately one year) can be used for the maintenance of school grounds. It is also advisable to involve pupils and students in the system (education, taking responsibility), for example by having them remove biowaste, check the quality of sorting, and care for the compost. The transformation of organic residues into compost and fertiliser is also an interesting topic for biology lessons.

Community fridge

Public spaces where unwanted but still usable items can be left and freely taken by others have two positive effects. They facilitate the act of "not throwing away things that I no longer need" and enable their donation beyond one's own family or friends. They also make it possible to donate items that can otherwise be given away (or accepted) only to a limited extent, in particular due to social conventions or feelings of embarrassment (unsuitable gifts, food, etc.). At the same time, items are not devalued (neither physically nor "emotionally"), for example by being left next to waste containers in the hope that someone might take them. Experience from the operation of similar "sharing points" (community fridges, clothing exchanges, libraries) shows that they are used both by people in genuine need (especially for clothing and food) and by people motivated by environmental concerns (consumption of "almost discarded" food), as well as simply by people willing to try something different and sufficiently open-minded, particularly students (for example with food and books).

In practice, community fridges are the most common form of such sharing points; however, in principle, any products can be shared in this way, provided that it is technically feasible, that sufficient supply and demand exist, and that people are willing to offer items free of charge and to take them from an "unverified source".

A community fridge requires a permanent electricity supply, daily monitoring (proper functioning of the refrigerator, inspection of contents, and removal of unsuitable or spoiled food), and placement in a location protected from weather conditions and direct sunlight. For these reasons, their maintenance is most often undertaken by operators of cafés or other facilities; some are located in university dormitory premises, while others are installed at municipal offices. In the case of a community fridge, it is essential to ensure strict operational management and to provide clear, prominent notices setting out the operating rules and informing users that consumption of stored food is at their own risk. These operating rules, which define what may be placed in the fridge and under what conditions, must be carefully formulated and publicly displayed. The safest items are purchased foods with an unexpired best-before date that remain unopened, as well as undamaged fruit and vegetables. In some community fridges, it is also possible to leave home-prepared food, as well as opened packages where this does not affect quality (eggs, pasta, shelf-stable foods), or shelf-stable foods with an expired best-before date for which any decline in quality is minimal (pasta, legumes). It is also advisable to designate an uncooled space for storing foods that do not tolerate cold and, in particular, humidity (such as potatoes), or that do not require refrigeration at all (shelf-stable foods).

Discounted food apps

The prevention of food waste has shifted markedly towards digital solutions in recent years, among which mobile applications connecting businesses with end consumers play a key role. In the Czech Republic, the most widely used platforms are *Nesnězeno (Uneaten)* and *Too Good To Go*, which enable customers to purchase unsold meals or food at a reduced price [22, 23]. This approach not only saves money for households but also helps to reduce the amount of food discarded and supports local food service businesses. While *Nesnězeno*, owing to its longer presence on the market, has built a strong network with more than 1,700 partner establishments, the newer *Too Good To Go* relies on international experience and technological innovations, including a tool using artificial intelligence for stock planning. Both apps primarily target urban and younger populations and employ the element of surprise, as customers often do not select a specific meal in advance but instead purchase a so-called rescue package. In the context of rising food prices, increasing pressure for sustainability, and the high share of households in overall food waste generation, these applications represent an important instrument for the systemic reduction of food losses.

Using tap drinking water instead of bottled water

Water as a food item is often overlooked. The public water supply provides high-quality water that is regularly monitored by the supplier for hygienic standards, is ideally stored (in cool, dark conditions), and, with continuous turnover, remains fresh. Compared with bottled water, it is very inexpensive; one litre of drinking water (water supply and sewerage charges) costs only a few halers, whereas a litre of bottled water costs several Czech crowns. Bottled water is also a source of large amounts of plastic waste, a substantial proportion of which is transported abroad for further processing. It is therefore necessary to focus on prevention rather than solely on recycling, which in itself represents a significant environmental burden (production, transport, and the recycling process itself).

In the Czech Republic, high-quality drinking water is taken for granted. Nevertheless, bottled water retailers have been so successful with their marketing campaigns that tap water is often perceived as inferior. This perception needs to be challenged through targeted activities and the promotion of tap water.

One simple yet effective preventive measure to reduce waste from single-use packaging is the provision of tap water to customers in restaurants and cafés. Promoting the consumption of tap water helps to limit the use of bottled beverages and thus also reduces the amount of plastic and glass packaging that ends up as waste. Municipalities can support this measure through awareness campaigns, labelling establishments that offer tap water, or providing technical support (for example, filtration systems).

Food banks

Food banks in the Czech Republic are key actors in the fight against hunger and food waste [24]. They represent an important component of the system providing assistance to people in need, while simultaneously actively combating food waste. Their primary mission is to collect safe food that would otherwise end up as waste and to distribute it to those who need it most. This system operates thanks to close cooperation with retail chains, food producers, farmers, volunteers, and an extensive network of recipient non-governmental organisations.

Food banks obtain food from a variety of sources. These include primarily surplus food from retailers (e.g. products approaching their minimum durability date or with damaged packaging), unsold products from manufacturers and growers, as well as donations from the public collected through food drives, such as the nationally well-known *Food Collection*.

The collected food is subsequently sorted, stored and distributed through partner charitable and humanitarian organisations. These organisations then ensure that the assistance reaches the target groups directly. The most common beneficiaries include families in crisis and single parents, seniors on low incomes, people experiencing homelessness, individuals with disabilities or chronic illnesses, and similar groups.

Improving the efficiency of sorting biodegradable waste

Municipalities in the Czech Republic have been obliged to enable the separate collection of biodegradable waste since 2015, initially only on a seasonal basis. Since 2019, municipalities have been required to ensure facilities for the separate collection of biowaste throughout the entire year. At least at a general level, such a system is therefore in place in the Czech Republic. However, MSW analyses carried out by the authors' team and other bodies indicate that the efficiency of these systems and their more substantial impact on reducing the amount of BMW in MSW disposed of in landfills have so far remained relatively low (*Fig. 6*).

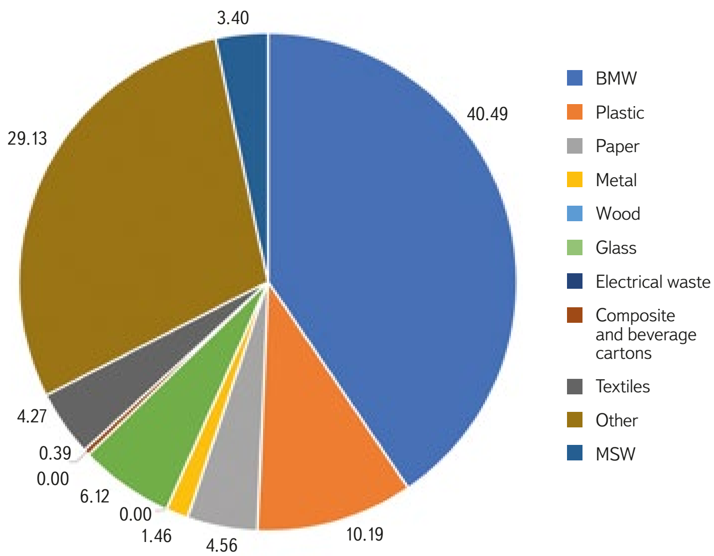

Fig. 6. The ongoing results of the MSW analyses carried out as part of the NAPO research project show that the share of usable BMW is still around 40 %

Separate collection and the introduction of catering (food) waste collection for municipal residents and businesses

Here, catering waste refers to waste classified under catalogue code *20 01 08 – Biodegradable waste from kitchens and canteens*. Leftovers of cooked meals and similar waste from catering facilities and households are usually not collected separately and largely end up in mixed municipal waste. Catering waste can only be composted to a limited extent due to the risk of rodents, insects and potential infection (especially meat and cooked food residues). As the level of separate collection of other waste fractions improves, the share of catering waste in mixed municipal waste increases. This is a waste fraction that can be further utilised (e.g. in biogas plants); however, is difficult to use directly for energy recovery (by incineration), and its disposal (as biodegradable municipal waste) in landfills is increasingly restricted by legislation. These factors all underline the need to divert this waste stream and to introduce consistent separate collection and recovery. As with other waste fractions, separation at the source is essential, because subsequent sorting is practically impossible and mixing significantly reduces the potential for further utilisation. A model example of good practice is the already mentioned *Třídím gastro* initiative [14].

Collection of edible oils at the point of use (canteens, restaurants)

Used edible oil from households and catering establishments still ends up in significant quantities in the sewer system or in mixed municipal waste. Such practices can cause pipe blockages, damage to sewerage infrastructure and increased maintenance costs.

Edible oils and fats, however, represent a recoverable raw material that is collected and sorted under catalogue code *20 01 25 – Edible oil and fat*. A number of companies are involved in the collection and reuse of this oil; the technology is well established and there is demand for the material, which is even purchased (typically for a few Czech crowns per litre). Selected locations can also serve as collection points for oil from households (most commonly schools or school canteens). The level of separate collection of this material (i.e. the proportion of oils ending up in the sewer system) is closely linked to public awareness of the potential damage caused by oil in pipes (blockages, the need for repairs).

Information and awareness campaigns

In the area of preventing the generation of BMW and food waste, the public is a crucial target group, capable of effectively influencing the quantity and type of waste produced in everyday life. An effective information campaign can therefore quickly create (and thus have an immediate impact) and, throughout the implementation of preventive measures, ensure the continuous operation of an openly accessible information base on waste prevention at various levels. It thus acts both immediately (short-term) and over the long term. The strategy for disseminating information in this area is considered one of the most important forms of intervention.

Awareness-raising is absolutely crucial to support the public in activities aimed at reducing waste generation. This is because such solutions are often less convenient for users (for example, the need to bring your own containers, cups, etc.), whereas waste seemingly "disappears" once discarded. It is therefore necessary to strengthen understanding of the connections involved (the link between a discarded cup and a landfill or incinerator, which are perceived negatively) while simultaneously promoting and disseminating proper, practical approaches for living with minimal waste. This applies across many levels – from individual citizens to small businesses, large companies, and public administration or institutions. Simultaneously, it should be noted that the actual effectiveness of information campaigns can vary widely. As confirmed by analyses of MSW in municipalities with intensive public awareness initiatives – encouraging residents to collect and separate BMW and food (catering) waste, including the provision of a sufficient number of street collection containers and bins for households – municipalities often struggle to achieve significant reductions in waste generation. This is largely due to residents' non-compliance and failure to follow the rules, meaning that even substantial financial investments do not always result in meaningful decreases in the amounts of these wastes (see *Fig. 7*).

Fig. 7. Citizen indiscipline and failure to respect basic rules for MSW collection and sorting remain evident in some municipalities, even after years of information and awareness campaigns (photo: authors' archive)

Information and awareness campaigns can encompass a wide range of activities targeting residents, while also linking them to community events, schools, or local businesses. Municipalities can use various channels to disseminate and promote these campaigns, such as the municipality's website, leaflets, local newspapers, labels on collection containers, mobile applications, official social media pages, and similar platforms. The range of possibilities is quite extensive and may focus on activities such as:

- regularly inform the public about current developments in the field of the circular economy and waste management within the municipality;
- inform about the types of waste collection containers, their colour coding, the placement of labels and internationally recognisable pictograms indicating accepted and non-accepted waste on the containers, and the use of QR codes enabling the reporting of issues related to collection points;
- organise guided visits to facilities that form part of the waste management system (landfills, sorting lines, recycling centres, composting plants, biogas plants, energy recovery facilities, manufacturers using returnable packaging, etc.); the purpose of these visits is to demonstrate real-life operations and to dispel myths and misconceptions about waste management, such as the claim that "separating waste makes no sense because it is all later dumped into a single refuse truck or landfill pit anyway";
- participate in science and research projects and inform the public about these activities;
- disseminate information on initiatives, events, and organisations whose activities aim to reduce food waste (such as *Neplýtvej potravinami*, *Zachraň jídlo*, *Kup, co* sníš, food banks, and similar initiatives)
- organise, or co-organise, courses promoting properly planned food purchasing and cooking from primary ingredients (unpackaged foods);
- disseminate information about social and communication platforms and applications for electronic devices;
- promote zero-waste shopping and related initiatives, provide information on local retailers, and explain the hygiene requirements that must be met (appropriate containers and subsequent storage of products at home to prevent deterioration);
- provide information on available financial support (grant programmes) aimed at supporting production and sales practices that minimise the generation of food waste (sales into customer-owned containers, use of returnable packaging in production and retail);
- disseminate information on examples of good practice;
- provide advisory support in legislative, accounting, and hygiene matters (in cooperation with public health authorities and retail operators) related to the sorting and management of food waste and the use of returnable/customer-owned packaging; consider issuing the manual in other languages as well (at least as a translation of the electronic version);
- provide financial incentives for, and differentiate between, citizens and entities that take a responsible approach to the sorting of food waste;
- create interactive maps indicating collection containers suitable for depositing food waste, community fridges, and zero-waste shops (including, for example, outlets offering coffee into customers' own containers), incorporating data filtering options, information on opening hours, contact details, and similar features;
- provide long-term support for municipal projects and recommend them to residents (home composters, community composting, pilot projects for collection and sorting, etc.);
- through schools, educational institutions, and leisure-time centres, organise public competitions (currently popular among pupils and students, for example photo competitions) focused on identifying and rewarding original ideas and solutions in the field of food waste prevention, proper food waste management, and the use of recycled materials (for example composts).

Revenues and expenditures in municipal waste management

Within municipal budgets, waste management is tracked through revenues, expenditures, and the financial relationships between them. These are further specified using budget items, paragraphs, and similar classifications, monitored according to the budgetary structure defined by Decree No. 412/2021. Capturing financial relationships in the budget is closely linked to the municipalities' waste management models. These financial relationships reflect different approaches, ranging from municipalities independently performing waste management activities through their offices, to purchasing services from collection companies, establishing municipal organisations, or cooperating within associations of municipalities. The choice of model depends primarily on the size of the municipality, its organisational capacity, and economic stability. Over the long term, a significant increase in the burden of waste management on municipal budgets can be observed. While in 2010 it amounted to CZK 2 billion, by 2024 it had risen to CZK 7 billion, representing an increase of 241 %. The overall net financial impacts of waste management in municipalities are mainly driven by the growth in municipal expenditures on waste management. From 2010 to 2024, total municipal spending on waste management increased from CZK 9.3 billion to CZK 19.7 billion. This 111 % increase was influenced by inflation; however, even after adjusting for inflation, there remains a real increase of 29 % (*Fig. 8*).

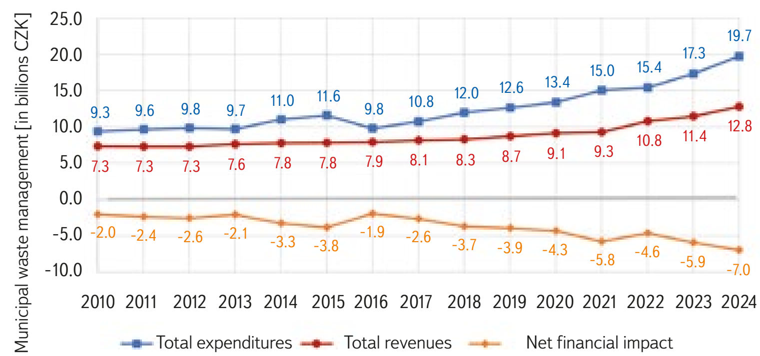

Fig. 8. Development of municipal waste management in 2010–2024 (Ministry of Finance, State Treasury Monitor)

Municipal expenditures on waste management mainly relate to costs for collection and transport, waste utilisation and disposal, prevention of waste generation, and monitoring (*Fig. 9*). Municipalities pay these costs to waste collection companies, and they also include fees for landfill disposal. Most of these expenses are operational, while capital expenditures cover items such as equipping collection yards, composting facilities, or acquiring collection vehicles. Expenditure levels vary according to the size of the municipality; in 2014–2015, smaller municipalities had higher capital expenses due to EU subsidies. Over the long term, the highest per capita costs are borne by the smallest municipalities, and differences between size categories are widening. Higher unit costs in small municipalities may be linked to lower collection efficiency, underutilisation of capacities, and limited opportunities for optimisation. This highlights the need for system rationalisation, increased prevention, and stronger support for waste separation.

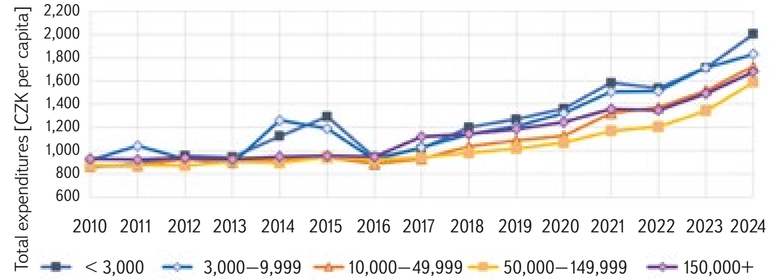

Fig. 9. Total municipal expenditures on waste management by size category in 2010–2024 (Ministry of Finance, Treasury Monitor / Czech Statistical Office)

The main source of municipal revenue in waste management is the local fee for the municipal waste management system and the fee for municipal waste disposal, set by a generally binding municipal ordinance. Some municipalities may also collect these fees through contractual arrangements. Other sources of revenue include payments for sorted waste, contributions from collective systems, and income from landfill disposal fees collected by the municipality where the facility is located. Additionally, some municipalities may charge fees for waste that they transport in bulk to landfills (e.g., construction debris), with the fee based on the costs of disposal.

Over the long term, it has been observed that per capita revenues are highest in the smallest municipalities and decrease as municipal size increases, with the exception of the very largest municipalities (*Fig. 10*). Between 2021 and 2024, revenues across all municipal size categories increased on average by about one third. This increase is primarily driven by the size of the local waste fee, which constitutes a major component of total municipal revenues.

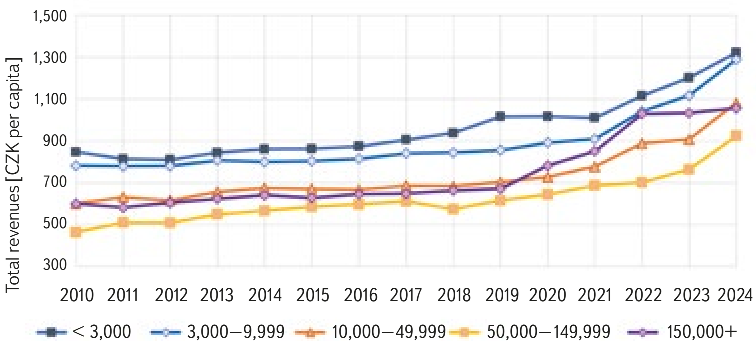

Fig. 10. Total municipal revenues from waste management by size categories (Ministry of Finance, Treasury Monitor / Czech Statistical Office)

DISCUSSION AND CONCLUSIONS

The transfer of responsibilities in the field of the circular economy and waste management to municipalities has been increasing in recent years. Municipalities are required not only to ensure the implementation of systemic measures and to achieve statutory targets, but also to cope with a shortage of qualified staff, limited access to relevant information, and growing pressure on municipal budgets. An analysis of the current situation indicates that, without long-term and systematic support for municipal activities in these areas, the Czech Republic may face significant difficulties in the future, both in achieving the expected transition to a circular economy and in ensuring the long-term sustainability of the waste management system, as well as in meeting (often very ambitious) environmental targets.

Measures to prevent food waste and reduce the generation of biowaste are not merely a cost; they represent an investment in a sustainable future – resource conservation, emission reductions, support for the local circular economy, and an improved quality of life. A municipality that becomes actively involved can achieve not only environmental benefits, but also financial savings, greater self-sufficiency, and strengthened civic responsibility.

In response to the growing financial burden, municipalities are seeking new motivational and systemic approaches. Some are introducing volume-based charging systems that encourage residents to reduce the generation of mixed municipal waste, while others make use of grant programmes (for example Operational Programme Environment and National Recovery Plan) to invest in waste collection centres, composting facilities, and biowaste infrastructure. An important trend is the development of inter-municipal cooperation, which makes it possible to share costs, optimise collection systems, increase the effectiveness of implemented measures, and achieve economies of scale.

Rising costs of operating waste management systems confirm that waste prevention, including food waste prevention, represents the most economically and environmentally effective strategy.

Long-term support for waste separation, reduction of mixed municipal waste volumes, public education, and, in particular, a strong emphasis on waste prevention can significantly contribute to increasing municipal revenues from waste management while simultaneously reducing the overall burden on municipal budgets. More efficient waste management thus represents not only an environmental but also an economic benefit for municipalities of all sizes.

From the perspective of food waste issues, the following concise conclusions can be defined on the basis of experience and available information to date:

— At present, there are two types of end facilities for the treatment of food waste in the Czech Republic: biogas plants and composting facilities. As stated in the analytical section of the Waste Management Plan of the Czech Republic for 2025–2035, with regard to the planned national targets, current capacities are insufficient. Investments in infrastructure will therefore be unavoidable in the coming years.
— Analyses of MSW carried out by the author team show that the proportion of BMW, which includes food waste, still accounts for around 40 % by weight, despite the fact that the separate collection of BMW at the municipal level has been in place since 2019.
— The analyses also show that even municipalities with relatively substantial information campaigns and financial incentives aimed at increasing the separate collection of BMW and catering waste have, in many cases, not yet achieved a significant reduction of these waste streams in MSW.
— For the prevention of food waste at the municipal level, continuous influence on citizens' behaviour is essential. However, despite considerable effort on the part of municipalities, effectiveness may remain low. In the future, increased pressure can be expected for greater financial incentives for responsible citizens who are actively engaged in the system.
— To improve the current situation, long-term and systematic support for municipalities by the state is absolutely essential. The most important aspects include providing information on examples of good practice, creating sharing mechanisms, standardising procedures, integrating the topic into the education system, publishing data and case studies, supporting effective systemic solutions, providing grant support, and ensuring mutual communication when planning new legislation and setting national targets in relation to municipalities.
— For Czech municipalities, it is advisable to start with measures that require low capital investment but deliver a high local impact. It is necessary to assess the local situation (MSW analyses, citizen participation) and to select appropriate technologies and approaches (home or community composters, collection systems, mobile applications). Available grant programmes and funding schemes should be actively utilised, and networks of cooperation should be established (for example between municipalities, associations, non-profit organisations, food banks, and farmers) to share experience and optimise costs.
— Among preventive measures, composting activities (home, community, and school-based) and food redistribution have proven to be relatively effective.
— Municipal budgets are coming under increasing pressure due to the growing demands of waste management and the circular economy. For small municipalities, one possible solution appears to be their grouping into larger units with greater bargaining power vis-à-vis collection companies and entities involved in the treatment of waste, including (but not limited to) food waste.
— The development of waste prevention systems and efficient management of biowaste delivers synergistic benefits: it reduces the carbon footprint, improves soil quality through the return of organic matter, supports the local

economy, and contributes to meeting the objectives of European strategies such as Fit for 55, the European Green Deal, and the United Nations Sustainable Development Goal No. 12 (Sustainable Development Goal 12 – Responsible Consumption and Production). Sustainable and self-sufficient waste management thus becomes not only an environmental, but also a strategic pillar of development for Czech municipalities.

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Current approaches to determining flood hazard in river confluence areas

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Keywords: hydraulic calculation — 2D numerical model — flood hazard — confluence

ABSTRACT

The study focuses on assessing changes in runoff conditions and approaches to determining flood hazard in confluence areas of river systems. Based on the analysis of several model catchments, the results of numerical simulations of water flow during floods with different return periods are presented. The analyses revealed that separate modelling of the main river and its tributaries produces distorted results, as the hydraulic conditions in confluence areas are characterized by complex interactions between individual streams. Therefore, the authors recommend a comprehensive approach using 2D numerical models, which allow for more accurate evaluation of inundation extent, water depths, and flow velocities. The study results include proposals for updating the methodological guidelines of the Ministry of the Environment, emphasizing a unified approach to the development of flood hazard and risk maps.

INTRODUCTION

The catastrophic floods of 1997, which primarily affected the Morava and Oder river basins, represented a major shock for most of society. In an effort to increase preparedness for similar events and to reduce their impacts in the future, the Flood Protection Strategy for the Territory of the Czech Republic was approved by the Government of the Czech Republic in 2000 [1]. The aim of this document was to establish a framework for defining specific procedures and preventive measures to enhance systemic flood protection in the Czech Republic. One of these measures was defined as the delineation of floodplain extents based on the preparation of a detailed digital terrain model.

At present, the method for delineating floodplains is defined by Decree No. 79/2018 Coll. [2] on the method and scope of preparing proposals for, and establishing, floodplains and their documentation. According to the Decree, a floodplain is delineated by the flood line corresponding to a flood with a return period of 100 years. The extent of the assessed area corresponds to the hydraulic conditions of a continuous reach of a watercourse and its inundation area and takes into account the officially designated floodplain. For the inundation area of each watercourse reach, flood hazard maps are prepared for floods with return periods of 5, 20, 100, and 500 years; these maps depict the extent of inundation, flow depths, and flow velocities. In 2025, floodplains in the Czech Republic were designated for 16,889 km of watercourse reaches.

EU Directive 2007/60/EC on the assessment and management of flood risks (hereinafter referred to as the Floods Directive) also requires Member States, inter alia, to prepare flood hazard and flood risk maps for areas with potentially significant flood risk. Flood hazard is defined by the extent of inundation, flow depths, and flow velocities; in the Czech Republic, flood hazard maps are prepared for floods with return periods of 5, 20, 100, and 500 years. Maps prepared in accordance with the requirements of the Floods Directive are updated in six-year cycles (for the first time in 2013). The extent of watercourses mapped in this way is significantly smaller than that of designated floodplains; in 2025, it covered just under 3,000 km of watercourses.

Procedures for fulfilling the requirements of the Floods Directive are described in the Methodology for the Preparation of Flood Hazard and Flood Risk Maps ([3], hereinafter referred to as the Methodology). This Methodology defines how the outputs of standard hydraulic models (flood extent, flow depths, and flow velocities) are to be represented in hazard maps and how these outputs are then used to prepare flood risk maps. The intention of the Methodology was not to standardise hydraulic modelling procedures, as this is a broad and complex topic that should be addressed in a separate document.

During preparations for the production of flood hazard and flood risk maps within the first planning cycle, a pilot study was carried out in 2011. This study outlined possible approaches to hydrodynamic modelling of watercourse confluences and proposed procedures for calculating flow parameters in these confluence areas [4]. The study divided the issue of modelling confluence areas into three basic schemes:

1. The hydraulic calculation is carried out only on the tributary, while water levels for the required *N*-year discharges are known on the main watercourse. The hydrodynamic model of the tributary is constructed independently, without considering the influence of the main watercourse.
2. The hydraulic calculation is carried out only on the tributary, while the model of the main watercourse has already been developed previously. The results of the previously prepared model of the main watercourse serve as boundary conditions for the tributary model. Outputs from the tributary model must be in a format compatible with that of the main watercourse model so that the two can be seamlessly integrated.
3. Both a tributary model and a main watercourse model are prepared. The models do not have to be schematised using the same approach (1D or 2D), do not have to be developed within the same modelling environment, and do not have to be prepared by a single contractor.

The aforementioned study [4] discusses the last variant in detail. It states that the simplest situation arises when the models for both watercourses are prepared by a single contractor within one computational environment and a single model is created for the entire confluence area. In such a case, the calculation is relatively straightforward, with the only challenge being the correct specification of boundary conditions.

In cases where each watercourse is modelled using a different schematisation, or by a different contractor, the study proposes addressing this situation by selecting an appropriate connection point for linking the two models on the tributary upstream of the confluence. This point should allow the transfer of boundary conditions from the main watercourse model to the tributary model. The outcome of this approach should be unified outputs of the flood hazard map characteristics (extent of inundation, depths, and velocities) covering the modelled confluence area without overlapping areas [4].

However, the two completed planning cycles under the Floods Directive have shown that this approach has not always been applied. Some confluence areas were modelled separately for the main watercourse and for tributaries, even though the entire confluence area was prepared by the same contractor. As a result, maps exist that display, within the confluence area, modelling outputs for only one watercourse at a time. This manner of presentation significantly reduces the informative value of flood hazard information for both professional users and the general public, as there is no clear overview of inundation extent, depths, and flow velocities across the entire confluence area simultaneously.

This paper analyses examples of hydraulic models of selected confluences, and on the basis of the results obtained, recommendations will be formulated for updating the Methodology and other methodological procedures of the Ministry of the Environment (MoE).

METHODOLOGY

The procedures proposed within the pilot project [4] reflect the state of knowledge at the time of their development approximately 14 years ago and, from today's perspective, some of them may be considered outdated. At present, hydraulic calculations of water flow in floodplains are carried out predominantly using 2D numerical models. The basic prerequisites for valid modelling of confluence areas are as follows:

4. From a hydraulic perspective, confluence areas are typically characterised by complex flow regimes; for this reason, it is desirable to model them using 2D numerical models that encompass the main watercourse, the inundation area, and any tributaries.

5. Combining different numerical model dimensions (1D and 2D) is undesirable; if the combination of different models is unavoidable, the connection between individual models should be implemented at a location where the flow is no longer influenced by the confluence area.

6. The connection and merging of results in the confluence area from different contractors is possible; however, a more reliable approach is to develop a single hydraulic model for the entire confluence area.

The following text presents three case studies that demonstrate different approaches to the treatment of confluence areas. These involve selected reaches of watercourses with significant flood risk, delineated within the 3rd planning cycle in accordance with the requirements of the Floods Directive:

- DYJ 09 Svitava, Křetínka, Třebětínka, Kladorubka,
- MOV 10 Valová, Hloučela, Romže, Český potok,
- MOV 01 Morava, Olšava, Dlouhá řeka, Okluky.

The hydrodynamic calculation was carried out using a 2D shallow-water flow model [13, 14]. The simulation results describe steady-state conditions of depth-averaged flow velocities and water depths for individual flood scenarios with an average return period of *N* years. For comparison of the calculation results, historical flood hazard data prepared within previous planning cycles [5] or as part of studies of runoff conditions and floodplains [8–12] were used. The case studies focus on issues related to confluence areas from the perspective of the availability of hydrological data (DYJ 09, MOV 10) and the possibilities for merging flood hazard data [5] derived using different computational approaches or prepared by different contractors (MOV 01).

DYJ 09 Svitava, Křetínka, Třebětínka, Kladorubka

The case study of reach DYJ 09 focuses on the procedure for determining upstream boundary condition (UBC) values in the given confluence area. The conceptual model is shown in *Fig. 1*, including the locations of upstream (UBC) and downstream (DBC) boundary conditions. At the UBC, the discharge *Q(t)* and the energy line slope I_E are defined. At the DBC boundary, a rating curve *h(Q, t)* is specified. The confluence model requires the definition of UBCs for individual flood scenarios on the delineated reaches as the corresponding value of the peak discharge Q_N on the selected watercourse and discharge contributions from related tributaries in the area [4].

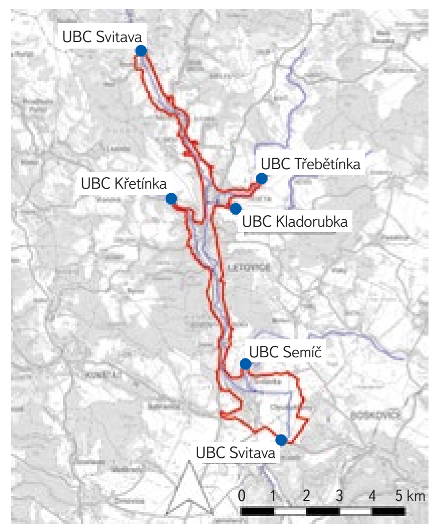

Fig. 1. Conceptual model DYJ 09

The procedure for determining all UBCs is documented for the loading scenario from the Svitava river at discharge Q_N. The hydrological profile closest to the downstream boundary condition (DBC) on the Svitava is Svitava – below Semíč (A) (*Fig. 2*). Similarly, the closest profile upstream of the confluence is Svitava – above Semíč (C). The discharge contribution from the UBC at Semíč can be derived according to [4] as follows:

$$\text{UBC Semíč} = Q_N(A) - Q_N(C) \qquad (1)$$

where:

$Q_N(A)$ is a value of the *N*-year peak discharge at the relevant profile A (*Fig. 2*).

Svitava – Rozhraní is the nearest profile in the upstream reach of the model above the confluence (*Fig. 2*). According to [4], the discharge contributions from the individual UBCs within the reach (*Fig. 2*) should satisfy the following condition:

$$\text{UBC Křetínka} + \text{UBC Kladorubka} + \text{UBC Třebětínka} = Q_N(C) - Q_N(G) \qquad (2)$$

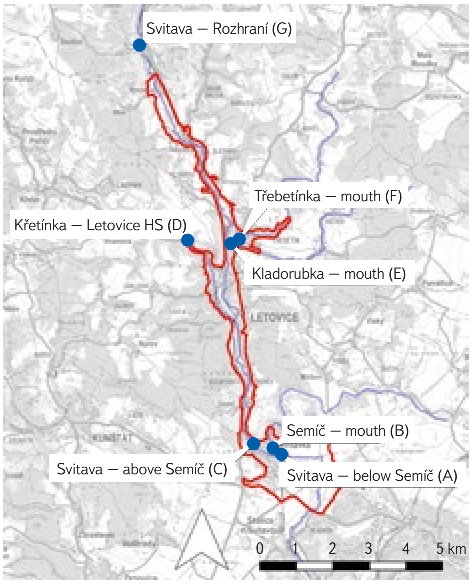

Fig. 2. Hydrological data at the confluence of Svitava – Semíč, Křetínka, Kladorubka, Třebětínka

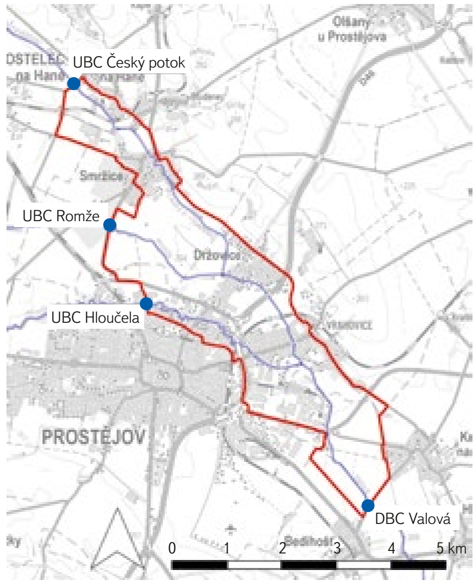

Fig. 3. Conceptual model MOV 10

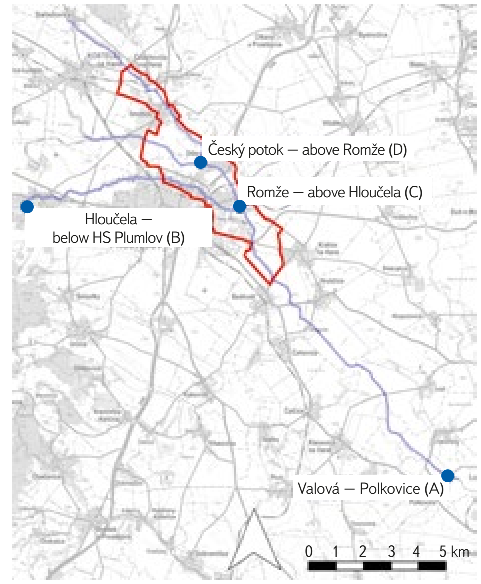

Fig. 4. Hydrological data at the confluence of Valová – Hloučela, Romže, Český potok

Given the number of unknowns in the equation for this reach, the method described in [4] cannot be applied, and the discharge contributions must be derived using alternative approaches. In the case study, a method based on the ratio of individual Q_N values was selected, derived from the following equations:

$$\text{UBC Křetínka} = [(Q_N(C) - Q_N(G)) / (Q_N(D) + Q_N(E))] \cdot Q_N(D) \quad (3)$$

$$\text{UBC Kladorubka} + \text{UBC Třebětínka} = [(Q_N(C) - Q_N(G)) / (Q_N(D) + Q_N(E))] \cdot Q_N(E), \quad (4)$$

which allows the determination of UBC values using the following equations:

$$\text{UBC Kladorubka} = [(\text{UBC Kladorubka} + \text{UBC Třebětínka}) / (Q_N(E) + Q_N(F))] \cdot Q_N(E) \quad (5)$$

$$\text{UBC Třebětínka} = [(\text{UBC Kladorubka} + \text{UBC Třebětínka}) / (Q_N(E) + Q_N(F))] \cdot Q_N(F) \quad (6)$$

MOV 10 Valová, Hloučela, Romže, Český potok

The case study of reach MOV 10 documents, analogously to the DYJ 09 reach, the procedure for determining UBCs for the given confluence area (*Fig. 3*).

The determination of all UBCs is carried out for the loading scenario Q_N from Český potok. The hydrological profile closest to the DBC on the Svitava is Valová – Polkovice (A) (*Fig. 4*). The discharge contribution from the UBC on the Hloučela will be:

$$\text{UBC Hloučela} = Q_N(A) - Q_N(C) \quad (7)$$

The discharge contribution from the UBC on the Romže can be determined as:

$$\text{UBC Romže} = Q_N(C) - Q_N(D) \quad (8)$$

Similarly, for the loading scenario Q_N from the Romže, the discharge contribution for the Hloučela UBC can be derived according to equation (7). Given the absence of hydrological data for the Romže upstream of its confluence with the Český potok, the discharge contribution from the UBC on the Český potok can be conservatively assumed to be zero:

$$\text{UBC Český potok} = 0 \text{ m}^3/\text{s} \quad (9)$$

The UBC on the Romže will then take the value of the corresponding loading scenario Q_N. When using the Q_N ratio approach, the UBCs for the Český potok and the Romže can be determined from the following equations:

$$\text{UBC Český potok} = Q_N(C) / (Q_N(C) + Q_N(D)) \cdot Q_N(D) \quad (10)$$

$$\text{UBC Romže} = Q_N(C) / (Q_N(C) + Q_N(D)) \cdot Q_N(C) \quad (11)$$

For the loading scenario Q_N from the Hloučela, the discharge contributions can be derived as:

$$\text{UBC Romže} + \text{UBC Český potok} = Q_N(A) - Q_N(B) \quad (12)$$

Using the Q_N ratio, the discharge contributions between the Romže and the Český potok can be determined as:

$$\text{UBC Romže} = (\text{UBC Romže} + \text{UBC Český potok}) / (Q_N(C) + Q_N(D)) \cdot Q_N(C) \quad (13)$$

$$\text{UBC Český potok} = (\text{UBC Romže} + \text{UBC Český potok}) / (Q_N(C) + Q_N(D)) \cdot Q_N(D) \quad (14)$$

MOV 01 Morava, Olšava, Dlouhá řeka, Okluky

The case study of reach MOV 01 presents possibilities for merging flood hazard data in a confluence area derived from inputs prepared by different contractors (see areas A, B, and C in *Fig. 5*), in all cases using 2D models. The analysed reach is significantly influenced by the confluence of the Morava river with the Olšava, Okluky, and Dlouhá řeka. The objective of the work was to create continuous datasets from the partial flood hazard maps [5] for the individual sub-areas A, B, and C.

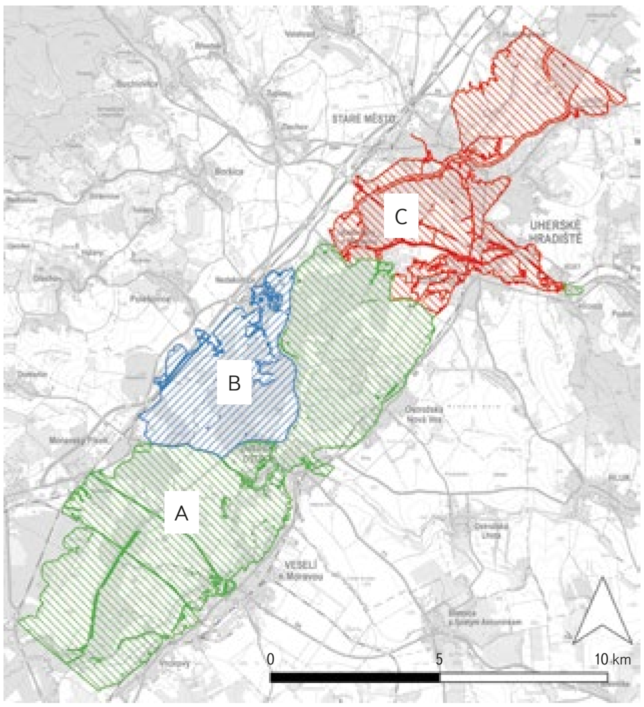

Fig. 5. River section MOV 01 with indication of sub-areas A, B, C calculated by different authors

The merging of inundation maps was carried out in the following steps and is demonstrated using the Q_{500} scenario as an example; the same procedure can be applied identically to the other Q_N scenarios:

1. The updated areas B and C were removed from the historical results for area A (see *Fig. 6*). The boundaries of polygons B and C were suitably selected at locations where approximately one-dimensional flow could be assumed (channel flow, embankment overtopping, flow through bridges and culverts).
2. The updated areas B and C were clipped to the extent of polygons B and C only. The resulting partial map for Q_{500} corresponds to *Fig. 6*.
3. At the contact lines between polygon boundaries, the datasets were merged and any singularities were removed (*Figs. 7* and *8*).

Based on the inundation maps processed in this way, the raster hazard maps (water depths, flow velocities, and water surface elevations) can subsequently be adjusted. The adjustments were carried out in the following steps:

1. Clipping the raster maps to the extent of the polygons of areas A, B, and C.
2. Merging the clipped raster layers.
3. Filling missing data in the rasters using bilinear interpolation (*Fig. 9*).

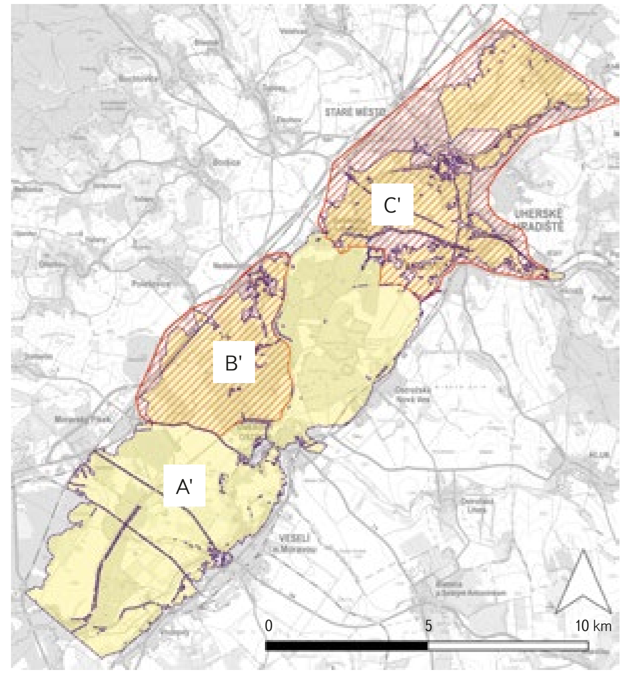

Fig. 6. The extent of data exclusion in the locations of updated areas B and C

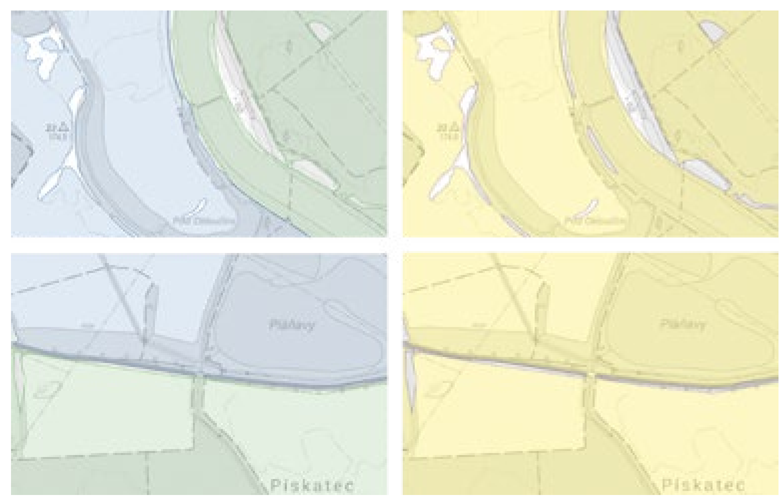

Fig. 7. Examples of polygon boundary merging between areas A and B

Fig. 8. Examples of polygon boundary merging between areas A and C

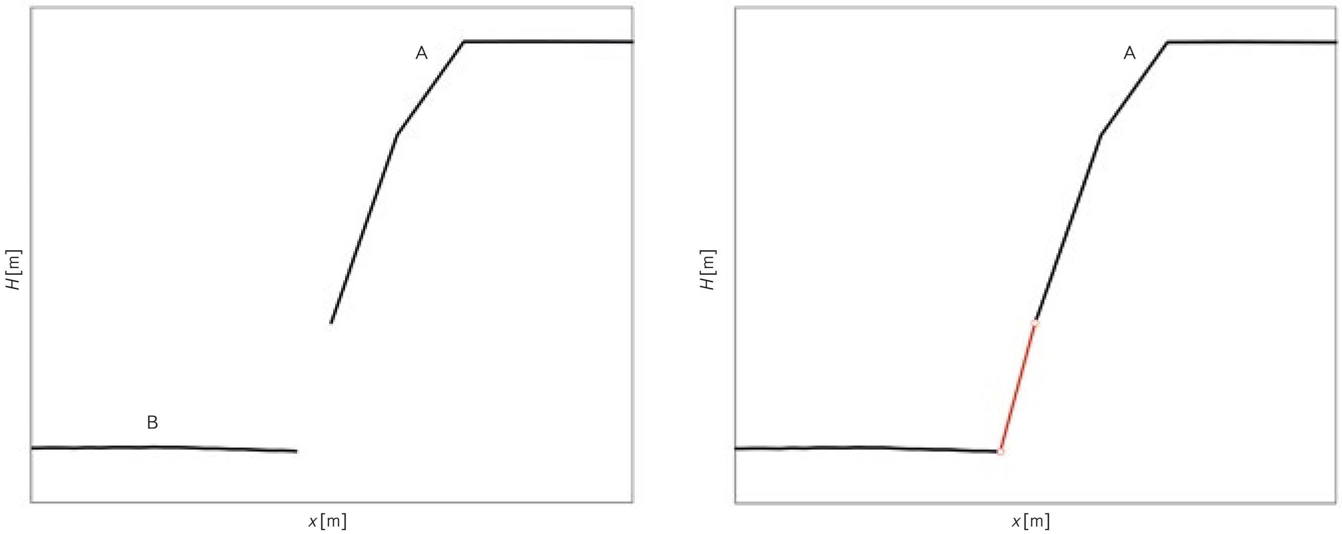

Fig. 9. Example of using bilinear interpolation to fill in missing values of level *H* during connection of sections A and B

RESULTS AND DISCUSSION

DYJ 09 Svitava, Křetínka, Třebětínka, Kladorubka

In this case, the confluence area is more complex than that considered in the LABEL pilot project [4]. Complete hydrological data were not available for all confluence profiles, in particular upstream and downstream of the analysed confluences. The missing hydrological data required for specifying boundary conditions had to be derived using equations (1) to (6).

The selected area cannot be addressed without considering the significant tributaries of the Svitava river. Given the relatively complex hydraulic conditions, it was necessary to treat the area as a whole using a 2D hydrodynamic model. The 2D model of the confluence area yields markedly different results compared to historical data that did not consider tributaries (*Figs. 10–12*).

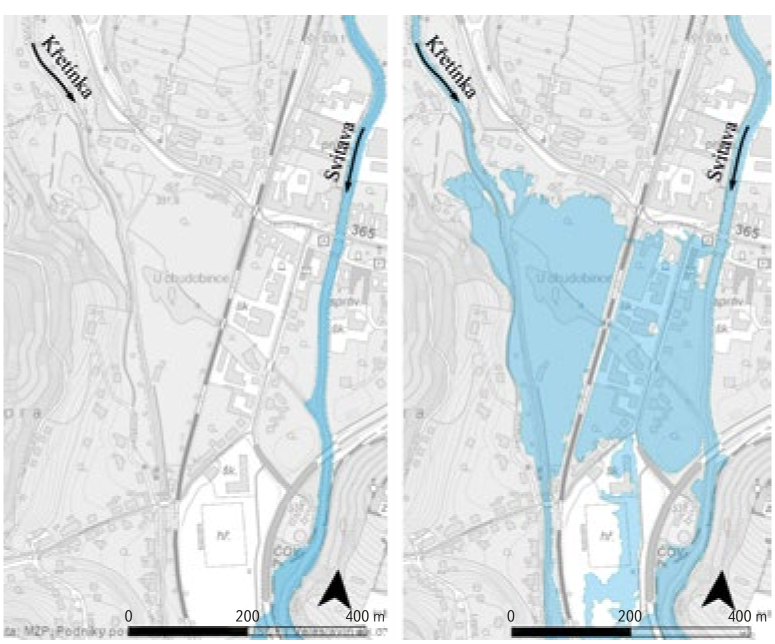

Fig. 10. Flood scenario with return period Q_{20} on confluence of the Svitava and Křetínka rivers; left – without confluence effect [6], right – with confluence

Fig. 11. Flood scenario with return period Q_{20} on confluence of the Svitava – Kladorubka and Křetínka rivers; left – without confluence effect [6], right – with confluence

Fig. 12. Flood scenario with return period Q_{100} on confluence of the Svitava – Kladorubka and Křetínka rivers; left – without confluence effect [6], right – with confluence

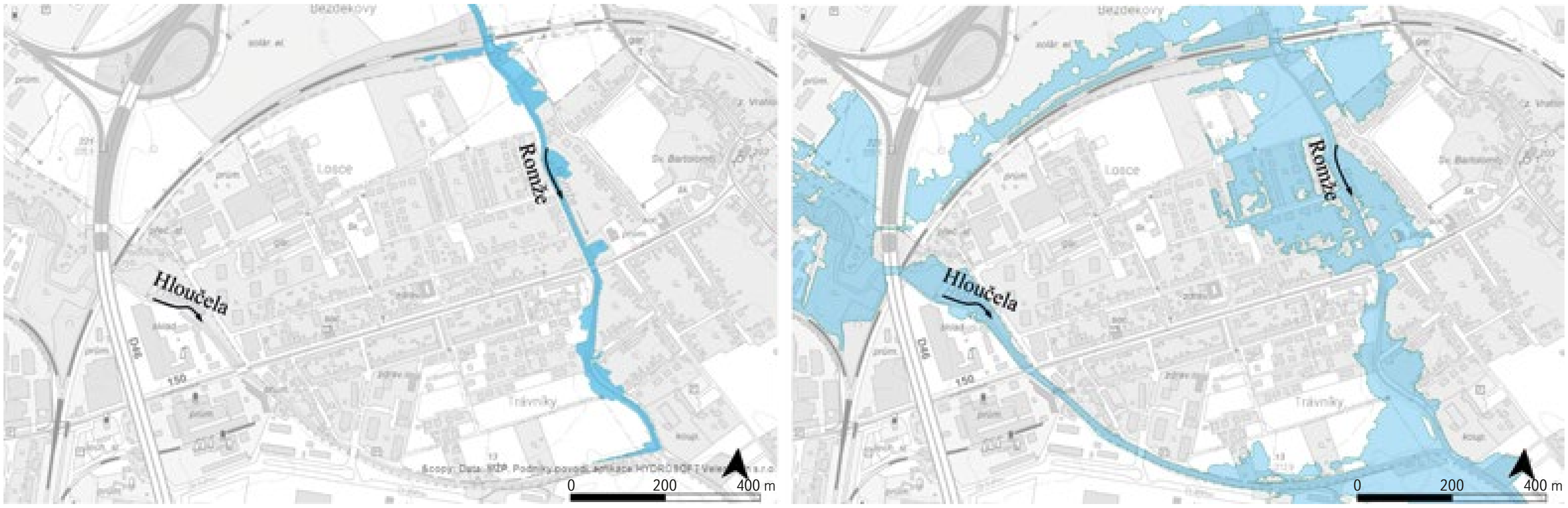

Fig. 13. Flood scenario with return period Q_{20} on confluence of the Hloučela – Romže rivers; left – without confluence effect [6], right – with confluence

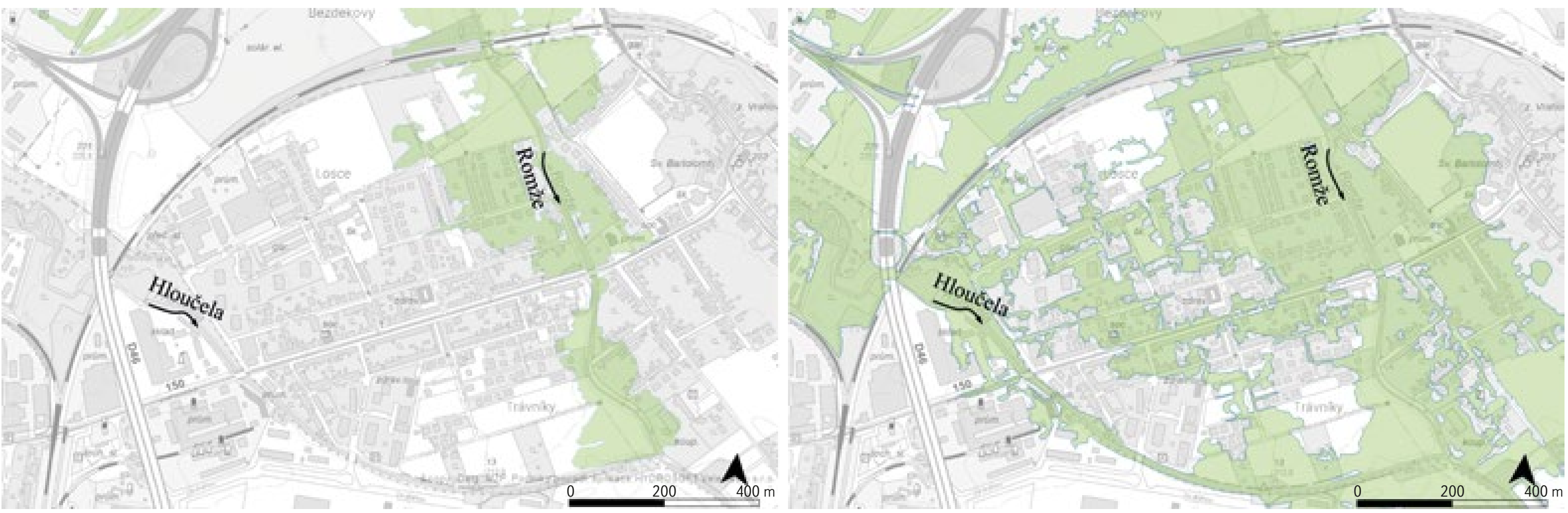

Fig. 14. Flood scenario with return period Q_{100} on confluence of the Hloučela – Romže rivers; left – without confluence effect [6], right – with confluence

MOV 10 Valová, Hloučela, Romže, Český potok

In the analysed area, it was not possible to apply the procedures for determining UBCs according to [4], primarily due to the unavailability of some hydrological data for all confluence profiles. The UBCs were therefore derived using equations (7) to (14).

Given the complex hydraulic conditions (for example, water transfers between the individual reaches), the area had to be treated as a whole (*Figs. 13* and *14*).

MOV 01 Morava, Olšava, Dlouhá řeka, Okluky

The pilot area confirmed that merging data produced by different contractors in confluence areas is feasible, but only under relatively strict conditions. Fundamentally important is particularly the existence of suitable profiles for linking the partial reaches. It is also desirable to maintain consistent parameters of the computational models (boundary conditions, surface roughness, and the digital terrain model). When connecting raster layers, it must be taken into account that profiles with completely identical values generally cannot be found, which necessitates creating transition zones and completing missing data, for example using simple bilinear interpolation. In view of the above, the linking of partial reaches in confluence areas should be regarded as a marginal solution and applied only in justified cases.

CONCLUSION

The quantification of flood hazard in confluence areas represents a time- and cost-intensive process, not only in terms of the hydraulic calculations themselves but also with regard to securing the necessary extent of required hydrological data. Hydraulic solutions based on 2D models typically require the creation of relatively extensive computational domains with a large number of calculation elements. In confluence areas involving multiple watercourses, this is further compounded by the need to perform a large number of simulations for partial scenarios with different combinations of boundary conditions.

Despite the above-mentioned challenges, it can be unequivocally recommended that confluence areas be modelled as a whole, without subdivision into separate individual watercourse reaches. The conducted case studies demonstrated that mutual interactions of flow between individual watercourses can have a fairly substantial influence on flood hazard values.

The conclusions presented will be incorporated into Chapter 4.9, Hydraulic calculations for the purposes of floodplain delineation, of the Methodology for the preparation of flood hazard and flood risk maps.

Acknowledgements

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Atmospheric deposition of polycyclic aromatic hydrocarbons in the pilot catchment area of Výrovka and urban areas of Prague and Ostrava

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Keywords: atmospheric deposition — polycyclic aromatic hydrocarbons — pollution — fingerprinting

ABSTRACT

Atmospheric deposition is the most significant source of polycyclic aromatic hydrocarbons (PAHs) in surface waters in the Czech Republic. These substances originate predominantly from combustion processes. Through deposition, PAHs reach the Earth's surface and are subsequently washed into surface waters. Although the state and the private sector have implemented a number of measures in recent decades to reduce emissions, not only from major pollution sources but also from households (local heating), these substances continue to have a significant impact on the aquatic environment. Selected PAHs are included on the list of priority substances due to their proven adverse effects on aquatic organisms and human health, and strict environmental quality standards have been set for them in surface water and biota matrices. Consequently, most surface water bodies do not achieve good chemical status according to the Water Framework Directive 2000/60/EC. Research in the Výrovka river basin (a tributary of the Elbe river) comprehensively addressed PAH contamination in relevant matrices of the aquatic environment and in Schreber's big stem red moss (*Pleurozium schreberi*), which is a suitable indicator of air pollution. At the same time, PAH fluxes in wet deposition in selected urban locations were monitored for comparison. The origin of PAHs was assessed using fingerprinting, based on the analysis of ratios between individual PAHs in the monitored matrices, enabling the distinction between petrogenic and pyrogenic sources.

INTRODUCTION

Polycyclic aromatic hydrocarbons (PAHs) are ubiquitous substances in the environment [1]. Their presence is due not only to the widespread use of substances and final products containing PAHs, but primarily to combustion processes, during which PAHs are formed by the incomplete combustion of fossil fuels and organic materials [2]. Primary emissions of PAHs into the atmosphere occur predominantly in the gaseous phase; however, relatively rapid condensation and sorption onto fine particulate matter take place as flue gases cool. The rate of sorption increases with increasing molecular weight [3], while very strong particle sorption and hydrophobicity are characteristic of PAHs with three or more aromatic rings. PAHs reach the Earth's surface through atmospheric deposition. Only a portion of them is subsequently transferred into surface waters by erosion, as confirmed in the model catchments of the Suchý and Martinický streams [3]. A substantial proportion of PAHs remains bound to the Earth's surface (vegetation, soil). In soils, PAHs undergo degradation at different rates depending on the specific hydrocarbon. This process is fastest in the case of naphthalene, which, due to its physicochemical properties, deviates from the behaviour of other PAHs; its DT_{50} is reported to be 6.1 weeks. In higher-molecular-weight PAHs, degradation is substantially slower: 168 weeks for benzo(a)pyrene and 522 weeks for benzo(k)fluoranthene [4].

Another important source comprises point and diffuse sources of pollution, including stormwater overflows of public sewer systems. PAHs enter waters both through runoff from impervious surfaces associated with roads and traffic [5] and from areas treated with coating materials and polyaromatic-based waterproofing products, as well as from the combustion of fossil fuels and smoking; according to Skupinská [6], a single cigarette releases 20–40 ng of benzo(a)pyrene into the environment.

Many PAHs exhibit toxic properties affecting aquatic organisms, animals, birds, and humans; mutagenic, carcinogenic and teratogenic effects, as well as adverse impacts on the immune system, have been demonstrated [7]. For these reasons, selected PAHs were classified as priority substances for the aquatic environment and designated as priority hazardous substances under Directive 2008/105/EC of the European Parliament and of the Council, as amended by Directive 2013/39/EU [8, 9]. Current environmental quality standards (EQS) are in the order of nanograms per litre; the strictest standard applies to the carcinogenic benzo(a)pyrene, at 1.7×10^{-4} µg · L^{-1} (annual average). The forthcoming amendment to Directive 2008/105/EC of the European Parliament and of the Council extends the list of PAHs for which environmental quality standards are established; some of these standards are revised, and a new comparison with EQS recalculated to a benzo(a)pyrene ecotoxicity equivalent is introduced. Although the environmental quality standard expressed as an annual average is abolished, a value at a comparable concentration level is newly established for fluoranthene (a tightening from the current 6.3×10^{-3} µg · L^{-1} to 7.62×10^{-4} µg · L^{-1}). For the above reasons, it remains necessary to continue addressing PAH emissions and their impacts on the environment and the status of waters.

The following article focuses on the assessment of PAH concentrations in atmospheric deposition, in Schreber's big red stem moss (*Pleurozium schreberi*), and in other environmental matrices within the Výrovka model catchment. It also presents a comparison with PAH loads from wet deposition in an urbanised environment.

Based on the ratios of individual PAHs, their origin was also assessed. For the purposes of this article, two main categories of pollution sources were considered: petrogenic (PETRO) and pyrogenic (PYRO).

The purpose of this comparison is to contribute to understanding the sources and pathways through which PAHs enter surface waters, where they lead to the failure to achieve good status under the Water Framework Directive. The Czech Republic ranks among the countries with the highest proportion of water bodies failing to achieve good status due to PAHs. This is associated with an obligation to implement measures aimed at reducing their inputs. In the model catchment, a substance balance was established with the objective of comparing atmospheric deposition of PAHs with their substance export under typical agricultural landscape conditions. The inclusion of additional matrices and sites was intended to confirm further risk factors and to address the following questions:

1. What is the PAH load from atmospheric deposition (short-term – precipitation, and long-term – moss and humus), and how is it influenced by additional factors such as urbanised areas, traffic, and industry?
2. What is the relationship between atmospheric deposition of PAHs and their occurrence in the watercourse – is there an influence of rainfall–runoff events? What proportion of deposited substances is exported from the catchment, and what proportion is retained by the environment?
3. Which PAH source is dominant for the aquatic environment, and how does the composition of PAHs differ among individual matrices?

METHODOLOGY

PAHs were monitored and evaluated that contribute to the failure to achieve good status of water bodies and at the same time exhibit a significant potential for long-range atmospheric transport, often over considerable distances from primary pollution sources.

For the purposes of the project, the Výrovka catchment was selected, specifically its upper part upstream of Plaňany hydrological station (operated by the Czech Hydrometeorological Institute; CHMI).

The Výrovka is a left-bank tributary of the Elbe, and its catchment lies entirely within the Central Bohemian Region. The part of the catchment upstream of the Plaňany profile covers an area of 264.35 km^2 and consists of 30 fourth-order sub-catchments. Catchment elevation ranges from 208 to 550 m a.s.l. The hydrographic network has a total length of 362 km of watercourses and includes 70 reservoirs.

According to data from the Land Parcel Identification System (LPIS), there is 19,000 ha of agricultural land within the area of interest, of which 94 % consists of arable land. The main crops that were the most widely cultivated in 2022 included winter wheat, winter oilseed rape, maize, spring barley, and sugar beet.

To compare the distribution of PAHs across different components of the environment, the following matrices were sampled:

- wet deposition in an open area (bulk) – monthly precipitation, 2021–2022,
- throughfall deposition – monthly precipitation, 2021–2022,
- surface water – grab sampling once per month, 2021–2022,
- suspended sediment load – daily composite sample, 2021–2023,
- suspended sediment contamination – centrifuged sample, 2021–2023,
- humus (biologically stable humified layer) – after removal of the litter and fermentation layers; two samplings at 10 sites, samples representing a longer time period (sampling in 2021 and 2022),
- Schreber's big red stem moss (*Pleurozium schreberi*) – two samplings at 10 sites, samples representing a longer time period of approximately three years (sampling in 2021 and 2022).

The Výrovka model catchment, with the location of the gauging station and sampling sites for individual matrices, is shown in *Fig. 1*.

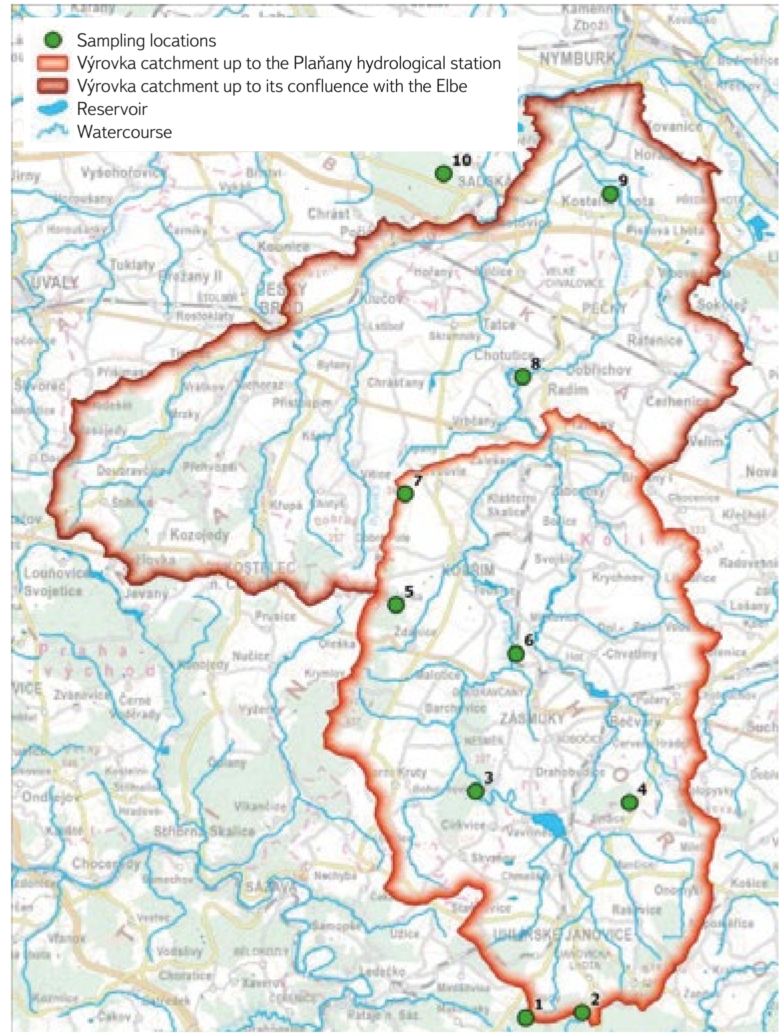

Fig. 1. Výrovka river catchment with locations of surface water and atmospheric deposition sites

Atmospheric deposition was collected using stainless steel rain gauges with a collection area of 52.4 cm^2 in order to obtain a sufficient sample volume for the analytical determination of PAHs (2,000 mL). The upper part of the rain gauges was fitted with a stainless steel bowl with 3 mm diameter openings to prevent the deposition of coarse particles and the ingress of insects. If an insufficient amount of precipitation was recorded in a given month, the sample was collected after a two-month exposure period. Monitoring of atmospheric deposition was carried out from June 2021 to June 2022 in an agricultural landscape between the municipalities of Třebovle and Klášterní Skalice. A second site was selected in a forest stand west of the municipality of Zásmuky (*Fig. 1*), where two rain gauges were installed (bulk and throughfall).

The volume of collected precipitation during individual sampling campaigns was measured and compared with precipitation totals for the same period obtained from the nearest CHMI climatological stations, namely Cerhenice and Vavřinec–Žíšov rain gauge stations. The mean monthly discharge for the Výrovka was calculated from mean daily discharges at the CHMI gauging profile No. 082000 – Výrovka–Plaňany, that is, at the same profile where surface water and suspended sediment sampling was carried out.

From the amount of precipitation and the determined concentrations of the monitored PAHs in precipitation, an estimate of the total atmospheric deposition for the Výrovka catchment was calculated. The calculation used concentration results of PAHs in deposition collected in an open area (bulk sampling). The annual substance export of individual PAHs by the watercourse was calculated by multiplying the mean monthly discharge by their measured concentrations in surface water. The daily substance export of PAHs associated with suspended sediment was derived from daily concentrations of total suspended solids multiplied by the mean value of the sum of PAHs measured in eight suspended sediment samples (2,161 $\mu g \cdot kg^{-1}$).

To compare the occurrence of PAHs in atmospheric precipitation in a highly urbanised environment, sites in Prague-Podbaba (within the TGM WRI premises) and Ostrava-Přívoz were selected at the end of 2021. At these sites, monthly bulk and throughfall precipitation sampling was carried out from December 2021 to October 2023.

The TGM WRI premises in Prague are located on the northern edge of the city between the heavily trafficked Podbabská road and the Vltava river, which flows around the central wastewater treatment plant. In the Ostrava-Přívoz district, rain gauges were installed on the roof of a garage belonging to the TGM WRI Ostrava Branch (bulk) and within the grounds of a nearby kindergarten on Špálova Street (throughfall). Approximately 1 km north of both monitoring stations is the Svoboda coking plant, and 3 km to the south-west are the BorsodChem MCHZ chemical works.

In aqueous samples, 15 PAHs (*Tab. 1*) were analysed using liquid chromatography on an Agilent 1260 Infinity II instrument with fluorescence detection. Separation was achieved using a Pinnacle II PAH column (4 µm, 150 × 4.6 mm, Restek) and a mobile phase composed of components A: methanol and B: water with the addition of 5 % methanol.

Tab. 1. List of analyzed PAHs and their abbreviations

Compound	Abbreviation	Compound	Abbreviation
Naftalene	NAP	Benzo[a]antracene	BAA
Acenaftylene	ACY	Chrysene	CHR
Acenaftalene	ACN	Benzo[b]fluorantene	BBF
Fluorene	FLU	Benzo[k]fluoranthene	BKF
Fenanthrene	FEN	Benzo[a]pyrene	BAP
Anthracene	ANT	Dibenzo[a,h]anthracene	DBA
Fluoranthene	FLT	Benzo[g,h,i]perylene	BGP
Pyrene	PYR	Indeno[1,2,3-cd]pyrene	INP

PAHs in moss and humus samples were analysed using gas chromatography with a triple quadrupole EVOQ GC-TQ (Bruker) by mass spectrometry in MS/MS mode.

Schreber's big red stem moss (*Pleurozium schreberi*) was collected during two sampling campaigns in spring 2021 and summer 2022 at 10 sites within the Výrovka catchment, and in 2023 at varying distances from road II/611 (Poděbradská) and the D11 motorway (Hradecká) west of the municipality of Sadská, in open areas (without the influence of throughfall deposition).

Samples for PAH determination were collected in aluminium foil bags. The bags were transported to the laboratory in an in-vehicle cooling box and subsequently stored in a freezer. Prior to analysis, frozen samples were gradually manually cleaned of unwanted impurities, and the green apical parts of the moss were separated for analysis. The green moss tissues were ground in a vibratory mill under liquid nitrogen and subsequently dried by vacuum lyophilisation. They were then analysed by liquid chromatography with MS/MS detection.

Humus samples were collected, transported, and stored until analysis in the same manner as moss samples. Frozen humus samples were sieved through a steel sieve with a mesh size of 2.00 mm, dried by lyophilisation, and analysed in the same way as moss.

To determine the origin of PAHs, published diagnostic ratios between selected PAHs were used to estimate their petrogenic or pyrogenic origin.

RESULTS

PAH concentrations in collected precipitation water varied considerably over the course of the year (*Fig. 2*). The results show a clear monthly pattern of PAH contamination in precipitation, as well as a marked difference between the winter and summer periods. The increase in PAH concentrations during winter is primarily influenced by local heating sources, depending on meteorological conditions. Among individual PAH compounds, fluoranthene, phenanthrene, pyrene, and benzo[a]pyrene predominated in atmospheric precipitation. Comparison of the summed PAH concentrations indicates that their levels in throughfall deposition (labelled THRO in the figures) are mostly higher than in bulk deposition (labelled BULK). This is attributable to the binding of PAHs to fine particulate matter (PM_{10}, $PM_{2.5}$), which is subsequently deposited on vegetation. From there, PAHs are washed off during precipitation events.

In the next step, the magnitude of atmospheric PAH deposition per unit area was calculated for the Výrovka catchment, expressed in $g \cdot km^{-2} \cdot yr^{-1}$, for both bulk and throughfall deposition. The highest values were observed for naphthalene, phenanthrene, fluoranthene, and pyrene. The graph for the Zásmuky site (*Fig. 3*) shows differences in deposition between bulk and throughfall for individual PAHs. Interestingly, for higher-molecular-weight PAHs, this difference is not as pronounced.

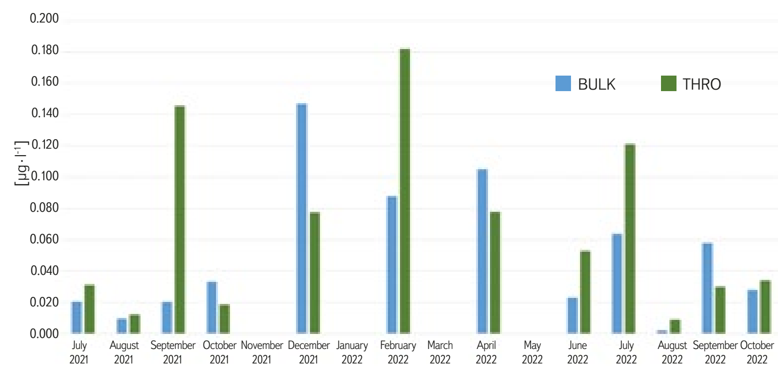

Fig. 2. Sum of PAHs in bulk and throughfall precipitation at the Zásmuky site

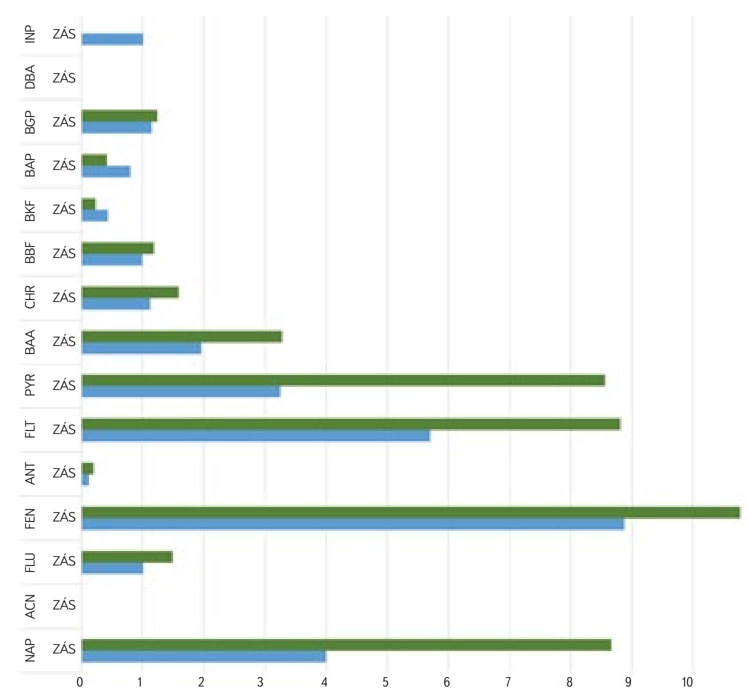

Fig. 3. Atmospheric deposition of PAHs per unit area by bulk deposition and throughfall at the Zásmuky site

The highest PAH concentrations in the surface water of the Výrovka were observed for naphthalene (January, June, and September). During winter, concentrations of naphthalene, phenanthrene, fluoranthene, and pyrene predominated. Based on the ratio of fluoranthene to pyrene, which exceeded 1 in most measurements, the origin of PAHs from combustion processes can be inferred [10]. It was found that the relative contribution of PAHs in surface water is significantly lower compared to atmospheric deposition.

Throughout the entire monitoring period, discharges at the Výrovka–Plaňany river profile were recorded at an hourly time step. From these data, mean daily and monthly discharges were calculated in order to perform an approximate balance of PAH export from the Výrovka model catchment. The results are compared with atmospheric deposition in *Tab. 2*. Despite differences between the two sites, the magnitude of atmospheric deposition in Zásmuky and Třebovle is comparable. When the determined annual deposition is multiplied by the area of the catchment upstream of the Výrovka–Plaňany river profile, the resulting PAH load in this catchment amounts to 8.075–8.448 kg · yr^{-1}. In contrast, PAH export at the Výrovka–Plaňany profile was substantially lower, reaching 1.089 kg · yr^{-1}. This relationship is clearly illustrated by the graph in *Fig. 4*. The upper soil layers and vegetation cover retain the majority of these non-polar organic substances from atmospheric deposition, which readily sorb onto fine particulate matter. They are subsequently transported into surface waters by erosional runoff. Another, albeit less significant, source of PAH contamination of surface waters is direct deposition onto water surfaces; there are several dozen fishponds within the catchment.

Tab. 2. Total atmospheric deposition of PAHs by wet deposition at the Zásmuky and Třebovle sites and PAHs transport by the Výrovka river in the Plaňany site

Substance	**Atmospheric deposition [g · yr^{-1}]**		**Atmospheric deposition per unit area [g · km^{-2} · yr^{-1}]**		**Substance export [g · yr^{-1}]**	**Substance export per unit area [g · km^{-2} · yr^{-1}]**	**Export-to-deposition ratio [%]**	
					Site			
	ZÁSMUKY	TŘEBOVLE	ZÁSMUKY	TŘEBOVLE	PLAŇANY	PLAŇANY	ZÁSMUKY	TŘEBOVLE
Naftalene	1,055.060	697.924	3.999	2.645	57.064	0.216	5.409	8.176
Acenaftalene	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Fluorene	266.748	265.748	1.011	1.008	23.487	0.089	8.803	8.831
Fenanthrene	2,342.448	2,387.474	8.879	9.049	253.563	0.961	10.825	10.621
Anthracene	32.312	36.511	0.122	0.138	19.971	0.076	61.809	54.701
Fluoranthene	1,504.359	1,606.667	5.702	6.090	173.794	0.659	11.553	10.817
Pyrene	857.966	1,079.756	3.252	4.093	159.160	0.603	18.551	14.740
Benzo[a]anthracene	517.349	687.646	1.961	2.606	108.568	0.412	20.986	15.788
Chrysene	296.317	393.469	1.230	1.491	54.250	0.206	18.308	13.788
Benzo[b]fluoranthene	262.737	313.643	0.996	1.189	68.871	0.261	26.213	21.959
Benzo[k]fluoranthene	114.274	141.629	0.433	0.537	30.117	0.114	26.356	21.265
Benzo[a]pyrene	211.956	216.956	0.803	0.819	64.072	0.243	30.229	29.650
Dibenzo[ah]anthracene	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Benzo[ghi]perylene	302.595	292.630	1.147	1.109	59.353	0.225	19.615	20.283
Indeno[1,2,3-cd]pyrene	267.280	312.053	1.013	1.184	16.717	0.063	6.255	5.350
Σ15PAHs	8,031.401	8,432.106	30.548	31.958	1,088.987	4.128	-	-

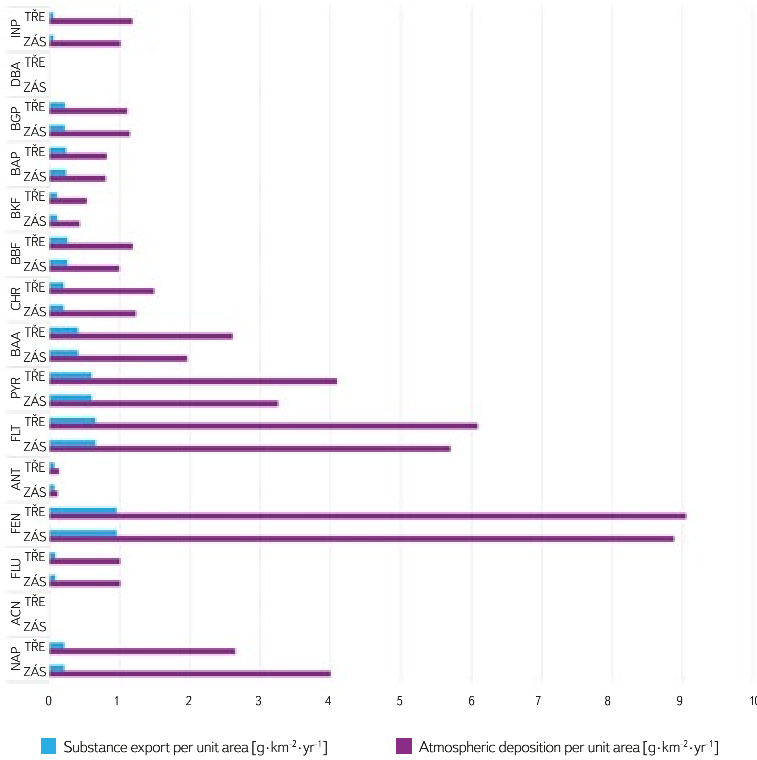

Fig. 4. Total atmospheric deposition (BULK) of PAHs at the Zásmuky and Třebovle sites and PAHs transport in the Výrovka-Plaňany river site

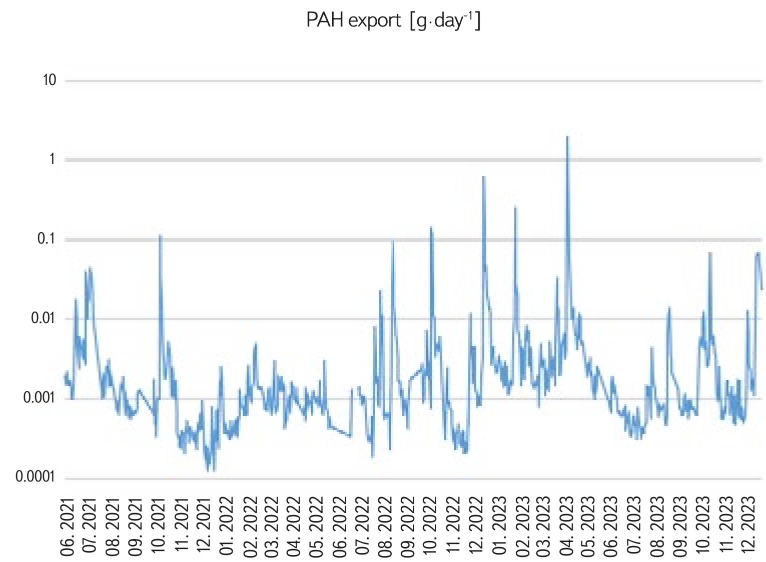

Fig. 5. Transport regime of PAHs in suspended sediments at the Plaňany profile, 2021–2023

The above-mentioned PAH export from the Výrovka catchment is in fact underestimated, as PAH concentrations in surface water increase at higher discharges during rainfall–runoff episodes. For this reason, PAHs were also analysed in suspended sediments and during periods of increased discharge caused by intensive precipitation. Suspended sediment sampling for PAH analyses was carried out under standard flow conditions ($n = 6$) and under increased discharges ($n = 2$) of approximately 0.9 $m^3 \cdot s^{-1}$ (the mean annual discharge is 0.688 $m^3 \cdot s^{-1}$) [11]. Daily PAH exports associated with suspended sediments are shown in *Fig. 5*. However, the overall PAH balance in suspended sediments is not significant: under maximum discharge conditions it amounted to 2 $g \cdot day^{-1}$, and a total of 6.2 g of PAHs was transported from the catchment by suspended sediments at the Plaňany profile over the monitored period.

In 2022, surface water sampling was carried out at the CHMI monitoring profile Výrovka–Plaňany during three rainfall–runoff episodes. Sampling was conducted using a remotely controlled automatic sampler. Precipitation totals recorded at the Cerhenice climatological station were highest during the third sampling episode on 29 June 2022, when 38.9 mm of precipitation fell within two hours (16:10–18:10). During this rainfall–runoff event, three partial water samples were collected, as documented in *Fig. 6*. The first sample was taken at the maximum water level reached in the receiving water body, while the subsequent two were taken during the recession phase of the discharge. PAHs were determined in a homogenised sample. PAH concentrations were highest at peak discharge (1,078 $ng \cdot L^{-1}$), after which they decreased markedly to 139–106 $ng \cdot L^{-1}$. For comparison, the mean annual concentration of Σ PAHs derived from monthly sampling at the Výrovka–Plaňany profile was 57 $ng \cdot L^{-1}$. PAH export during the three-hour period of increased discharge in the receiving water body (17:00– 20:00) was estimated at 1.13 g. This day recorded the highest precipitation total in 2022 and was followed by a further seven days with daily precipitation totals exceeding 25 mm. Although PAH concentrations increase substantially during rainfall–runoff episodes, particularly in their initial phase, the total export from the catchment also increases but remains far below the magnitude of atmospheric deposition over the total catchment area.

At higher temperatures, oxidation processes involving atmospheric trace gases (NO_X, SO_2, O_3) are more effective, and therefore PAH degradation proceeds more rapidly in summer than in winter. In the gaseous phase, PAHs become part of wet atmospheric deposition through interfacial gas-liquid exchange during below-cloud scavenging, whereas PAHs associated with solid particles are more efficiently removed by in-cloud scavenging processes as a result of diffusion, impaction, and interception [12].

As already mentioned in the introduction, sites in Prague-Podbaba (within the TGM WRI premises) and Ostrava-Přívoz were selected to compare the occurrence of PAHs in atmospheric precipitation in a highly urbanised environment. At these sites, monthly bulk and throughfall precipitation sampling was carried out from December 2021 to October 2023.

Urbanised environments are significant areas for PAH deposition due to the high concentration of emission sources and specific conditions that influence their distribution and deposition. Differences in PAH concentrations between the two urban sites are pronounced. The Ostrava region has long ranked among the areas most heavily burdened by PAHs in the Czech Republic. Although the PAH load at the Prague site was lower than in Ostrava, it was higher than at the Zásmuky and Třebovle sites within the Výrovka catchment. Elevated PAH concentrations at the selected sites clearly confirm the influence of the urbanised environment on atmospheric PAH deposition. Data from Zásmuky, Prague-Podbaba, and Ostrava-Přívoz also indicate marked differences in PAH concentrations between throughfall and bulk precipitation. These differences reflect the variability of pollution sources and environmental conditions across different urbanised environments.

Using the same approach as applied at the monitored sites within the Výrovka catchment, the magnitude of atmospheric PAH deposition per unit area was calculated for urbanised environments (*Fig. 7*). However, deposition was not compared with PAH export by surface waters, as both monitoring stations represented only small areas within large urban agglomerations. The results are presented in *Tab. 3*.

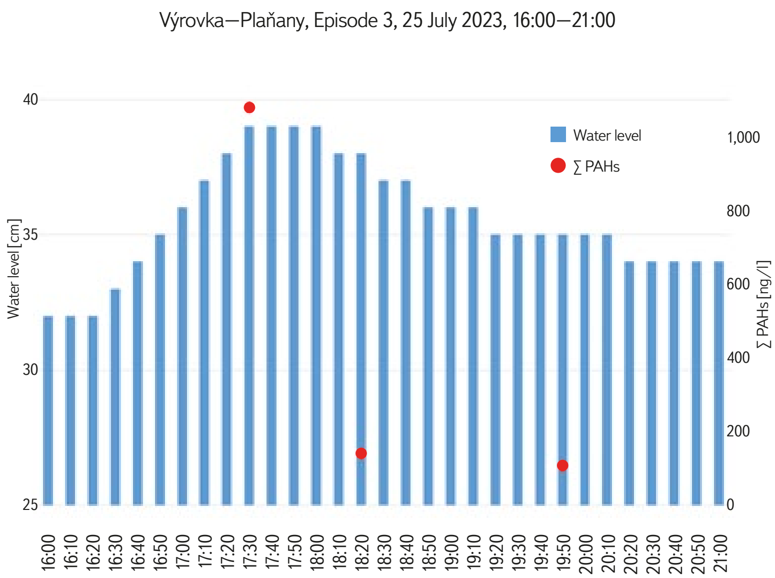

Fig. 6. Concentration of PAHs in surface water during precipitation-runoff episode No. 3

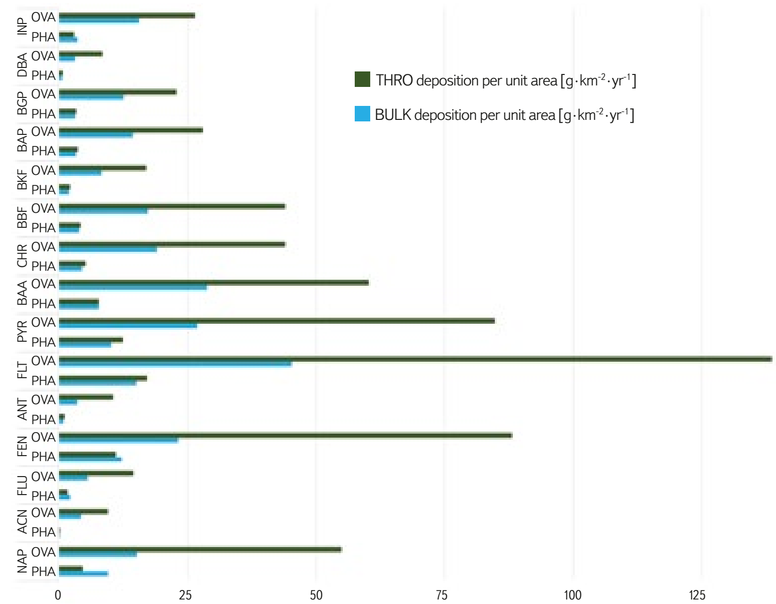

Fig. 7. Comparison of atmospheric deposition in bulk and throughfall at the Ostrava-Přívoz and Prague-Podbaba sites

Tab. 3. Total atmospheric deposition of PAHs at the Ostrava-Přívoz and Prague-Podbaba sites

Substance	**Atmospheric deposition per unit area – BULK [g·km⁻²·yr⁻¹]**		**Atmospheric deposition per unit area – THRO [g·km⁻²·yr⁻¹]**		**BULK/THRO ratio**	
	PRAGUE	OSTRAVA	PRAGUE	OSTRAVA	PRAGUE	OSTRAVA
	9.593	15.188	4.637	54.963	2.069	0.276
Naftalene	0.214	4.316	0.214	9.506	1.000	0.454
Acenaftalene	2.235	5.620	1.687	14.490	1.325	0.388
Fluorene	12.221	23.214	11.057	88.060	1.105	0.264
Fenanthrene	0.932	3.583	1.106	10.556	0.843	0.339
Anthracene	15.114	45.356	17.118	138.626	0.883	0.327
Fluoranthene	10.183	26.910	12.464	84.760	0.817	0.317
Pyrene	7.805	28.865	7.750	60.261	1.007	0.479
Benzo[a]anthracene	4.514	19.065	5.194	44.051	0.869	0.433
Chrysene	3.962	17.298	4.202	44.051	0.943	0.393
Benzo[b]fluoranthene	2.033	8.291	2.190	16.949	0.928	0.489
Benzo[k]fluoranthene	3.341	14.391	3.644	27.989	0.917	0.514
Benzo[a]pyrene	0.682	3.175	0.783	8.482	0.871	0.374
Dibenzo[ah]anthracene	3.221	12.612	3.345	22.825	0.963	0.553
Benzo[ghi]perylene	3.617	15.618	3.617	15.618	1.000	1.000
Indeno[1,2,3-cd]pyrene	79.667	243.502	79.008	641.187	-	-
Σ15PAHs						

Tab. 4. Comparison of total atmospheric deposition of PAHs at the Zásmuky, Třebovle, Prague-Podbaba, and Ostrava-Přívoz sites

Substance	**Atmospheric deposition per unit area — BULK [g·km^{-2}·yr^{-1}]**			
	Site			
	ZÁSMUKY	TŘEBOVLE	PRAGUE	OSTRAVA
Naftalene	3.999	2.645	9.593	15.188
Acenaftalene	0.000	0.000	0.214	4.316
Fluorene	1.011	1.008	2.235	5.620
Fenanthrene	8.879	9.049	12.221	23.214
Anthracene	0.122	0.138	0.932	3.583
Fluoranthene	5.702	6.090	15.114	45.356
Pyrene	3.252	4.093	10.183	26.910
Benzo[a]anthracene	1.961	2.606	7.805	28.865
Chrysene	1.230	1.491	4.514	19.065
Benzo[b]fluoranthene	0.996	1.189	3.962	17.298
Benzo[k]fluoranthene	0.433	0.537	2.033	8.291
Benzo[a]pyrene	0.803	0.819	3.341	14.391
Dibenzo[ah]anthracene	0.000	0.000	0.682	3.175
Benzo[ghi]perylene	1.147	1.109	3.221	12.612
Indeno[1,2,3-cd]pyrene	1.013	1.184	3.617	15.618
Σ15PAHs	30.548	31.958	79.667	243.502

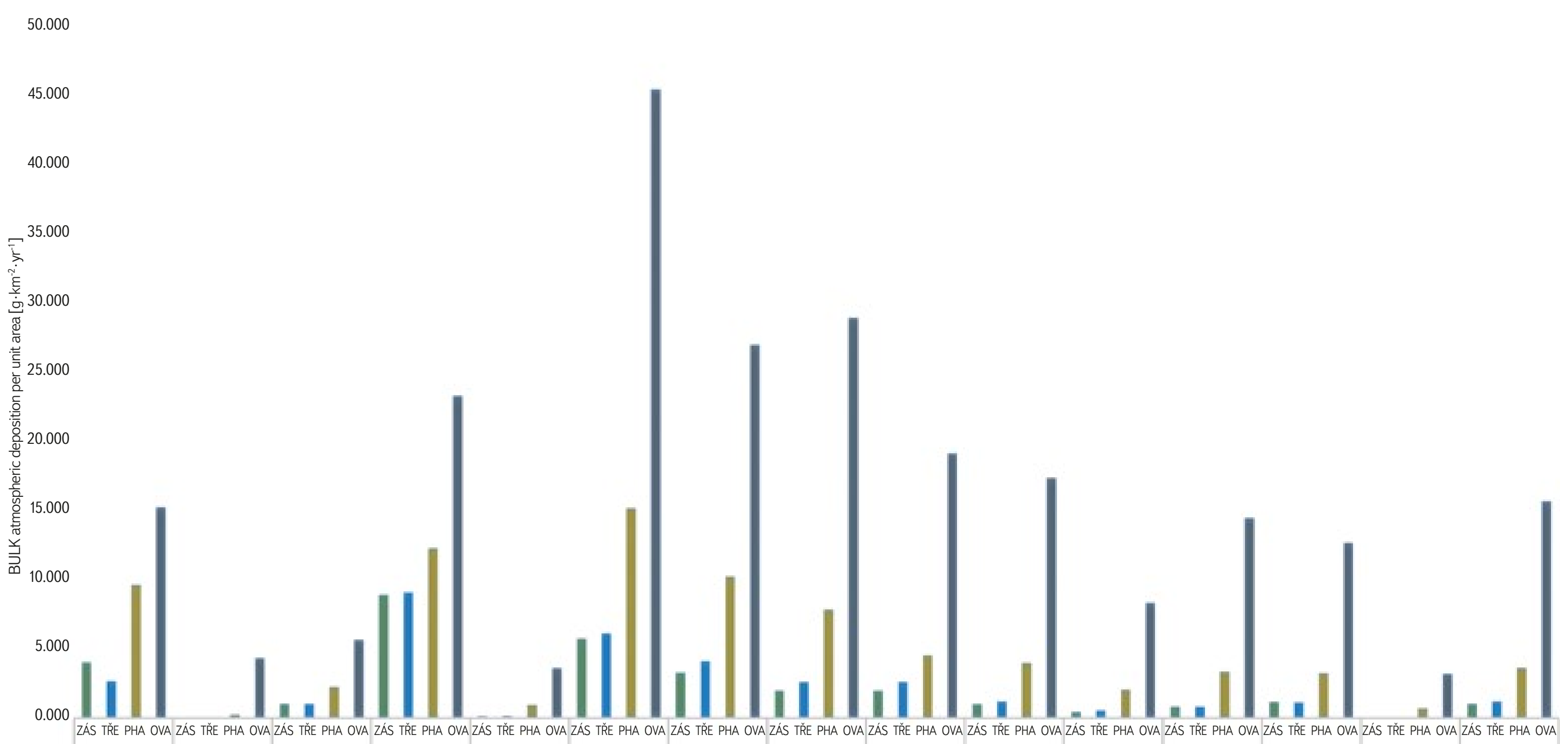

Fig. 8. Comparison of total atmospheric deposition of PAHs at the Zásmuky, Třebovle, Prague-Podbaba and Ostrava-Přívoz sites

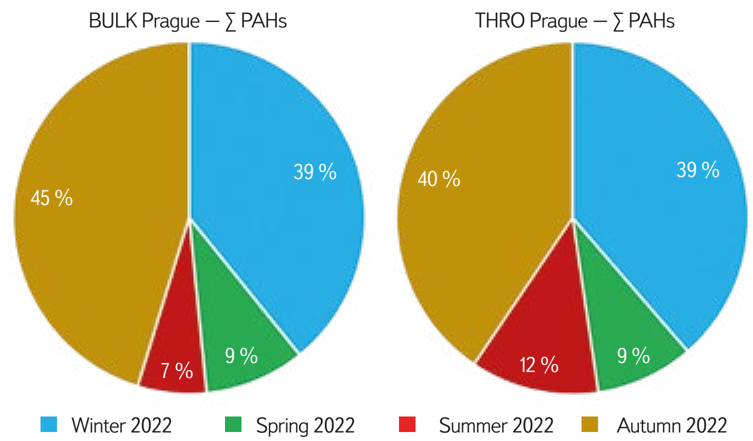

Fig. 9. Total PAHs concentration in precipitation by seasons in 2022, Prague-Podbaba site

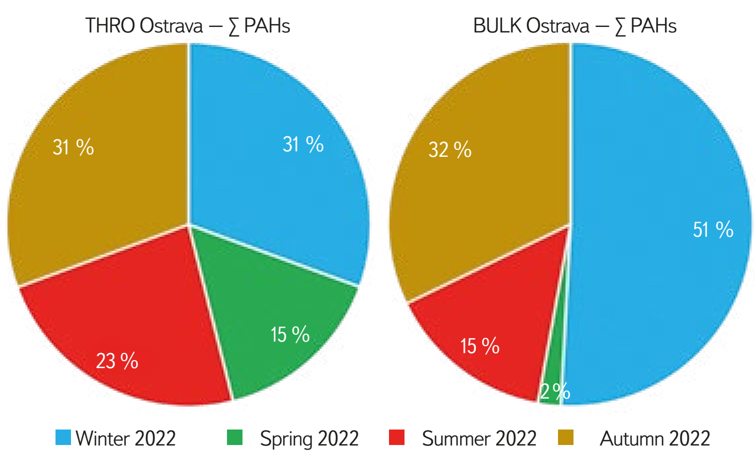

Fig. 10. Total PAHs concentration in precipitation by seasons in 2022, Ostrava-Přívoz site

A comparison of the total atmospheric PAH deposition at all four monitored sites is presented in *Tab. 4* and *Fig. 8*.

The results presented in *Tab. 4* and *Fig. 8* demonstrate that in terms of PAH emissions, the Ostrava-Přívoz site represents an extremely heavily burdened area. Given that local heating sources burning solid or liquid fossil fuels are virtually absent at this site, the observed load is associated primarily with intensive industrial activity and, to a lesser extent, with increased traffic density in the area. The PAH load at the Prague-Podbaba site is substantially lower than at Ostrava-Přívoz; however, compared to sites within the Výrovka catchment, it is more than double. The relatively high PAH deposition values observed in Prague can be attributed to a large extent to traffic density along the adjacent main arterial road, as well as to other potential sources. The Zásmuky and Třebovle sites exhibit lower and nearly identical levels of PAH emissions, which may be explained by lower settlement density, limited industrial activity, and lower traffic intensity. The Třebovle site, located in the lower part of the Výrovka catchment, is slightly more affected by PAH deposition than the Zásmuky site, which is situated in a forest stand between the municipalities of Zásmuky and Barchovice. Total PAH deposition at the Ostrava-Přívoz site is approximately 7.6 times higher than at the Třebovle site.

The graphs shown in *Figs. 9* and *10* indicate considerable variability in Σ PAH concentrations over the course of the calendar year.

A comparison of deposition data from Prague and Ostrava, with regard to the degree of urbanisation and industrial activity, provides an informative perspective on the environmental influences affecting both cities. Prague, as the capital of the Czech Republic, has a pronounced urban character, with extensive areas inhabited by a dense urban population. Although Prague is also an industrial centre, urban development and the service sector prevail over heavy industry, which influences both the magnitude and composition of PAH emissions and their subsequent deposition.

Ostrava has historically been known as a major centre of heavy industry, particularly metallurgy and chemical production; however, at present only the coking industry remains from the original industrial spectrum. This sector continues to represent a key source of emissions of harmful substances into the atmosphere, especially PAHs released during high-temperature coal processing. These emissions contribute substantially to the local environmental burden and, through atmospheric deposition, are associated with degraded air quality.

PAHs in moss and humus in the Výrovka catchment

In moss, the highest relative contributions to the sum of PAHs were observed for NAP, FEN, FLT, PYR, and BBF, while the lowest contributions were found for ANT, ACY, and ACN. In 2021, the highest Σ PAHs in moss were measured at samples from the nearby sites 3 and 4 in the southern part of the catchment (*Fig. 1*). A large number of cases with elevated concentrations of individual PAHs was also identified in moss from site 7, where higher deposition of heavy metals (HMs) had been indicated. By contrast, the lowest Σ PAHs were measured in moss at the spatially distant sites 5 and 9. In 2022, the highest Σ PAHs were recorded in moss samples from sites 4 and 2 in the southern part of the Výrovka catchment, while the lowest values were observed at sites 10 and 6 in the northern and central parts of the catchment. Σ PAHs in moss in 2022, which was on average 2 °C warmer than 2021, were approximately 60 % higher than in 2021, with the largest increase observed for NAP. Although sorption of PAHs onto solid sorbents decreases with increasing temperature, the elevated PAH levels in 2022 were probably associated with increased atmospheric PAH deposition from more polluted air, for example as a result of enhanced volatilisation and sublimation of PAHs from major sources in the surrounding area. In contrast to HMs, the central part of the catchment, with the exception of site 7, contains lower Σ PAHs than the southern and northern margins of the catchment, probably due to the influence of emissions from a denser road network. The main sources of PAHs in the catchment include the combustion of organic fuels in local and nearby domestic and commercial heating units, exhaust emissions from road traffic, and specific industrial activities such as the production and recycling of asphalt mixtures (Běchovice, Kolín, Poříčany, Kutná Hora). Long-range transport of PAHs from more distant large-scale sources, such as the Prague and Pardubice agglomerations, may also be considered. In the summer of 2022, the entire study area was affected for several days by smoke from a forest fire in Bohemian Switzerland.

In the Výrovka catchment, PAHs from local and distant sources become mixed, and therefore relatively large temporal and spatial variations in instantaneous PAH deposition levels can be expected.

PAH contents in moss from the Výrovka catchment were 42 % lower in 2021 and 13 % higher in 2022 than those measured in moss from the forested area of Šumava in 2018. The results indicate relatively high background PAH levels even in Šumava.

Long-term accumulated Σ PAHs in humus were 1.5–15 times higher than in moss. PAH contents are influenced by the humus (carbon) content of the collected sample. Unfortunately, in the Výrovka catchment, particularly in its central part, younger coniferous forests prevail, and a warm and relatively dry climate leads to slow spruce growth and the formation of a thin humus layer with an increased proportion of the mineral soil fraction. Such conditions complicate reproducible humus sampling in individual years. At the northern and southern margins of the Výrovka catchment, the humus layer in pine and spruce forests is thicker. In humus samples, the highest PAH contents were determined for CHR, FLT, PYR, and FEN, while the lowest contributions to Σ PAHs were observed for ACN, ANT, and ACY. The highest PAH contents in humus in 2021 were measured in samples from sites 3 and 7, while the lowest were recorded at sites 9 and 10 in the northern part of the catchment. In 2022, the highest PAH contents were found in samples from sites 3 and 8, whereas the lowest values were observed at sites 2 and 10, located at opposite ends of the catchment. The high variability of the results is attributed to pronounced differences in forest humus quality within the Výrovka catchment, as well as to long-term local variability in PAH deposition resulting from a higher number of local PAH sources and the absence of a more homogeneous (background) PAH concentration in the atmosphere.

Fig. 11 illustrates the distribution of PAHs in forest surface humus in the Výrovka catchment in 2021.

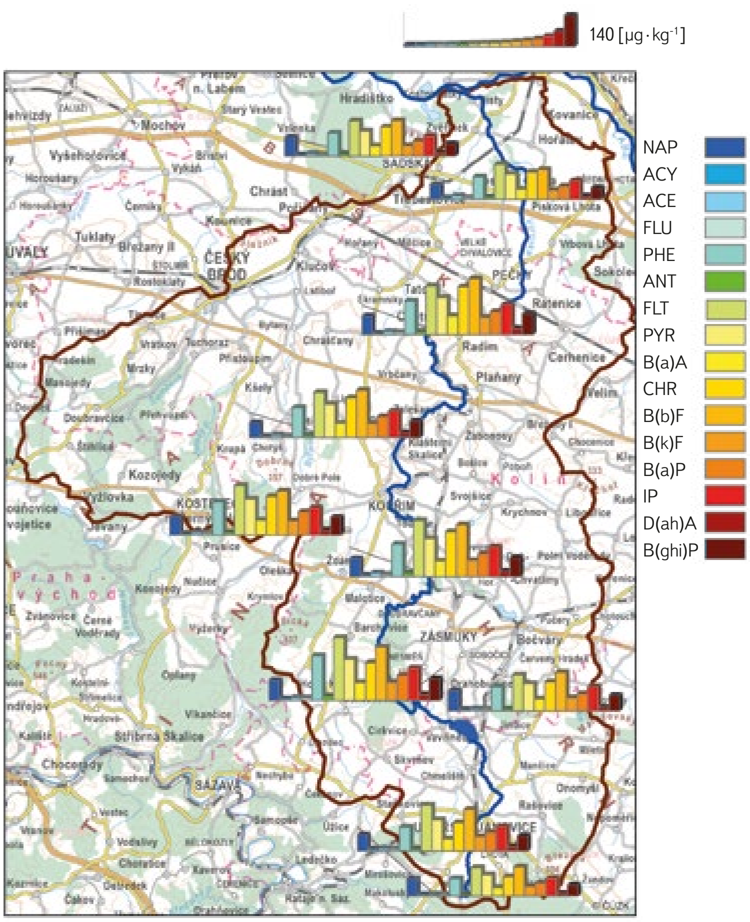

Fig. 11. Distribution of PAHs contents in forest humus in the Výrovka catchment in 2021

Forest humus in the Výrovka catchment contained lower Σ PAHs in 2021 and 2022 than reference forest humus from a forested area in Šumava. This is due to the less developed humus layer in the Výrovka catchment, with a higher proportion of the mineral fraction of forest soil (22–30 %), which has a lower adsorption capacity for binding PAHs than the mineral fraction in humus from Šumava (6–17 %). In the forests of the Výrovka catchment, PAHs are adsorbed within a relatively shallow surface layer of forest soil as a result of the poorly developed humus layer. In contrast, in Šumava forests, PAHs are bound to humus horizons and do not penetrate into the underlying mineral soil, provided that the humus layer is not disturbed by animal activity or forest management practices.

PAH contamination in the vicinity of roads

In the immediate vicinity of road II/611, relatively high contents of NAP, FLT, FEN, and BBF were detected in moss, while the lowest contents were observed for ACN, ACY, and ANT. Similarly, near the D11 motorway, the highest PAH contents in moss were recorded for NAP, BBF, FLT, and FEN, and the lowest for ACN, ACY, and ANT.

Σ PAHs in moss along road II/611 decrease on both sides to a distance of about 100 m, while along the D11 motorway Σ PAHs decrease to a distance of approximately 200 m, but not beyond. These distances therefore represent the main deposition zones along the monitored road segments. As in the case of heavy metals, a solid barrier in the form of an earthen embankment or a high road fill on the southern edge of road II/611 and the northern edge of the D11 motorway significantly slows the dispersion of PAH aerosols into the surrounding area and increases the level of current PAH deposition in the immediate vicinity of the roads. This situation is clearly illustrated in *Fig. 12* for the case of BAP. Sucharová and Holá [13] reported statistically significantly higher PAH contents in moss within 50 m of the D1 motorway near Divišov in 2010. They also observed a very rapid increase in PAH contents in moss at a reference site as a result of forest residue burning after timber harvesting, even at a considerable distance from the moss sampling location [13].

Although the solubility of PAHs in water is low, runoff of PAHs bound to dust particles and oil leaks into watercourses from drainage systems conveying runoff from road surfaces and their surroundings must be considered, even at distances of tens or, in some cases, hundreds of metres.

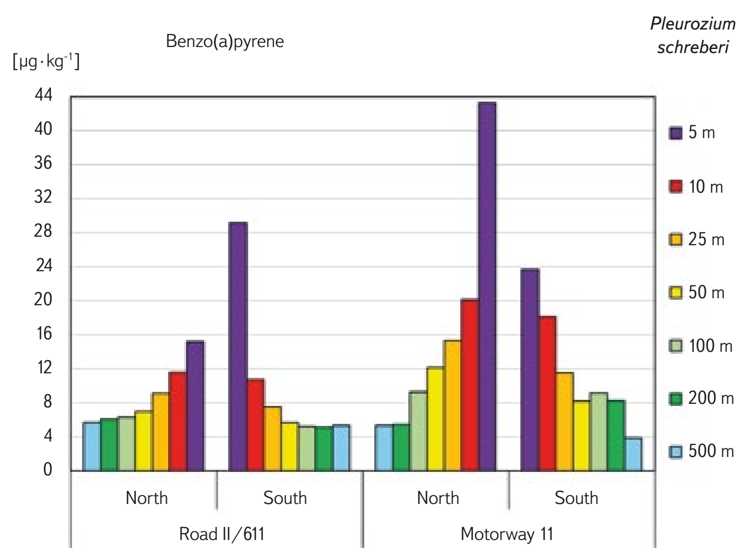

Fig. 12. Decrease in BAP content in moss with distance from road II/611 and motorway D11 near Sadská in the summer of 2023

Relatively the highest contributions to Σ PAHs along road II/611 were identified for BBF, FLT, CHR, and PYR, while the lowest contributions were observed for ACN, ACY, ANT, and BAA. Σ PAHs in humus on both sides of the road decrease up to a distance of approximately 50 m. This is followed by fluctuations in PAH contents in humus at greater distances as a result of logging and other forestry activities on the northern side at the *U Kocánka* site, while the end of the southern transect is apparently influenced by deposition from the D1 motorway. In the vicinity of the D11 motorway, low Σ PAHs were detected in humus up to a distance of 25 m, due to the removal of the original humus layer and the still insufficient development of a new humus layer. Σ PAHs depend on the type of humus and its organic carbon content [14]. North of the D11 motorway, Σ PAHs decrease up to a distance of approximately 200 m, whereas on the southern side this decrease is disrupted by increased Σ PAHs at distances of 100 m and 500 m south of the motorway.

The irregular pattern of Σ PAHs is caused by fluctuations in carbon content in the samples (the relationship is not statistically significant, probably due to the small number of samples), logging and forestry activities that disturb the humus horizon, as well as the potential influence of activities at a shooting range and an industrial zone, including asphalt mixture production, on the southern edge of the forest near Poříčany. Along the D11 motorway, the main contributors to Σ PAHs in humus are NAP, PYR, FLT, and FEN, while ACN, ACY, DBA, and ANT contribute the least. These results further indicate that elevated, long-term accumulated Σ PAHs in forest soils extend to distances of several tens of metres and at least up to 100 m from the edges of heavily trafficked roads. From PAH-contaminated zones adjacent to roads, PAHs can most readily enter watercourses via drainage systems, either bound to low-molecular-weight humus fractions or associated with solid humus and soil particles transportable by water.

Determination (Estimation) of PAH origin

Determining the origin of PAHs represents a key step in assessing environmental burden and in designing effective measures to reduce their emissions. PAH sources can generally be divided into two main categories: pyrogenic (products of incomplete combustion of organic materials and fossil fuels) and petrogenic (associated with leaks of petroleum products and their processing). Estimation of PAH origin in the environment is most commonly based on a combination of diagnostic chemical ratios of individual PAH compounds, knowledge of local sources, and analysis of spatial and temporal trends in concentrations.

To distinguish PAH sources, so-called diagnostic ratios between the concentrations of defined compounds are used. The principle of the method is based on the assumption that different hydrocarbons are generated depending on the specific PAH formation process and its temperature conditions. A typical example is the fluoranthene/pyrene ratio (FLT/PYR), for which values greater than 1 indicate a pyrogenic origin, while values below 1 suggest a petrogenic origin. Other commonly used indicators include the ratios ANT/(ANT + FEN), BAA/(BAA + CHR), and INP/(INP + BGP), which together allow for a more robust classification of sources [15–21].

Fig. 13 shows the average composition of PAHs in selected matrices sampled in the Výrovka catchment, Prague, and Ostrava. The evaluation is based on a total of nine selected PAH diagnostic ratios. The categories used to determine source origin are PYRO, PETRO, NON-SPECIFIC (ratios were calculated but do not clearly indicate a specific type of pollution source), and NO DATA (concentrations required for ratio calculations were below the limit of quantification or unavailable).

In the case of significantly or extremely polluted urbanised sites, the origin of PAH contamination could be specified most clearly (Prague, Ostrava). A predominantly pyrogenic origin of PAHs was confirmed, including in Prague at a distance of approximately 25 m from the main arterial road Podbabská. By contrast, at the Zásmuky and Třebovle sites, concentrations of selected PAHs were below the limit of quantification (LOQ), and the diagnostic ratio method could therefore be applied only to some compounds. In such cases, the ratio between the sum of low-molecular-weight and high-molecular-weight PAHs whose concentrations exceeded the LOQ (Σ LMW / Σ HMW) was used to estimate source origin. When this ratio is less than 1, a pyrogenic origin can be inferred; when greater than 1, a petrogenic origin is indicated [21]. *Fig. 14* illustrates a clear difference in PAH origin in total wet deposition (bulk) at the Třebovle site, with months of the non-heating season arranged on the left side of the graph and months of the heating season on the right. During the summer months, petrogenic and pyrogenic PAH sources were nearly balanced, whereas in the colder part of the year a pyrogenic origin predominated. In summer, PAH concentrations were lower and more frequently below the LOQ; consequently, a smaller number of diagnostic ratios between individual PAHs could be used to estimate their origin. For example, in contrast to the winter months, during the period from May to June 2022 only LMW hydrocarbons exceeded the LOQ, which are primarily of petrogenic origin. The proportional representation of sources is expressed as percentages in *Fig. 15*.

A comparison of the same matrix at the substantially more heavily burdened site in Ostrava is summarised in *Fig. 15*. In contrast to Třebovle, a weaker seasonal influence is observed for pyrogenic PAHs at this site, whereas petrogenic PAHs were present only during the heating season and in September 2023, which was characterised by below-average temperatures. These differences are related to higher industrial activity, the size of the urban agglomeration, and probably also to more frequent fuel handling.

Results obtained using diagnostic ratios should be interpreted with caution, as their values may change under the influence of environmental processes. It is possible to apply correction factors that account for the effects of the physicochemical properties of PAHs and changes caused by inter-phase transport and degradation [21]. Even with the application of correction factors, however, the results remain only an estimate.

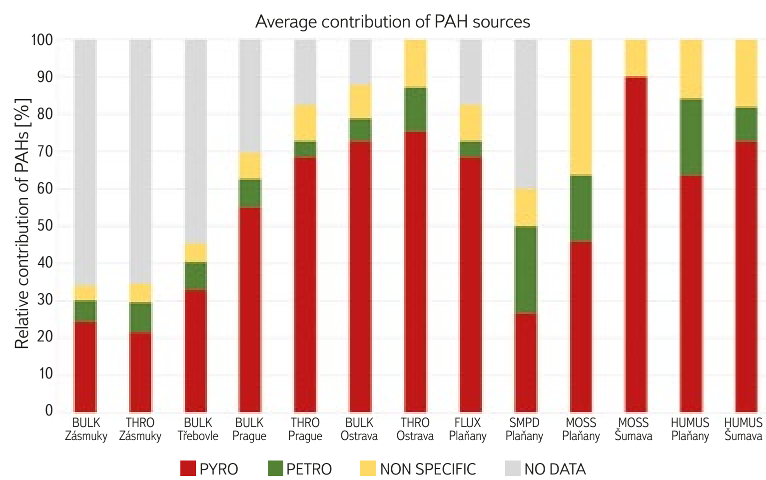

Fig. 13. Average contribution of PAHs sources in selected matrices

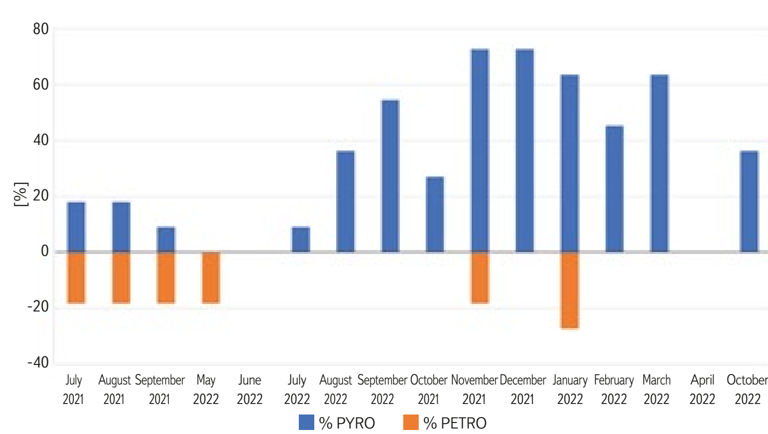

Fig. 14. Origin of PAHs in wet atmospheric deposition (bulk) at the Třebovle site

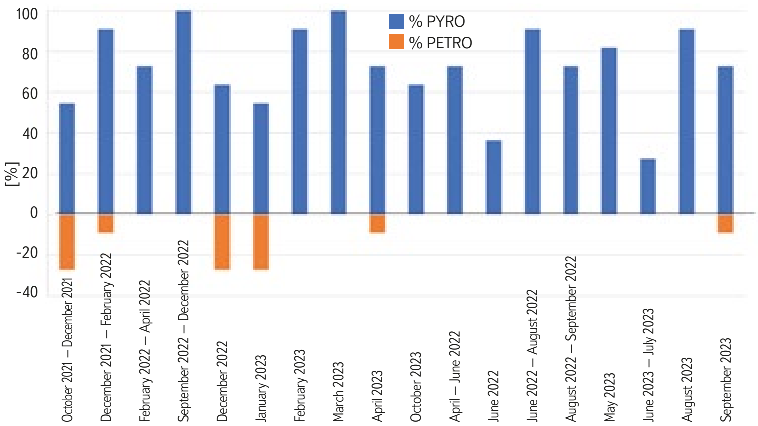

Fig. 15. Origin of PAHs in wet atmospheric deposition (bulk) at the Ostrava site

DISCUSSION

Research conducted in the Výrovka catchment model catchment and in urbanised areas (Ostrava, Prague), focusing on the analysis of PAHs in various types of environmental matrices, provided a more detailed insight into the dynamics of their concentrations over the course of the calendar year, their behaviour in the environment, and the factors influencing their levels.

Atmospheric deposition represents the dominant pathway by which PAHs enter subsequent components of the environment. Environmental load expressed as deposition per unit area and year was comparable at both Zásmuky and Třebovle sites within the Výrovka catchment (Σ 15PAHs 30.548 and 31.958 g · km^{-2} · yr^{-1}, respectively), although the sites differ in character (forest versus agricultural land use). In Prague, in the vicinity of a major arterial road (TGM WRI premises along Podbabská street), PAH deposition was 2.5 times higher than at the sites within the Výrovka catchment. An extremely high PAH load was confirmed in the urban area of Ostrava-Přívoz (243.5 g · km^{-2} · yr^{-1}), located near a coking plant approximately 800 m north of the monitoring site, in an area dominated by westerly, south-westerly, and north-westerly wind directions. Ostrava-Přívoz is thus burdened by PAH deposition more than seven times compared with the rural sites of Zásmuky and Třebovle. For the carcinogenic benzo(a)pyrene, deposition at the Prague site was more than four times higher (3.341 g · km^{-2} · yr^{-1}) than at the Výrovka catchment sites, while deposition at the Ostrava site was more than seventeen times higher (14.391 g · km^{-2} · yr^{-1}). The contribution of benzo(a)pyrene to the Σ 15PAHs deposition amounted to 2.6 % at the Výrovka sites, 4.5 % at the Prague site, and 5.9 % at Ostrava-Přívoz.

PAH concentrations were higher in throughfall precipitation than in wet deposition collected in open areas (bulk). This indicates that vegetation – particularly leaves and tree branches – provides surfaces for the adsorption of PAHs from the atmosphere, as confirmed at the Zásmuky and Ostrava-Přívoz sites, where throughfall deposition exhibited markedly higher PAH concentrations than bulk wet deposition. In some cases, however, PAH concentrations may be higher in bulk deposition, which can be attributed to specific meteorological conditions or emission events during the sampling campaign, as observed at the Prague-Podbaba site during summer.

Calculated PAH fluxes associated with wet deposition and surface water in the Výrovka catchment confirmed that the larger proportion of deposited PAHs remains within the environment, with only a fraction entering surface waters through erosion and, to a lesser extent, through direct deposition onto water surfaces. Σ 15PAHs deposition over the catchment area upstream of the Plaňany profile was calculated to be 8.075–8.448 kg · yr^{-1}, whereas PAH export at the Výrovka–Plaňany profile was substantially lower, amounting to 1.089 kg · yr^{-1}. During rainfall–runoff events, PAH concentrations increase during the initial rise in discharge and at peak flow, as confirmed by the analysis and mass balance of PAHs in suspended sediments; however, this increase was not as pronounced as initially expected. The cumulative PAH export via suspended sediments amounted to 6.2 g over the period 2021–2023 and 1.13 g during the first three hours of the most significant storm event in 2022 (38 mm in 3 h and 50 mm in 24 h).

The spatial distribution of PAH contents in moss and humus further highlights the importance of transport corridors and local heating sources. Elevated PAH contents in the vicinity of roads II/611 and D11 confirm that emissions from road traffic constitute a significant contribution of PAHs to the environment, primarily via particulate matter contaminated by incomplete fuel combustion and tyre wear.

The observed differences between individual years and seasons document not only the influence of local sources but also the possible involvement of long-range transport and episodic events. In 2022, for example, an increase in PAH contents in moss was recorded, which can be partly explained by the influence of a smoke plume from the forest fire in Bohemian Switzerland. These findings underline that even in relatively less burdened areas, substantial increases in PAH concentrations may occur as a result of regional or transboundary transport.

CONCLUSION

Analysis of diagnostic ratios, seasonal dynamics, and spatial distribution indicates that pyrogenic processes represent the dominant source of PAHs at the assessed sites, in particular the combustion of fossil fuels in local heating systems and industrial sources, with a substantial contribution from road traffic. Petrogenic sources play only a supplementary role; nevertheless, their influence cannot be entirely excluded, especially in the immediate vicinity of roads or industrial areas. The results confirm the need for a combined approach to PAH source assessment, integrating chemical indicators with analyses of emission scenarios and the influence of long-range transport.

PAHs are ubiquitous substances and, particularly in urbanised areas, pose a significant risk not only to the aquatic environment but also to human health. The currently discussed amendment to Directive 2008/105/EC proposes a substantial tightening of the environmental quality standard (annual average) for fluoranthene and introduces the recalculation of selected PAHs to a benzo(a) pyrene-equivalent risk. Following the adoption and transposition of the directive into national legislation, new approaches to the assessment of the chemical status of surface water bodies will need to be implemented.

The conducted research confirmed that atmospheric deposition is a significant source of PAHs in the environment, particularly in industrial areas and in the vicinity of intensive road traffic. However, its influence is not negligible even in agricultural landscapes. At the same time, the results confirm that the land surface and its properties play a crucial role in the retention of PAHs and in the protection of watercourses. In addition to the necessary improvement of air quality, appropriate measures to achieve good water status with respect to PAHs therefore include erosion control and improved stormwater management.

Nevertheless, a need remains for more detailed research and monitoring of PAHs across individual environmental matrices, including atmospheric deposition, wind erosion, and rainfall–runoff episodes, together with the evaluation of measures aimed at reducing their emissions.

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Environmental objectives and aquatic environment limits for stone crayfish

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Keywords: stone crayfish — water quality — environmental objectives — pollution limits for salmonid waters

ABSTRACT

The stone crayfish (*Austropotamobius torrentium*) is a critically endangered species listed on the Red List of Invertebrates of the Czech Republic. It is protected under Decree No. 395/1992 Coll. and designated as a priority species according to Council Directive 92/43/EEC on the conservation of natural habitats, wild fauna, and flora. It is generally assumed that stone crayfish requires water quality that meets at least the emission limits for salmonid waters as defined by Government Regulation No. 71/2003 Coll., as amended, and also by Government Regulation No. 401/2015 Coll., as amended. Stable and abundant populations, however, require stricter environmental objectives, both in terms of limit values and the range of monitored parameters. To establish these objectives, 14 sites were selected. These sites are either unaffected or only slightly influenced by human activities, with confirmed current occurrence of stone crayfish or historical presence where disappearance was probably due to crayfish plague. The sites were sampled monthly over one year. Using principal coordinate analysis (PCoA) and non-metric multidimensional scaling (NMDS), the sites were separated in ordination space based on the $ANC_{4.5}$ (Total Alkalinity) (with a dividing criterion of an annual median of 2 mmol/l) and closely correlated indicators (calcium, magnesium, conductivity). This resulted in two groups of sites with distinct environmental conditions. Environmental objectives were set separately for these two groups. For sites with low acid neutralization capacity (< 2 mmol/l), stricter objectives were applied to parameters indicating pollution. For both groups, some environmental objectives are considerably stricter (e.g. annual median BOD_5 = 1.2 mg/l) than the limits used for water body assessment under the Water Framework Directive (2000/60/EC), depending on the water type (1.5–2.5 mg/l). Environmental objectives for some parameters are also stricter than those in Government Regulation No. 71/2003 Coll., although direct comparison of median and C_{95} values is not possible. For parameters that naturally fluctuate in aquatic environments, we consider it is important to use the median to assess site conditions, rather than short-term fluctuations that are not limiting for stone crayfish (e.g., BOD_5). In contrast, minima and maxima should be applied for parameters where even a single exceedance could be harmful (e.g., pH, toxic free ammonia) or to detect accidental pollution events.

INTRODUCTION

The stone crayfish (*Austropotamobius torrentium*) is a critically endangered species listed in the *Red List of Invertebrates of the Czech Republic* [1] and is also classified as critically endangered under Decree No. 395/1992 Coll. [2]. At the level of the European Union, it is protected as a priority species listed in Council Directive 92/43/EEC on the conservation of natural habitats and of wild fauna and flora [3]. To ensure its protection in the Czech Republic, 13 of the most valuable sites have been designated within the Natura 2000 network as Sites of Community Importance (SCIs) [4]. An overview of the designated SCIs and their basic characteristics is presented in *Tab. 1*. However, targeted monitoring has gradually identified additional sites with the occurrence of the stone crayfish (by 2024, a further 32 sites had been recorded), demonstrating that the designation of the original SCIs alone is insufficient for the effective protection of the species. In order to ensure maximum protection of the stone crayfish at its sites of occurrence, a Rescue programme was approved in 2024, which, among other measures, defines the water environment conditions necessary for the long-term survival of the species. Rescue programmes aimed at the conservation of endangered species are a widely used tool and are being applied with increasing frequency both in the Czech Republic and abroad [5]. An important advantage of rescue programmes is that protecting a single target species also has a positive effect on other species inhabiting the same habitat, reflecting the umbrella species concept with beneficial impacts on the entire ecosystem [6].

The stone crayfish (*Austropotamobius torrentium*) is among the largest invertebrates inhabiting both flowing and standing waters. Like other crayfish species, it is omnivorous and feeds on a wide range of food items. In freshwater ecosystems, it therefore plays an important role in nutrient cycling by shredding and processing organic matter, thereby making it available to other organisms [7, 8]. The stone crayfish is one of the native crayfish species in the Czech Republic; however, its original distribution range within the country cannot be precisely defined, as the gradual discovery of its occurrence continues to the present day and the original pattern of settlement can no longer be reliably reconstructed. The current distribution of the stone crayfish (*Austropotamobius torrentium*) is concentrated in central, northern and western Bohemia, together with one isolated population occurring in the Krkonoše foothills [9]. It inhabits slightly meandering natural streams flowing through mixed forests, where fast-flowing sections alternate with slower reaches forming pools. The stream bed is typically composed of stones or coarse-grained substrate. Its occurrence is influenced not only by the hydromorphological condition of the site and the quality of the aquatic environment [4, 10], but also by the presence of non-native crayfish species, which act as carriers of crayfish plague. The causative agent of crayfish plague is the fungus-like microscopic pathogen *Aphanomyces astaci*, which represents one of the most serious threats to native crayfish species. Another major threat to the stone crayfish is the loss of shelter availability, caused both by occupation by invasive species (including non-infected ones) and by insensitive modifications of watercourses, infilling of shelters with fine-grained material originating from agricultural land and fishponds, as well as sludge discharged from wastewater treatment plants. In recent years, climate change has added further pressure, particularly through

Tab. 1. Overview of designated Special Areas of Conservation in the Czech Republic where the stone crayfish is listed as a species of conservation interest (source: Nature Conservation Information System Portal, NCA CR)

SCI name	Natura 2000 code	Region	Area [ha]	State Nature and Landscape Conservancy Authority
Nameless tributary of Trojhorský stream	CZ0423198	Ústí nad Labem	1.95	NCA CR – RP SCHKO České středohoří
Bradava	CZ0323145	Pilsen	25.63	Pilsen Region Authority, NCA CR – Central Bohemia
Huníkovský stream	CZ0423001	Ústí nad Labem	4.26	NCA CR – České středohoří PLA
Luční stream – Třebušín	CZ0423219	Ústí nad Labem	0.66	NCA CR – České středohoří PLA
Luční stream in Krkonoše Foothills	CZ0523823	Hradec Králové	5.69	Hradec Králové Region Authority
Mešenský stream	CZ0323156	Pilsen	1.04	Pilsen Region Authority, NCA CR – Central Bohemia
Padrťsko	CZ0214042	Pilsen, Central Bohemian	829.9	NCA CR – Central Bohemia
Přešínský stream	CZ0323161	Pilsen	1.33	Pilsen Region Authority
Radbuza – Nový Dvůr – Pila	CZ0323166	Pilsen	11.20	NCA CR – Český les PLA
Stroupínský stream	CZ0214039	Central Bohemian	5.94	Central Bohemian Region Authority, NCA CR – Central Bohemia
Týřov – Oupořský stream	CZ0214011	Central Bohemian	1,341.2	NCA CR – Central Bohemia
Zákolanský stream	CZ0213016	Central Bohemian	10.10	Central Bohemian Region Authority
Zlatý stream	CZ0323170	Pilsen	1.87	Pilsen Region Authority

the increasingly frequent drying of watercourses [11]. Additional significant negative impacts may include, for example, pesticides originating from agriculture or industrial applications, which can enter watercourses as a result of improper use [12].

The stone crayfish is an aquatic organism that is dependent on a high quality of the ecosystem as a whole. In the past, it was considered a better bioindicator of water quality than the noble crayfish [13], another of our native crayfish species. However, recent research shows that the water quality requirements of both species are approximately the same [14]. Nevertheless, the truth is that at sites where stable populations of stone crayfish occur at high abundance, the overall quality of the ecosystem is high, including water quality [9].

Research into the water quality requirements of the stone crayfish in the Czech Republic began after 2000. The first studies focused on surveys of known sites with occurrences of stone crayfish, where water quality monitoring was carried out, including sites where crayfish abundance was very low and water quality poor. At some sites, longer-term monitoring was conducted, but at most of the other watercourses only two samples per year were taken [15]. Data collected by the Nature Conservation Agency of the Czech Republic (NCA CR) and TGM WRI within these studies between 2006 and 2010 formed the basis for establishing the first threshold values of the aquatic environment for the occurrence of stone crayfish [4, 14, 16, 17]. In order to eliminate data representing sites unfavourable for the longer-term persistence of stone crayfish, sites with long-term reduced water quality, sites affected by episodic pollution incidents, and sites where data were obtained immediately before or during crayfish mortality events were excluded from the dataset. From the original set of sites, 19 sites with stone crayfish were selected, for which mean values and interquartile ranges were calculated for the most important water quality parameters [4, 14, 16]. The obtained results were compared with the applicable legislation, in particular Government Regulation No. 71/2003 Coll., on the designation of surface waters suitable for the life and reproduction of native fish species and other aquatic organisms and on the detection and assessment of the quality status of these waters [18], as amended. The calculated values were closest to the target immission limits for salmonid waters (*Tab. 2*); therefore, these limits from the government regulation were also adopted in the Rescue Programme for the Stone Crayfish as binding limits. Limits for salmonid waters are also secondarily specified in Government Regulation No. 401/2015 Coll., on indicators and permissible values of pollution of surface waters and wastewater, the requirements of permits for the discharge of wastewater into surface waters and sewerage systems, and on sensitive areas [19], as amended..

Tab. 2. Immission limits set by Government Regulation No. 71/2003 Coll. [18] and by Government Regulation No. 401/2015 Coll. [19] for salmonid waters. When assessing according to Regulation No. 71/2003 Coll., the 95th percentile (C_{95}) is calculated if 12 or more values are available. If fewer data are available, the maximum value is used. When assessing according to Regulation No. 401/2015 Coll., the annual average is calculated, except for the temperature parameter, where the maximum value is applied

Indicator	Unit	Government Regulation No. 71/2003 Coll.		Government Regulation No. 401/2015 Coll.
		Target values C_{95}	Permissible values C_{95}	Mean
Temperature	[°C]		21,5 (maximum)	29 (maximum)
Dissolved oxygen	[mg/l]	9 (median) 7 (minimum)	9 (median)	> 9
BOD_5	[mg/l]	3		1.8
pH	[pH]		6–9	5–9
Suspended solids	[mg/l]	25 (median)		20
Ammonium ions (NH_4^+)	[mg/l]	0.04	1	0.038
N-NH_4	[mg/l]	0.03		0.03
Free ammonia (NH_3)	[mg/l]	0.005	0.025	
Nitrites (NO_2^-)	[mg/l]	0.6		0.26
N-NO_2	[mg/l]	0.18		0.08
N-NO_3	[mg/l]			5.4
Chlorides	[mg/l]			150
Dissolved copper (Cu)	[mg/l]	0.04*		
Total chlorine – as HClO	[mg/l]		0.005	
Total zinc (Zn)	[mg/l]		0.3*	
Total phosphorus	[mg/l]			0.05
COD_{Cr}	[mg/l]			26
Total organic carbon	[mg/l]			10
Total nitrogen	[mg/l]			6
Dissolved solids (dried)	[mg/l]			750
Ignited dissolved solids	[mg/l]			470
Sulphates	[mg/l]			200
Magnesium	[mg/l]			120
Calcium	[mg/l]			190

Note: * The target value varies depending on the total water hardness at the site; for details see Government Regulation No. 71/2003 Coll., Annex 2.

Tab. 3. Environmental objectives for aquatic environment quality indicators for the stone crayfish according to the methodology for assessing the conservation status of protected areas [20]

Indicator	Unit	Characteristic value		
		Median	**Maximum**	**Minimum**
Water temperature	[°C]	9.5	21.5	
Dissolved oxygen	[mg/l]			7
Oxygen saturation	[%]		110	80
BOD_5	[mg/l]	1		
Electric conductivity	[μS/cm]	500		
pH		7.8	8.4	7
$ANC_{4.5}$	[mmol/l]	4		0.5
Total phosphorus	[mg/l]	0.07		
PO_4-P	[mg/l]	0.05		
NO_3-N	[mg/l]	2.2		
NH_4-N	[mg/l]	0.035		
Chlorides	[mg/l]	17		
Calcium	[mg/l]	55		18
NO_2-N	[mg/l]	0.01		
Free ammonia*	[mg/l]	0.0007		
NL_{105}	[mg/l]	3		
Total iron	[mg/l]	0.13		

Note: * The value for free ammonia is determined by calculation from the values of NH_4^+, water temperature, and pH.

As subsequent research has shown, the requirements of the stone crayfish do indeed necessitate water quality that meets at least the target immission limits for salmonid waters [9, 16, 17]. However, for crayfish populations to be stable and characterised by high abundance, water quality should tend towards more stringent environmental objectives, both in terms of limit values and the range of assessed parameters. Such environmental objectives were newly defined within the TA CR Beta 2 Project No. TITSMZP701 *Methodology for the assessment of the status of protected areas designated under the Water Framework Directive for the protection of habitats or species*, which made use of previous extensive datasets and information from reference and other sites obtained within several TGM WRI research projects [11]. Within the TA CR Beta 2 project, these datasets were supplemented by two pilot sites (Chejlava and Hůrecký stream), at which monitoring was conducted at monthly intervals from November 2018 to October 2019. On the basis of these data and their evaluation, environmental objectives were established for a set of indicators listed in *Tab. 3* [20]. The environmental objectives were defined as annual medians of 12 values, or alternatively as maximum or minimum target values, depending on the type of indicator assessed and its relationship to the type and character of pollution.

Even these newly established environmental objectives, however, exhibited lower reliability, as most of the underlying monitoring data did not include year-round observations. Therefore, within the research project No. SS02030027 *Water Systems and Water Management in the Czech Republic under Climate Change (Water Centre)*, a monitoring campaign was carried out at reference sites and the best available sites with documented current or historical occurrence of stone crayfish. The data obtained formed the basis for the establishment of revised environmental objectives. This article focuses on the methodology of data collection and evaluation, the new setting of environmental objectives, and their comparison with previously applied limit values.

METHODOLOGY

The refinement of environmental objectives for water environment indicators at sites with the occurrence of stone crayfish was initiated by the selection of suitable reference sites. On the basis of available information on both current and historical occurrences of stone crayfish, as well as previously measured values of physicochemical parameters in watercourses, appropriate monitoring profiles were identified. Within the Czech Republic, a total of 14 reference or slightly anthropogenically influenced sites were selected, where the long-term occurrence of stable populations of stone crayfish had been confirmed or where the disappearance of formerly abundant crayfish populations had apparently been caused by crayfish plague rather than by pollution or accidental contamination events. An overview of the monitored sites is provided in *Tab. 4* and *Fig. 1*.

Tab. 4. Overview of reference and best available sites for the stone crayfish used for establishing new environmental objectives

Site code	Watercourse	Occurrence of stone crayfish during the sampling period	Altitude [m a.s.l.]	Stream order (Strahler)	Catchment area [km²]	Slope [‰]	Distance from the source [km]
BERP	Bertinský stream	YES	303.1	1	5.21	21.6	4.79
HRAP	Hrádecký stream	NO	375.3	2	11.77	16.7	4.70
KUBP	Kublovský stream	NO	335.4	2	15.11	26.6	6.69
LUP	Luční stream	YES	303.9	3	4.17	50.0	2.80
MEDP	Medvědí stream	NO	465.8	3	5.04	17.5	2.70
PARP	Pařezový stream	BO	334.4	2	5.45	24.5	3.94
PMIT	Mítovský stream tributary	YES	503.1	1	4.60	55.0	1.96
PNEM	Nemanický stream tibutary	YES	548.7	2	1.53	69.5	1.51
PODP	Podhrázský stream	YES	474.1	1	4.89	27.2	2.31
PSKO	Skořický stream tributary	YES	460.1	2	2.65	33.7	2.59
RADB	Radbuza	YES	474.6	4	31.15	14.2	10.81
UPOP	Úpořský stream	NO	423.9	1	9.19	29.0	3.39
VALP	Valdecký stream	YES	245.4	2	8.16	12.5	3.88
ZUBR	Zubřina	YES	461.8	2	11.67	10.8	5.00

The selected sites were monitored at monthly intervals from July 2021 to June 2022. At each site, dissolved oxygen and oxygen saturation, pH, conductivity, and water temperature were measured using a field multiparameter probe HQ40d multi (HACH-LANGE), and an estimate of the current discharge was recorded. Simultaneously, a grab water sample was collected from the main current for the determination of additional physicochemical parameters (BOD_5, chlorides, sulphates, ammonium nitrogen, nitrate nitrogen and nitrite nitrogen, nitrates and nitrites, phosphate phosphorus, total phosphorus and phosphates, suspended solids, acid neutralisation capacity $ANC_{4.5}$, calcium, magnesium, iron, and the ammonium ion). The set of indicators also included water environment parameters whose relationship to the occurrence of stone crayfish at sites had not yet been documented in literature. These indicators (for example iron, magnesium, and sulphates) were included in the monitoring programme in order to verify their potential significance. The collected samples were cooled and transported to TGM WRI, where the analyses were carried out in an accredited laboratory.

The collected data were processed using the software Canoco 5. Principal coordinate analysis (PCoA) was applied, which displays samples in an ordination

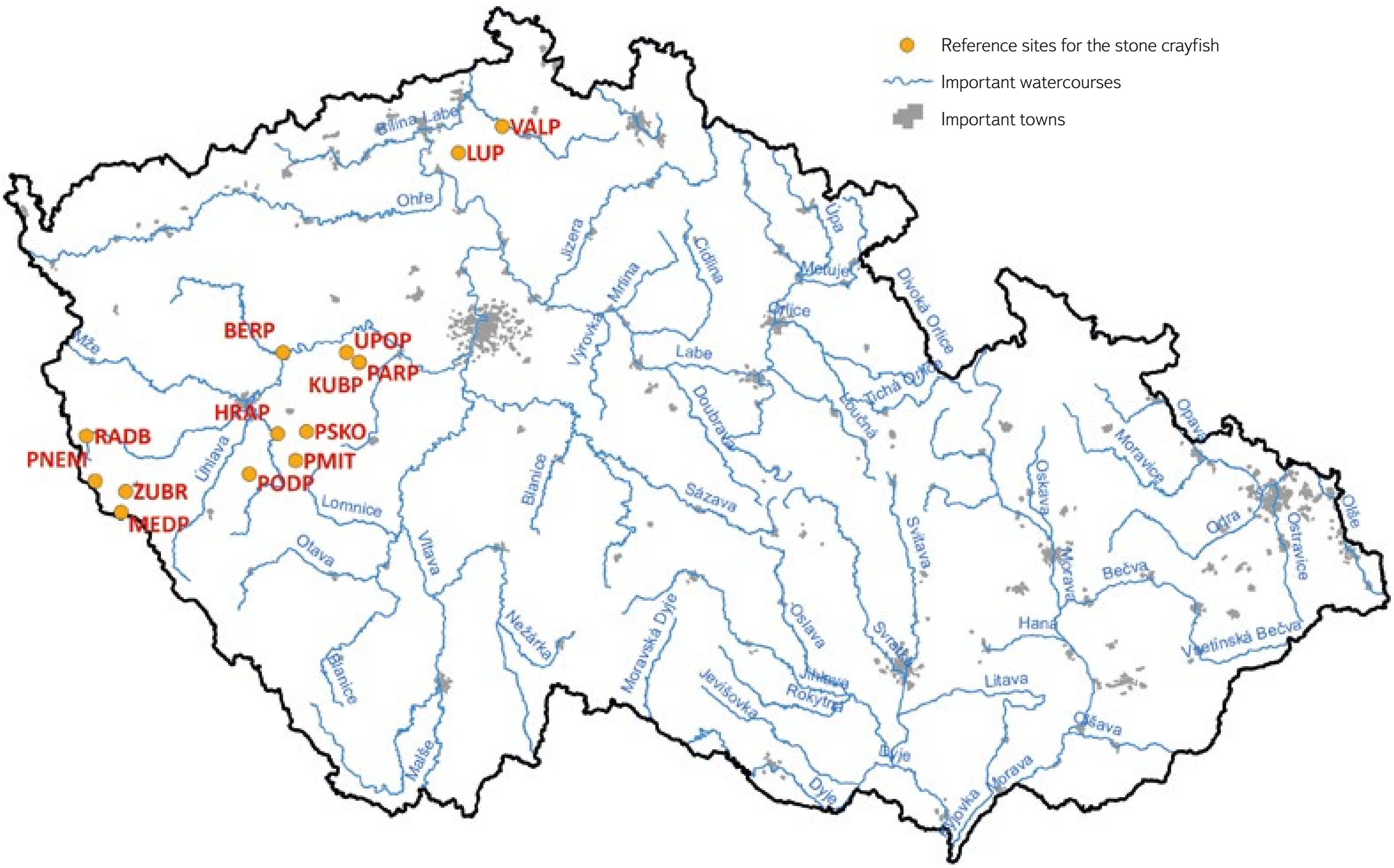

Fig. 1. Location of sampled sites for establishing environmental objectives for the stone crayfish. BERP – Bertinský stream, HRAP – Hrádecký stream, KUBP – Kublovský stream, LUP – Luční stream, MEDP – Medvědí stream, PARP – Pařezový stream, PMIT – Mítovský stream tributary, PNEM – Nemanický stream tributary, PODP – Podhrázský stream, PSKO – Skořický stream tributary, RADB – Radbuza river, UPOP – Úpořský stream, VALP – Valdecký stream, ZUBR – Zubřina river

space in such a way that similar samples are positioned close to each other, whereas dissimilar samples are more distant. For clearer visualisation, non-metric multidimensional scaling (NMDS) was also used. This method does not preserve absolute distances between objects (samples) but represents the positions of objects from an n-dimensional space in a two-dimensional display as faithfully as possible by maintaining rank-order relationships; thus, distant objects are displayed far apart and similar objects close together. For subsequent analyses of groups of sites identified during testing in Canoco 5, a two-sample t-test was applied, as the measured data showed a normal distribution. This test compares two independent datasets with unequal variances.

The obtained results were further compared with the limit values specified in Government Regulation No. 71/2003 Coll. [18] and Government Regulation No. 401/2015 Coll. [19], as well as with the environmental objectives used for the assessment of general physicochemical components of the ecological status of water bodies [21] and with the objectives applied in the assessment of the conservation features of Natura 2000 SCIs [20]. It is necessary to bear in mind that the individual legislative frameworks use different characteristic values: in Government Regulation No. 71/2003 Coll., the assessment is based predominantly on the 95th percentile; in Government Regulation No. 401/2015 Coll., on the annual mean; whereas the environmental objectives for stone crayfish were established on the basis of the annual median, or, where appropriate, minimum or maximum values. These methodological differences were taken into account when comparing the results.

RESULTS

The results of sample analyses and field measurements from all 14 sites were evaluated, and basic descriptive statistics (median, minimum, and maximum) were calculated for each parameter. The results are summarised in *Tab. 5*.

The results of the principal coordinate analysis (PCoA, *Fig. 2*) and non-metric multidimensional scaling (NMDS, *Fig. 3*) showed that the 14 assessed sites form two clearly separated clusters in ordination space. The PCoA explained 75.3 % of the total data variability (axis 1 = 50.6 %, axis 2 = 22.6 %), with the most important environmental variables correlating with the first and second axes at r = 0.98 and r = 0.88, respectively. The NMDS analysis produced comparable results and explained 89 % of the data variability (axis 1 = 62.6 %, axis 2 = 31.4 %), with correlations between environmental variables and the first two axes reaching r = 0.98 and r = 0.94. In the PCoA plot, samples with the highest weights corresponding to the first two axes are displayed; samples from the Podhrázský and Úpořský streams are not shown, as they project along the third axis. Both ordination methods revealed a consistent structure: five sites (Group 1) are separated along gradients of $ANC_{4.5}$, electrical conductivity and related parameters, while the remaining nine sites form a less compact cluster. The vertical spread of this group is primarily driven by the markedly higher discharge of the Radbuza river compared to the other, predominantly small watercourses.

Tab. 5. Median and measured minimum and maximum values for individual indicators at stone crayfish sites

	Profile code	Calcium	Water temperature	Dissolved oxygen	Water oxygen saturation	BOD_5	Electric conductivity	pH	$ANC_{4.5}$	Total phosphorus	PO_4-P	NO_3-N	NH_4-N	Chlorides	NO_2-N	Free ammonia	NL_{105}	Total iron
		[mg/l]	[°C]	[mg/l]	[%]	[mg/l]	[µS/cm]		[mmol/l]	[mg/l]	[mg/l]	[mg/l]	[mg/l]	[mg/l]	[mg/l]	[mg/l]	[mg/l]	[mg/l]
Medians	BERP	63.85	8.8	10.34	88.86	0.77	520.0	8.24	3.00	0.032	0.011	2.705	0.014	28.60	0.004	0.00043	6.2	0.13
	PARP	56.75	8.1	10.20	86.24	1.43	533.5	8.24	4.71	0.072	0.022	0.583	0.029	10.55	0.003	0.00093	20.0	0.19
	KUBP	51.80	7.4	10.47	87.95	1.11	507.0	8.15	3.49	0.256	0.209	4.110	0.020	23.00	0.007	0.00075	5.2	0.07
	LUP	65.30	8.2	10.65	87.84	1.17	520.0	8.16	3.35	0.062	0.016	1.275	0.015	9.85	0.005	0.00052	31.5	0.56
	VALP	48.45	6.1	10.45	84.33	1.26	384.0	7.97	2.54	0.085	0.041	1.195	0.040	10.09	0.013	0.00082	14.0	0.61
	HRAP	25.40	9.0	10.03	88.98	1.52	247.0	8.08	1.75	0.040	0.008	1.335	0.013	6.30	0.007	0.00039	4.0	0.27
	MEDP	15.70	10.0	9.74	87.84	1.07	186.8	7.75	0.72	0.040	0.011	3.830	0.022	12.20	0.009	0.00026	5.2	0.48
	PMIT	12.10	9.5	9.97	87.41	0.74	160.5	7.92	0.83	0.030	0.010	0.895	0.009	8.71	0.002	0.00019	5.2	0.13
	PNEM	4.35	9.3	9.81	86.69	0.81	62.2	7.51	0.23	0.019	0.005	0.758	0.008	1.73	0.001	0.00004	3.8	0.16
	PODP	29.75	8.9	9.13	83.15	1.04	306.5	7.82	2.02	0.061	0.020	2.880	0.018	18.30	0.009	0.00029	7.4	0.34
	PSKO	12.35	8.8	10.00	87.56	0.69	126.0	7.87	0.93	0.015	0.005	0.630	0.007	3.44	0.002	0.00013	1.4	0.15
	RADB	8.26	9.4	10.17	88.33	1.05	95.8	7.83	0.57	0.049	0.019	0.729	0.019	2.89	0.004	0.00020	5.8	0.82
	UPOP	23.70	8.2	10.27	85.41	0.98	248.5	7.86	1.21	0.028	0.008	0.614	0.015	7.53	0.002	0.00024	3.2	0.07
	ZUBR	15.70	10.0	9.56	85.32	1.76	172.9	7.81	0.86	0.080	0.014	2.355	0.032	6.63	0.014	0.00051	11.4	0.66
Minimum values	BERP	58.30	0.4	9.42	85.64	0.48	478.0	7.95	2.49	0.011	0.003	1.650	0.001	27.20	0.002	0.00008	1.2	0.04
	PARP	47.00	0.1	8.79	80.53	0.79	454.0	8.07	3.84	0.028	0.005	0.014	0.006	6.69	0.002	0.00028	5.6	0.04
	KUBP	48.50	0.2	9.32	83.19	0.50	460.0	7.97	2.51	0.160	0.129	3.010	0.006	19.20	0.002	0.00012	0.8	0.02
	LUP	53.00	0.8	7.24	70.76	0.70	409.0	7.37	2.77	0.016	0.005	1.010	0.007	7.73	0.002	0.00015	5.2	0.07
	VALP	34.40	0.8	7.60	73.26	0.80	295.0	6.99	1.23	0.032	0.016	0.643	0.014	6.25	0.003	0.00021	2.0	0.28
	HRAP	14.40	1.4	8.52	84.68	0.50	151.3	7.66	0.62	0.014	0.004	0.228	0.008	3.90	0.001	0.00016	0.4	0.11
	MEDP	14.40	1.7	8.32	81.72	0.50	168.9	7.40	0.43	0.020	0.007	2.940	0.010	11.40	0.003	0.00010	2.0	0.24
	PMIT	5.50	2.6	8.85	82.50	0.50	95.8	7.50	0.17	0.017	0.006	0.244	0.005	4.33	0.001	0.00002	2.0	0.07
	PNEM	3.54	1.1	8.86	81.29	0.49	50.5	6.74	0.02	0.008	0.001	0.336	0.002	1.08	0.000	0.00001	0.4	0.05
	PODP	18.20	1.5	8.13	71.23	0.66	190.6	7.39	0.47	0.019	0.010	0.738	0.008	12.30	0.003	0.00012	0.4	0.11
	PSKO	8.65	2.0	8.86	81.70	0.50	92.8	7.41	0.32	0.004	0.001	0.336	0.001	2.57	0.001	0.00003	0.4	0.05
	RADB	6.46	2.1	8.74	80.22	0.50	72.5	7.29	0.24	0.032	0.013	0.452	0.006	2.15	0.002	0.00010	1.2	0.31
	UPOP	14.40	0.3	8.47	77.74	0.50	176.3	7.13	0.38	0.009	0.006	0.318	0.003	3.77	0.001	0.00003	0.4	0.01
	ZUBR	12.60	2.7	7.97	80.89	0.75	137.6	7.31	0.53	0.032	0.006	0.959	0.009	5.05	0.003	0.00016	1.6	0.21
Maximum values	BERP	70.20	16.2	12.51	97.29	4.69	548.0	8.42	3.41	0.091	0.021	4.310	0.034	37.40	0.022	0.00084	26.0	0.33
	PARP	64.10	15.5	12.16	92.45	10.00	636.0	8.46	5.53	0.217	0.033	0.888	0.055	32.30	0.012	0.00183	120.0	0.33
	KUBP	52.70	12.6	12.54	92.47	4.83	558.0	8.36	3.66	0.515	0.429	6.910	2.390	31.50	0.105	0.04220	17.0	0.54
	LUP	75.30	16.6	12.81	92.42	2.86	580.0	8.27	3.58	0.221	0.097	3.380	0.236	12.80	0.015	0.00327	140.0	2.23
	VALP	53.90	16.6	12.35	90.30	2.70	473.0	8.34	2.83	0.241	0.077	4.150	0.119	16.90	0.030	0.00251	100.0	3.49
	HRAP	29.90	18.3	12.49	92.05	2.74	281.0	8.27	2.37	0.075	0.025	4.990	0.029	8.14	0.021	0.00059	10.0	0.50
	MEDP	17.50	16.5	11.53	93.27	1.80	200.6	8.06	0.81	0.153	0.107	6.730	0.051	17.50	0.013	0.00050	12.0	0.89
	PMIT	19.00	16.9	11.42	101.08	3.98	187.9	8.29	1.53	0.125	0.023	2.970	0.019	19.60	0.010	0.00052	22.0	0.68
	PNEM	6.00	15.0	12.06	91.41	1.20	73.2	8.15	0.52	0.036	0.008	2.090	0.019	2.26	0.003	0.00032	9.6	0.28
	PODP	33.30	16.6	11.43	90.43	1.93	328.0	8.13	2.63	0.315	0.065	5.360	0.079	29.90	0.035	0.00136	58.0	1.44
	PSKO	14.90	16.0	11.70	91.16	3.47	148.6	8.09	1.30	0.055	0.012	1.930	0.024	4.26	0.007	0.00025	8.4	0.42
	RADB	9.28	16.3	12.16	95.49	2.39	104.0	8.20	0.70	0.158	0.050	1.980	0.034	3.77	0.011	0.00056	26.0	1.95
	UPOP	34.10	15.5	11.87	91.97	11.00	314.0	8.16	2.17	0.049	0.018	1.950	0.101	9.71	0.017	0.00113	19.0	0.57
	ZUBR	17.30	18.1	11.28	89.99	4.58	184.5	8.05	1.10	0.146	0.035	6.260	0.094	7.82	0.047	0.00154	44.0	1.97

Sites belonging to group 1 with a median of acid neutralization capacity at pH 4.5 ($ANC_{4.5}$) ≥ 2 mmol/l are marked in green, while sites belonging to group 2 with $ANC_{4.5}$ median < 2 mmol/l are marked in blue
BERP – Bertinský stream, HRAP – Hrádecký stream, KUBP – Kublovský stream, LUP – Luční stream, MEDP – Medvědí stream, PARP – Pařezový stream, PMIT – Mítovský stream tributary, PNEM – Nemanický stream tributary, PODP – Podhrázský stream, PSKO – Skořický stream tributary, RADB – Radbuza river, UPOP – Úpořský stream, VALP – Valdecký stream, ZUBR – Zubřina river

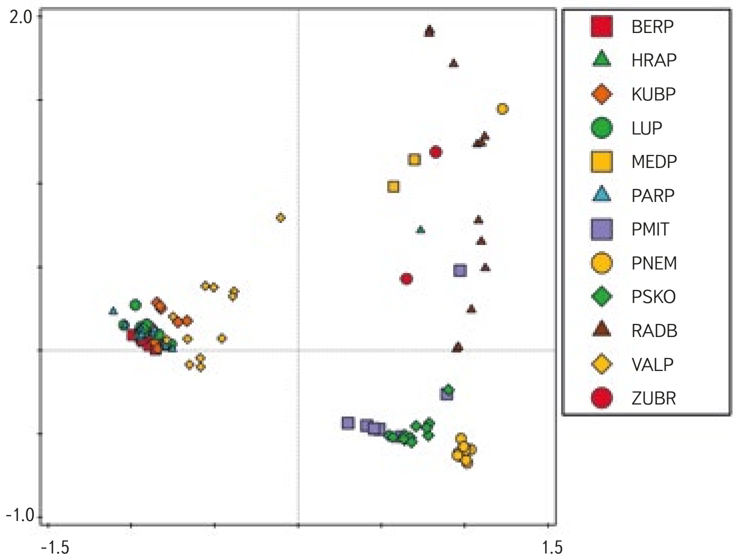

Fig. 2. PCoA analysis (Canoco 5) for the assessed sites characterized by monthly values of measured indicators, 1st and 2nd axes shown, cumulative variability explained by the displayed axes is 73.12 %
BERP – Bertinský stream, HRAP – Hrádecký stream, KUBP – Kublovský stream, LUP – Luční stream, MEDP – Medvědí stream, PARP – Pařezový stream, PMIT – Mítovský stream tributary, PNEM – Nemanický stream tributary, PSKO – Skořický stream tributary, RADB – Radbuza river, VALP – Valdecký stream, ZUBR – Zubřina river (samples from Podhrázský and Úpořský streams are not displayed because they are projected along the third axis)

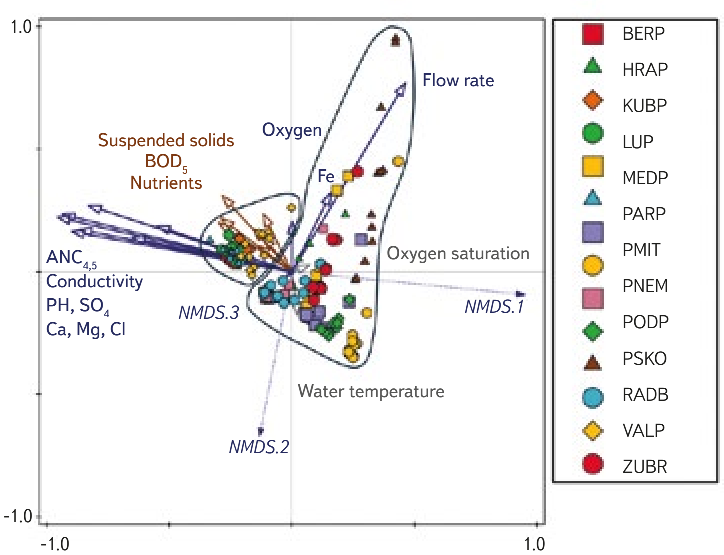

Fig. 3. NMDS analysis (Canoco 5) for the assessed sites characterized by monthly values of measured indicators, 1st and 2nd axes shown, cumulative variability explained by the displayed axes is 94 %. BERP – Bertinský stream, HRAP – Hrádecký stream, KUBP – Kublovský stream, LUP – Luční stream, MEDP – Medvědí stream, PARP – Pařezový stream, PMIT – Mítovský stream tributary, PNEM – Nemanický stream tributary, PODP – Podhrázský stream, PSKO – Skořický stream tributary, RADB – Radbuza river, UPOP – Úpořský stream, VALP – Valdecký stream, ZUBR – Zubřina river

The analysis indicates a division into two groups based on alkalinity (parameter $ANC_{4.5}$) and closely correlated variables (calcium, magnesium, conductivity). As alkalinity is a complex parameter that is only weakly influenced by human activity and describes the natural character of a site, subsequent analyses were conducted for two groups of sites, with the dividing criterion defined on the basis of the analysed data as an annual median $ANC_{4.5}$ value of 2 mmol/L (see the clear separation of groups in *Fig. 4*). For these defined groups, statistical evaluation of differences in individual parameters was performed using a two-sample t-test (comparing two independent samples with unequal variances; a significance level of $p = 0.001$ was applied). The results of the testing are summarised in *Tab. 6*.

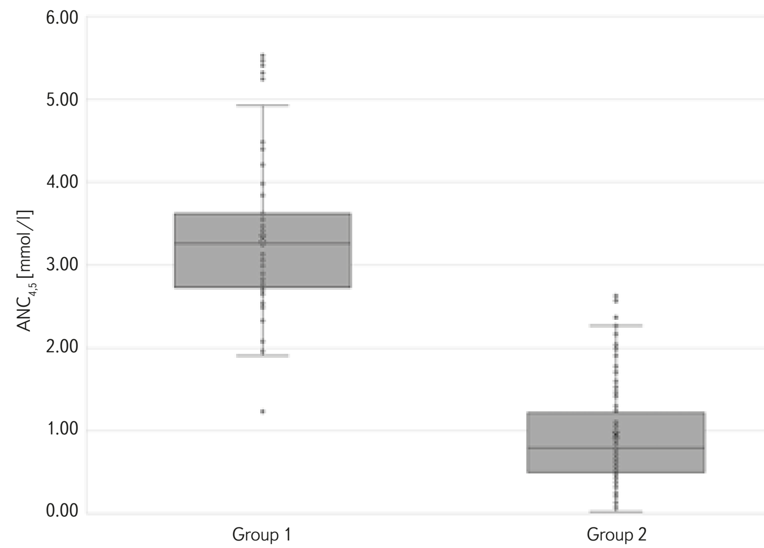

Fig. 4. Boxplot for the $ANC_{4.5}$ indicator with sites divided into groups based on PCoA and NMDS analyses; group 1 = sites with higher base ion content – $ANC_{4.5} \geq 2$ mmol/l, group 2 = sites with lower base ion content – $ANC_{4.5} < 2$ mmol/l

Tab. 6. Range of values measured in two groups of sites classified by base ion content, with indication of the statistically significant differences in all measured values of the respective parameter between the groups

Indicator	Unit	Range of measured values in site group 1 ($ANC_{4,5} \geq 2$ mmol/l)		Range of measured values in site group 2 ($ANC_{4,5} < 2$ mmol/l)		Two-sample t-test with unequal variances p – value	Statistical significance: * p < 0.05 *** p < 0.001
		MIN	MAX	MIN	MAX		
$ANC_{4.5}$	[mmol/l]	1.23	5.53	0.021	2.63	2.091×10^{-31}	***
Electric conductivity	[μS/cm]	295	636	50.5	328	1.076×10^{-55}	***
pH		6.99	8.46	6.74	8.29	7.590×10^{-14}	***
Water temperature	[°C]	0.1	16.6	0.3	18.3	0.2260	
Dissolved oxygen	[mg/l]	7.24	12.81	7.97	12.49	0.1511	
Oxygen saturation	[%]	70.76	97.29	71.23	101.08	0.7285	
BOD_5	[mg/l]	0.475	10	0.49	11	0.2709	
NH_4-N	[mg/l]	0.001	2.39	0.001	0.101	0.0915	
NO_3-N	[mg/l]	0.014	6.91	0.228	6.73	0.1834	
NO_2-N	[mg/l]	0.002	0.105	0.0004	0.047	0.0624	
Total phosphorus	[mg/l]	0.011	0.515	0.004	0.315	2.620×10^{-5}	***
PO_4-P	[mg/l]	0.003	0.429	0.001	0.107	0.0001	***
Suspended solids	[mg/l]	0.8	140	0.4	58	0.0006	***
Calcium	[mg/l]	34.4	75.3	3.54	34.1	1.814×10^{-55}	***
Magnesium	[mg/l]	10.1	36.8	1.39	13.6	8.932×10^{-24}	***
Iron	[mg/l]	0.024	3.49	0.014	1.97	0.9148	
Chlorides	[mg/l]	6.25	37.4	1.08	29.9	1.930×10^{-10}	***
Sulphates	[mg/l]	32.1	120	5.16	54.2	1.035×10^{-31}	***
Free ammonia	[mg/l]	0.000082	0.042	0.000014	0.002	0.0384	*

Statistically significant differences between the groups were identified for calcium, electrical conductivity, pH, chlorides, total phosphorus, orthophosphate phosphorus, and suspended solids. For these parameters, environmental objectives related to the stone crayfish were defined separately for each group of sites. For the remaining parameters (water temperature, dissolved oxygen and oxygen saturation, BOD_5, nitrate, ammonium and nitrite nitrogen, free ammonia, and iron), no statistically significant differences were detected at the selected significance level of $p = 0.001$; therefore, a single environmental objective was applied uniformly to both groups of sites.

The resulting environmental objectives, as presented in *Tab. 7*, were established with regard to the degree of anthropogenic influence at the sites based on the measured parameter values. For indicators documenting the impact of pollution (in particular nutrients and organic matter expressed as BOD_5), significantly impacted sites were excluded from the dataset and the objectives were derived solely from unimpacted sites. Target median values were set according to the calculated median of the relevant dataset, with expert judgement applied to take into account mean parameter values at individual sites and the occurrence of extreme values. Minimum values were defined based on the lowest value in the dataset (for the given group of sites or for the entire dataset), adjusted by rounding down, while maximum values were set by rounding up.

Tab. 7. Environmental objectives of selected aquatic environment parameters for the stone crayfish (Austropotamobius torrentium), divided into two groups according to the $ANC_{4.5}$ indicator; parameters for which a statistically significant difference between the site groups was identified are marked in blue

Indicator	Unit	Characteristic value					
		Sites with median ($ANC_{4,5} \geq 2$ mmol/l)			Sites with median ($ANC_{4,5} < 2$ mmol/l)		
		MED	MAX	MIN	MED	MAX	MIN
Calcium	[mg/l]			30			5
Water temperature	[°C]	9.5	21.5		9.5	21.5	
Dissolved oxygen	[mg/l]			7			7
Oxygen saturation	[%]		105	75		105	75
BOD_5	[mg/l]	1.2			1.2		
Electric conductivity	[μS/cm]	550			300		
pH			8.4	7.5		8.3	6.7
$ANC_{4.5}$	[mmol/l]			1			0.2
Total phosphorus	[mg/l]	0.07			0.05		
PO_4-P	[mg/l]	0.03			0.02		
NO_3-N	[mg/l]		3			3	
NH_4-N	[mg/l]	0.035			0.035		
Chlorides	[mg/l]	15			10		
NO_2-N	[mg/l]	0.01			0.01		
Free ammonia	[mg/l]	0.0007	0.005		0.0007	0.005	
NL_{105}	[mg/l]	15			6		

DISCUSSION

The newly derived environmental objectives differ from the original objectives presented in the methodology for assessing the status of protected areas [20] primarily in that they are not defined uniformly for all sites, but are divided into two groups according to the mean $ANC_{4.5}$ value (alkalinity), which distinguishes sites with high and low concentrations of basic ions. Based on statistical testing of the data in both groups, statistically significant differences were identified in the concentrations of certain parameters that are related both to the natural composition of waters and to indicators potentially associated with pollution. In the previous methodology, environmental objectives were established on the basis of a markedly limited dataset, whereas the new monitoring of reference and additional sites enabled a more robust data analysis and statistical evaluation of the two resulting groups.

Compared with the objectives specified in the above-mentioned methodology [20], not only the absolute target values were revised, but changes were also made to the characteristic values, which are now newly determined as limit values. For the parameters calcium and $ANC_{4.5}$, the median value is no longer used and the limit is defined solely as a minimum value. The median is also no longer applied for pH, for which only a range between minimum and maximum values is now specified. In view of the nature of pollution and the risk of the transfer of additional substances from agriculturally managed land, the characteristic value used for nitrate nitrogen was also revised. The target is now defined as a maximum value instead of the previously used median value. For this parameter, the requirement for water quality has therefore been made more stringent, bringing it closer to the assessment approach applied under the so-called Nitrates Directive [22]. In order to protect crayfish during critical periods of the year characterised by high temperatures and an increased risk of free ammonia formation, a target value for the permissible maximum was newly established for this indicator, while the median value was retained simultaneously.

In general, stricter objectives were established for sites with low acid neutralising capacity (annual median $ANC_{4.5}$ < 2 mmol/L) for parameters characterising anthropogenic pollution. This applies in particular to total phosphorus, orthophosphate phosphorus, chlorides and suspended solids. As shown by the statistical evaluations performed, the $ANC_{4.5}$ indicator correlates, among other factors, with calcium concentrations in waters. Previous studies have shown that crayfish are able to survive even under poorer environmental conditions and tolerate a certain level of pollution if sufficient bioavailable calcium is present in their environment [4].

In the original methodology for assessing the status of protected areas [20], a target value was also defined for total iron. At the individual reference sites, a wide range of values was observed without any direct relationship being identified with the presence or absence of crayfish. Based on the results obtained, we conclude that iron does not have a direct influence on the occurrence of the stone crayfish at the sites, and therefore no environmental objective was defined for this parameter. Similarly, environmental objectives were not established for other measured parameters exhibiting a wide range of values (magnesium, sulphates, and the estimated instantaneous discharge recorded at the time of sampling).

Particular attention in the setting of environmental objectives was paid to the indicator characterising the content of readily biodegradable organic matter in waters, namely BOD_5 values. Previous research and measurements at sites with the occurrence of stone crayfish indicated that target values should be very low. However, these limit values were derived from datasets that did not include complete year-round measurements but focused solely on seasonal monitoring. Analyses of samples from reference sites carried out within the present study showed that the central tendencies of the datasets point to the need to increase the environmental objective for this indicator. The main reason is the overall annual dynamics of the BOD_5 indicator, which is related to the cycling of organic matter in watercourses. It is necessary to recognise that, particularly during the period of leaf fall in autumn, a large accumulation of organic matter occurs within watercourses. Crayfish belong to the group of shredders and, as omnivores, play a substantial role in the breakdown of this organic matter. These fluctuations, which are most often manifested by elevated BOD_5 values in autumn, were recorded in all monitored watercourses. Certain differences were also identified between sites with the presence and absence of crayfish. Whereas at sites with a current occurrence of stone crayfish BOD_5 values did not exceed 4 mg/l, in watercourses where crayfish had disappeared, for example as a consequence of crayfish plague, these values were higher, in some cases reaching up to 10 mg/l BOD_5. At sites without anthropogenic pollution, elevated BOD_5 values during routine monitoring were observed mostly only in the autumn period, when the streambed was covered with fragmented leaf litter. Although these sites met the newly established environmental objective for the median BOD_5 of 1.2 mg/l, the C_{95} limit for biochemical oxygen demand of 3 mg/l for salmonid waters [18] was exceeded due to the period of leaf fall. In the subsequent months, BOD_5 values then declined to the usual low level.

For both groups of sites, the original requirement of the methodology for the assessment of the status of protected areas [20] concerning the central value of BOD_5 was therefore relaxed. Nevertheless, the new value (1.2 mg/l) remains considerably more stringent than the limit required under the methodology for the assessment of water bodies according to the Water Framework Directive [21] (ranging, depending on water type, from 1.5 mg/l to 2.5 mg/l). The new environmental objective values were incorporated into the completed Rescue Programme for the Stone Crayfish [9] and will be applied in the forthcoming update of the methodology for the assessment of SCIs [20] planned for 2026.

The importance of the BOD_5 indicator from the perspective of stone crayfish survival is further demonstrated by the assessment of water quality in the Zákolanský stream SCI. This watercourse ranks among the most polluted streams with recorded occurrence of stone crayfish. At the Dobrovízský stream site (Dobrovíz downstream) within this SCI, high BOD_5 values ranging from 9 to 16 mg/l were recorded in six samples collected during 2023. These values exceed both the new environmental objective for the water environment for stone crayfish and the limit set by Government Regulation No. 71/2003 Coll. [18], as well as the limit required to achieve good ecological status of water bodies [21]. Although this site was designated as an SCI for stone crayfish, in recent years the stone crayfish has become extinct in this part of the SCI as a result of severe municipal pollution.

For the reasons outlined above, we consider it important, when assessing the status of the water environment at sites with stone crayfish, to use the median value as the primary environmental objective for pollutants such as BOD_5, total and phosphate phosphorus, or chlorides, rather than evaluating short-term fluctuations in measured values that regularly occur under natural conditions and are not limiting for the occurrence of stone crayfish. Minimum and maximum values (including the C_{95} value used in Government Regulation No. 71/2003 Coll. [18]) are important for capturing extreme conditions, for example during pollution incidents, and it is meaningful to apply them to parameters for which even a single exceedance of the established limit could pose a threat to stone crayfish (pH, nitrate nitrogen, toxic free ammonia, etc.). Ideally, therefore, the assessment of the water environment at stone crayfish sites should combine evaluation against both species-specific environmental objectives and the objectives defined for salmonid waters [18].

The newly established environmental objectives were therefore further compared with the target values for salmonid waters, as specified primarily in Government Regulation No. 71/2003 Coll. [18] and secondarily in Government Regulation No. 401/2015 Coll. [19]. When comparing individual limits from Government Regulation No. 71/2003 Coll. [18] with the environmental objectives, it must be borne in mind that the environmental objectives are based on characteristic values derived from the median, minimum, and maximum of 12 monthly measurements, whereas the limits for salmonid waters are based predominantly on the 95th percentile when all 12 values are available, or on the maximum when fewer values are available. Direct comparison of the limits is therefore not possible; nevertheless, when measured data from reference sites were compared, some parameters were found to be set at comparable levels (for example water temperature or ammonium nitrogen), whereas others were more stringent. More stringent environmental objectives were established for free ammonia (NH_3), which is highly toxic to aquatic organisms due to its ability to penetrate cell membranes, as well as for nitrites (NO_2^-) and suspended solids (NL_{105}). At sites with crayfish, suspended solids cause increased turbidity, settle on crayfish gills, and also lead to the clogging of suitable refuges within the watercourse. The upper limit of pH has likewise been set more strictly, since pH values above 8.5, in combination with higher temperatures, promote the dissociation of NH_4^+ into toxic NH_3. At the same time, it should be noted that, compared with Government Regulation No. 71/2003 Coll. [18], the new set of objectives for stone crayfish includes a larger number of parameters. The government regulation, by contrast, additionally specifies limits for dissolved copper, total zinc, and total chlorine (as HOCl).

The limits for salmonid waters, which are also secondarily listed in the table of immission limits in Government Regulation No. 401/2015 Coll. [19], are defined as annual mean values, with the exception of the pH range and water temperature, which is specified as a maximum value. Owing to the use of annual means, however, situations may arise (in contrast to the use of the C_{95} value in Government Regulation No. 71/2003 Coll. [18]) in which the established immission limits are formally met even if an accidental pollution event occurs at a site or if a source operates intermittently for only a few months per year. Nevertheless, populations of most aquatic organisms may be severely affected in such watercourses, or even decimated. Although median and mean values may appear to be relatively similar, the mean, unlike the median, is easily influenced by extreme and outlying values. Direct comparison is therefore possible only for the maximum water temperature limit, which is permitted to be substantially higher under Government Regulation No. 401/2015 Coll. (29 °C), and for the pH range, which is specified more broadly in this regulation (5–9) [19]. When median and mean values derived from measured data at reference sites are compared, the immission limits set out in this government regulation appear more permissive than the environmental objectives also for other parameters (BOD_5, suspended solids, chlorides, etc.).

An interesting perspective is also provided by a comparison of the newly proposed environmental objectives with the limits used for the assessment of the ecological status of water bodies for general physicochemical components [21]. This methodology was developed for the purposes of assessing river-type water bodies in accordance with Water Framework Directive (Directive 2000/60/EC of the European Parliament and of the Council of 23 October 2000 establishing a framework for Community action in the field of water policy; hereinafter WFD) [23]. One of its objectives is to achieve at least the second class, that is, good ecological status, in water bodies, where the values of biological quality elements of a given type of surface water body show a slight level of disturbance caused by human activity, yet differ only slightly from those that typically occur in this type of water body under undisturbed conditions [23].

The limits established for the assessment of water bodies under the WFD requirements differ among individual water body types. These limits, like the environmental objectives, are defined as medians or, where appropriate, as minimum and maximum values, which allows for direct comparison of the respective values. As noted above, the WFD requires that at least good ecological status be achieved. It is therefore relevant to compare the values of the environmental objectives with the threshold separating moderate and good ecological status. Water bodies are characterised on the basis of river basin, altitude, geological substrate, and stream order derived by the Strahler method [21]. For the purposes of our comparison with the environmental objectives, only altitude can be used, as the other characteristics (such as river basin) do not affect the applicable limit values within the given altitude range.

In watercourses situated at altitudes above 800 m a.s.l., the threshold between moderate and good ecological status for BOD_5 is set at 1.5 mg/l; for watercourses at 500–800 m a.s.l. at 1.7 mg/l; for those at 200–500 m a.s.l. at 2.2 mg/l; and for watercourses below 200 m a.s.l. at 2.5 mg/l. In all cases, these limits are less stringent than the environmental objective defined for stone crayfish, whose core distribution lies at mid-altitudes, that is, between 200 and 800 m a.s.l. The same value of 1.2 mg/l for this parameter is specified only as the boundary between good and very good ecological status in watercourses above 800 m a.s.l., that is, in very clean mountain streams without anthropogenic influence. Similarly stringent is the environmental objective set for water temperature (9.5 °C), whereas the annual median limit separating moderate and good status according to the methodology for the assessment of water bodies [21] is 10, 11, 12, and 13 °C for the respective altitude categories listed above, and a value of 9 °C is specified only as the threshold between good and very good status for watercourses above 800 m a.s.l.

Phosphate phosphorus is set more stringently in the environmental objectives for stone crayfish for watercourses below 500 m a.s.l. in both groups of sites defined by base ion content; at higher altitudes, the limit is already comparable. The environmental objective for ammonium nitrogen is more stringent across all altitude categories. A stricter maximum value is also defined for nitrate nitrogen (3 mg/l) for watercourses up to 800 m a.s.l. (under the WFD-based assessment, 4.6 mg/l applies for altitudes of 500–800 m a.s.l. and 5.6 mg/l below 500 m a.s.l.). In the altitude category above 800 m a.s.l., assessment according to the methodology for the evaluation of water bodies [21] is more stringent for this parameter, with a value of 1.4 mg/l. Furthermore, the environmental objective for the maximum oxygen saturation (105 %) is set more strictly, whereas the threshold between moderate and good ecological status is 125 % for watercourses below 500 m a.s.l. and 120 % for watercourses between 500 and 800 m a.s.l. For the remaining parameters, the values of the environmental objectives and the limits under the WFD are set at broadly comparable levels.

CONCLUSION

At 14 reference and best available sites suitable for the occurrence of stone crayfish, year-round monitoring of physicochemical water quality indicators was carried out and the resulting data were statistically evaluated. The evaluation revealed that sites suitable for stone crayfish can be divided into two types according to natural conditions, with the separating parameter being alkalinity expressed as a median $ANC_{4.5}$ value of 2 mmol/l. Based on the statistical assessment of sites within these two groups, indicators that differ significantly were identified, for which different environmental objectives can be used. At the same time, the remaining indicators were identified for which environmental objectives were set identically for both groups. More stringent requirements for the state of the water environment for stone crayfish were established for the group of sites with a low content of base ions.

From the perspective of water environment quality, the stone crayfish can be considered an umbrella species only for certain parameters. The BOD_5 parameter can be described as strictly limited, as it corresponds to the upper limit of the oligosaprobic level [24, 25] and is defined much more strictly than the limit established for achieving good ecological status for the relevant type of water body under the WFD. From the perspective of maximum measured values, however, the C_{95} value for salmonid waters under Government Regulation No. 71/2003 Coll. is also set relatively strictly; this value was exceeded at some of the monitored reference sites due to elevated BOD_5 values during the period of leaf fall. In many cases, these were sites where the presence of a stone crayfish population was not confirmed during the sampling period. In comparison with the limits under the WFD, parameters indicating thermal and oxygen conditions, as well as parameters assessing nutrient conditions in the watercourse, are also limited more stringently. In comparison with the limits for salmonid waters, the environmental objectives are more stringent for free ammonia, nitrites, and suspended solids. Direct comparison, however, is possible only with the limits under the WFD, where, as in the case of the environmental objectives, characteristic values are defined as medians or, where appropriate, as minimum and maximum values. Comparison with Government Regulation No. 71/2003 Coll. and Government Regulation No. 401/2015 Coll., which are based on C_{95} values and annual means, was therefore carried out using data from the measured reference sites.

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Application of thermometry in the exploration of mineral springs – Mariánské Lázně and Karlovy Vary

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Keywords: thermometry – mapping of mineral springs – Mariánské Lázně – Karlovy Vary

ABSTRACT

Thermometry is a non-invasive technique suitable for detecting hidden mineral water springs. Its applicability was evaluated in two contrasting hydrogeological settings: Mariánské Lázně, characterized by cold, CO_2-rich mineral springs, and Karlovy Vary, dominated by thermal springs.

In Mariánské Lázně, the objective was to identify previously undocumented springs. Ground thermometry with a thermal infrared (TIR) camera proved highly effective. The survey was supplemented by measurements of free dissolved CO_2 (Härtl tube), temperature, electrical conductivity, and pH. A total of 131 thermal anomalies were recorded along 20 km of watercourses, 14 of which were confirmed as new mineral springs. The actual number of springs is likely higher, as CO_2 analyses are limited in springs strongly diluted by surface water.

In Karlovy Vary, the aim was to localize and quantify wild thermal springs (up to 73.4 °C) within the bed of the Teplá river, which influence the equilibrium of the entire spring system. TIR imaging was ineffective due to rapid dilution by river water. Therefore, point temperature measurements were performed in a regular grid over a 1,300 m^2 area of the riverbed. This approach revealed 14 untapped so-called *wild* thermal springs. In parallel with water temperature measurements, electrical conductivity was also continuously recorded, and at the end of the mapping a summary discharge balance of the springs was attempted, unsuccessfully, using a FlowTracker device based on water flow measurements in the Teplá. Ultimately, the total yield of the wild springs in the study area, that is, in the vicinity of the Vřídlo springs, was estimated at 2–3 l/s. This estimate is based on long-term changes in pressure conditions within the Vřídlo structural system.

The results of both thermometric surveys demonstrate that, when an appropriate workflow is applied, thermometry represents a highly versatile and effective method for the qualitative assessment of mineral water discharges. However, for successful application, the methodology must always be adapted to the specific hydrogeological and hydrological conditions of the site. The results of both partial surveys provided information on the distribution of mineral springs and will serve as a basis for defining the protection of spring structures.

INTRODUCTION

In hydrogeological practice, thermometry is most commonly used to identify concealed inflows of groundwater into surface waters. It represents an alternative to simple discharge measurements in a watercourse, where differences in flow are assumed to be caused by groundwater inflow. Thermometry is based on the premise that groundwater usually exhibits a more stable temperature throughout the year compared with the more variable temperatures of surface water [1]. The temperature of groundwater in the near-surface zone of the geological environment approaches the mean annual air temperature and increases with depth below ground as a result of the geothermal gradient. This thermal contrast creates anomalies in watercourses or receiving waters at locations where groundwater emerges [2], which can be detected using probe thermometers, cameras recording in the infrared thermal spectrum (TIR), or standard conductometers with a temperature sensor, both through in situ measurements and remote sensing [3]. The thermal contrast can be understood as a natural non-conservative tracer. Its advantage lies primarily in its ubiquity, natural occurrence, non-invasive nature, and ease of detection, which enables rapid mapping [4]. Unlike conservative tracers, whose concentrations are directly related to mixing ratios [5], the quantitative interpretation of thermal anomalies in terms of discharge estimation is indirect and complex [6]. The measured temperature signal is influenced by the temperature of groundwater, surface water, the degree of mixing with surface water, and heat exchange with the atmosphere, which depends, inter alia, on the thermal capacity of water. For these reasons, thermometry is considered a qualitative, or in some cases semi-quantitative, method.

The effectiveness of detecting a thermal signal is directly related to the magnitude of the temperature difference (ΔT). Under conditions in the Czech Republic, thermometric surveys are most effective in winter, when relatively warm groundwater contrasts with cold water in streams or receiving waters. However, diurnal temperature fluctuations are also important. Surveys conducted at night or under complete cloud cover minimise disturbing effects [3]. Detection is further influenced by seasonal variability in stream discharge: at higher flows, the detection threshold increases and sensitivity decreases. In general, better results can be achieved under calm conditions and during periods without recent precipitation, which tends to homogenise the temperature of the water column. Heat exchange is influenced by conduction, convection, and radiation, as well as by transport processes, predominantly advection, whereby heat is transported with the movement of groundwater and, respectively, surface water [6]. The second main transport mechanism is thermal dispersion, which arises as a result of differing flow velocities [7]. Although it is sometimes simplified or neglected in models, particularly at low flow velocities, dispersion can be important for the accurate interpretation of heat transport processes [7]. The combination of these processes determines the size, shape, and intensity of the thermal signal. In qualitative assessments, it is assumed that the intensity and size of a thermal signal reflect the discharge or temperature of a spring (a larger or more pronounced anomaly approximately corresponds to higher discharge or a higher inflow temperature) [6]. The shape of the thermal signal is influenced by flow direction and mixing dynamics [8]. In quantitative applications, the main difficulty is the aforementioned non-conservative nature of the "tracer". It is necessary to take into account the thickness of the water column above the discharge point, the degree of mixing, the velocity of surface water flow, and the influence of atmospheric conditions. There is no universal calibration for quantification, and each site must therefore be assessed individually [9, 10].

Experience with the use of thermometry for locating concealed springs is extensive both internationally and within the Czech context. However, in the field of natural medicinal resources, this method has not yet become part of routine practice, and experience with its application remains limited. Thermometry was used, for example, in the mapping of the tectonic structure of western Bohemia, including the wider surroundings of Mariánské Lázně. This work was carried out between 1984 and 1988, and areas such as the Pott valley in Mariánské Lázně were surveyed using thermometric methods [11]. The results, however, were intended primarily to verify the hypothesis that abundant groundwater discharges are tectonically predisposed, while issues related to natural medicinal resources were largely not addressed, reportedly also due to the low sensitivity of the detectors available at that time. In Karlovy Vary, so-called commission inspections using thermometry were conducted in 1980 [12], but their purpose was not to quantify measurements; rather, they served as reconnaissance of the site in connection with ongoing remediation works. Measurement data from these inspections in Karlovy Vary are not available.

OBJECTIVES

The main objective of the thermometric survey in both Mariánské Lázně and Karlovy Vary (*Fig. 1*) was to identify previously unknown mineral water discharges. Knowledge of the spatial distribution of mineral springs is crucial for the appropriate design of both preventive and remedial protection measures, including those related to already recorded and exploited discharges. A partial objective was to describe the specific aspects of the application of thermometry in the exploration of mineral water outlets, with two contrasting sites deliberately surveyed in order to verify the applicability of the method across a broader range of conditions. The Mariánské Lázně area is spatially extensive and is characterised by discharges of cold mineral waters enriched with free dissolved (hereafter f. d.) CO_2, whereas the Karlovy Vary area is spatially limited and typical of thermal water discharges. Mariánské Lázně was selected because the search for cold mineral springs places higher demands on the applied technology, which ultimately results in a higher explanatory value of the outcomes obtained from testing thermometry in mineral spring detection. Sub-objectives were defined separately for each site.

Fig. 1. Areas studied with thermometric survey

Sub-objectives for the Mariánské Lázně site

The sub-objective was to use newly identified mineral water springs for sampling and, on this basis, to better understand spatial patterns in their composition. The current concept of the hydrochemical zonation of mineral waters is based solely on data from recorded springs [13]. The significance of identifying additional, less abundant, unrecorded mineral springs or seepages is also related to the requirement of the Slavkovský les Protected Landscape Area (PLA) to register and protect mineral water springs as a whole, regardless of whether or not they have designated protection zones. Without knowledge of their location and physical and chemical properties, it is not possible to ensure effective protection of discharging mineral waters. This is also closely linked to the question of the tectonic control of water chemistry and the spatial distribution of springs.

Sub-objectives for the Karlovy Vary site

The sub-objective of the thermometric measurements in Karlovy Vary was to verify whether the current natural and artificial sealing layers at the bottom of the Teplá river channel are sufficiently effective in preventing uncontrolled discharges of thermal water in the lowest parts of the valley. The quality of sealing has always played a crucial role in the trouble-free exploitation of the Vřídlo spring; therefore, the spring sedimentation forming the natural sealing layer had to be continuously supplemented with additional artificial sealing elements to prevent undesirable breakthroughs of thermal water [14]. However, the artificial sealing was never completed over the entire area of the Teplá river channel in the centre of the discharge zone. This area is thus still affected by numerous leakages of thermal water as well as spring gas directly into the surface recipient [15]. In the event of more significant damage to the sealing of the channel bottom in the vicinity of the Vřídlo spring, a decrease in the yield of nearby small springs occurs and degassing of the structural centre takes place. The results of the survey will serve as baseline material for the administrators of the local natural medicinal resources.

STUDY AREAS

Mariánské Lázně

In Mariánské Lázně and its surroundings, more than 100 mineral springs emerge, all of which are characterized by high CO_2 degassing, low temperatures ranging from approximately 7 to 12 °C, and relatively low yields from 0.01 to 1 l/s. The springs differ from one another primarily in their highly variable total dissolved solids (TDS), ranging from 0.2 to 12.0 g/l, as well as in their chemical composition [13, 16]. Based on chemical composition, four main groups of springs can be distinguished, with each group being formed under specific lithological conditions. The first group is associated with serpentinites, the second with amphibolites, the third probably with infiltrated fossil mineralization. The fourth is a so-called transitional group, in which the chemistry is influenced by combined lithology, too short a contact time with the bedrock, or by lithology that does not exhibit a clearly defined chemical signature [16]. These general findings concerning the spring system formed the basis for the design of an appropriate methodology for the thermometric survey.

Karlovy Vary

The discharges of the Karlovy Vary thermal waters, with a maximum temperature of 73.4 °C and a total dissolved solids of 6.4 g/l, together with emissions of spring gas, are confined to an approximately 1,700 m long and about 150 m wide discharge zone within granites. The total yield of the spring structure is approximately 33 l/s. From the perspective of the distribution of thermal water and spring gas yields, the centre of the discharge zone lies close to the historical position of the Vřídlo spring, which accounts for about 95 % of the yield of all Karlovy Vary springs. All thermal springs in Karlovy Vary are chemically identical, with the exception of the Hadí and Štěpánčin springs, which have lower mineralisation. Individual springs differ from one another only in temperature and CO_2 concentration [17]. The temperature of the springs is influenced primarily by the ascent velocity of the thermal water along favourable discontinuities towards the surface and, to a certain extent, also by the distance of the discharge point from the centre of the structure. A completely specific phenomenon within the discharge zone is the presence of carbonate spring sediments (aragonite shield) with a thickness of more than 10 m in places [14, 18]. In Karlovy Vary, untapped ("wild") springs (*Fig. 2*) have been known for centuries and have always had a significant impact on the exploited springs. The causes of wild springs resulting from failures in the sealing of the riverbed are both natural (river erosion, changes in pressure within the structure, etc.) and anthropogenic (construction works, krenotechnical systems; *facilities for the collection and distribution of thermal spring water to hotels, translator's note*, etc.) [19]. The regime of the Karlovy Vary springs is also influenced, for example, by tidal forces [20]. These general insights into the structure formed the basis for the design of an appropriate methodology for thermometric mapping of wild springs.

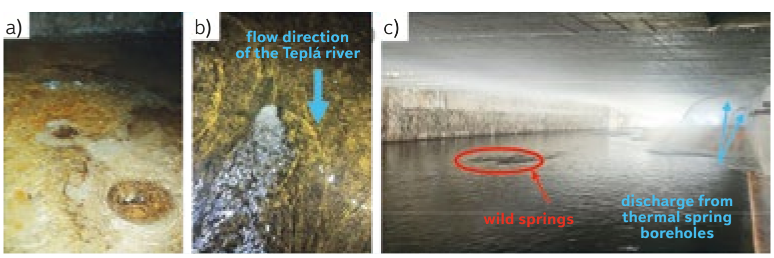

Fig. 2. Untapped "wild" springs; a) springs in the old basement of the Vřídlo, b) wild springs in the Teplá riverbed, c) general view under the bridge with visible untapped springs

METHODOLOGY

For publication purposes, a mineral water spring in the case of Mariánské Lázně is defined as one exhibiting a free CO_2 concentration > 1 g/l, i.e., a carbonated mineral spring, and in the case of Karlovy Vary as one with a temperature > 20 °C, i.e., a thermal spring. A temperature anomaly refers to any thermal irregularity detected by a thermal camera. A new or "wild" mineral water spring is defined as a thermal anomaly where an elevated free CO_2 concentration has been detected using the Härtl shaking apparatus (hereinafter referred to as the Härtl tube), or where the temperature is at least approximately 3 °C higher than the background water temperature.

Mariánské Lázně

In the study area (*Fig. 4*), watercourses were first identified using the Basic Geographic Data Base of the Czech Republic (ZABAGED). The thermometric survey itself took place from January to March 2023, using a FLIR C5 TIR camera (USA), capable of measuring temperatures from -20 °C to +400 °C with a capture frequency of 8.7 Hz and a resolution of 240 × 320 pixels in its basic mode, i.e., with automatic calibration. The sequence of activities following the identification of a temperature anomaly of unknown character included: marking the site with a stake, photographic documentation, GPS positioning using a mobile phone, measurement of conductivity, temperature, and pH using a WTW Multi 340i device with a TetraCon 325 probe and a pH-Electrode SenTix 41, and finally, determination of flow rate and free dissolved CO_2 concentration using Härtl tube. Although all identified temperature anomalies were surveyed, sampling for chemical analysis was carried out only for those anomalies in which the presence of free dissolved CO_2 was detected using the Härtl tube, i.e., at new mineral water springs. The most significant new mineral water springs, in terms of flow rate and CO_2 content, were assigned not only an identification number but also names corresponding to nearby springs. For improved spatial accuracy, the temperature anomalies were geolocated in March–April 2023 using an RTK (Real-Time Kinematic) GPS station. Subsequently, an interpretation was carried out and the data were compared with the temperatures and electrical conductivities of previously recorded mineral springs, taking into account that the water temperature in exploited mineral water boreholes increases with depth by an average of 1.6 °C per 100 m (*Fig. 3*), and that some abstraction points have overflow, which further reduces interpretability. All new mineral water springs were monitored regularly until July 2024 to verify that they were not of a temporary character.

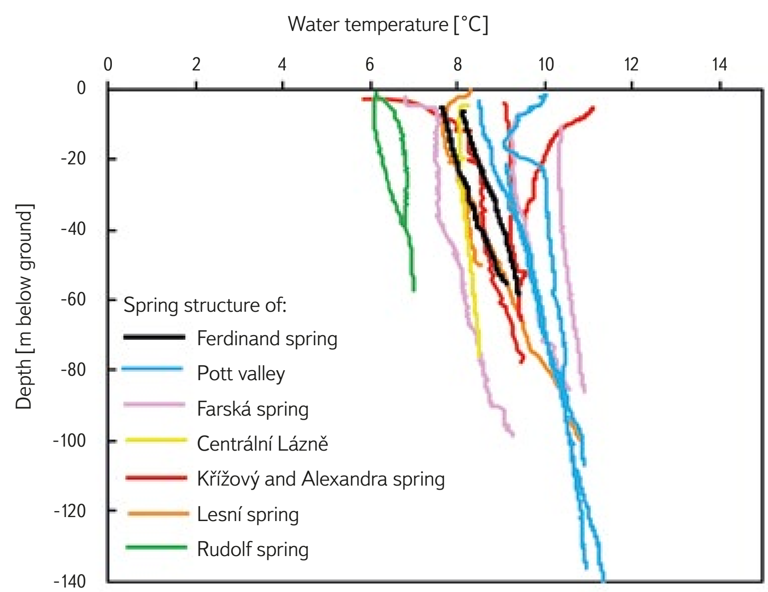

Fig. 3. Change in water temperature with depth in exploited mineral water boreholes in individual spring structures in Mariánské Lázně (adapted from [21])

Karlovy Vary

The methodology for locating the thermal spring sources was adapted to the smaller areal extent of the area, the higher temperature of the springs, and the higher dilution ratios, as the Teplá river carries approximately 1.5 m^3/s with a water column of about 0.4 m, which precludes the use of a TIR camera. Point measurements were carried out using a conductometer with a temperature sensor arranged in a defined grid. For measuring temperature and electrical conductivity, a Greisinger (Germany) G 1410 instrument was used, allowing temperature measurements from −5.0 to 105.0 °C with an accuracy of ± 0.3 °C. The temperature sensor was encased in insulating foam to ensure that it measured only the temperature at the bottom of the Teplá riverbed. Thermal profiling was conducted over an area of approximately 1,300 m^2 on 11 September 2024. For profiling purposes, a regular grid was established from Janský most to Vřídelní lávka, i.e., in areas without additional artificial sealing. The spacing between measurement points was 5 m, or 2 m and 1 m in locations where thermal spring discharges were expected. At points with anomalously high temperatures, the exact location of the thermal spring was manually identified and recorded. Subsequent spatial evaluation was performed using the deterministic interpolation method IDW (Inverse Distance Weighting). This methodology was chosen with the understanding that a potential spring could be located even outside the measured points. Thermometry was complemented by flow measurements of the Teplá river, taken both upstream and downstream of the area of interest using a FlowTracker device. These measurements were intended to help balance the total discharge of the wild springs.

RESULTS

Mariánské Lázně

Using thermometry along 20 km of watercourses in the study area, 14 new mineral water springs were identified, while a total of 131 thermal anomalies were recorded (*Fig. 4*). The thermal anomalies most commonly exhibited an elliptical shape, elongated in the direction of surface water flow. In the case of the new mineral water discharges, it was often observed that the water emerged above the stream bed, overflowing the edges of the spring sediments (*Fig. 5a*). The new mineral water discharges were distributed unevenly across the area; except for one occurrence (P013A Chudá), their location was restricted to the western part of the area (*Fig. 4*). Thermal anomalies were also detected in the very centre of Mariánské Lázně, where an anomaly with a temperature of 5 °C and a conductivity of 1,725 µS/cm was measured at the bottom of the partially drained Labutí jezírko. However, the dissolved CO_2 content could not be measured using the Härtl tube, and therefore this trace was not classified as a new mineral water spring.

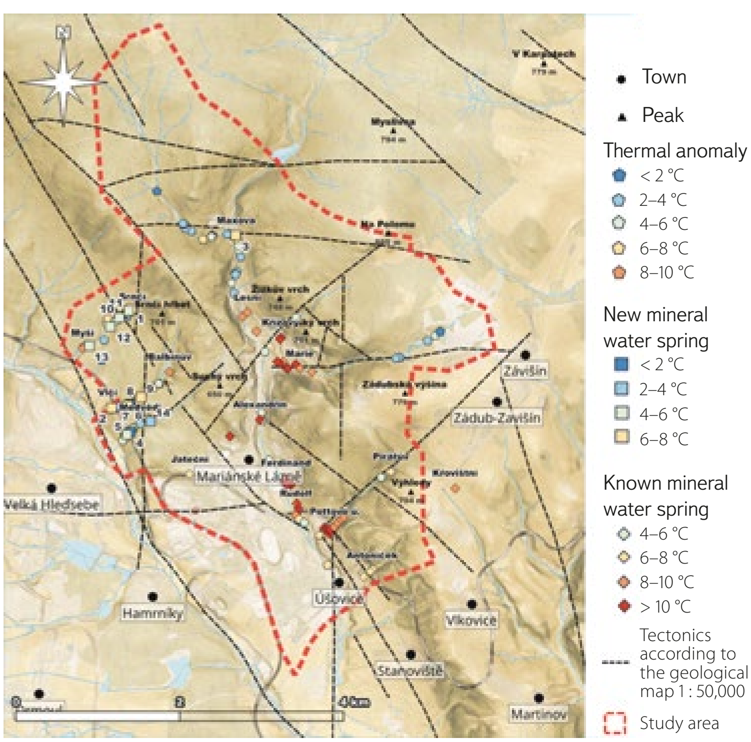

Fig. 4. Thermometric measurements in Mariánské Lázně
1 = P004/P069 Žabí, **2** = P011, **3** = P013A Chudá, **4** = P035, **5** = P037D Ježčí, **6** = P045A, **7** = P047 Mravenčí, **8** = P053 Šnečí, **9** = P054 Sýkorčí, **10** = P059B, **11** = P067A, **12** = P071, **13** = P073, **14** = P116 (Source: map: DMR 5G)

Thanks to thermometry carried out in freezing conditions, it was possible to detect thermal anomalies at absolute temperatures as low as 1.9 °C (*Fig. 5b*). Many of the new mineral water discharges were accompanied by iron coatings, emissions of gaseous CO_2, distinctive organoleptic properties, and resistance to freezing. All 14 new mineral water springs consistently exhibited a pH value below 7. For some thermal anomalies, the dissolved CO_2 content could not be measured due to significant dilution by surface water. For this reason, it cannot be excluded that the actual number of mineral water springs is higher. Although the entire discharge system is generally associated with the Mariánské Lázně fault zone, the influence of local tectonics on the spatial distribution of discharges could not be determined (*Fig. 4*).

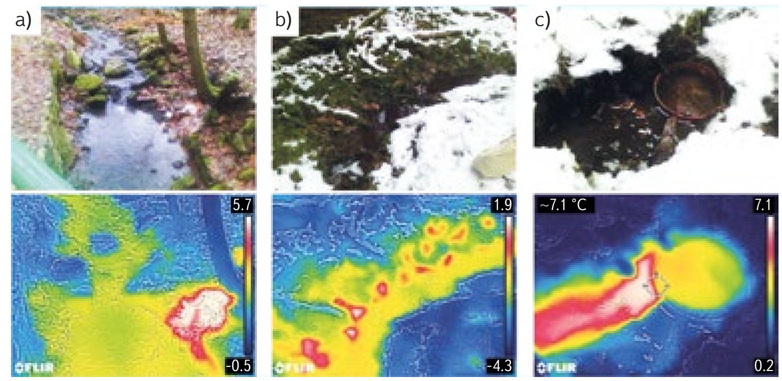

Fig. 5. Thermal camera images; a) Lučina kyselka, b) small springs in the river floodplain, c) Žabí kyselka springing outside the spring catchment

Supplementary conductivity measurements of the thermal anomalies revealed a poor correlation with temperature (*Fig. 6*). A slightly better correlation is observed when the dataset of new and existing mineral water discharges is divided into hydrochemical groups. In general, however, water temperature is not a suitable predictor for estimating conductivity. The highest coefficient of determination, $R^2 = 0.718$, was observed for the Na-HCO_3 / SO_4 group, while the other groups showed significantly lower determination coefficients (R^2 = 0.315 and 0.386). The only group showing a decreasing temperature with increasing conductivity was Mg-HCO_3 (R^2 = 0.497); however, this dataset is limited to only four discharges. It was found that higher spring discharge results in lower annual water temperature fluctuations.

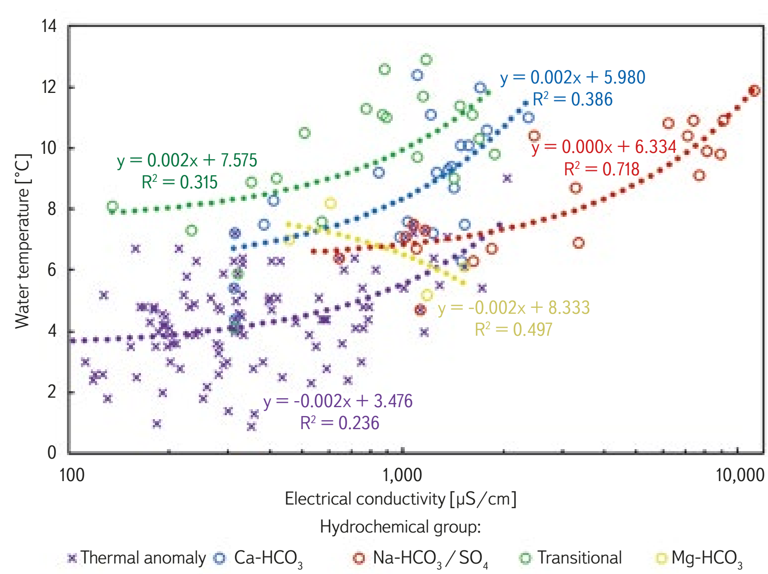

Fig. 6. Relationship between seepage temperature and conductivity for temperature anomalies and all known seepages (new and existing) divided by hydrochemical groups in Mariánské Lázně

Beyond its original purpose, the TIR camera proved to be a suitable tool for verifying the status of mineral water discharge record. *Fig. 5c* shows that Žabí kyselka, a newly discovered and provisionally recorded spring, discharges outside the collection system. Repeated monitoring of the new mineral water discharges revealed significant seasonal variations in both temperature and flow rate, with the lowest temperatures occurring in winter and the highest in summer. In contrast, conductivity and pH values remain almost stable. Out of the 14 new mineral water springs, 11 were sampled for chemical analysis, and the results will be used for the future revision of protection zones within the Slavkovský les PLA.

Karlovy Vary

The thermometric survey, supplemented by conductometry of the Teplá riverbed around the Vřídelní Collonade, revealed the presence of 14 wild discharges of thermal mineral water over an area of 1,300 m^2. In terms of spatial distribution, the wild discharges are concentrated along the right bank of the Teplá riverbed, with the highest density at the level of the Wolker Spa House. Only four discharges were identified in the centre of the flow or outside the Wolker Spa House section. The fact that wild discharges are predominantly found along the right bank of the Teplá opposite the Wolker Spa House aligns with the historical and current intake points of the Vřídlo (BJ 35–37, 70), which have always been located on the right bank. The highest concentration of wild mineral springs is located near the bases of the inclined spring boreholes BJ 35, BJ 36, and BJ 70. A wild mineral water spring was also found above the fourth spring borehole, BJ 37, although its temperature reaches only 23.3 °C. Even though it was not possible to completely prevent contact between surface water and the temperature/conductivity probe, the highest recorded temperature of a wild spring was 71.3 °C, and the highest measured conductivity was 7,470 μS/cm – values almost identical to those of the Vřídlo spring. Beyond the original scope, six main sites of gaseous CO_2 escape through the Teplá's water column were visually identified.

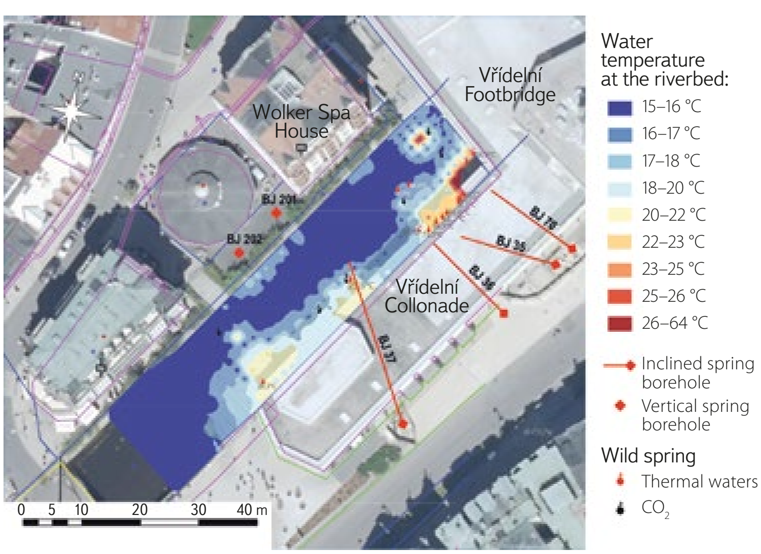

Fig. 7. Thermometric measurements in Karlovy Vary

Due to the well-known long-term variations in the discharge of the structure and pressure changes at the regulating wells, it has been estimated that wild discharges currently flow into the Teplá riverbed with a total flow rate of approximately 2 to 3 l/s, including an unknown amount of gaseous CO_2. The total flow of the wild springs was also tentatively assessed using a FlowTracker device, but due to its ± 10 % accuracy, the measurements did not yield the expected results.

Analysis of the data revealed a correlation between water conductivity in the defined network and temperature, with a coefficient of determination $R^2 = 0.585$. Although the coefficient is very similar for the already recorded springs ($R^2 = 0.520$), the distribution of values is entirely different. The Hadí spring is the only recorded spring with a distinctly different conductivity. It is the most distant discharge from the centre of the structure, has the highest concentration of dissolved CO_2, and is also the coldest (*Fig. 8*). Therefore, it can be excluded from the dataset. By analogy with wild mineral water springs, it can be concluded that water temperature is not a reliable precursor for determining conductivity, because if dilution by the Teplá is prevented, the conductivity for all new wild springs would be the same, i.e., ± 7,300 μS/cm, while the water temperature would vary depending on the discharge rate of the thermal water.

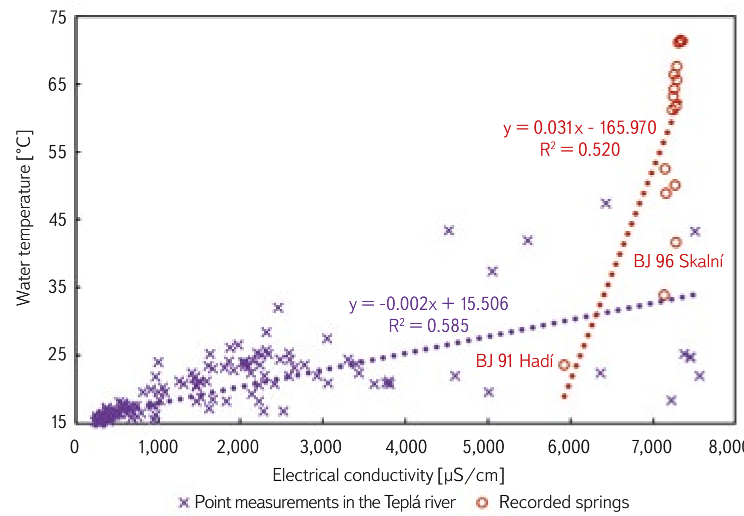

Fig. 8. Relationship between point measurements of water temperature at the bottom of the Teplá riverbed and recorded springs on conductivity

DISCUSSION

The methodology for the thermometric survey must reflect the required nature of the survey results. The data collection typology in Mariánské Lázně was adapted to the considerable spatial extent of the area, whereas in Karlovy Vary it was adjusted to the high temperature gradient between surface and thermal waters. Both methodologies proved to be highly effective and each led to the successful identification of mineral water springs.

The results of the survey have practical implications at both sites. In Mariánské Lázně, they are particularly relevant for the Nature Conservation Agency of the Slavkovský les PLA, which seeks to adopt an objective approach to protecting even the less significant mineral water discharge structures. In Karlovy Vary, the findings are important for the administrators of natural medicinal resources (Administration of Natural Medicinal Resources and Colonnades), who are implementing the results in a sealing works project near the Vřídelní Colonnade. The high total discharge of the wild springs into the Teplá river may be linked to the recent reconstruction of part of the Vřídelní Colonnade between 2019 and 2023, which, due to pressure changes, reactivated the wild springs.

Although thermometric measurements, whether using a TIR camera or a temperature probe, proved to be a highly effective tool for locating water discharges and measuring the CO_2 content of mineral water springs, it should be noted that it was not possible to perform Härtl tube measurements on all the identified thermal anomalies in Mariánské Lázně due to the impossibility of isolating surrounding watercourses. Therefore, the total number of new mineral water springs within the set of 131 thermal anomalies may be higher, which is why all thermal anomalies are included in the study results. The discrepancy between the number of detected thermal anomalies and the number of confirmed mineral springs is primarily due to the fact that discharges of ordinary water are far more frequent, even under the conditions in Mariánské Lázně. Even though mineral water discharges are generally warmer during frosty conditions, the methodology was followed consistently: all anomalies exceeding the background temperature by approximately 3 °C were marked. Discharges that were not detected may have been diluted by surface water, which complicates their identification. In Karlovy Vary, a limiting factor was the measurement grid with intervals of 1 to 5 m, which undoubtedly led to some discharges not being identified because they fell between measurement points. Continuous temperature measurement was not a viable solution, as the sensor's response time was insufficiently fast. At the same time, despite efforts to minimise other interfering factors, it should be emphasised that in Mariánské Lázně it was not possible to maintain completely consistent meteorological conditions, such as daily temperature cycles, thaws, etc., throughout the entire duration of the thermometric survey.

Comparison of the new measurement results with data from the 1980s, both in Mariánské Lázně and Karlovy Vary, shows that modern technologies can significantly increase the success of surveys. While the authors of the study conducted between 1984 and 1988 in the wider Mariánské Lázně area reached rather inconclusive results, springs were successfully located in the survey carried out in 2023–2024. The earlier thermometric survey was conducted without the use of a TIR camera, which would have sped up, improved the accuracy of, and reduced the cost of data collection. The 1980 survey in Karlovy Vary was more of a reconnaissance in nature, so the authors' conclusions were purely qualitative, for example, leaks of thermal water were found along the casing perimeters of the wells in the riverbed.

Quantification of discharge could not be achieved from either the thermometric data or the supplementary conductometric data. It should be noted that in Mariánské Lázně the mineral water springs exhibit highly variable conductivity but nearly uniform temperature, whereas in Karlovy Vary the springs have almost identical conductivity but differing temperatures. Furthermore, while in Karlovy Vary only the temperature of the mineral water increases with depth of abstraction, in Mariánské Lázně it is primarily the conductivity that increases, as confirmed, for example, in the Ferdinand spring structure [16]. The fact that the springs in Mariánské Lázně have similar temperatures could facilitate the quantification of discharge; however, this would require ideal conditions, as mentioned in the introduction. Subsequently, in the case of parallel conductivity measurements, it would even be possible to calculate the conductivity of a spring using a mixing equation. Within the study, the relationship between conductivity and temperature was tested, but the results are inconclusive. Correlating conservative conductivity with non-conservative temperature presents considerable challenges, even though, in the context of this study, the two parameters are not independent, as evidenced by the data from the recorded springs (*Fig. 6*). In Karlovy Vary, the unknown temperature of the spring as it emerges into the channel is additionally problematic. This is caused by the varying rate of thermal water discharge to the surface, partly by the distance from the centre of the discharge zone, and consequently the depth of capture. For this reason, in the case of recorded smaller springs (e.g., Skalní, Mlýnský, Sadový), the temperature of the springs has previously increased, as a preferential pathway was created, shortening the residence time within the rock matrix [17].

CONCLUSION

The research focused on the use of thermometry as an effective tool for locating mineral water discharges. However, this method cannot be regarded as self-sufficient for the identification of mineral springs and should be complemented, for example, by measurements of free CO_2 or electrical conductivity. Thermometry was applied at two contrasting sites: Mariánské Lázně, characterised by cold springs, and Karlovy Vary, with thermal springs. In Mariánské Lázně, the use of a TIR camera enabled the identification of 14 new, low-yield mineral water discharges. It can be concluded that thermometry alone is not sufficient to unambiguously determine the presence of emerging non-thermal, gas-rich springs (< 20 °C). On the other hand, when combined with measurements using a Härtl tube, a conductometer, and a pH meter, it represents the most effective and also the least costly method for locating even low-yield discharges of gas-rich mineral waters. It should be noted that thermometry is naturally applicable also to the detection of non-mineral groundwater outflows. The results will be submitted to the administration of the Slavkovský les PLA for the purposes of registration and improved protection of mineral waters in the area.

For the survey in the channel of the Teplá in Karlovy Vary, a point-based measurement method using a conductometer with an integrated temperature sensor arranged in a regular grid was selected. The thermometric analysis demonstrated the presence of 14 wild discharges of thermal water in the channel of the Teplá over an area of 1,300 m^2, reaching temperatures of up to 71.3 °C and conductivities of up to 7,470 µS/cm. The total yield of the wild discharges in the area of interest was estimated at approximately 2–3 l/s. The thermometric results constitute a key basis for the planned remediation works in the Teplá riverbed. Repeating the measurements after the remediation has been carried out can be considered desirable in order to verify its effectiveness.

Thermometry is suitable for rapid mapping of interaction zones between groundwater and surface water, particularly due to its non-invasive nature. The effectiveness of the method depends on optimal timing of the measurements (diurnal and seasonal periodicity) and on the magnitude of the temperature difference (ΔT) between groundwater and surface water. Quantitative interpretation of thermal anomalies in terms of discharge is complicated, as temperature is a non-conservative tracer. Quantification therefore requires calibration for the specific site and conditions. The research confirmed that, despite the general limitations regarding quantification, thermometry is well suited for the qualitative assessment of concealed springs. Application in the field of mineral waters, as demonstrated by both parts of the study, is highly effective, but requires careful consideration of local conditions when selecting the appropriate methodology. In the future, further increases can be expected in the sensitivity and refresh rate of TIR sensors, their affordability, and the availability of additional sensors (including hyperspectral sensors). Simultaneously, improvements are anticipated in atmospheric correction algorithms, emissivity measurements, and the use of artificial intelligence and machine learning, as well as in the fusion of these data with remote sensing data, particularly from drones. This will lead to simplification of spatio-temporal monitoring and enable broader application in hydrology and hydrogeology.

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Interview with Assoc. Prof. Ing. David Stránský, Ph.D., Head of the Department of Municipal Water Management, Faculty of Civil Engineering, CTU in Prague

Six years ago, Assoc. Prof. David Stránský spoke in the *Priorita* journal about the fact that by linking rainwater with urban greenery, a city can obtain a form of cheap air conditioning. Since then, the topic of water management in cities has advanced not only in terms of legislation and technologies, but also in the approach of the public and local authorities. How does he view developments in this field today, where is research at the Department of Municipal Water Management at CTU heading, and what does he consider to be the key to a sustainable urban environment? These were the questions we addressed in the following interview.

Professor, could you please look back on your early professional beginnings? What led you to the field of water management, and why did you decide to devote yourself to this particular area?

Looking back, I can see that to a large extent it was a matter of family background. My father taught water-related subjects at the secondary technical school in Hradec Králové and later worked for the local water supply and sewerage utility. Water management was also the professional field of my uncle and two cousins.

For a short time I did consider a career in IT, but at CTU I was persuaded by teachers who showed me how diverse and meaningful work with water can be. They also demonstrated that in this field there is (and will be for a long time) a great deal of work to be done if we are to move closer to global standards.

What do you consider to be the greatest advance or achievement in research and teaching at your department?

In teaching, it is certainly the modernisation of the content of all courses. We strive to adapt them to current trends and to what students genuinely need for their future professional careers. We invite a wide range of practitioners to share their experience with students.

However, I consider the change in the approach to teaching to be fundamental. We teach students to perceive water not as an isolated technical discipline, but as an integral part of society, the landscape, and the urban environment. We want them to understand the interconnections and the responsibility that is associated with their decisions.

In research, we have been particularly successful in the areas of rainwater management, water recycling, optimisation of wastewater treatment plants, and the use of heat from wastewater. The outputs include methodologies, software, and patents – in short, results that are closely linked to practical application. This has been our long-term objective.

When you look back, how has student interest in water management topics developed over time? Do you observe a growing interest in sustainable solutions or in so-called blue–green infrastructure?

Overall, there are fewer students today; roughly one fifth of the number that used to be typical around the turn of the millennium now enrol in our field. However, I see a much stronger interest among those who do choose to study water management. They are often more motivated, ask more questions, and remain in the profession after graduation.

Interest in sustainability, including issues related to blue–green infrastructure, is growing strongly among students. Approximately one third of qualification theses at the department now focus on this topic. I am also very pleased that we teach blue–green infrastructure at the Faculty of Architecture of CTU as well, because cooperation between water management professionals and landscape architects is absolutely essential for achieving good results.

Which projects or initiatives have been the most professionally fulfilling for you in recent years?

Over the long term, I have found fulfilment in working on a wide range of documents related to rainwater management and blue–green infrastructure – from the initial amendments to legislation, through standards and methodologies, to today's support for municipalities in setting their own standards and decision-making processes. All of this has been a fulfilling and at times even adventurous journey.

And then there are projects where it has been possible to combine my profession with a personal interest in history, such as a blue–green infrastructure study for the national cultural monument of Vyšehrad, filming videos about water at Strahov Monastery, and work for the Dejvice campus. I found these projects particularly enjoyable.

In 2019, in an interview for the *Priorita* journal, you spoke about "cheap air conditioning" for cities, meaning the use of rainwater and greenery to cool the urban environment. How has this topic developed since then?

In the field of urban planning, six years is a relatively short period of time. However, when I look at developments over a horizon of two decades, the direction of change is clear.

At the turn of the millennium, rainwater management began as a purely water management issue, which gradually started to become linked with greenery, the landscape, and adaptation measures. Today, this integration is already a standard part of both the debate and practical design.

What has been crucial is a change in the way of thinking. In the past, we had to spend a great deal of time explaining why it makes sense to retain and use water within a given area. Today, municipalities tend to ask instead how to do it in the best possible way. That represents an enormous shift.

And, in retrospect, it was perhaps around 2019 that we moved from a phase in which we were "pushing the cart uphill" to a phase in which it is already moving on its own. Our task now is mainly to ensure that it does not veer off course.

What is your view on the current situation in rainwater management in Czech towns? Have you observed any specific changes recently in the way municipalities think about this issue?

Very positive. Municipalities understand far more than in the past that working with rainwater is not merely an economic consideration, but a matter of future quality of life.

Larger towns and cities are already developing their own rainwater management standards and are seeking to better coordinate decision-making processes across departments and municipal organisations. Smaller municipalities, in turn, are more frequently requesting consultations and actively looking for solutions that are realistic for their specific conditions. This is a development I would not have expected ten years ago.

What do you think is holding back the wider implementation of blue–green measures in practice – legislation, finance, or rather a lack of courage?

It is certainly a combination of several factors.

A major legislative issue is the exemption from charges for rainwater discharged into sewer systems for public use. This applies to most producers and reduces the economic incentive to implement blue–green infrastructure.

There is also a widespread assumption that blue–green solutions are often more expensive than conventional ones, particularly if only the direct construction costs are considered. However, we should learn to take into account the associated benefits as well: reduced damage during extreme events, improved microclimate, and better public health. If the issue is viewed in a comprehensive manner, the economic balance may look entirely different.

At times, there is also a lack of willingness to step outside established procedures. It is easier to look for reasons why something cannot be done than to seek ways in which it could be achieved. Here too, however, the situation is gradually improving, thanks to interdisciplinary cooperation, which is becoming increasingly common.

In recent years, there has been a great deal of discussion about the climate resilience of cities. What role do you think water – and water management professionals – can play in this context?

A fundamental one. During periods of drought, the key issue is ensuring a sufficient supply of good-quality water; during periods of extreme rainfall, it is flood prevention, and the protection of water quality is also essential. Equally important is the microclimatic function – linking rainwater runoff with greenery can reduce temperatures in streets and make the urban environment more pleasant.

It is a highly complex matter, because all of these functions must be ensured for a city simultaneously, while we also know that building a climate-resilient city cannot be achieved all at once, but only through gradual steps linked to the natural renewal of urban areas. It is a long-distance endeavour, extending over many years or even decades, and all the more reason to start immediately, even with small but well-considered steps. There will therefore be more than enough work for water management professionals.

How do you view cooperation between academia and practice – are you successful in transferring research outputs into real-world projects?

To some extent, yes. Above all, this is achieved through methodologies, standards, and various calculation tools that help to establish effective approaches to design, construction, and operation. The problem is that these tools are sometimes perceived more as obstacles to established practices, and the introduction of new approaches requires a great deal of explanation and awareness-raising. Unfortunately, our capacity for this is limited, although we are greatly supported by the Czech Water Association and other professional organisations.

At the same time, we seek to implement these innovations in real construction projects, but this tends to happen mainly at the request of clients or designers.

And if we look at it the other way round – do practical issues inspire you in shaping teaching and research?

I see it as a never-ending cycle: research generates new knowledge, this is applied in real projects, feedback then comes back from practice, and this in turn influences further research and teaching. I do not think we could ever say that we have reached the goal. It is precisely the fact that our field evolves alongside the needs of society that makes it so rewarding.

How do you relax after demanding days spent dealing with such complex topics?

I walk to and from work every day. It is a simple way to organise my thoughts and both start and close the working day. And it is often while walking that the best ideas come.

At weekends, I try to escape outdoors, clear my head, and do a little quiet reflection. Silence and movement in the countryside are the most effective form of rest for me.

Do you have a personal motto or principle that guides you both in your work and in life?

I have four of them, and they come from the book *The Four Agreements* by Miguel Ángel Ruiz: be impeccable with your word, do not take anything personally, do not make assumptions, and always do your best. They are not easy to follow, but when one succeeds, one goes to sleep in the evening with a clear conscience – and that is an important life principle for me.

In a sewer beneath Kampa during the filming of educational videos, 2024

If you were to advise students or young professionals who wish to pursue a career in water management, what would you tell them?

They may earn more money elsewhere, but in water they will find a field that becomes part of their life. Water is a fascinating world and, at the same time, the foundation of our survival. When you look at it more closely, work turns into a hobby and, over time, perhaps even into a calling. And I would add a thought by Paulo Coelho: "an entire city can move, but a well cannot".

What would you like to see changed in the relationship between Czech society and water and the landscape?

That we realise that the environment is not an abstract concept, but the space in which we live – not only we as humans, but all other living beings as well. We cannot do without it. This does not mean that we cannot make use of it, but we should do so with respect and with an awareness of the reversibility, or irreversibility, of our actions.

Finally, allow me a personal question. What is your dream or goal that you would like to fulfil professionally?

I see my professional path as a long-term process. I do not try to set myself grand goals; rather, I focus on doing what needs to be done each day. And I hope that our generation will leave behind something that others can build upon, rather than something they will have to fix.

However, I did in fact fulfil one long-held dream. When I first attended the largest conference in our field in Sydney in 1999, I thought how wonderful it would be if one day it could be held in Prague. And in 2017 we managed to achieve this, together with Ivana Kabelková and Vojta Bareš. When I recall the 700 participants and the excellent atmosphere, pleasant memories still come back to me to this day.

Today, this is being followed up by the biennial CzWA conference in Litomyšl, and that may well be the true goal for the future: to create a space where the professional community can meet, engage in open discussion, and continue to develop our field.

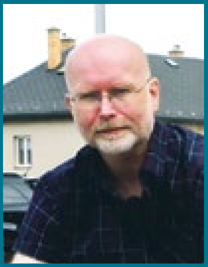
Professor, thank you for the interview and for providing the photographs.

Ing. Josef Nistler

The interview was conducted in the fall of 2025 as part of the preparation of the February issue of VTEI. Our aim was to follow up on the earlier discussion from 2019 and to map how the topic of water management in cities has evolved over time – in professional, academic, and human terms (editor's note).

Lost in the Danube Delta towards the end of the voyage from Komárno to the Black Sea, 2018

doc. Ing. David Stránský, Ph.D.



Assoc. Prof. Ing. David Stránský, Ph.D., was born in 1972 in Hradec Králové. He graduated from the Faculty of Civil Engineering at CTU, specialising in Water Structures and Water Management, with a focus on municipal water management. From 1998, he worked at the Laboratory of Ecological Risks of Urban Drainage, where his activities focused on the reliability of sewer networks, modelling rainfall–runoff processes in urbanised areas, and the impacts of urban drainage on the environment. Since 2005, he has been working at the Department of Municipal Water Management at the Faculty of Civil Engineering, CTU (formerly the Department of Sanitary and Environmental Engineering), specialising primarily in rainwater management and blue–green infrastructure. He has headed the department since 2016. He has been involved in the implementation of numerous grant projects funded by the Technology Agency of the Czech Republic, the Czech Science Foundation, the Ministry of Education, Youth and Sports, and the European Union. He collaborates with state administration and local authorities and publishes in both national and international professional journals. Since 2013, he has served as Chair of the Czech Water Association (CzWA).

Water management in the Czech Republic in the context of climate change – expert findings from the 5th *Water Centre* conference

The Fifth *Water Centre* conference, held on 25 November 2025 at TGM WRI, focused on water management in the Czech Republic under conditions of ongoing climate change. The event, organised with the support of the Ministry of the Environment and the Technology Agency of the Czech Republic, presented current research results in the fields of water resources modelling, landscape water retention, water quality, and adaptation to extreme weather events. The conference followed on from previous years, which have long provided a platform for the presentation of research outcomes in water management and for fostering interdisciplinary dialogue between experts from both the academic and applied spheres. It also confirmed the growing importance of interdisciplinary cooperation in addressing environmental challenges and presented a number of practically applicable insights for water management practice.

Fig. 1. The opening address was delivered by Ing. Tomáš Fojtík, TGM WRI Director

Main thematic areas and expert contributions

The conference programme was divided into two parts, reflecting both current research directions and practical issues related to the impacts of climate change on the aquatic environment. The morning session focused on the prediction of climate change impacts and the use of modern tools for their modelling and monitoring:

P. Vyskoč, J. Dlabal and A. Vizina from the TGM WRI presented the results of Work Package WP1 of the *Water Centre* project, which assesses future water demand in the Czech Republic up to 2050 and its consistency with available water resources. The analysis combines socio-economic scenarios with the impacts of climate change in order to determine water requirements across individual sectors and to identify where water deficits may arise. The outputs are published in several specialised public databases and include abstractions for industry, energy production, agriculture, irrigation, public water supply, and livestock consumption, as well as the identification of areas at risk of water scarcity and projections of water resource security.

T. Laburda and colleagues from the Czech Technical University in Prague presented new experimental research demonstrating that grass buffer strips can significantly reduce surface runoff and soil erosion on agricultural land. Testing on model plots showed that fully grassed strips reduce sediment export by up to 85 % and delay the onset of runoff, thereby increasing landscape water retention capacity. The study thus confirms that even relatively short grassed sections can represent an effective and readily applicable tool for the protection of soil and watercourses.

L. Jačka and his team from the Czech University of Life Sciences Prague have been monitoring soil microclimate over the long term in the pilot area known as the "Amálie Smart Landscape" in the Rakovník region. Data from hundreds of sensors confirm that the type of vegetation cover has a significant impact on both soil temperature and soil moisture. Forest stands keep the soil up to 7 °C cooler on hot days than open agricultural land, while grassed buffer strips with tree avenues are able to mitigate overheating and improve water infiltration in arable fields. The study thus demonstrates that stable vegetation increases landscape resilience to drought and extreme temperatures and may represent a key element of adaptation to climate change.

J. Bernsteinová from CzechGlobe presented the concept of a digital twin of the Dyje River basin as a tool that integrates hydrological, climatic, soil and water-management data into a dynamic, living model of the catchment. This model enables the safe testing of the impacts of climate scenarios as well as various adaptation measures, such as changes in land use, agricultural practices or water-reservoir management. The model shows that an effective response to the expected decline in runoff requires a combination of measures across the entire system. The digital twin therefore provides a modern evidence base for decision-making on the future management of water resources under conditions of climate change.

R. Bachan and M. Hlavňa from TGM WRI demonstrated the use of unmanned aerial vehicles (UAVs) for rapid and accurate monitoring of the impacts of intense rainfall events. The combination of drones and photogrammetry makes it possible to map newly formed erosion gullies in detail, determine the volume of soil loss, and assess the characteristics of the affected slopes. The method is flexible and efficient and provides valuable data for the design of soil-erosion control and flood-protection measures. UAV technologies thus introduce a new standard for documenting extreme rainfall events in the Czech landscape.

The presentations highlighted that issues related to water availability and water quality require a combination of technological, landscape-based and legislative solutions.

The afternoon session was opened by a presentation by H. Nováková and M. Forejtníková (TGM WRI) which focused on the catchments of selected sites designated for surface water accumulation (SWAS). These sites may in the future serve to enhance water resources or to provide protection against drought and flooding. The research shows that current planning instruments primarily protect the area of the future reservoir itself, rather than the quality of the water

Fig. 2. The fifth conference of the *Water Centre* project had more than ninety participants, both in person and online

Fig. 3. Screenshot of the project website

and the condition of its catchment. An analysis of 61 sites identified risks associated with erosion, diffuse sources of pollution, agricultural land use and the presence of hazardous substances. The outcome of the study is a recommendation to introduce targeted protection of the catchments of future reservoirs, particularly where they are intended to serve as sources of drinking water. The lecture session continued with the following contributions:

J. Musil, T. Daněk and a team of authors from TGM WRI presented the results of research showing that harmonizing hydropower with nature conservation is possible, provided that the ecological impacts of hydropower plant operation are more effectively taken into account. A questionnaire survey conducted among representatives of public authorities and hydropower operators revealed differing priorities between the two groups: while public institutions place emphasis on ecosystem protection, energy producers give greater consideration to economic and operational aspects. At the same time, respondents identified scope for cooperation and the search for compromises. The project therefore aims to develop a methodology for so-called environmental bonuses, which would incentivize power plant operators to implement measures reducing ecological pressure, such as improving fish migration conditions or limiting sediment transport.

T. Mičaník and a team of authors (TGM WRI) mapped the occurrence of selected emerging pollutants in industrial wastewater in the Czech Republic. The analyses confirmed the presence of substances that are not yet subject to standard regulation – particularly per- and polyfluoroalkyl substances (PFAS), flame retardants and bisphenols – across the chemical, paper and other industrial sectors. In some facilities, measured concentrations exceeded several hundred ng/L. However, in the case of PFAS, only a very small number of facilities exceeded the reporting threshold of 50 g of substances per year.

H. Zvěřinová Mlejnková, Š. Šabacká and K. Sovová (TGM WRI) presented the results of systematic monitoring of antibiotic resistance in surface waters in the Czech Republic. The research combines culture-based methods with molecular DNA analysis and shows that resistant bacteria and resistance genes occur in all types of monitored waters, most frequently in the inflows to and outflows from wastewater treatment plants. Multidrug-resistant microorganisms and clinically significant types of resistance were also detected. The study confirms that the aquatic environment can play an important role in the spread of antimicrobial resistance and highlights the need for long-term monitoring and preventive measures at the level of healthcare, industry and municipal infrastructure.

P. Kožený (TGM WRI) and a team of authors summarised the results of research confirming that nature-based modifications of small watercourses improve their ecological status. An analysis of 36 reaches across 13 streams showed that renatured and natural channels support a higher diversity and abundance of aquatic invertebrates than technically modified watercourses. Nevertheless, these differences are not always reflected in the resulting assessment indices, as biological communities respond in complex ways and are influenced by multiple factors beyond the morphology of the watercourse alone. The study therefore emphasises that renaturation measures are important not only for biodiversity but also for the hydrological and landscape-forming functions of watercourses and should be systematically supported within climate change adaptation strategies.

Summary of Results and Conference Contributions

The discussions that followed the individual presentations confirmed that climate change is having a profound impact on the availability and quality of water resources in the Czech Republic. The results presented highlighted the need for an integrated approach that combines modelling, field research and practical water management. The conference also produced specific recommendations aimed at improving data support for decision-making processes, advancing landscape-based adaptation measures, and strengthening cooperation between research institutions and public authorities.

The fifth *Water Centre* conference once again confirmed the importance of long-term collaboration between research institutions, universities and public authorities. The *Water Centre*, funded through the Technology Agency of the Czech Republic, continues to serve as a key platform for sharing scientific knowledge and advancing innovation in sustainable water management. At the conclusion of the conference, it was emphasised that adaptation to climate change must be based on a combination of scientific analysis, modern technologies and responsible landscape management – principles on which the *Water Centre* has built its long-term activities.

The conference results, including the individual presentations, can be found at: https://www.centrum-voda.cz/aktuality/vodni-hospodarstvi-v-cr-v-podminkach-zmeny-klimatu-poznatky-z-5-konference-centra-voda

Ing. Josef Nistler

An informative article that is not subject to peer review.

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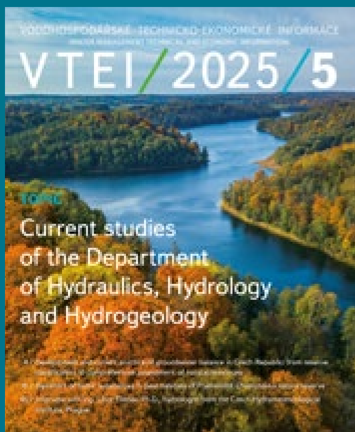
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A THOUSAND SUNS

Nature macro photography is, in its own way, a world within a world. Each morning, nature's imagination creates thousands of perfect details of colour and form. At high magnification, a realm is revealed where the laws of physics seem to fade, colours appear pure, and the surrounding world feels far away.

I captured my first image somewhat by chance on New Year's Eve 1997 in the Low Tatras, below Kráľova hoľa. After three days of gale-force winds, the sun suddenly broke through: –15 °C, windswept frozen plains, and some 300 metres below the summit an extraordinary play of light appeared in the ice crystals. Using an old Nikon F90x with slide film, I tried to capture this interplay of sun and ice – until my fingers were almost frozen and the batteries ran out. Thus my first macro photograph, *A Thousand Suns*, was created, and a new photographic horizon suddenly opened up before me. I fell into the world of miniature wonders like Alice through the looking-glass.

Since then, for more than 25 years, I have been seeking macro images of water in all its states on dewy or frozen mornings, whether as dew, raindrops, ice crystals, or frost. Although photographic, digital, and printing technologies have advanced significantly and the number of photographers of all genres has grown considerably, for me, macro photography has remained the same union of three simple elements: nature's playfulness, my way of seeing the world through the lens, and a great deal of patience and enthusiasm. And every successful shot always reminds me of how perfect nature is, and that we as humans should approach it with greater respect – many things are, after all, trivial when compared with such beauty.

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

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